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Editorial Board Office:
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fax (48-22) 826 98 15, phone (48-22) 826 12 81 ext. 206
e-mail: akustyka@ippt.pan.pl http://acoustics.ippt.pan.pl

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Preface

Noise in the working and living environment

Noise is one of the most common physical risks in the workplace. Long-term exposure to its high levels can pose a significant threat to workers' health, including hearing loss. According to the report State of the Environment in Poland 2011. Signals, trends in environmental noise indicate an increased risk of traffic noise as well as reduced growth or downwards trends in industrial noise. Noise seems to be the environmental factor that is the greatest nuisance. This issue of Archives of Acoustics is dedicated to the problems of noise; it brings full texts of selected papers presented at the XVI International Conference Noise Control 2013.

Noise Control is the most important international acoustics conference organized on a regular basis in Poland. The XVI International Conference Noise Control 2013 is taking place in Ryn, June 26–29, 2013. It is organized by the Central Institute for Labour Protection – National Research Institute (CIOP-PIB), the Committee on Acoustics of the Polish Academy of Sciences with the cooperation of the Department of Mechanics and Vibroacoustics of the AGH University of Science and Technology.

Patrons of the Conference:

- Minister of Labour and Social Policy,
- Chief Labour Inspector,
- Chief Inspector of Environmental Protection,
- President of the City of Olsztyn.

Plenary and special interest sessions focus on the results of activities in fundamental sciences, education, occupational safety and health management, and specific technical solutions involved in noise control. Outstanding foreign and Polish researchers are presenting their papers. Their abstracts can be found in this issue of the Archives of Acoustics, which all participants of the Conference have received.

I hope that readers will find these materials interesting, and that the problems of noise control will thus become more accessible.

An exhibition is taking place at the same time as the Conference; companies have an opportunity to present their latest achievements in measurement equipment and technical solutions for noise control.

The Organization Committee expresses it heartfelt thanks to members of the Scientific Committee of the Conference and referees for their effort and great involvement. Sincere thanks also go to Conference participants for accepting our invitation.

Wiktor M. Zawieska

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Research Papers

Global Index of the Acoustic Quality of Classrooms

Jan RADOSZ

Central Institute for Labour Protection – National Research Institute
Czerniakowska 16, 00-701 Warsaw, Poland; e-mail: jarad@ciop.pl

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Acoustic quality of a classroom is a term proposed to describe acoustic properties that contribute to a subjective impression received by a human, such as speech intelligibility, external noise, or vocal effort. It is especially important in classrooms, where suitable conditions should be provided to convey verbal content to students, taking into account their age. The article presents a method for assessing the acoustic quality of classrooms based on a single number global index and taking into account a number of factors affecting the outcome of the assessment. Partial indices are presented and their weights are proposed based on an analysis of factors determining whether a room meets applicable acoustic requirements. Results of the assessment of the acoustic quality carried out with the use of the developed method in selected classrooms are also presented.

Keywords: acoustic quality index, classrooms, schools, room acoustics.

1. Introduction

The author defines acoustic quality of classrooms as a term used to describe acoustic properties that contribute to a subjective impression received by a human, including speech intelligibility, external noise, or vocal effort. Acoustic quality of classrooms indicates whether a room satisfies applicable requirements, such as ensuring the following:

- adequate speech intelligibility,
- low level of background noise,
- no need to speak in a raised voice,
- teaching and learning comfort.

Acoustic quality is particularly important for primary school rooms, where students, because of their age, should be provided with the best possible conditions for the transmission of verbal content (Sato, Bradley, 2008). Moreover, children with health problems such as hearing loss, patterns deficits, ADHD, APD, etc. need good acoustic conditions not only in terms of acquisition of knowledge, but also in terms of equalizing educational opportunities and create environment conducive to the development (Crandell, Smaldino, 2000).

Acoustic quality of rooms is affected by many factors (Mikulski, Radosz, 2010). Bad acoustic quality, which can be described for example by excessive reverberation time, deteriorates verbal communication, causes higher noise levels in rooms used for teaching and learning (Fig. 1) and, what is important for safety reasons, interferes with the reception of messages broadcast through modern warning signals (Sato, Bradley, 2008; Radosz, 2012). One option for reducing noise in classrooms and improving conditions for educational activities is to improve the acoustic quality of rooms used for teaching and learning. In order to achieve this, it is necessary to develop an unambiguous method of acoustic quality assessment of such rooms. This assessment should cover a number of important factors: room acoustic parameters, internal and external noise as well as intelligibility and clarity of speech.

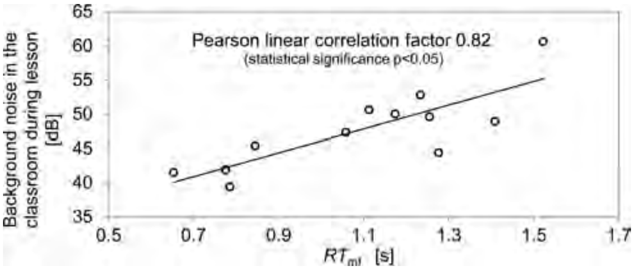


Fig. 1. Relationship between reverberation time RT_{mf} and the level of background noise during lessons (Mikulski, Radosz, 2012), where RT_{mf} is the arithmetic mean of the reverberation time from 500 Hz, 1 000 Hz and 2 000 Hz octave bands.

Room acoustics, particularly with respect to rooms used for teaching and learning, is a popular issue, which is often discussed in the literature (Rudno-Rudzińska, Czajkowska, 2010; Kotus *et al.*, 2010). Every year there are new publications in this field. In the EU, there are guidelines, criteria, and requirements to be met by such rooms, e.g. Building Bulletin 93 guidelines (United Kingdom), DIN 18041:2004-05 standard (Germany), SFS 5907:2004 standard (Finland), and ÖNORM B 8115-3 standard (Austria). However, they do not include all the relevant acoustic parameters, and most of them only provide the required insulation values of partitions, the background noise level (in empty rooms), and reverberation time.

One of the possibilities for a comprehensive assessment of classrooms, which takes into account a number of important factors affecting acoustic quality, is the index method. It involves determination of a single number-valued global index based on partial indices (Fig. 2). It has a number of applications on all aspects of vibroacoustics (Piechowicz, 2004; Pleban 1999; 2010; 2011). Index method was used in assessing the acoustic quality of church buildings and is still being developed (Engel *et al.*, 2007; Kosała, 2011; 2012) in this regard. The index method used to evaluate church buildings is also applied outside Poland (Carvalho, Silva, 2010). The index method proposed in this paper for assessing the acoustic quality of classrooms is based on similar assumptions as the method proposed by Engel (2007), but because of a different intended use, it is based on other partial indices and their weights.

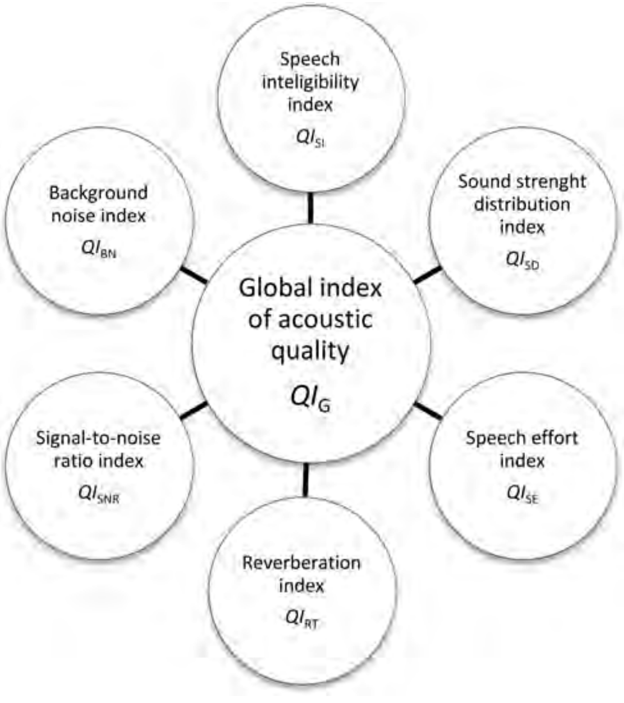


Fig. 2. The global index of classroom acoustic quality.

2. Assumptions for the index method of classroom acoustic quality assessment

Assumptions for the proposed classroom acoustic quality assessment method are based on the following:

- commonly used measurement methods (ISO 3382-1:2009, EN 60268-16:2011),
- results of measurements of acoustic properties of more than 100 classrooms (Mikulski, Radosz, 2011),
- analysis of factors affecting the intelligibility of content, low level of background noise, teacher's speech effort, and the comfort of teaching and learning (Sato *et al.*, 2008; Radosz, 2012; Mikulski, 2012),
- experimental tests in selected classrooms.

To complete a global classroom assessment with the use of the index method, it is necessary to carry out the following measurements:

- room impulse response (reverberation time RT, speech transmission index STI, clarity C_{50}, relative sound strength G_{rel}) in empty but furnished classrooms,
- sound level identifying teacher's speech effort during classes,
- signal-to-noise ratio (SNR) for the duration of classes,
- background noise level in empty but furnished classrooms.

Based on the measured acoustic parameters, values of the individual partial indices are determined and then, after taking into account their respective weights, the global index QI_G is determined according to the following formula:

$$QI_G = \frac{\sum\limits_{i=1}^{n} QI_i \eta_i}{\sum\limits_{i=1}^{n} \eta_i}, \tag{1}$$

where QI_i is the i-th partial index, η_i is the weight of the i-th partial index, and n is the total number of partial indices.

To determine the global acoustic quality index of classrooms, 6 partial indices are proposed, which are presented in Fig. 2.

For the proposed partial indices, the global index of classroom acoustic quality is expressed by the following formula:

$$QI_G = \Big(QI_{RT}\eta_{RT} + QI_{SI}\eta_{SI} + QI_{SE}\eta_{SE} + QI_{SD}\eta_{SD} + QI_{BN}\eta_{BN} + QI_{SNR}\eta_{SNR}\Big) \Big/ \Big(\eta_{RT} + \eta_{SI} + \eta_{SE} + \eta_{SD} + \eta_{BN} + \eta_{SNR}\Big), \tag{2}$$

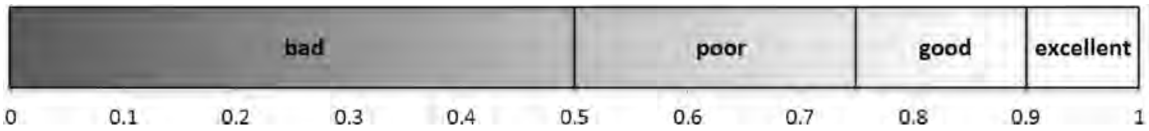


Fig. 3. Assessment scale of the global index of classroom acoustic quality.

where QI_{RT} is the reverberation index, QI_{SI} is the speech intelligibility index, QI_{SE} is the speech effort index, QI_{SD} is the sound strength distribution index, QI_{BN} is the background noise index, QI_{SNR} is the signal-to-noise ratio index, η_{RT} is the reverberation index weight, η_{SI} is the speech intelligibility index weight, η_{SE} is the speech effort index weight, η_{SD} is the sound strength distribution index weight, η_{BN} is the background noise index weight, and η_{SNR} is the signal-to-noise ratio weight.

The global index has a value of 0 to 1. The better the acoustic quality of a classroom, the higher the value of the global index. This assumption results from the analogy to other applications of the index method (Engel *et al.*, 2007) and objective evaluation methods of acoustic parameters (EN ISO 9921:2003). In order to facilitate the assessment of the acoustic quality of a classroom, assessment intervals were adopted to classify unambiguously the tested room depending on the value of the global index (Fig. 3). The classification is the result of the analysis of acoustic parameters of tested classrooms and recommendations and standards for this type of rooms.

A vast majority of classrooms (about 95%) in Polish schools have volumes between 155 m^3 and 200 m^3 (Mikulski, Radosz, 2011). Therefore, it was assumed that the proposed assessment method applies only to rooms within the above volume range, with the exception of special-purpose rooms, such as music rooms or speech therapy rooms. However, the author does not preclude future expansion of the scope of the proposed assessment method.

Weights of partial indices are shown in Table 1. Weight values do not the result from close relationships. They have been adopted on the basis of analysis of the factors affecting the acoustic quality of classrooms and based on the results of experimental tests conducted in selected rooms. Justification of the adopted weights is provided in the discussion of individual partial indices.

Table 1. Weights of partial indices.

η_{RT} – the reverberation index weight	0.8
η_{SI} – the speech intelligibility index weight	1
η_{SE} – the speech effort index weight	0.3
η_{SD} – the sound strength distribution index weight	0.5
η_{BN} – the background noise index weight	1
η_{SNR} – the signal-to-noise ratio weight	0.5

3. Methods for determining partial indices

3.1. Reverberation index

Reverberation time, because of a strong correlation of the reverberation time and auditory impressions, is one of the most important criteria for assessing acoustic quality of a room. This parameter is usually determined in octave frequency bands. Studies (Sato *et al.*, 2008) show that the difficulty in understanding speech is affected by the reverberation effect in the frequency range of 1–4 kHz. These studies also show a strong correlation between reverberation time in the octave band with a centre frequency of 2 kHz and subjective speech intelligibility tests. This is also confirmed by research carried out by CIOP-PIB (Mikulski, 2012). Therefore, to determine the reverberation index, reverberation time in the octave band with a centre frequency of 2 kHz was adopted. A reverberation index curve (Fig. 4) was determined empirically, based on the results of research carried out in Poland and other countries (Sato, Bradley, 2008; Leśna, Skrodzka, 2010; Mikulski, Radosz, 2011; Mikulski, 2012) and the criteria and requirements for this type of rooms (Building Bulletin B93, ANSI S.12.60, SFS 5907:EN). To plot the curve, students' acoustic absorption was taken into account and its value was adopted as 0.41 m^2 per person for a frequency of 2 kHz (Sato, Bradley, 2008). The reverberation index takes the value 1 for the reverberation time $RT_{2\,\mathrm{kHz}}$ in the range 0.45–0.55 s. It is the optimal value of the reverberation time for classrooms with a capacity of less than 200 m^3 according to many studies in this field (Bradley, 1986; Sato, Bradley, 2008; Sato *et al.*, 2008; Leśna, Skrodzka, 2010). The curve is also corresponding to the criteria and requirements of the above mentioned standards. The reverberation index value QI_{RT} can be determined from the curve presented below or by using the formula:

$$\begin{aligned} QI_{RT} = {} & -0.48\{RT_{2\,\mathrm{kHz}}\}^4 + 2.55\{RT_{2\,\mathrm{kHz}}\}^3 \\ & - 4.77\{RT_{2\,\mathrm{kHz}}\}^2 + 3.13\{RT_{2\,\mathrm{kHz}}\} + 0.34, \end{aligned} \tag{3}$$

where $\{RT_{2\,\mathrm{kHz}}\}$ is the numerical value of the reverberation time in the octave band with a centre frequency of 2 kHz, in seconds.

Based on the analysis of the results of studies by Sato and Bradley (2008) and the results of own experimental research, the value of the weight of the reverberation index $\eta_{RT} = 0.8$ was adopted.

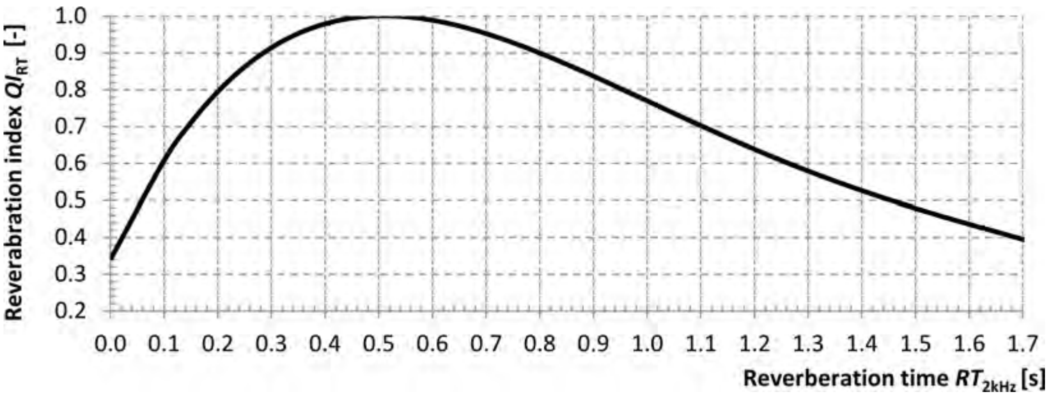


Fig. 4. Relationship between the reverberation time $RT_{2\,\mathrm{kHz}}$ and the reverberation index QI_{RT}.

The reverberation index provides also a basis for the approximate evaluation of acoustic quality with use of the singular value decomposition (SVD) method (Kosała, 2012).

3.2. The speech intelligibility index

Speech intelligibility is very important in the process of teaching and learning. For an objective assessment of speech intelligibility, the speech transmission index STI is used, which is highly correlated with subjectively perceived speech intelligibility. The values of the indicator are adopted in the range between 0 and 1, where 1 indicates perfect intelligibility (EN ISO 9921).

For objective assessment of speech intelligibility in classrooms, clarity C_{50} can also be used which is the ratio of the signal energy received by listener during the first 50 ms to its total energy (a value of 50 ms is related to the time constant of the ear). Clarity C_{50} is an important measure of classroom acoustics because it determines the perception of sounds occurring in quick succession. As in the case of the reverberation time, it is provided in octave frequency bands. Due to a strong correlation with the subjective speech intelligibility (Bradley, 1986), to determine the speech intelligibility index the octave band with centre frequency of 1 kHz was adopted. To determine the value of the speech intelligibility index QI_{SI}, it is necessary to determine the value of an auxiliary index, conventionally adopted as the clarity index CI. It is determined on the basis of clarity $C_{50(1\,\mathrm{kHz})}$, assuming that above $C_{50(1\,\mathrm{kHz})} = 4$ dB, the value the auxiliary clarity index CI will be 1. The auxiliary clarity index curve (Fig. 5) is based on the research by Bradley and Bistafa (2002). The auxiliary clarity index CI can be determined from the curve presented below or by using the formula

$$CI = -0.00616\{C_{50(1\,\mathrm{kHz})}\}^2 + 0.0615\{C_{50(1\,\mathrm{kHz})}\} + 0.85, \tag{4}$$

where $\{C_{50(1\,\mathrm{kHz})}\}$ is the numerical value of the clarity in the octave band with a centre frequency of 1 kHz.

Fig. 5. Relationship between the clarity $C_{50(1\,\mathrm{kHz})}$ and the auxiliary clarity index CI.

On the basis of the research by Bradley (1986) and the results of our own research (Mikulski, Radosz, 2010) it was assumed that speech intelligibility will depend on the speech transmission index and the clarity, therefore it was assumed that it will be determined with the use of the formula:

$$QI_{SI} = 0.55STI + 0.44CI, \tag{5}$$

where STI is the speech transmission index and CI is the auxiliary clarity index.

Due to the intended purpose of classrooms, speech intelligibility is very important, therefore, it was assumed that the weight of the speech intelligibility index η_{SI} will be equal to 1.

3.3. The speech effort index

According to studies conducted by various research centres (Koszarny, 1992; Bronder, 2003; Augustyńska *et al.*, 2010) teachers, especially primary school teachers, complain about a need to speak in a raised voice during lessons. This leads not only to an increased speech effort, but also to a fast growth of fatigue. A significant percentage of teachers who find it necessary to speak in a raised voice during lessons, negatively assesses the conditions of their work and physical well-being.

The sound pressure level of the speech is one of objective parameters determining the speech effort. According to EN ISO 9921:2003, normal speech effort is equivalent to A-weighted sound pressure level of 60 dB at 1 metre from the mouth of the speaker (Table 2). The above-mentioned standard does not specify the methodology for measurement in real conditions such as conducting classes. However, for the purpose of the proposed index method, a noise dosimeter was used with appropriate correction due to distance from the mouth. The speech effort was deduced from time history of A-weighted sound pressure levels during several classes.

Table 2. Speech effort of a male speaker and associated A-weighted sound pressure level at a distance of 1 m from the mouth (EN ISO 9921:2003).

Speech effort	A-weighted sound pressure level (in dB)
Very loud speech	78
Loud speech	72
Raised voice	66
Normal speech	60

Based on the above data, a curve (Fig. 6) was plotted to determine the speech effort index QI_{SE} based on the teacher's A sound level at a distance of 1 m. Assuming that for the level of the teacher's voice $L_{Aeq,1\,\mathrm{m}} = 60$ dB and below, the value of $QI_{SE} = 1$ for the speech effort index is adopted, the following formula can also be used:

$$QI_{SE} = -0.041\,\{L_{Aeq,1\,\mathrm{m}}\} + 3.46, \tag{6}$$

where $L_{Aeq,1\,\mathrm{m}}$ is the numerical value of A-weighted sound pressure level of the teacher's voice at a distance of 1 m.

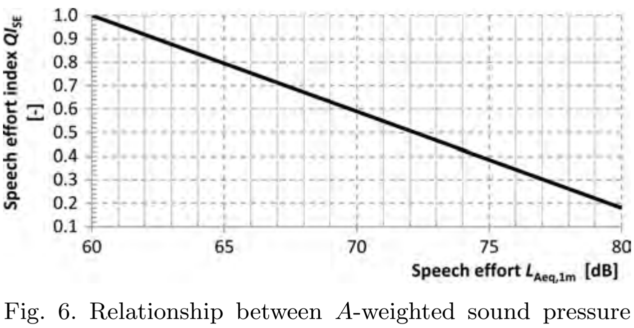


Fig. 6. Relationship between A-weighted sound pressure level of teacher's voice at a distance of 1 m and the speech effort index QI_{SE}.

Excessive speech effort lasting for an extended period of time is a cause of chronic diseases of the voice organ, but it is largely dependent on the teacher, therefore the value of the weight of the speech effort index $\eta_{SE} = 0.3$ was adopted.

3.4. The sound strength distribution index

An important criterion for assessing the classroom is the sound (teacher's voice) level distribution in the room. The more uniform the distribution, the better the classroom acoustic quality. For this purpose, the parameter of relative sound strength was used the due to a possibility of determining it from the room impulse response. It is usually determined in octave frequency bands. In the case of the distribution of sound pressure in the room, the most informative parameter is the difference between extreme values of the relative sound strength ΔG_{rel}.

To determine the values of sound strength distribution index in a given octave frequency band $QI_{SD,f}$, the following relationship was empirically adopted:

$$QI_{SD,f} = -0.08\,\{\Delta G_{\mathrm{rel},f}\} + 1, \tag{7}$$

where $\{\Delta G_{\mathrm{rel},f}\}$ is the numerical value of the difference between extreme values of the relative sound strength ΔG_{rel} for the frequency band f. The above relationship is also shown in Fig. 7.

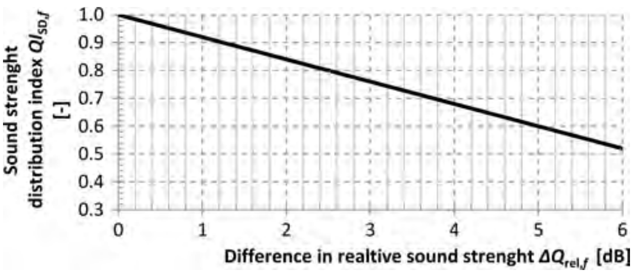


Fig. 7. Relationship between difference in relative sound strength $\Delta G_{\mathrm{rel},f}$ and the value of sound level distribution index $QI_{SD,f}$ for a given frequency.

To determine the values of sound strength distribution QI_{SD}, relevant frequency bands and their weights should be taken into account. It was assumed that frequency bands of 1 kHz, 2 kHz and 4 kHz will be taken into account because of their importance for verbal communication (Sato *et al.*, 2008), and the relationship will be expressed by the formula:

$$\begin{aligned} QI_{SD} = {} & 0.296 QI_{SD,1\,\mathrm{kHz}} + 0.37 QI_{SD,2\,\mathrm{kHz}} \\ & + 0.333 QI_{SD,4\,\mathrm{kHz}}, \end{aligned} \tag{8}$$

where $QI_{SD,1\,\mathrm{kHz}}$ is the sound strength distribution index in the octave band with a centre frequency of 1 kHz, $QI_{SD,2\,\mathrm{kHz}}$ is the sound strength distribution index in the octave band with a centre frequency of 2 kHz, and $QI_{SD,4\,\mathrm{kHz}}$ is the sound strength distribution index in the octave band with a centre frequency of 4 kHz.

The value of the sound strength distribution index weight is adopted as $\eta_{SD} = 0.5$. The sound strength distribution in a room is a very important parameter that takes into account the distance of the speaker from the listener; however, in the case of the classrooms under consideration (method assumptions), because of their volume, it is less important for assessing acoustic quality.

3.5. The background noise index

In Poland, background noise can be estimated on the basis of the PN-B02151-02 standard. According to this standard, the equivalent A-weighted sound pressure level of noise penetrating into classrooms and school rooms (except school workshop rooms) must not exceed the following values:

- total noise from all sources $L_{Aeq} = 40$ dB,
- from the building plant and other equipment inside or outside the building $L_{Aeq} = 35$ dB.

The value of background noise level permitted in classrooms acceptable in Poland ($L_{Aeq} = 40$ dB) is therefore within the limits of values adopted in most countries. Also the acceptable level of noise penetrating into school rooms from building equipment corresponds to the levels adopted in other countries.

Based on the above data, a curve (Fig. 8) was plotted to determine the background noise level QI_{BN} based on A-weighted background noise level in an empty classroom during classes in other classrooms (taking into account all sources of noise). Assuming that for the background noise level $L_{Aeq} = 40$ dB and below, the background noise level index is $QI_{BN} = 1$, and above 60 dB this value is $QI_{BN} = 0$, the following formula can be used:

$$QI_{BN} = 0.002\,\{L_{Aeq}\}^2 - 0.246\{L_{Aeq}\} + 7.64, \qquad (9)$$

where $\{L_{Aeq}\}$ is the numerical value of A-weighted background noise level in an empty classroom.

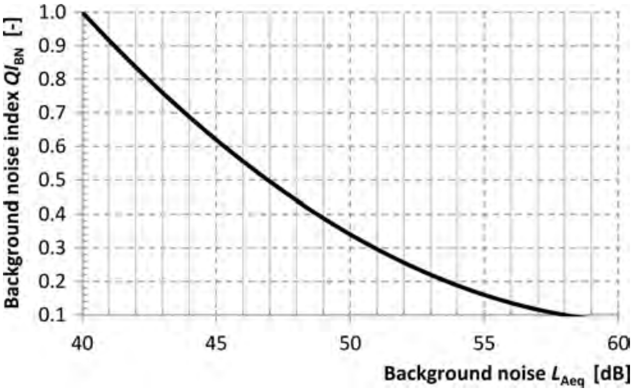
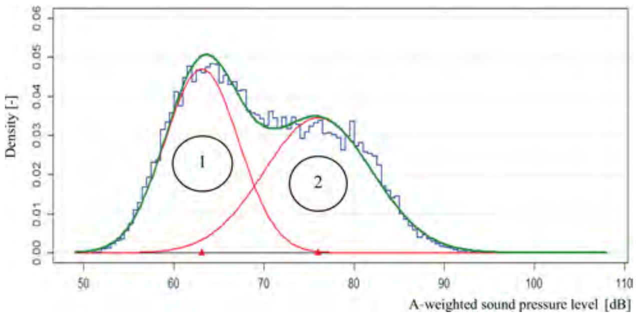


Fig. 8. Relationship between A-weighted background noise level in an empty classroom and the background noise index QI_{BN}.

Background noise has a significant impact on reception of messages in the process of speech understanding. Furthermore, limit values acceptable for the background noise level are defined by standards. Therefore, the value of weight of the background noise level index was assumed as $\eta_{BN} = 1$.

3.6. The signal-to-noise ratio index

The signal-to-noise ratio (SNR) is a parameter determining the distance of the speech signal from the background noise level at the place of the recipient at the time of the actual teaching/learning conditions (during classes/lectures). To measure this parameter, a sound meter/analyser is used that can record sound pressure level over time. Histograms (Fig. 9) are analysed to determine difference between medians of the distributions which correspond to the level of teacher's/lecturer's speech and the background noise level related to students' activity (Hodgson *et al.*, 1999). For this purpose, R software can be used with the Mixtools add-on. A measuring point is determined in the room based on the relative value of the sound strength G_{rel} where the difference of this parameter with respect to the reference value is the greatest.



	Component of the distribution	Observation belonging to the component [%]	Distribution [dB]	
			Median	Standard deviation
1	Backround noise during classes (in fixed measurement point)	49	63.1	4.1
2	A-weighted sound pressure level of teacher's speech (in fixed measurement point)	51	76.0	5.9

Fig. 9. Example of histogram of the A-weighted sound pressure level in classroom during a lecture.

The optimum SNR value to ensure the proper reception of content should not be less than 15 dB (Sato, Bradley, 2008). Therefore, to determine the signal-to-noise ratio index QI_{SNR}, the relationship shown below was empirically adopted, assuming that the value of $SNR = 15$ dB and above, the signal-to-noise ratio index has a value of $QI_{SNR} = 1$.

$$QI_{SNR} = 0.058e^{0.18\{SNR\}+0.14}, \qquad (10)$$

where SNR – is the numerical value of the signal-to-noise ratio in actual teaching/learning conditions. The above relationship is also shown in Fig. 10.

The signal-to-noise ratio has a significant impact on the received content in the process of understanding speech. Low values of this parameter virtually prevent communication. However, the SNR value depends

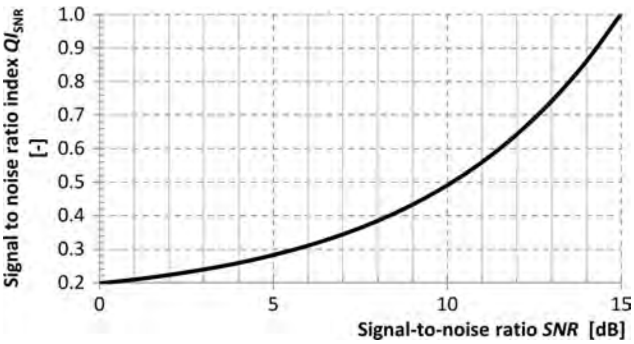


Fig. 10. Relationship between the signal-to-noise ratio SNR and the signal-to-noise ratio index QI_{SNR}.

in part on the teacher and his control over the class, therefore the value of the weight of the signal-to-noise ratio was adopted as $\eta_{SNR} = 0.5$.

4. Acoustic quality assessment of selected classrooms

Nine classrooms were selected (Table 3) to evaluate the acoustic quality in locations with diverse environmental noise. Selection was based on results of previous research (Mikulski, Radosz, 2010). The classrooms concerned had no acoustic adaptation.

Table 3. The tested classrooms.

No	Type of school	Classroom	Volume [m^3]	Number of students	Traffic noise L_{DWN} [dB]
1	Primary	A	160	24	55–60
2		B	160	22	55–60
3		C	157	28	< 50
4		D	157	32	< 50
5		E	158	30	50–55
6		F	158	32	50–55
7	Secondary	G	157	34	< 50
8		H	157	34	< 50
9.		I	157	38	< 50

L_{DWN} – A-weighted long-term average sound pressure level (reference interval equal to all days of the year).

The following measuring equipment was used for testing purposes:

- omnidirectional sound source B&K 4296 with an amplifier meeting the requirements of ISO 3382 and the directional sound source ADAM A5X,
- measuring microphone DPA 4007,
- measuring card RME UFX,
- a portable computer,
- B&K Dirac software,
- class 1 sound meter/analyser SVAN 945.

Measurement results (Table 4) confirmed previous study (Mikulski, Radosz, 2011) – in most cases values of parameters obtained from impulse response (reverberation time $RT_{2\,\mathrm{kHz}}$, speech transmission index STI, clarity $C_{50(1\,\mathrm{kHz})}$ and relative sound strength $\Delta G_{(\mathrm{rel},f)}$ are similar between classrooms. It results from the volume and the shape of classrooms. There are also similar equipment and furnishing which influence acoustics.

Measurement of A-weighted sound pressure level of the teacher's voice indicates that in most cases the speech effort correspond to raised voice (according to EN ISO 9921:2003).

The results of background noise obtained from measurements in classrooms were the result of:

- traffic noise around the schools not exceeding 60 dB,
- sound insulation of external partitions with windows (R'_{A1} from 30 to 36 dB),
- sound insulation of internal partitions (R'_{A1} from 49 to 56 dB),
- sound insulation of internal partitions with doors (R'_{A1} from 23 to 29 dB),
- the lack of activity in corridors,

where R'_{A1} – sound insulation index (airborne sound insulation).

Only one classroom meets the requirements for the SNR parameter. High levels of teachers' voice and low

Table 4. The results of measurements in tested classrooms.

Classroom	$RT_{2\,\mathrm{kHz}}$ [s]	STI	$C_{50(1\,\mathrm{kHz})}$ [dB])	$L_{Aeq,1\,\mathrm{m}}$ [dB]	$\Delta G_{\mathrm{rel},1\,\mathrm{kHz}}$ [dB]	$\Delta G_{\mathrm{rel},2\,\mathrm{kHz}}$ [dB]	$\Delta G_{\mathrm{rel},4\,\mathrm{kHz}}$ [dB]	L_{Aeq} [dB]	SNR [dB]
A	1.22	0.54	−2.3	66.0	2.8	1.2	1.8	23.9	11.1
B	1.00	0.59	−1.0	63.8	2.2	1.3	1.4	24.0	13.5
C	1.08	0.56	−1.5	62.8	3.3	2.4	2.0	25.9	11.2
D	1.18	0.63	−3.1	69.1	2.5	2.2	1.6	25.7	16.3
E	1.46	0.51	−3.7	68.3	1.4	2.1	2.6	24.6	7.7
F	1.12	0.56	−1.8	62.4	1.9	2.0	2.8	23.6	12.4
G	0.65	0.65	0.8	60.6	3.5	2.9	3.6	27.2	13.2
H	1.18	0.54	−3.3	65.8	3.1	2.5	2.3	27.8	12.4
I	1.14	0.64	−2.4	61.7	3.0	2.2	2.1	26.9	12.1

See text for explanation of symbols.

Table 5. Partial indices and the global index of acoustic quality of the tested classrooms.

Classroom	QI_{RT}	QI_{SI}	QI_{SE}	QI_{SD}	QI_{BN}	QI_{SNR}	QI_G	Scale of assessment
A	0.63	0.60	0.75	0.85	1	0.49	**0.73**	Poor
B	0.77	0.68	0.84	0.87	1	0.76	**0.82**	Good
C	0.72	0.64	0.89	0.80	1	0.50	**0.76**	Good
D	0.65	0.62	0.63	0.83	1	1.00	**0.79**	Good
E	0.50	0.52	0.66	0.84	1	0.27	**0.65**	Poor
F	0.69	0.63	0.90	0.82	1	0.62	**0.77**	Good
G	0.97	0.76	0.98	0.74	1	0.72	**0.87**	Good
H	0.65	0.56	0.76	0.79	1	0.62	**0.73**	Poor
I	0.68	0.65	0.93	0.81	1	0.59	**0.77**	Good

See text for explanation of symbols.

levels of background noise in classrooms indicate high levels of noise coming from the activity of the students in most of the classrooms.

Based on the results of the measurements, partial indices were determined and then the global index of acoustic quality of classrooms taking into account the weights (Table 5).

Test obtained for 9 selected classrooms have shown differences both in the individual partial indices and the global index of acoustic quality. An exception was the background noise index, because in none of the tested classroom the value of acceptable A-weighted sound pressure level of noise penetrating into classrooms and school rooms from all sources combined was exceeded (according to PN-B02151-02). The values of the global index of acoustic quality ranged between 0.65 and 0.87 (three classrooms with poor quality and six classrooms with good quality). All classrooms failed to meet the requirements to qualify as a room with excellent sound quality.

5. Summary

The paper presents a possibility of using the index method in the evaluation of acoustic quality of classrooms. The method is based on a set of objective acoustic parameters such as reverberation time RT, speech transmission index STI, clarity C_{50}, relative sound strength G_{rel}, pressure of a teacher's voice, and the background noise. Thanks to the proposed weights of partial indices, the global index of acoustic quality includes the assessment of the following: speech intelligibility, external noise level (background noise), teacher's speech effort, and the comfort of teaching and learning. Values assigned to the weights of the partial indices are arbitrary, however they correspond to various research and requirements in the field of classroom acoustics.

The proposed method has been verified on a sample of several selected classrooms. The results showed that some of the rooms required an appropriate adjustment of acoustic conditions. These conditions can be improved by increasing the acoustic absorption of rooms (including the appropriate design of wall and ceiling covered with sound-absorbing materials and the use of room equipment with high sound absorption). In particular, this is true for the rooms of the youngest students where the global index of acoustic quality to be aimed at should be above 0.9, which corresponds to excellent acoustic quality.

Due to the complexity of measurements, taking into account all the factors in the acoustic assessment is a difficult task. For this reason, the author intends to use the singular value decomposition (SVD) method to assess the acoustic quality which will allow for completing the assessment in the absence of complete information on all factors affecting this assessment (Kosała, 2011).

Next stage of research concerns experimental studies with different kind of linguistic material (isolated words, sequences of numbers and sentences) for developing subjective intelligibility tests to ensure the reliability and repeatability of tests. The results of subjective and objective (index method) assessment of classrooms will be statistically analyzed to verify both methods of acoustic quality assessment.

It is assumed that utilisation of unambiguous assessment of acoustic quality of classrooms using the index method will increase the awareness of architects, designers, school personnel and occupational health and safety specialists of the impact of room acoustic properties on noise pollution. It is also envisaged that proposed index method will affect acoustic requirements in the construction of new school buildings as well as in the expansion and upgrading of the existing ones.

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Ultrasonic Noise Sources in a Work Environment

Bożena SMAGOWSKA

Central Institute for Labour Protection – National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland; e-mail: bosma@ciop.pl

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The use of ultrasonic energy has created versatile possibilities of their applications in many areas of life, especially in hydro location and underwater telecommunications, industry and medicine. The consequence of a widespread use of high intensity ultrasonics in technology is the increased number of people who are exposed to such ultrasonic noise. Therefore it is important to determine the types of machines and other devices that are responsible for the emission of ultrasonic noise (10–40 kHz of central frequencies of one-third octave bands) as harmful and annoying hazard in the work environment. This paper presents ultrasonic noise sources frequently used in industry and preventive measures reducing the exposure to ultrasonic noise. Two types of ultrasonic noise sources have been distinguished: machines and other devices used to carry out or improve production processes, the so-called technological sources and sources in which ultrasonic noise exists as a non-intentional result of operation of many machines and systems, the so-called non-technological sources of ultrasonic noise. The emission of SPL has been determined for each groups of devices based on own measurement results.

Keywords: ultrasonic noise, assessment, exposure, sources.

1. Introduction

Acoustic vibrations of frequency over 16 kHz (above the audible range) spreading in a form of elastic waves in gas environments, fluids and solids are defined as ultrasounds or ultrasonics. The practical use of ultrasonics is very versatile and the upper frequency limit is 10 GHz (Pawlaczyk-Łuszczyńska, 1999; Śliwiński, 2001; Nowicki, 2010). The consequence of the common use of high intensity ultrasonics in technology, medicine and everyday life is an increase of the number of people who are exposed to such ultrasonic noise. In respect of the frequency ranges, the low frequency ultrasonics (not exceeding 100 kHz) and high frequency ultrasonics (exceeding 100 kHz) are classified. The frequency range of ultrasonic noise according to the practical agreement definition used in Poland and other countries (*Regulation of the Minister of Labour and Social Policy of 29 November*, 2002) includes audible high frequency components (10–16 kHz of central frequencies of one-third octave bands) and low ultrasonic frequencies (up to 40 kHz band) that has extended the noise frequency spectrum with regard to the audible noise measuring range (usually covering the range from 125 Hz – 8 kHz of central frequencies of one-third octave bands).

Tests concerning the impact that ultrasonic noise has on people carried out so far show that this factor may have a harmful influence on the auditory system, causing loss of hearing, and may have a negative impact on the ear vestibule resulting in a perturbation of balance and nausea (Pawlaczyk-Łuszczyńska *et al.*, 2001). As regards impacts other than those related to hearing, it turned out that occupational exposure to ultrasonic noise of levels exceeding 80 dB in the audible frequency range and over 100 dB in the low ultrasonic frequency range cause vegetative-vascular changes (Pawlaczyk-Łuszczyńska *et al.*, 1999; 2001).

Examination of the hearing damage of people exposed to noise in a work environment is carried out mainly in low frequency ranges, i.e. 125–8000 Hz (as above mentioned), due to frequencies responsible for the understanding speech. On the basis of hearing loss examinations of people exposed to audible industrial noise over 85 dB for over an 8-year period of working in high frequency ranges (>8 kHz), it was proven that in the examined group of people quicker and higher changes of the hearing thresholds occur in high frequency audiometry (8–20 kHz) (Przeklasa *et al.*, 2008; Amir *et al.*, 2011). During the operation of some ultrasonic devices (e.g. during ultrasonic welding), the generated noise is similar to an impulse noise, which has an essential impact on the hearing damage (Pawlaczyk-Łuszczyńska *et al.*, 2007a; 2007b; Smagowska, 2010). Moreover, the operation of ototoxic agents (organic solvents, substances causing suffocation and heavy metals) on people occupationally exposed to noise may accelerate the process of shifting the hearing threshold (Śliwińska-Kowalska *et al.*, 2000).

To prevent the consequences of exposure to ultrasonic noise and the hearing damage, this factor has been listed as a health hazard (*Regulation of the Minister of Labour and Social Policy of 29 November*, 2002). As already mentioned the assessment of the exposure to ultrasonic noise in the work environment in Poland is carried out within the range of 10 kHz to 40 kHz central frequencies of third octave bands (*Regulation of the Minister of Labour and Social Policy of 29 November*, 2002). Thus, the identification of ultrasonic noise sources, i.e. machines and other equipment in the surrounding area, which cause the emission of ultrasonic noise as a harmful or bothersome factor in the work environment, is essential (Engel *et al.*, 2005; 2009) for the assessment of the hazard factor.

In this article, we have specified the method of the assessment of the exposure to ultrasonic noise at work stations and presented the assessment results for two kinds of ultrasonic noise sources distinguishing the so called technology (Smagowska, Mikulski, 2008), and non-technology sources of the professional exposure to these factors (Smagowska, 2012b) (as per own testing). On the basis of the long term own testing, we have provided, in a further section of this article, measurement results of equivalent sound pressure levels for selected workstations in that operated equipments that emit ultrasonic noise. Measurements were taken in the surrounding area of machines or devices during their operation in places where the worker is stationed and at a distance of 0.5–1 m (except for the furnace servicing station in the rolling-mill, which was measured at a distance of ca. 4 m). Preventive actions are also specified, regarding the limitation of exposure to this hazard factor.

2. Assessment of the exposure to ultrasonic noise

The assessment of the exposure to ultrasonic noise is carried out by the comparison of the selected values of the sound pressure level for a given one-third octave frequency band to the determined admissible values. For the purpose of assessing the exposure of a worker at a given work station to a particular type of noise, the measurement of ultrasonic noise is carried out at locations typical for the worker at the given work station considering all operations carried out by that person and standard conditions of the use of a tool, machine or device being the source of such noise (PN-N-18002:2011).

The admissible values of ultrasonic noise in respect of health protection (MAI – Maximum Admissible Intensity values) for workers in general, valid in Poland, are specified in the Regulation of the Minister of Labour and Social Policy of 29 November 2002. On the basis of the measurements, the physical values characterizing ultrasonic noise are identified as follows:

- equivalent sound pressure levels determined for the one-third octave frequency bands with the center frequencies f of: 10 kHz, 12.5 kHz, 16 kHz, 20 kHz, 25 kHz, 31.5 kHz and 40 kHz, in reference to an 8-hour labour day, $L_{feq,8\,\mathrm{h}}$ (or to a labour week $L_{feq,w}$ – in the case of exposure of a human body to ultrasonic noise at an irregular manner over individual days in a week or if a person works another number of days a week than 5);
- maximum sound pressure levels determined for the one-third octave frequency bands with the center frequencies f of: 10 kHz, 12.5 kHz, 16 kHz, 20 kHz, 25 kHz, 31.5 kHz and 40 kHz, $L_{f\,\max,d}$ during a labour day (or a labour week $L_{f\,\max,w}$).

Tables 1–3 specify the admissible values of ultrasonic noise at workstations for workers in general with the consideration of particular risk groups: pregnant women and young persons.

Table 1. Admissible values of equivalent sound pressure levels and maximum sound pressure levels at workstations for ultrasonic noise for general workers.

Central frequencies of terce bands of frequency f [kHz]	Admissible equivalent sound pressure levels $L_{feq,8\,\mathrm{h,dop}}$ or $L_{feq,w,\mathrm{dop}}$ [dB]	Admissible maximum equivalent sound pressure levels $L_{f\,\max,d,\mathrm{dop}}$ or $L_{f\,\max,w,\mathrm{dop}}$ [dB]
10; 12.5; 16	80	100
20	90	110
25	105	125
31.5; 40	110	130

Table 2. Admissible values of equivalent sound pressure levels and maximum sound pressure levels at workstations for ultrasonic noise in the case of pregnant women being employed.

Central frequencies of terce bands of frequency f [kHz]	Admissible equivalent sound pressure levels $L_{feq,8\,\mathrm{h,dop}}$ or $L_{feq,w,\mathrm{dop}}$ dB	Admissible maximum equivalent sound pressure levels $L_{f\,\max,d,\mathrm{dop}}$ or $L_{f\,\max,w,\mathrm{dop}}$ dB
10; 12.5; 16	77	100
20	87	110
25	102	125
31.5; 40	107	130

Table 3. Admissible values of equivalent sound pressure levels and maximum sound pressure levels at workstations for ultrasonic noise in the case of young persons being employed.

Central frequencies of terce bands of frequency f [kHz]	Admissible equivalent sound pressure levels $L_{feq,8\,\mathrm{h,dop}}$, or $L_{feq,w,\mathrm{dop}}$ [dB]	Admissible maximum equivalent sound pressure levels $L_{f\,\max,d,\mathrm{dop}}$, or $L_{f\,\max,w,\mathrm{dop}}$ [dB]
10; 12.5; 16	75	100
20	85	110
25	100	125
31.5; 40	105	130

3. Technology ultrasonic noise sources

Technologies using ultrasonics are increasingly widely used, e.g. in typography, electronics, automotive, textile, alimentary, watch-making, jewellers, optical and PVC producing industries (including packaging producing plants), mechanic workshops (including automotive workshops), medical centres, dentist and prosthetics offices, in laboratories and dispensaries as well as in medicine: diagnostics, physical therapy and surgery (Pawlaczyk-Łuszczyńska, 1999; Śliwiński, 2001; Nowicki, 2010). Densities of ultrasound power used for industrial purposes are within the range of 10 mW/cm^2 to 10 000 W/cm^2.

Apart from industrial production processing, ultrasonics are used for: powder pressing, dust removal, production of emulsify agents, aerosols, hydrosols etc., or in such commonly used equipment as: anti-burglary alarm equipment, dog whistles, bird and rodent deterrent equipment, air humidifiers and inhalation units. Moreover, ultrasonics are generated by medical equipment such as: diagnostic, physical therapy and surgical equipment. For physical therapy purposes, ultrasonics within the range of 0.5–1 MHz are used for deep treatments and 2.5–3 MHz for surface treatments (Pawlaczyk-Łuszczyńska, 1999). For diagnostic purposes, low power ultrasounds within the frequency range of 1–10 MHz are used (up to 30 MHz in ophthalmology). The intensities of ultrasounds generated by such equipment vary from 0.06 mW/cm^2 to 4 W/cm^2.

The main sources of ultrasonic noise in the work environment are technology sources of ultrasonic noise, i.e. machines and other equipment in which ultrasonics are used to execute or improve certain production processes. They generate ultrasound vibrations with a nominal frequency of 16–40 kHz (Pawlaczyk-Łuszczyńska et al., 2007a; 2007b; Śliwiński, 2001; Nowicki, 2010). Most of these devices include the word "ultrasonic" as designation in their names. Namely, the technology ultrasonic equipment group includes: ultrasonic washers, ultrasonic welders (for plastic, metal and hardly wieldable materials), ultrasonic drills, manual soldering units, ultrasonic crucibles, fabric treatment machines (jet machines, lace machines and quilting machines), dental devices used for tartar removing – so called scalars, as well as ultrasonic guillotines, ultrasonic knives or ultrasonic curtains.

The basic frequency of operation of ultrasonic washers is within the range of 20–40 kHz with the ultrasonic component levels reaching 135 dB (Pawlaczyk-Łuszczyńska et al., 2001).

For ultrasonic welders, the basic frequency of operation is within the range of 18–22 kHz with the ultrasonic component levels reaching 140 dB (Pawlaczyk-Łuszczyńska et al., 2001). For ultrasonic drills the operation frequency range is typically between 16–30 kHz. The equivalent sound pressure levels at workstations with drills, depending on whether casings are provided for the equipment or not, varies between 90–120 dB (Smagowska, Mikulski, 2008).

The following figures present few examples of measurement results characterising ultrasonic noise sources in the work environment. Figure 1 presents example values of equivalent sound pressure levels in reference to 8 hours at technology work stations with the following ultrasonic equipments: a welder, a washer and a drill. The highest values exceeding those characterizing ultrasonic noise at these workstations occur in the one-third octave-bands centre frequencies close to the nominal frequency of operation (this is most often the 20 kHz central frequency band).

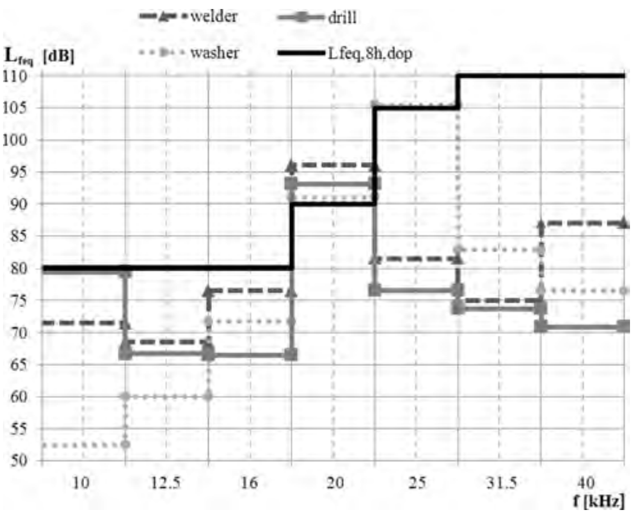

Fig. 1. Measurements results of equivalent sound pressure levels at work stations with: a typical welder, a washer and a drill ($L_{feq,8\,\mathrm{h,dop}}$ = MAI).

Over the last years, a significant group of technology ultrasonic equipment of low frequencies has been composed of ultrasonic machines for the finishing of fabric products or for decorative finishing of fabrics (e.g. jet machines, lace machines and quilting machines). The nominal frequency of operation of such equipment is within the range of 20–40 kHz with the ultrasound component levels reaching 120 dB.

Figure 2 presents the results of measurements of equivalent sound pressure levels in the one-third octave-bands at a workstation with a jet machine (a machine used for welding decorative stones into fabric). The highest value of this parameter occurs in the one-third octave-band centre frequency of 25 kHz and reaches the admissible value defined for this frequency band (105 dB).

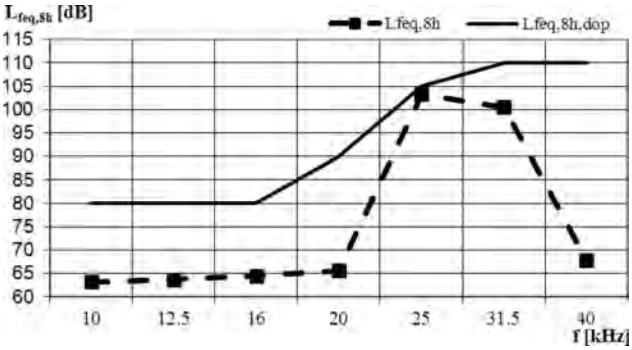

Fig. 2. Results of measurements of equivalent sound pressure levels in one-third octave frequency bands at a workstation with a jet machine ($L_{feq,8\,\mathrm{h,dop}}$ = MAI).

Increasingly more often automatic units and production lines are installed in production plants (e.g. for the production of disposable head covers of nonwoven fabric, shoe covers, disposable head covers of plastic foils or knives for cutting of tags or edible masses) using ultrasonic converters in their operation processes within the range of 20–40 kHz. In most cases, such equipment has covers, but even minuscule gaps may be a source of the ultrasonic noise component penetrating outside the cover, where the levels of such noise may reach up to ca. 110 dB and, depending on the location of the work station, may have a harmful effect on the operating person.

Moreover, ultrasonic guillotines and knives are commonly used in the food industry, the nominal frequency of operation of which is 20 kHz with the ultrasound component levels reaching 100 dB. Figure 3 presents the results of measurements of equivalent sound pressure levels in one-third octave-bands at a workstation for servicing a document cutting line. The highest value of this level is 95 dB in the one-third octave-band centre frequency of 20 kHz and exceeds the admissible value 90 dB defined for this frequency band.

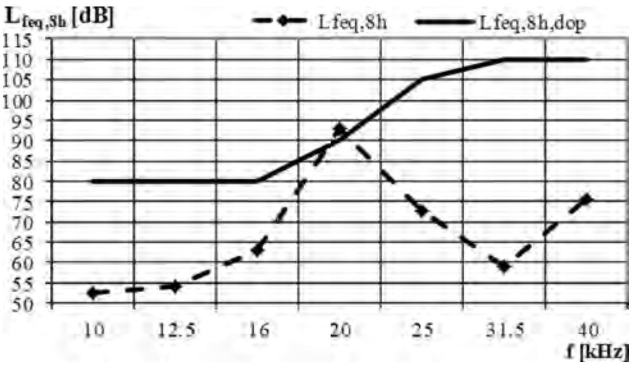

Fig. 3. Equivalent sound pressure levels in one-third octave frequency bands at a workstation of a document cutting line ($L_{feq,8\,\mathrm{h,dop}}$ = MAI).

The next work environment in which ultrasonic equipment is used are dentists' offices, in which units removing tartar are used, the so called scalers. The nominal frequency of operation of such equipment is 25 kHz with the ultrasonic component levels reaching 80 dB. Low frequency ultrasonic technology equipment includes also soldering units and ultrasonic crucibles used for soldering and galvanizing of various elements. Their industrial use is, however, significantly limited in respect of other equipments described above (Śliwiński, 2001).

4. Non technology sources of ultrasonic noise

Apart from the equipment listed above in which ultrasound vibrations are a working factor used in the technology process, ultrasonic noise is also generated as a non-intentional result of operation of many machines and equipment units and are described as non-technology sources of ultrasonic noise. Such equipment does not bear the name "ultrasonic device". Its identification as sources of potential ultrasonic noise at a workstation is difficult since the ultrasound components are not audible. Such identification I can be achieved only as a result of measurements. Most often, the noise spectrum emitted by such equipment includes significant sound pressure levels in a high audible frequency range and are recognized by persons exposed to such factors as squeaking, whistling and whooshing sounds. The small amount of literature available states that the presence of ultrasound components of significant sound pressure levels has been encountered in the surrounding areas of such equipment units during the operation of which aerodynamic or mechanic phenomena occur, as well as during other processes, such as e.g. welding or plasma cutting (Pawlaczyk-Łuszczyńska *et al.*, 2001; 2007a; Smagowska, Mikulski, 2008; Smagowska, 2012a).

The first group of equipment (during operation of which aerodynamic phenomena occur) includes among others: compressors, press units, burners, valves and pneumatic tools (including e.g. manual pneumatic tools, pneumatic wrenches and grinding machines).

Figure 4 presents as an example the results of equivalent sound pressure levels at workstations with vulcanisation press, washer tearing and cutting machines. The highest value of the emitted noise level oscillates around 83 dB in the one-third octave-band

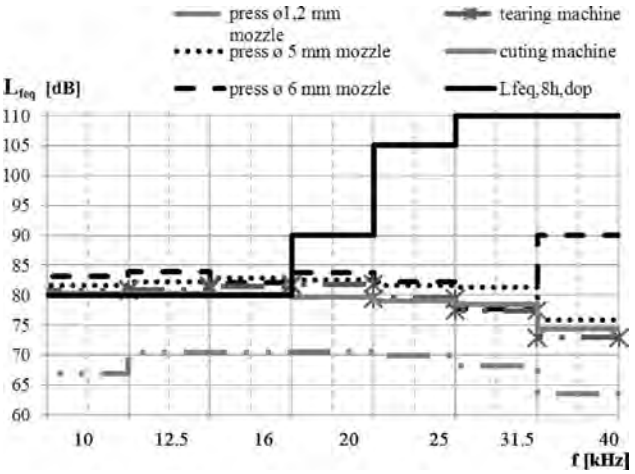

Fig. 4. Measurement results of equivalent sound pressure levels at workstations with a vulcanization press as well as the washer tearing and cutting machines ($L_{feq,8\,\mathrm{h,dop}}$ = MAI).

centre frequency of 12.5 kHz and exceeds the admissible value (80 dB) defined for this frequency band (Smagowska, 2010).

At detail cleaning workstations, during the use of valves with compressed air the equivalent sound pressure level in one-third octave-bands centre frequencies of 10 kHz; 12.5 kHz and 16 kHz is within the range of 90–98 dB. Figure 5 presents the results of equivalent sound pressure levels at workstations where detail drying (screen printing mask) and cleaning (printed plates and dishes) occur using compressed air. The exceeding of the admissible value of this parameter occurs at one-third octave-bands centre frequencies: 10 kHz; 12.5 kHz, 16 kHz and 20 kHz during the detail cleaning (Smagowska, 2010).

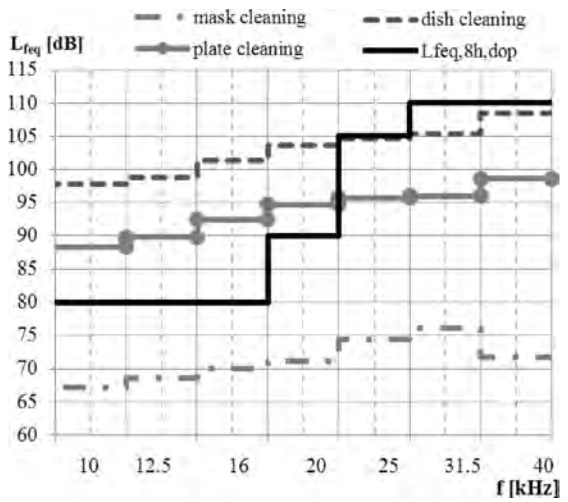

Fig. 5. Measurement results of equivalent sound pressure levels at workstations with detail drying and cleaning units using compressed air ($L_{feq,8\,\mathrm{h,dop}}$ = MAI).

For the group of such pneumatic tools as: chase rammers, pneumatic wrenches and grinders, the equivalent sound pressure levels, mainly in the one-third octave-band of centre frequency of 10 kHz vary between 85–92 dB. During the work with use of pneumatic hammers and compressors, the value of this level in one-third octave-bands centre frequencies of 10 kHz, 12.5 kHz and 16 kHz occurs within the range of 100–115 dB.

Another group of equipment generating ultrasonic noise components (in which the source of ultrasounds are mechanical processes) includes such units as: high-speed planers, milling machines, grinders, circular saws and some textile manufacturing machines (e.g. looms, throttles, stretching machines, twisters, winders and cards). For mechanical processing machines, i.e. timber planers and milling machines, the equivalent sound pressure level in the one-third octave-bands centre frequencies of 10 kHz and 12.5 kHz reaches 98 dB. For (angle) grinders and sledgehammers (with weights of 1,500 and 2,000 kG), the equivalent sound pressure level in the one-third octave band of central frequency of 10 kHz reaches 91 dB.

For the group of circular saws and cross saws for timber as well as belt saws for metal, the equivalent sound pressure level in the one-third octave-bands centre frequencies of 10 kHz, 12.5 kHz and 16 kHz occurs within the range of 95–100 dB. Figure 6 presents an example of results of the equivalent sound pressure levels in the one-third octave-bands during metal grinding using an angle grinder. The admissible values of this level (80 dB) are exceeded in the one-third octave-band of centre frequencies of 10 kHz, 12.5 kHz and 16 kHz.

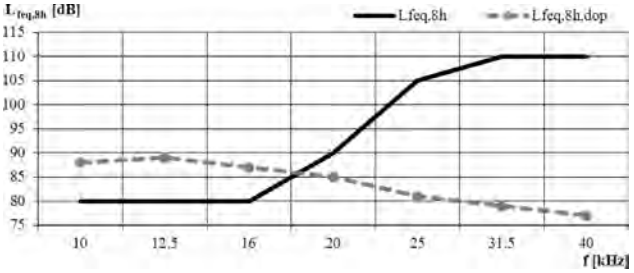

Fig. 6. Results of measurements of equivalent sound pressure levels in the one-third octave frequency bands at a workstation with a grinder ($L_{feq,8\,\mathrm{h,dop}}$ = MAI).

For the group of textile manufacturing machines (e.g. looms, throstles, stretching machines, twisters, winders and cards) the equivalent sound pressure levels vary within the range of 80–90 dB and the highest level values are measured in one-third octave-bands centre frequencies of 10 kHz, 12.5 kHz and 16 kHz (Smagowska, 2012a).

Figure 7 presents example values of equivalent sound pressure levels in reference to 8 hours at textile manufacturing workstations. For such ultrasonic noise sources, the highest values of levels characterizing ultrasonic noise occur in one-third octave-bands centre

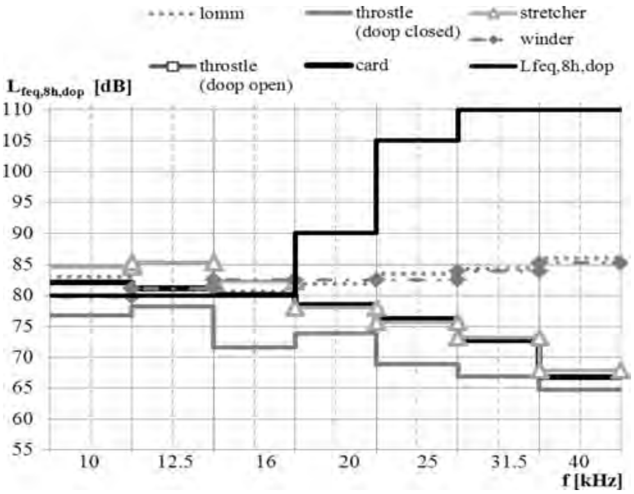

Fig. 7. Measurement results of equivalent sound pressure levels at textile manufacturing workstations ($L_{feq,8\,\mathrm{h,dop}}$ = MAI).

frequencies of 10 kHz, 12.5 kHz and 16 kHz. On the basis of the noise level results at a throstle workstation it is seen that major differences between the sound pressure levels (10 dB) occur in such bands both with open and closed doors to the machine.

Moreover, significant sound pressure levels in the scope of ultrasonic noise occur during welding (72 dB), cutting a metal sheet by means of an oxy-fuel cutting torch (75 dB), plasma cutting (87 dB) or rolling processes (80 dB).

Figure 8 presents example values of sound pressure levels in the one-third octave-bands while cutting a 25 mm thick metal sheet by an oxy-fuel cutting torch and cooling furnace semi-products (in a rolling-mill). For such operations, the highest values of the sound pressure levels occur in the one-third octave-band centre frequencies of 10 kHz, 12.5 kHz and 16 kHz and vary within the range of 75–80 dB.

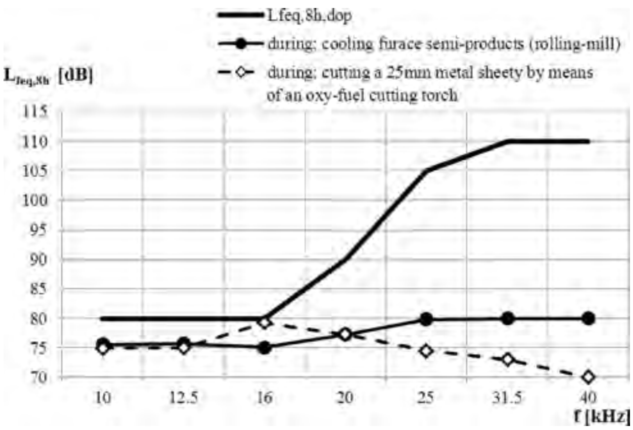

Fig. 8. Sound pressure levels during cooling furnace semi-products (rolling-mill) and cutting a 25 mm metal sheet by means of an oxy-fuel cutting torch ($L_{feq,8\,\mathrm{h}}$ = MAI).

5. Summary and conclusions

It should be stated that in reference to the technology ultrasonic noise sources, the highest values characterizing this hazard factor occur most often within the operating frequency of the equipment and in case of non-technology ultrasonic noise sources, in the three first one-third octave bands of central frequencies of 10 kHz; 12.5 kHz and 16 kHz. Due to the fact that these frequency bands overlap clearly with the upper range of audible sound frequencies, the risk of occurrence of hearing damage is assessed as high. Information presented in the article regarding machines and other equipments being non technology ultrasound noise sources is important to bring attention to the problem of exposure to this hazard factor in a work environment.

The harmful impact of ultrasonic noise may be limited in the case of exposure to operators in a work environment by taking the following relevant prevention steps (*Regulation of the Minister of Health and Social Policy of 30 May*, 1996; *Regulation of the Minister of Economy and Labour of 5 August*, 2005; PN-N-18002:2011; Dobrucki, 2010):

- limiting ultrasonic noise emission by changing the structure of the ultrasonic equipment,
- training the operating workers to use the ultrasonic equipment according to the principles of proper and safe unit servicing,
- educating the operating workers on the harmful impact of ultrasounds on the human body,
- use of common protection means (covers, casings and acoustic screens) limiting noise propagation,
- use of ear protection (properly selected for the noise spectrum) and head covers (helmets with transparent visors, e.g. made of Plexiglas),
- limiting the exposure by organizational methods (e.g. by proper location of workstations, forming silent centres and the rotation of staff),
- in case of exposure to noise in reference to an 8-hour work time being above the NDN values a shorter time of work should be adopted,
- carrying out initial and periodical preventive medical examinations (Engel *et al.*, 2005).

Moreover as a general conclusion one should state that the problem of assessment of ultrasonic noise in a work environment as a hazard factor present and is an important problem to recognize by further research and measurements. The classification of the ultrasonic noise sources in two groups the technology and non-technology ones as presented in the paper is a useful way in distinction of two kinds of situations existing in the ultrasonic noise impact on the human body and especially on hearing losses that seems to be more evident in the case of the second type of sources.

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Method of Determining the Sound Absorbing Coefficient of Materials within the Frequency Range of 5 000–50 000 Hz in a Test Chamber of a Volume of about 2 m^3

Witold MIKULSKI

Central Institute for Labour Protection – National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland; e-mail: wimik@ciop.pl

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Sound absorption coefficient is a commonly used parameter to characterize the acoustic properties of sound absorbing materials. It is defined within the frequency range of 100–5 000 Hz. In the industrial conditions, many appliances radiating acoustic energy of the frequency range of above 5000 Hz are used and at the same time it is known that a noise within the frequency range of 5 000–50 000 Hz can have a harmful effect on people,hence there is a need to define the coefficient in this frequency range. The article presents a proposal for a method of measurement of the sound absorption coefficient of materials in the frequency range from 5 000 Hz to 50 000 Hz. This method is a modification of the reverberation method with the use of interrupted noise.

Keywords: ultrasonic noise, sound absorption coefficient of materials.

1. Introduction

Sound absorption coefficient is a commonly used parameter to characterize the acoustic properties of sound absorbing materials. Its variation called the sound absorption coefficient (EN ISO 354:2003) is defined by means of a measuring and computational method in a special reverberation chamber in conditions of diffuse field, with the use of interrupted noise or the impulse method (Blough *et al.*, 2007). Sizes of the studied sample of material are 10–12 m^2, and the volume of the test room is about 200 m^3.

Another method of defining the sound absorption coefficient and in particular its variation, the sound absorption coefficient (dependent on the angle of incidence of acoustic wave), is a measuring and computational method involving examination of small samples of material within the field of the standing wave in the so-called Kundt's tube. Both methods define this coefficient within the frequency range of about 5 000 Hz. In a range above this frequency the used methods cannot be applied. In the first case, diffuse field cannot be created in the examined room (which is an assumption of the applied method) because of a high level of attenuation of the sound in the air which is considerably higher than the measurable effect of multiple attenuation of the acoustic wave during its reflecting from the surface of the material sample being examined in a room of a volume of 200 m^3. In the second case, the measurements in a Kundt's tube are not possible for technical reasons. They are particularly limited by the diameter of the tube (the upper frequency of the measurements is limited by the condition that the wave must be twice as long as the diameter of the tube). (It has to be mentioned, that in some laboratories it has been attempted to define the coefficient of absorption in the examined frequency range, in the free field, i.e. in anechoic rooms, however, so far there have been no extensive reports on them (Pleban, 1990)). Hence the author suggests the use of a modification of the first method in a room (test chamber) of a reduced size (Dobrucki *et al.*, 2010).

2. The room for measurements of the reverberation time within the frequency range of 5 000–50 000 Hz – the test chamber

To define the sound absorption coefficient, the author suggests the research method applied in the diffuse field with the use of interrupted noise. The reason for adopting this method is the fact that the sound absorption coefficient of material should be determined in conditions similar to their use in practice. The use of sound-absorbing materials in the sources enclosures is expected.

The volume of a standard test room where the sound absorption coefficient is studied is about 200 m^3. The density of acoustic energy during propagation of the acoustic wave from the source decreases as a result of: an increase of the area of the surface wave front (for the point source – a sphere), losses of the acoustic energy during reflecting from the surfaces enclosing the room, and the attenuation of the acoustic energy during propagation in the air (ISO 9613-1:1993). All the three phenomena interact simultaneously and are taken into account in the method used up to this point. The influence of the second and third of these phenomena depends strongly on the frequency, however, within the frequency range investigated so far, 100–5 000 Hz, it is not too large for the conditions of the diffuse field not to be maintained (relatively small attenuation of the acoustic wave energy on the propagation path enables the recording of the acoustic signal above the acoustic background even after multiple reflections of the wave from the walls of the room – sufficiently long path on which the level of the sound pressure of the acoustic wave radiating from the source is higher than the acoustic background). The spectrum of the sound power level of the source is adjustable and can be relatively flat in the frequency range of 5 000–50 000 Hz (Mikulski, Radosz, 2009; 2010).

This is the basis for extraction of the energy losses during reflections from the influence of the three phenomena. It consists in setting the so-called decay curves of the sound pressure level after turning off the source and, from them, defining the reverberation time (from which the sound absorption coefficient is calculated).

In a standard test room (of about 200 m^3 volume), within the frequency range of above 5 000 Hz, sound attenuation by a material and the walls of the room and on the propagation path in the air is so high that the level of sound pressure decreases rapidly in the function of the distance. It makes it impossible to record the acoustic wave after multiple reflections and the impact of the reflection of a wave from the examined material cannot be extracted from the resultant impact of the three above mentioned phenomena. As a matter of fact, the distance covered by the acoustic wave whose density of acoustic energy is higher than the density of the acoustic field is so short that not only does it disable the occurrence of diffuse field but also makes it impossible to record even a few reflections of the wave from the walls of the room – which is a condition for measurement of the decay curve and, as a result, measurement of the reverberation time and the sound absorption coefficient. However, the author believes that this adverse state of matters can be changed. Since it is impossible to lengthen the above mentioned distance that depends, among others, on the attenuation of sound in the air, the number of reflections of the acoustic wave from the examined material sample on this distance should be increased. Then, the influence of the wave reflection on the attenuation in the air will be higher and it will be possible to create a quasi-homogeneous field (if not a diffuse field). Hence, it will be possible to measure the decay curves that will be most significantly influenced by the phenomenon of reflection of the wave from the examined material. The author suggests application of this solution by the use of two modifications of the applied standard method of defining the sound absorption coefficient in the diffuse field. The first, through a considerable reduction of the size of the test room and the second, through covering all the walls of the test room with the examined material (in the standard room 5% of the walls in the room are covered). This new room with a reduced size will still be called the test chamber.

The area of the inner surface of the test chamber has to be of the size of a standard sample of the examined material, i.e. about 10 m^2, it means that the minimal linear dimension (in meters) of the test chamber l (it was earlier assumed that it is a cube) is:

$$l \geq \sqrt{S_v/6} = 1.29 \text{ m}, \tag{1}$$

where S_v is the area of the inner surface of the chamber, in square meters.

Taking into account the standard thickness of the material sample, i.e. 0.05 m, the inner linear dimensions of the test chamber are assumed to be 1.4 m.

Figure 1 presents a section of the test chamber, its photograph, and a photograph of the research equipment.

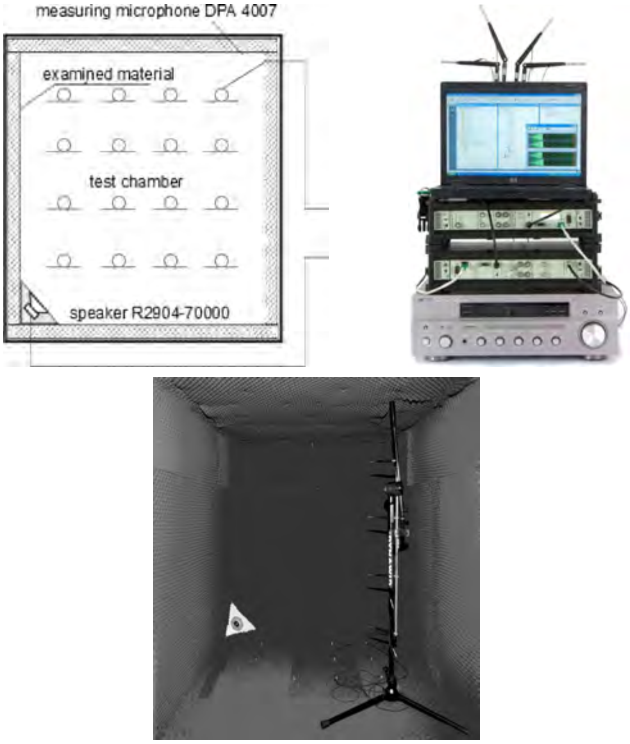

Fig. 1. Scheme (a scheme of the test chamber, the Pulse measuring system for the measurements in the examined frequency range (Mikulski, Radosz, 2009; 2010), a photograph of the test chamber).

3. Results of the measurements of the distribution of the sound pressure and the reverberation time in the test chamber

In the designed test chamber the research of the homogeneity of the created acoustic field in a steady state (of the level of the sound pressure on a spatial net, 64 points) and of the distribution of the reverberation time was carried out by means of the interrupted noise method. 64 measured points are in three-dimensional rectangular net $4 \times 4 \times 4$, i.e. four heights of 16 points Fig. 1. The distance from the net to the walls of the test chamber is 0.3 m). Both parameters were defined in 1/3 octave frequency bands, of mid-band frequencies of 5 000–50 000 Hz, in an empty chamber (wood) and with the examined materials: the polyurethane foam (Fig. 2) and mineral wool 50 mm.

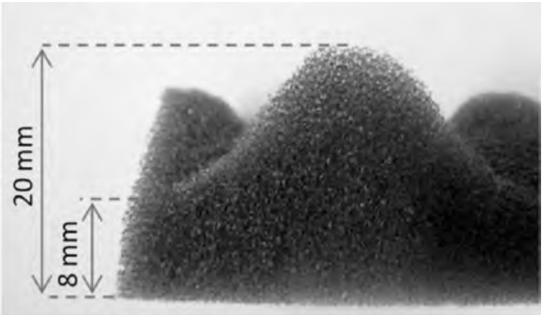

Fig. 2. Examined materials – the polyurethane foam.

The results of the tests are presented in:

- Fig. 3 – levels of the sound pressure,
- Fig. 4 – reverberation times.

The measurement results of the distribution of sound pressure level show that in the test chamber a homogeneous acoustic field occurs at a distance of more than about 0.5 m from the speaker, hence, every test should be carried out at a distance of more than 0.5 m from the speaker (compare Fig. 3 with 5 and 4 with 6). Figures 3 and 4 shows the results of measurements in 64 measurement points in the whole chamber (the closest measurement point is about 0.2 m from the speaker), and in Figs. 5 and 6 the results of measurements in 8 measurement points located in the middle of the test chamber are shown, the closest measurement point is about 0.6 m from the speaker.

It should also be noted that this condition is not critical, as in a standard test room creation of reverberant field is necessary because diffuse field is required due to a small area of the sample in relation to the size of the room. However, in the suggested test chamber, where all the walls are covered with the examined material, providing a diffuse field is not that significant.

The results of the measurements of the reverberation times do not vary significantly with respect to the value of this parameter in the test chamber. Thus, the choice of the point of measurement inside the chamber does not influence the measurement results of the reverberation time.

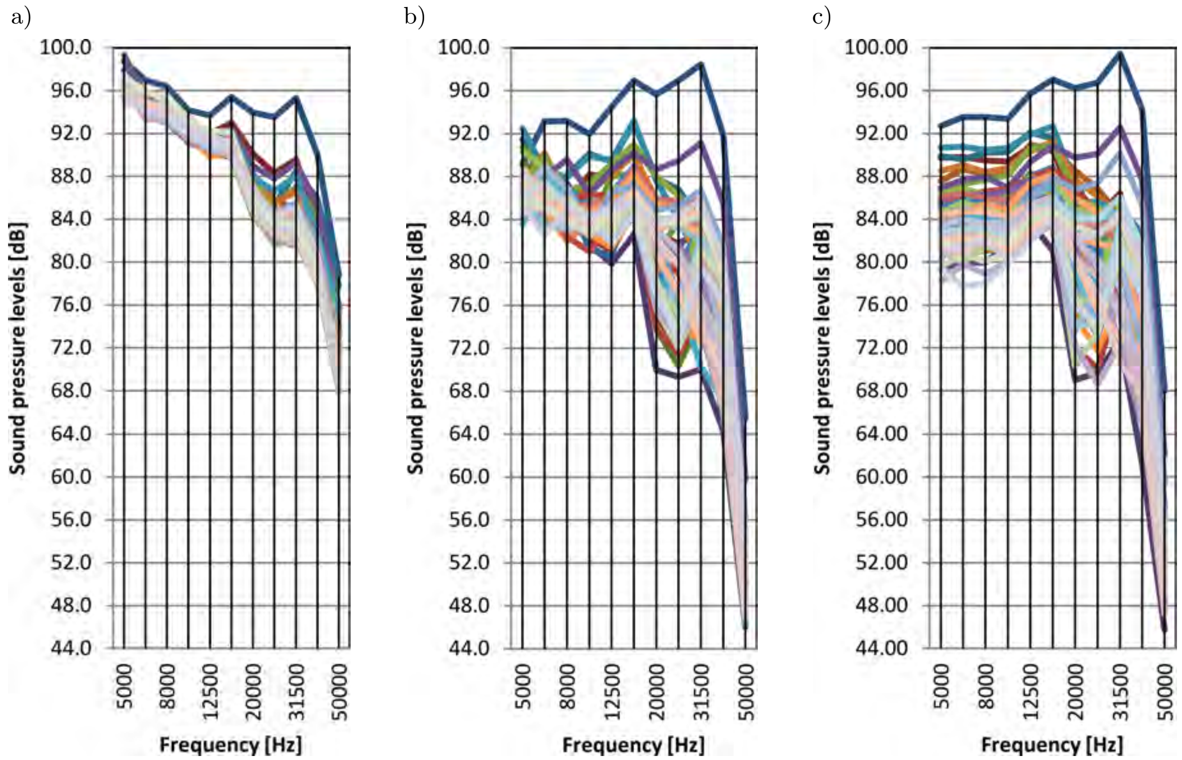

Fig. 3. Sound pressure levels in 1/3 octave frequency bands in the test chamber in a steady state: a) in an empty chamber, b) with polyurethane foam (Fig. 2), c) with mineral wool 50 mm, for 64 measurement point.

However, taking into account the maximum reduction in scatter of the measured values and limit of the number of measurement points, it is assumed that the optimal area in which the tests should be carried out is a sphere of the radius of 0.3 m in the centre of the test chamber (result of the level of the sound pressure inside the sphere presented in Figs. 5a–c – levels of the sound pressure, Figs. 6a–c – reverberation times).

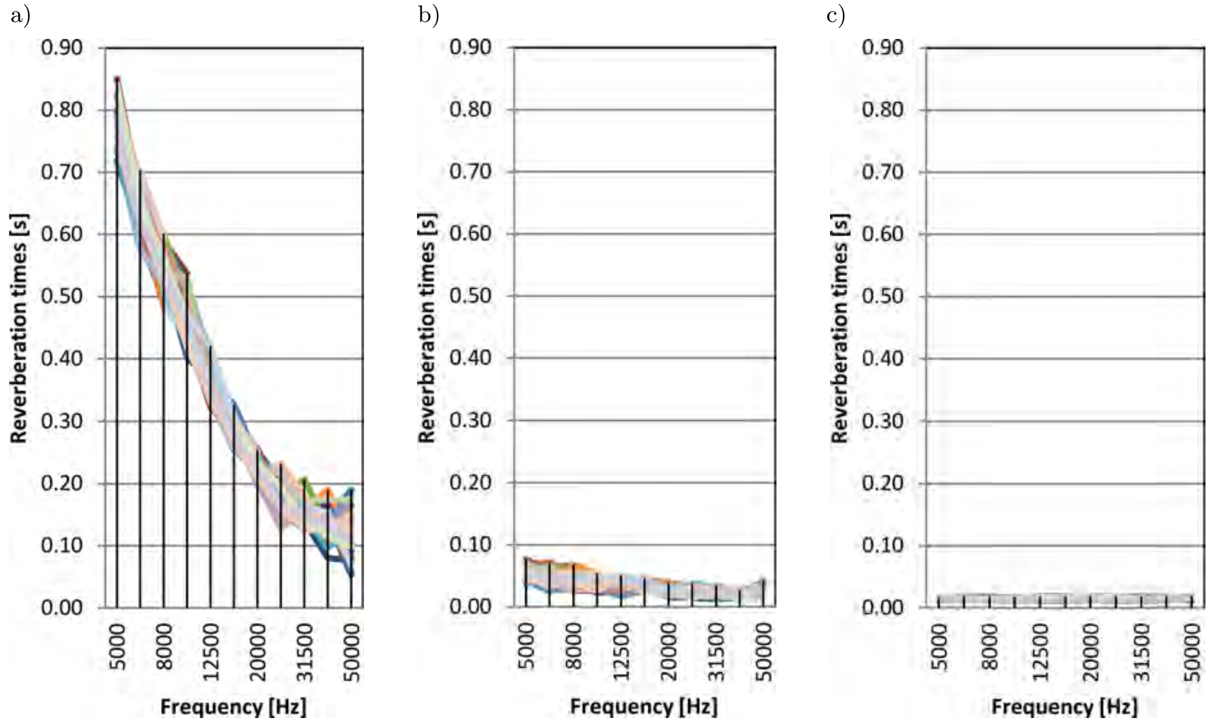

Fig. 4. Reverberation times in 1/3 octave frequency bands in the test chamber: a) in an empty chamber, b) with polyurethane foam, c) with mineral wool, for 64 measurement point.

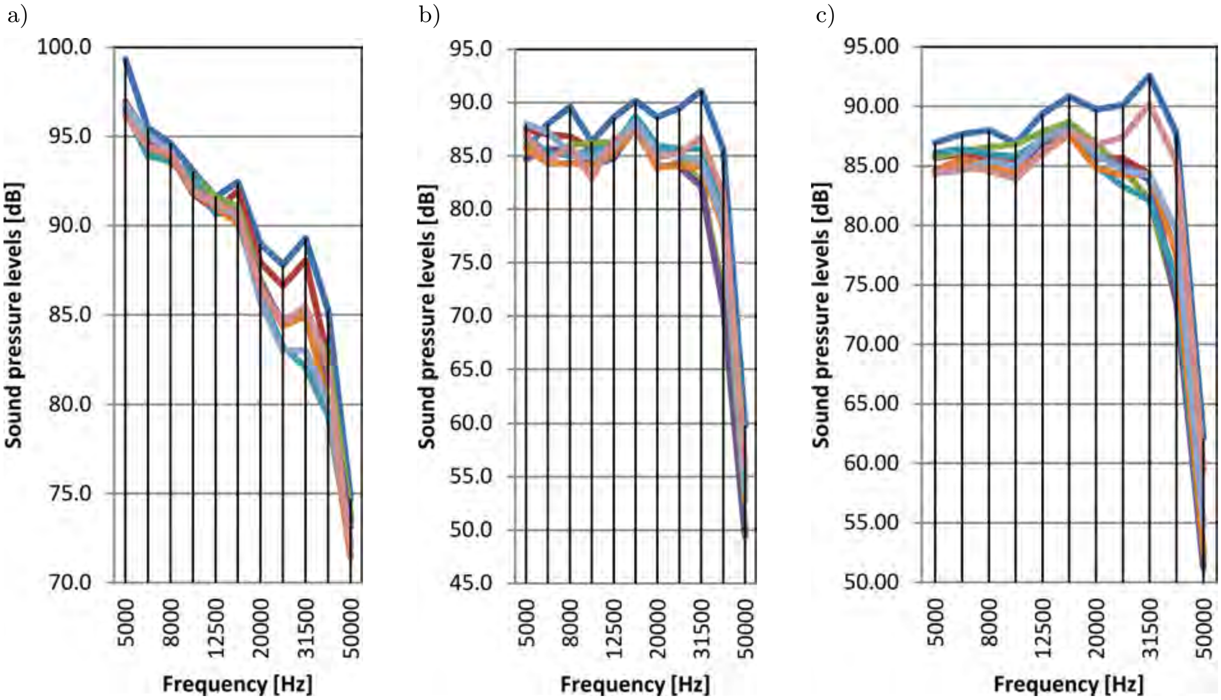

Fig. 5. Sound pressure levels in 1/3 octave frequency bands in the test chamber in a steady state: a) in an empty chamber, b) with polyurethane foam, c) with mineral wool, for 4 measurement point in the centre of the test chamber.

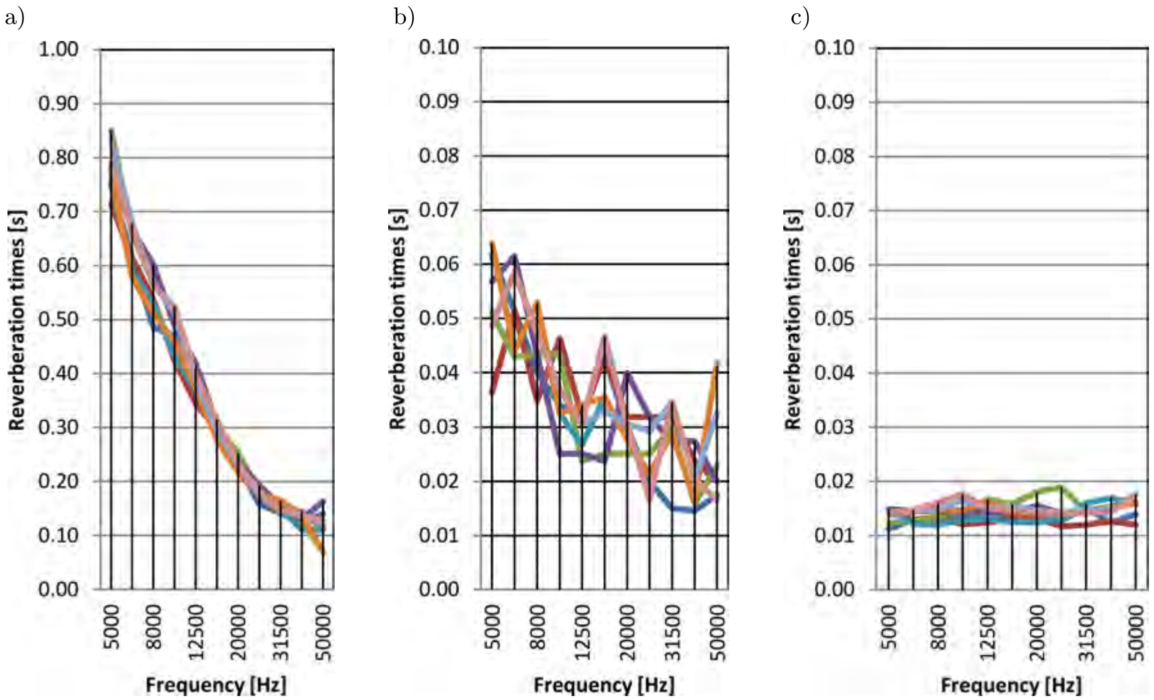

Fig. 6. Reverberation times in 1/3 octave frequency bands in the test chamber: a) in an empty chamber, b) with polyurethane foam, c) with mineral wool, for 4 measurement point in the centre of the test chamber.

4. Method of defining the sound absorption coefficient in the test chamber

While defining the sound absorption coefficient α in the test chamber from the results of the measurements of the reverberation time,we used the Knudsen formula which takes into account the high absorption properties of the material and the room $\alpha > 0.2$) and the sound attenuation in the air (that depends also on the humidity). Reverberation time (in seconds) in a room is defined by the use of the following formula:

$$T = \frac{0.161V}{-S_v \ln(1-\alpha_s) + 4mV}, \tag{2}$$

where T is the reverberation time in a room, in seconds; V is the volume of the test chamber, in cubic meters; S_v is the area of the inner surface of the chamber, in square meters; α_s is the average sound absorption coefficient in the room; m is the coefficient taking into account the attenuation of the sound in the air, dependent on the frequency and air humidity, in m^{-1} (for laboratory conditions the assumed values are in accordance with Table 1).

In the suggested method the sound absorption coefficient is defined after a transformation of Eq. (2), in frequency bands f, from the formula:

$$\alpha_f = 1 - e^{\frac{V}{S_v}\left[-\frac{0.161}{T_f} + 4 \cdot m_f\right]}, \tag{3}$$

where T_f is the reverberation time in the room, in 1/3 octave frequency bands of mid-band frequencies f (within the range of 5 000–50 000 Hz), in seconds; V is the volume of the chamber, in cubic meters; S_v is area of the inner surface of the chamber, in square meters; m_f is the coefficient taking into account sound attenuation in the air, in 1/3 octave frequency bands of mid-band frequencies f (within the range of 5 000–50 000 Hz), in m^{-1}.

Table 1. Coefficient m depends on the relative air humidity and frequency (for laboratory conditions).

Frequency [Hz]	Coefficient taking into account the attenuation of the sound in the air m [m^{-1}]
250	0.00009
500	0.00025
1000	0.0008
2000	0.0025
4000	0.007
8000	0.02

The coefficient m taking into account sound attenuation in the air depends on the frequency and humidity of the air and it is defined (at this stage of the research) by the use of the extrapolation method for the investigated frequency range of the coefficient given in Table 1. Power curve was used as the extrapolating function (the value of the correlation coefficient $R^2 = 0.9996$). The coefficient m_f (in m^{-1}) for laboratory conditions is defined from the formula (the values of this coefficient shall be specified by the author by means of the measurement method in later studies):

$$m_f = 2 \cdot 10^{-8} \cdot f^{1.57}. \tag{4}$$

The sound absorption coefficient of the room in 1/3 octave frequency bands α_f of mid-band frequencies within the range of 5 000–50 000 Hz, for laboratory conditions is defined from the formula:

$$\alpha_f = 1 - e^{\frac{V}{S_v}\left[-\frac{0.161}{T_f} + 8\cdot 10^{-8}\cdot f^{1.57}\right]}, \tag{5}$$

where V is the volume of the test chamber, in cubic meters; S_v is the area of the inner surface of the test chamber (or with the examined material, the area of the material from the inner side of the chamber), in square meters; T_f is the reverberation time in the test chamber, in 1/3 octave frequency bands of mid-band frequencies f, in seconds; f – the mid-band frequency of 1/3 octave band, in Hz.

In the suggested method, the measurements of very short reverberation times are limited by the measuring equipment. Because this method is based on the measurement of sound fading in a room, it is necessary that the fading is slower than ringing out of the source. In the investigated measuring system, the established limiting value – the lower value of the reverberation time (defined in free field) – is equal to about 0.01 s, which corresponds in the investigated test chamber to a sound absorption coefficient $\alpha > 0.9$. Higher values of the sound absorption coefficient cannot be defined by means of this method; however, this limitation can be accepted taking into account the fact that in practical conditions there is no need to define the sound absorption coefficient above 0.9.

5. Measurement results of the reverberation time and sound absorption coefficient of a few selected materials

While calculating the sound absorption coefficient of materials within the frequency range of 5 000–50 000 Hz, formula (5) is used after measuring the reverberation time in the test chamber (presented in Fig. 1). To increase the accuracy of the measurements, the reverberation time measuring must be performed in 8 points of measurement on the measurement surface of a sphere of the radius of 0.3 m with its centre in the centre of the test room. Results should be averaged (arithmetically).

Verification of the method of determining the sound absorption coefficient was carried out in the frequency range in which one can conduct research in both the test chamber and the standard reverberation chamber. Figure 7 presents the result of the measurement of the sound absorption coefficient of a material made of polyurethane foam performed:

- in the reverberation chamber (Laboratory of the Building Research Institute in Warsaw, room volume of about 200 m^3) with a standard equipment for measuring the sound absorption coefficient of materials (method defined in the standard EN ISO 354:2003, derogation from this method: 2 500–10 000 Hz frequency range under consideration, the sound absorption coefficient is calculated from the formula (5),
- in the test chamber (Noise Laboratory in the Central Institute for Labour Protection – National Research Institute, volume of about 2 m^3) with the equipment set presented in Fig. 1, in the frequency band of 5 000–50 000 Hz.

It can be observed, that in the common frequency range, i.e. 2 000–4 000 Hz, the obtained results were similar, which proves the adequacy of the suggested method.

Figure 8 presents the sound absorption coefficient: of an empty chamber (wood), of a material made of polyurethane foam (Fig. 2), and mineral wool (50 mm).

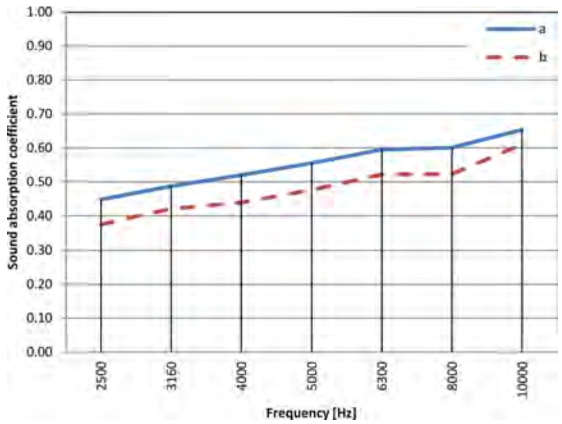

Fig. 7. Sound absorption coefficient of a material made of polyurethane foam in the frequency band 2 500–10 000 Hz: a – defined in a reverberation chamber in standard laboratory (volume 200 m^3), according to the method EN ISO 354:2003, b – defined by means of the suggested method in the test chamber.

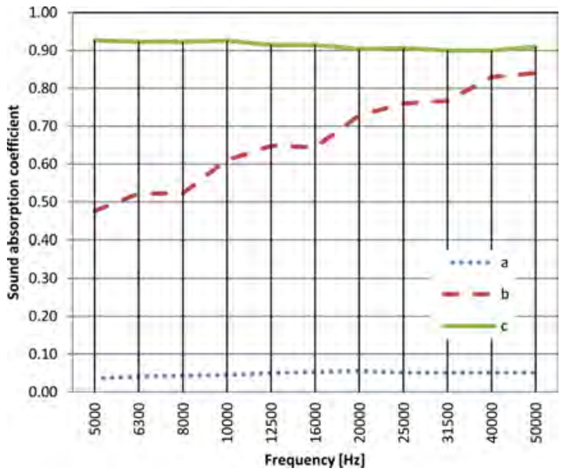

Fig. 8. Sound absorption coefficient of materials in 1/3 octave frequency bands of the test chamber: a – in an empty chamber (wood), b – with polyurethane foam, c – with mineral wool.

6. Result synthesis

The presented method makes it possible to define, by means of a measuring and computational method (with measurement of the reverberation time using the interrupted noise method), the sound absorption coefficient of a material in the frequency range of 5 000–50 000 Hz. The suggested method is defined as an assessment method, since further research has to be performed to enable estimation of its accuracy. It will be a difficult procedure, as in this frequency range properties of materials were not defined and investigated, so no data that could be used as reference is known to exist.

7. Conclusions

The elaborated method can be recognized as a research method which gives approximate results and in the future, after its validation, will be a method of defining acoustic properties of materials in the range of 5 000–50 000 Hz, with respect to their use as sound-absorbent materials for the surfaces of screens or insides of casings, etc.

Acknowledgments

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Active Noise Reduction Algorithm Based on NOTCH Filter and Genetic Algorithm

Paweł GÓRSKI, Leszek MORZYŃSKI

Central Institute for Labour Protection – National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland; e-mail: {pawel; lmorzyns}@ciop.pl

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Application of active noise reduction (ANR) systems in hearing protectors requires the use of control algorithms to ensure stability of the ANR system and at the same time highly effective active noise reduction. A control algorithm based on NOTCH filters is an example of solutions that meet these criteria. Their disadvantage is operation over a narrow frequency band and a need for prior determination of frequencies to be reduced. This paper presents a solution of the ANR system for hearing protectors which is controlled with the use of modified NOTCH filters with parameters determined by a genetic algorithm. Application of a genetic algorithm allows to change the NOTCH filter reference signal frequency, and thus, adapt the filter to the reduced signal frequency.

Keywords: active noise reduction, hearing protectors.

1. Introduction

The commonly used passive hearing protectors, like most passive noise hearing protection measures, are characterized by low attenuation in the low-frequency band (Bismor, 2012). Increased attenuation in the low frequency range is associated primarily with an increase in the weight and size of the hearing protector, which is limited to a certain extent. For this reason, the use of the passive hearing protectors means that employees are not always adequately protected from low frequency noise (Kotarbińska, Kozłowski, 2009). Additionally, non-uniform frequency attenuation of passive hearing protectors (lower attenuation of low frequency sounds and higher attenuation of high frequency sounds) has an adverse impact on the intelligibility of speech of people using hearing protection (Mejia *et al.*, 2008; Canetto, 2009). Sounds of higher frequencies carrying the main information message of the speech signal are attenuated very well, while low-frequency sounds which are the masking signal for the speech signal are poorly attenuated. These problems can be solved by application of active noise reduction systems which allow for a more effective reduction of low-frequency noise (Oinonen *et al.*, 2006). The use of lighter hearing protectors with poorer attenuation in the high-frequency band additionally provided with active noise reduction systems increasing their attenuation in the higher-frequency band often results in improved intelligibility of speech of individuals using hearing protectors (Prashanth, 2010; Pawełczyk, Latoś, 2010).

Active noise reduction (ANR) has been a dynamically developing branch of science since the ‘60s. Active noise reduction is based on the phenomenon of mutual compensation of acoustic waves leading to a decrease in the sound pressure level at a given point in space (Engel *et al.*, 2010). A compensating acoustic wave is created by means of an additional sound source. The acoustic compensation wave has to have in the point of space (point of observation) the same amplitude as the acoustic noise wave and opposite phase. The main issue in the application of ANR systems in hearing protectors is ensuring stability of the ANR system operation and at the same time a highly effective active noise reduction (Pawełczyk, 2004). The ANR system should analyze a noise signal and generate adequate compensating signal taking into account transmittances of the electroacoustic path, including phase shift results from different distances between sources and point of observation (Morzyński, Makarewicz, 2003; Krukowicz, 2010). An example of solutions that meet these criteria is an ANR system which is controlled with the use of NOTCH filters (Mojiri, Bakhshai, 2004). Their disadvantage is operation over a narrow band and a need for prior determination of frequencies to be reduced. Despite the narrow-band nature of operation, these systems can be used to reduce noise of a number of specific groups of machines and equipment found in industry. A number of these sources, such as pumps, ventilation systems, turbines, and others, produce narrowband stationary noise (Engel *et al.*, 2010). In the case of such noise, to achieve the required attenuation performance of an active hearing protector it is sufficient to reduce noise in selected frequency bands.

2. Active noise reduction system with modified NOTCH filters

This paper presents a solution of the ANR system for hearing protectors which is controlled with the use of modified NOTCH filters with parameters determined by a genetic algorithm (Goldberg, 1989; Gwiazda, 2007; Makarewicz, 2007). It is assumed that the active noise reduction system will comprise a number of modified NOTCH filters, connected in parallel.

Typical NOTCH filters, in order to operate correctly, need two sinusoidal reference signals, out of a phase 90° (i.e. $\sin(\theta)$ and $\cos(\theta)$), synchronized with the noise signal. The compensating signal $y(n)$, described by use of the Eq. (1), constitutes a sum of component signals $y_1(n)$ and $y_2(n)$

$$y(n) = y_1(n) + y_2(n) = w_1(n)\sin(\omega(n)) + w_2(n)\cos(\omega(n)) = A\sin(\omega(n) + \varphi). \quad (1)$$

The signals $y_1(n)$ and $y_2(n)$ are products of a reference signal and amplification factors called filter coefficient. Usually values of these factors are settled with use of the LMS algorithm (Bismor, 2012), according to the following equations:

$$w_1(n+1) = w_1(n) + \mu e(n)\sin(\omega(n)), \quad (2)$$

$$w_2(n+1) = w_2(n) + \mu e(n)\cos(\omega(n)), \quad (3)$$

where μ is the value of adaptation coefficient, n is the consecutive number of a sample.

The NOTCH filter modification (Górski, Morzyński, 2012) consists in enabling the change in the reference signal frequency (and consequently adaptation to the reduced signal frequency) by introducing an additional coefficient determining the frequency of the generated reference signal, as shown in Fig. 1.

In the modified NOTCH filter, an additional coefficient w_3 is introduced for determining the frequency of the generated reference signal. This modification allows adaptation of the filter to the frequency of the reference signal. In the modified NOTCH filter, the compensating signal $y(n)$, described with use of the

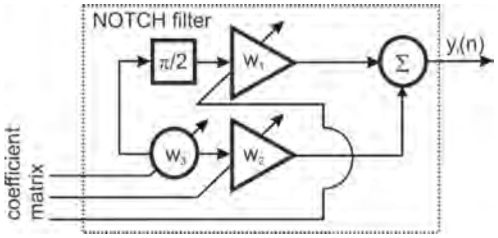

Fig. 1. Block diagram of the modified NOTCH filters.

Eq. (4), constitutes a sum of component signals $y_1(n)$ and $y_2(n)$

$$y(n) = y_1(n) + y_2(n) = w_1\sin(w_3\omega(n)) + w_2\cos(w_3\omega(n)) = A\sin(w_3\omega(n) + \varphi). \quad (4)$$

In this case, it is not possible to apply the LMS algorithm. Figure 2 shows a block diagram of a hearing protector with an active noise reduction system, operating with the use of modified NOTCH filters and a genetic algorithm. The objective of the genetic algorithm is to determine the coefficients of NOTCH filters that allow for achieving the highest possible efficiency of the ANR system and minimize noise reaching the user of the hearing protector; in particular, determining frequencies to be reduced.

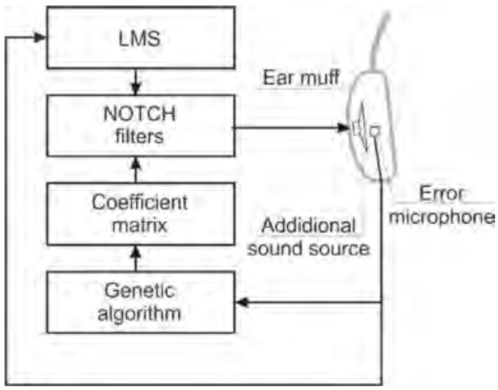

Fig. 2. Active noise reduction system with modified NOTCH filters.

After establishing a set of NOTCH filter coefficients, active noise reduction system switches to the operation mode in which coefficients responsible for frequency change are not changed, and the coefficients w_1 and w_2 are adapted using the LMS algorithm with a very small adaptation step. The user will be able to initiate the process of determination of parameters for the control algorithm using a genetic algorithm whenever such a need arises (e.g. after changing the work room).

Operation of the active noise reduction system control algorithm starts with a genetic algorithm (Fig. 3) creating the initial population of individuals (sets of filter coefficients). Its size is selected experimentally on the basis of numerical simulations. The number of

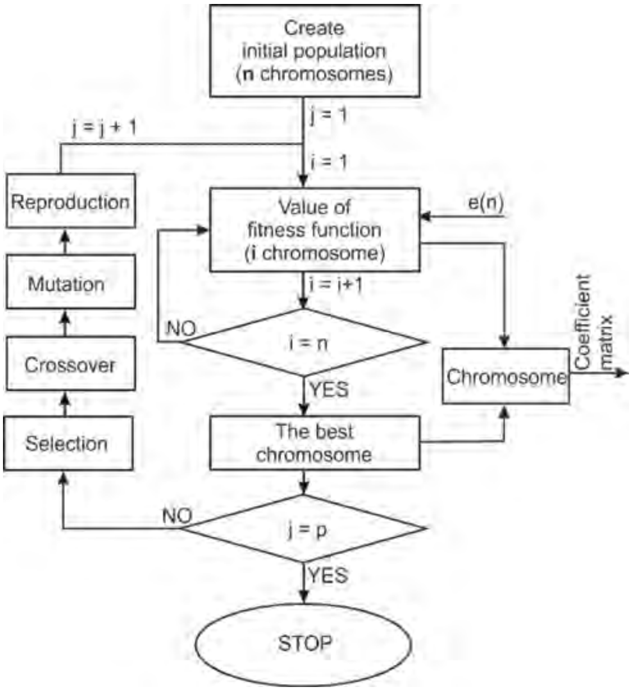

Fig. 3. Block diagram of the genetic algorithm used in an active noise reduction system.

genes in each individual depends on the number of implemented NOTCH filters. Three coefficients will need to be determined for each filter. Their values are real numbers in the range from −1 to 1.

During simulations, calculation of the fitness function involves determination of the simulated error signal vector corresponding to the vector of the sample recorded by the error microphone in a real active noise reduction system. Values of fitness function are calculated for each individual in the population. The same noise signal vector is used to calculate the value of the fitness function for each individual in the population, which is a significant simplification compared to real conditions. In real conditions, the error signal vector is recorded one by one for each individual. For this reason, changes in the (reduced) noise signal cannot be excluded, which can lead to ambiguity in determination of fitness for individuals of a given population.

Selection of the best individual consists in finding an individual with the best fitness. For this individual, the NOTCH filter coefficients are read and assigned to the vector of filter coefficients. After verifying the end condition, which in the algorithm concerned is a certain number of generations, the genetic algorithm ends the operation or enters the stage of the development of new individuals. At the selection stage, a group of individuals with the greatest fitness is selected with the assumed probability. At the stage of crossover of selected individuals in pairs, particular genes are modified in order to obtain individuals with intermediate characteristics. At the stage of mutation of selected individuals, particular genes are modified in order to obtain new values of coefficients which are absent in the selected population. Then, a group of n individuals is selected out of the group of individuals undergoing selection, crossover, and mutation operations to form a new population. After stopping the genetic algorithm and selecting the best individual, the active noise reduction system switches to the operation mode in which it operates using the LMS algorithm. The LMS algorithm is applied due to the fact that the genetic algorithm selects the reduced frequency with a finite accuracy. The genetic algorithm is a stochastic algorithm, the errors of a selected frequency can vary greatly at subsequent runs of the same algorithm. The results of the numerical simulations show that these errors are typically in the range of ±15 Hz.

The effect of the non-ideal determination of the reduced frequency is a generation of two signals with slightly different frequencies, and, consequently, a phenomenon known as beat (Fig. 4).

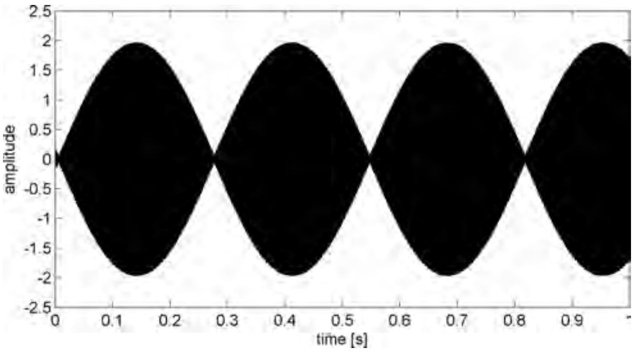

Fig. 4. Sample error signal over time with application of an active noise reduction system with modified NOTCH filters.

3. Numerical simulations

The active noise reduction system presented above was tested using numerical simulations. In order to carry out these tests, the ANR system in the Matlab computing environment was developed. During numerical simulations, analyses were carried out of the impact of modifications in the parameters describing the ANR system. The impact of the size of the initial population, the probability of crossover and mutation and the number of generations was analysed in the group of features describing the genetic algorithm. In the group of describing the ANR system, the number of component frequencies, a change in the frequency of noise signal and the length of the vector of test samples were taken into account.

The main objective of the numerical simulations was to determine the possibility of using the LMS algorithm to reduce the error in determining the reduced signal frequency and estimate the effectiveness of the proposed solution of the ANR system.

Figure 5 shows the waveforms of the noise signal (a tone with a frequency of 400 Hz) before reduction and the reduced signal for the active noise reduction system without the aid of the LMS algorithm. In this case, the genetic algorithm has allowed for signal reduction by about 80%.

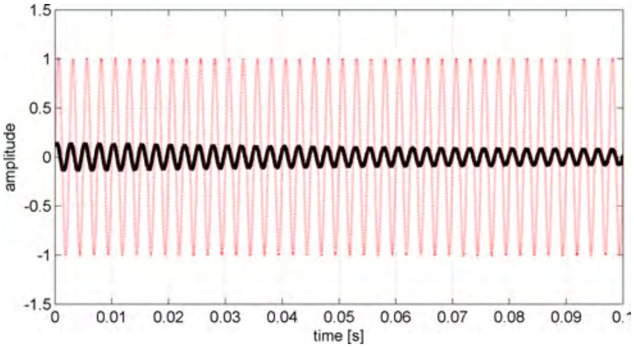

Fig. 5. Waveforms of the noise signal (dotted line) and error signal (solid bold line)with application of an ANR system with modified NOTCH filters.

For the analysed time span, the effectiveness of active noise reduction is about 10 dB (Fig. 6). However, about 0.2% error in determining the reduced signal frequency caused the algorithm to operate correctly only at an early stage (the beat effect).

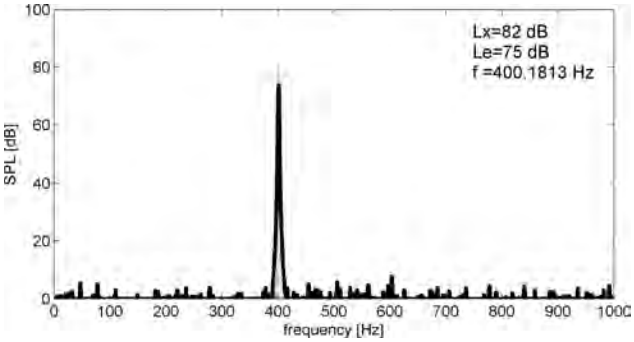

Fig. 6. Spectrum of the noise signal (dotted line) and error signal (solid bold line) with th application of an ANR system with modified NOTCH filters.

Introduction of the LMS algorithm to compensate determination of the reduced frequency error signal by the genetic algorithm eliminated the beat effect and provided a more accurate compensation of the noise signal (Fig. 7). This modification improved the effectiveness of the active noise reduction by up to about 50 dB (Fig. 8).

A similar principle of operation of an active noise reduction system can be applied to multi-tone signals. Figures 9 and 10 show the noise spectrum of a dual-tone signal with the frequencies 400 and 600 Hz, and an error signal. In the first case, the active noise reduction system operated only with the modified NOTCH filters, and in the second case the LMS algorithm was also used.

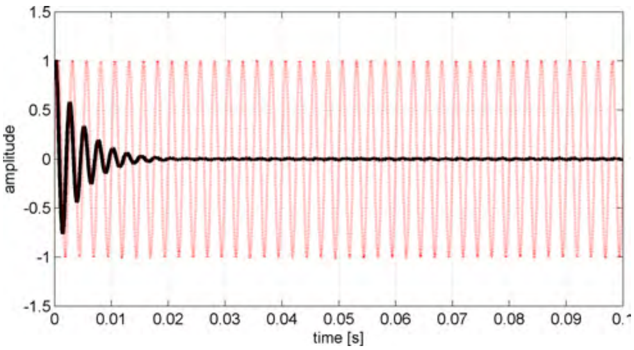

Fig. 7. Waveforms of the noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters and the LMS algorithm.

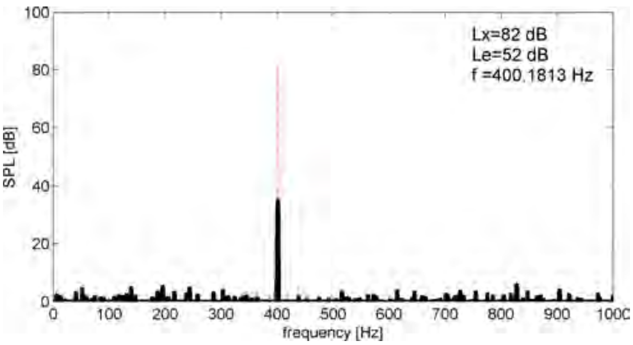

Fig. 8. Spectrum of the noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters and the LMS algorithm.

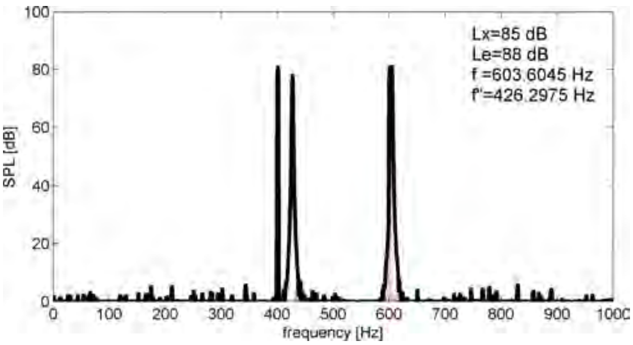

Fig. 9. Spectrum of the two-tone noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters.

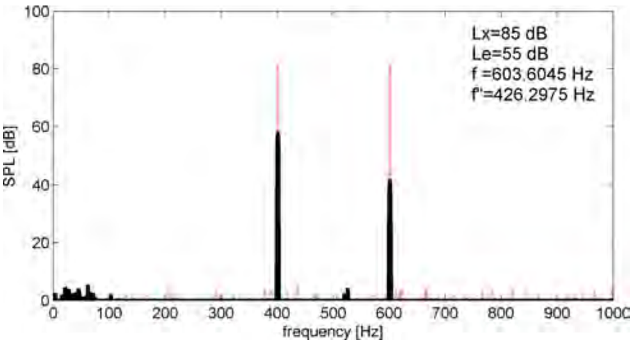

Fig. 10. Spectrum of the two-tone noise signal (dotted line) and error signal (solid bold line) with the application of an ANR system with modified NOTCH filters and the LMS algorithm.

The effectiveness of the active noise reduction with the use of only modified NOTCH filter is about −2 dB (Fig. 9). The genetic algorithm error in determining the reduced signal frequency is about 15–20 Hz. Introduction of the LMS algorithm to compensate the determination error of the reduced frequency signal by a genetic algorithm improved the effectiveness of active noise reduction by up to about 30 dB (Fig. 10).

Figure 11 shows the waveforms of the noise signal (a two-tone with a frequency of 400 and 600 Hz) before reduction and the reduced signal for the ANR system with the application of the modified NOTCH filters and the LMS algorithm. In this case, the genetic algorithm has allowed for signal reduction by about 90%.

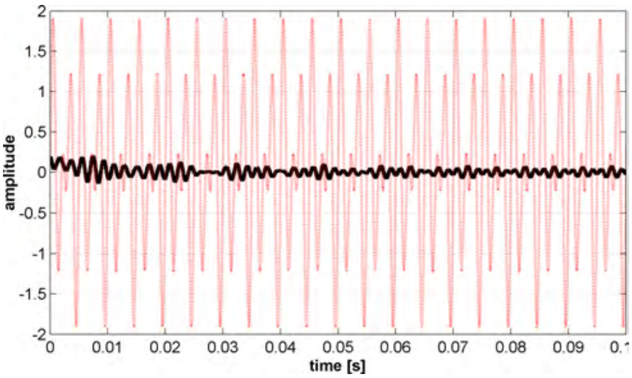

Fig. 11. Waveforms of the two-tone noise signal (dotted line) and error signal (solid bold line) with application of an ANR system with modified NOTCH filters and the LMS algorithm.

4. Summary

A solution of the ANR system for hearing protectors has been presented. In this solution, modified NOTCH filters with parameters determined by a genetic algorithm were used. The ANR system was tested using numerical simulations. The main objective of the numerical simulations was to determine the possibility of using the LMS algorithm to reduce the determination error of the reduced frequency signal and estimate the effectiveness of the proposed solution of the ANR system.

Application of the LMS algorithm to compensate the error in determining the reduced signal frequency by the genetic algorithm can significantly reduce the operation time of the genetic algorithm and considerably improve the efficiency of the entire system. Numerical simulations have shown that for errors in determination of a frequency signal to be reduced by the genetic algorithm of 5 Hz, the maximum design efficiency of active noise reduction is about 55 dB. Lower maximum effectiveness of active noise reduction is achieved for multi-tone signals (about 40 dB). The problem in this case is the appropriate selection of the adaptation step, which has a significant effect on the activation of the ANR system.

Acknowledgments

This paper has been based on the results of a research task carried out within the scope of the second stage of the National Programme "Improvement of safety and working conditions" partly supported in 2011–2013 – within the scope of research and development – by the Ministry of Science and Higher Education/National Centre for Research and Development. The Central Institute for Labour Protection – National Research Institute is the Programme's main coordinator.

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Method of Testing of Sound Absorption Properties of Materials Intended for Ultrasonic Noise Protection

Dariusz PLEBAN

Central Institute for Labour Protection – National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland; e-mail: daple@ciop.pl

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Efficient ultrasonic noise reduction by using enclosures requires the knowledge of absorbing properties of materials in the frequency range above 4 kHz. However, standardized methods enable determination of absorption coefficients of materials in the frequency range up to 4 kHz. For this reason, it is proposed to carry out measurements of the sound absorption properties of materials in the free field by means of a tone-burst technique in the frequency range from 4 kHz to 40 kHz at angles of incidence varying from $0°$ to $60°$. The absorption coefficient of a material is calculated from the reflection coefficient obtained by reflecting a tone-burst from both a perfectly reflecting panel and a combination of this panel and the sample of the tested material. The tests results show that mineral wool and polyurethane open-cell foam possess very good absorbing properties in this frequency range.

Keywords: ultrasonic noise, sound absorption coefficient, tone burst technique, sound absorbing material.

1. Introduction

A trend towards a growth of both the production efficiency and the quality level has contributed, among others, to development of technological applications of ultrasonic devices in which ultrasounds are generated for the purpose of either execution or acceleration or facilitation of assumed technological processes. These devices are characterized by relatively high power and their nominal frequencies in most cases are between 18 kHz and 40 kHz.

Ultrasonic cleaners are the most common devices. The ultrasonic cleaning technology applied for both miniature elements and large structures allows to obtain such a high surface cleanness degree that it is not possible to be achieved with other methods.

The ultrasonic cleaners are followed by ultrasonic drilling machines and ultrasonic welding devices. Ultrasonic drilling is particularly useful for making profile hollows or holes of any shape and high required accuracy regardless of the machined material. This method is used for machining of glass, quartz, natural and synthetic stones of any kind, porcelain, ceramics, titanium, as well as hardened steel and other metals difficult to machine. On the other hand, plastic and metal ultrasonic welding technologies are applied in joining plastic elements (eliminating sizing technologies), in microwelding processes, and in joining fragile and/or hard-weldable materials.

Besides technological ultrasonic devices, there is also a large group of industrial machines and devices which also emit ultrasounds as an unintended accompanying additional factor. The sources of the ultrasounds are phenomena of aerodynamic nature (flow or outflow of compressed gases) or mechanical nature (high rotational speed of machine elements). The presence of ultrasonic components with significant sound pressure levels can be found in the noise in the surroundings of compressors, burners, valves, pneumatic tools and such high-speed machines as planers, millers, grinders, circular saws and certain textile machines. Most of the sound energy emitted by these machines to the environment is within high audible frequencies and low ultrasonic frequencies.

Working in the environment of the above-mentioned technological ultrasonic devices and machines creates hazards not only to the organ of hearing (Smagowska, Mikulski, 2008; Smagowska, 2011) but it can be also bothersome and even harmful due to extra-auditory effects of ultrasounds. It is estimated that about 25 000 employees in Poland are exposed to ultrasonic noise emitted by technological ultrasonic devices and a similar number of employees are exposed to ultrasonic noise emitted by other machines and pieces of equipment.

In relation to the above, the permissible values of ultrasonic noise at work stations were defined in Poland (Minister of Labour and Social Policy, 2002). At the same time, the ultrasonic noise was defined as a noise in the spectrum in which components of high audible frequencies and low ultrasonic frequencies exist (from 10 kHz to 40 kHz) (Augustyńska, Pośniak, 2010).

Low frequency ultrasounds generated by the above-mentioned sources (technological ultrasonic devices, in particular) can penetrate the human body by means of contact (e.g. contact with an ultrasonic transducer or ultrasound-excited fluid). However, the sound energy originating from those sources is always transferred to the human body by means of air. The three basic methods or their combinations of lowering transferred ultrasonic energy are:

- isolation of the source (encapsulation),
- isolation of the receiver (hearing protectors),
- partitions between the source and the receiver.

Considering these primary ways of ultrasonic energy transfer to the human body, it is obvious that the most efficient way of limiting ultrasonic noise hazards are activities taken by device manufacturers consisting in encapsulation of ultrasound sources (in the case of technological ultrasonic devices) and limitation of noise source emissions (in the case of other machines). Due to the specificity of ultrasonic noise (short ultrasound waves) consisting in the occurrence of exposures mainly in the direct neighbourhood of noise sources, the most efficient protective means will be enclosures and acoustic screens which limit noise on its way of propagation. However, efficient noise reduction using the above-mentioned technical methods requires, among others, the knowledge of acoustic properties of materials (including the values of sound absorption coefficients for the materials) in the frequency range above 4 kHz.

2. Methods of determination of sound absorption coefficient

The impedance tube is typically used to measure the physical (normal) sound absorption coefficient. There are many types of impedance tubes. Some tubes are made of metal; other tubes, of a larger cross-sectional area, are made of air-tight and smooth concrete. The cross section of the tubes is usually circular and – less frequently – rectangular. The physical sound absorption coefficient can be determined by two standard methods: the method using the standing wave ratio (EN ISO 10534-1, 2001) or the transfer-function method (EN ISO 10534-2, 2001). Moreover, the physical sound absorption coefficient for materials can be determined in the free field conditions using one of the following three methods (Hirosawa *et al.*, 2009) consisting in:

- measuring acoustic impedance at a single point in the vicinity of the material,
- estimating impedance based on the transfer function between sound pressures measured at two points,
- estimating impedance based on the transfer function between sound velocities measured at two points.

However, for a dissipated (or dispersed) sound composed of waves propagating in all directions, the absorption coefficient has a certain mean value called the reverberant sound absorption coefficient α_s. This parameter characterizes a sound absorbing material and is determined on the basis of measurements made in laboratory conditions – in a reverberation room (EN ISO 354, 2003).

The above methods allow to determine the values of sound absorption coefficients for materials in a limited frequency range from 100 Hz to 5 kHz. The bibliography (Sikora, 2011; Tijs, Druyvesteyn, 2012) or catalogues (*Acoustic absorption data* (n.d.)) sporadically present results of determining sound absorption coefficients in the frequency range up to 6 300 Hz or 8 000 Hz. In principle, there is no data available for a higher frequency range since the commonly applied reverberant standard methods can not be used in a high-frequency range due to strong sound absorption by air.

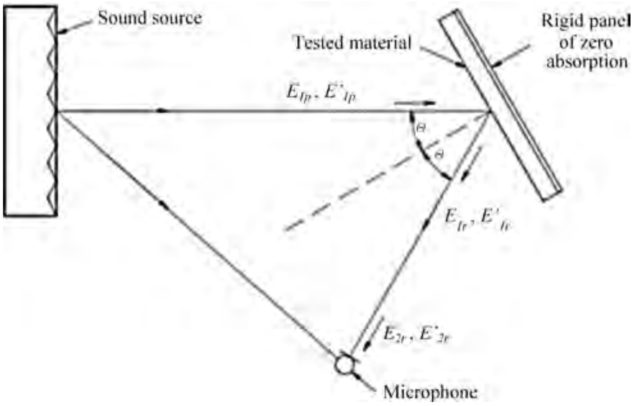
A solution to this problem could be the application of the reverberant standard method in a special miniaturized test chamber (Dobrucki *et al.*, 2010) or the use of the impulse method (the tone-burst technique).

3. Impulse method

The tone-burst technique consists in determination of sound absorption coefficient for a material using the impulse method as a function of a sound wave incidence angle in the free field conditions. Figure 1 presents the general principle of this method.

Assuming that:

- free field conditions exist,
- sound sources emit plane wave,
- the dimensions of the tested material are several times larger than the incident acoustic wave length,
- the sound absorption coefficient of the rigid panel is equal to zero,
- the energy losses between the tested material and the microphone do not depend on the tested material,



E_{1p} – energy of an impulse incident at a rigid panel of zero absorption,
E'_{1p} – energy of an impulse incident at a sample of the tested material placed on the panel,
E_{1r} – energy of an impulse reflected from the panel,
E'_{1r} – energy of an impulse reflected from the sample of the material,
E_{2r} – energy of an impulse reflected from the panel reaching the microphone,
E'_{2r} – energy of an impulse reflected from the sample of the material reaching the microphone,
Θ – sound wave incidence angle.

Fig. 1. Principle of the sound absorption coefficient measurement using the impulse method.

the sound reflection coefficient can be expressed by the formula:

$$r - \frac{E'_{2r}}{E_{2r}} = \left(\frac{p'_{2r}}{p_{2r}}\right)^2 \tag{1}$$

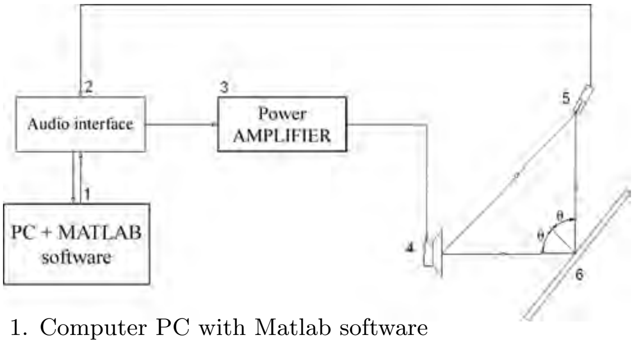
and the sound absorption coefficient can be determined from the relation:

$$\alpha = 1 - \left(\frac{p'_{2r}}{p_{2r}}\right), \tag{2}$$

where p'_{2r} is the sound pressure of an impulse reflected from the tested material placed on the rigid panel, and p_{2r} is the sound pressure of an impulse reflected from the rigid panel.

Equation (2) implies that measurements of the sound pressure levels for both the impulse reflected from the tested material and the impulse reflected from the rigid panel should be carried out in order to determine the sound absorption coefficient.

A variable sound wave incidence angle with respect to the panel/tested material is obtained by a change of the panel position angle or by a possibility of controlling the position of the microphone and the sound impulse source. Figure 2 shows a diagram of a designed and constructed test stand for the measurement of the directional sound absorption coefficient using the impulse method in the frequency range from 4 kHz to 40 kHz.



1. Computer PC with Matlab software
2. RME Fireface 400 audio interface
3. B&K 2706 power amplifier
4. Sound source
5. 1/4" B&K 4135 measurement microphone
6. Panel assumed as perfectly reflecting acoustic energy (the assumption is valid for the frequency range of 4 kHz – 40 kHz)

Θ – sound wave incidence angle.

Fig. 2. Diagram of a test stand for the measurement of sound absorption coefficients for materials using the impulse method in the frequency range up to 40 kHz.

4. Test results

The experimental tests included sound absorption coefficient measurements in the frequency range from 4 kHz to 40 kHz for the following material samples:

- mineral wool with thickness of 60 mm, with a glass fibre mat (ROCKWOOL ROCKTON 60),
- mineral wool with thickness of 80 mm (ROCKWOOL ROCKTON 80),
- mineral wool with thickness of 100 mm (ROCKWOOL ROCKTON 100),
- polyurethane open-cell foam, with the corrugated front surface (APAMA G classic),
- furniture fibreboard with thickness of 4 mm over a distance of 1 cm from the rigid panel (on the frame around).

The measurements were performed in the abovementioned frequency range in 200 Hz steps for the following sound wave incidence angles: 0°, 10°, 20°, 30°, 40°, 50°, and 60°. Examples of the measurement results are presented in Figs. 3, 4, and 5.

No significant effect of the sound wave incidence angle on the absorption coefficient value for mineral wool with thickness of 60 mm (Fig. 3) was found. The determined values of the coefficient in the examined frequency range and for the analysed angles of incidence are high, i.e. from 0.79 to 0.99, and the values exceeding 0.9 prevail. It can be noticed that local decreases of the sound absorption coefficient values generally occur for the same or neighbouring frequency bands for the given sound wave incidence angle.

However, an analysis of the results presented in Fig. 4 for mineral wool shows that there is no significant effect of the sample thickness on the sound

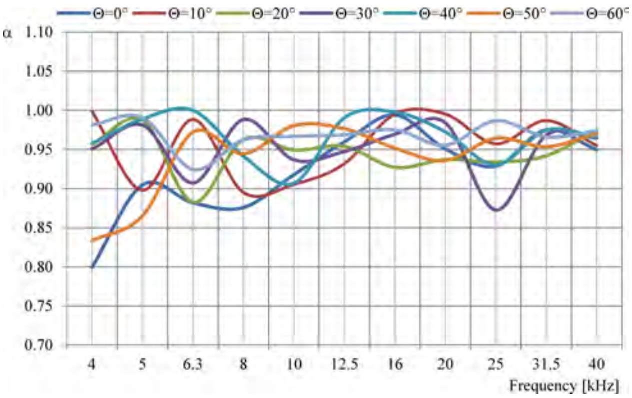


Fig. 3. Values of the directional sound absorption coefficients for mineral wool with thickness of 60 mm (ROCKWOOL ROCKTON 60) for the sound wave incidence angles of 0°, 10°, 20°, 30°, 40°, 50° and 60°.

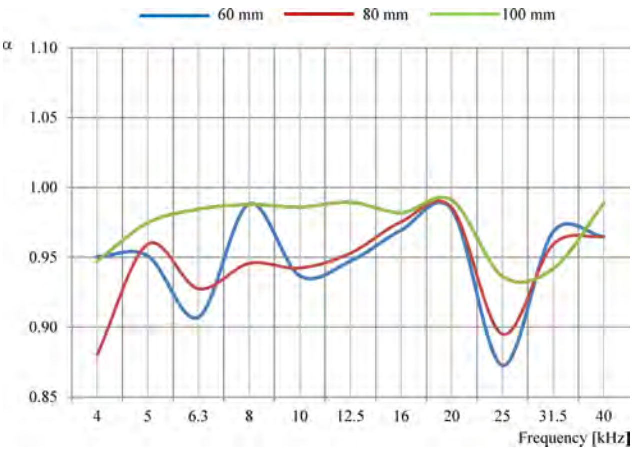


Fig. 4. Values of the directional sound absorption coefficient for mineral wool (ROCKWOOL ROCKTON) with thickness of 60 mm, 80 mm, 100 mm for the sound wave incidence angle of 30°.

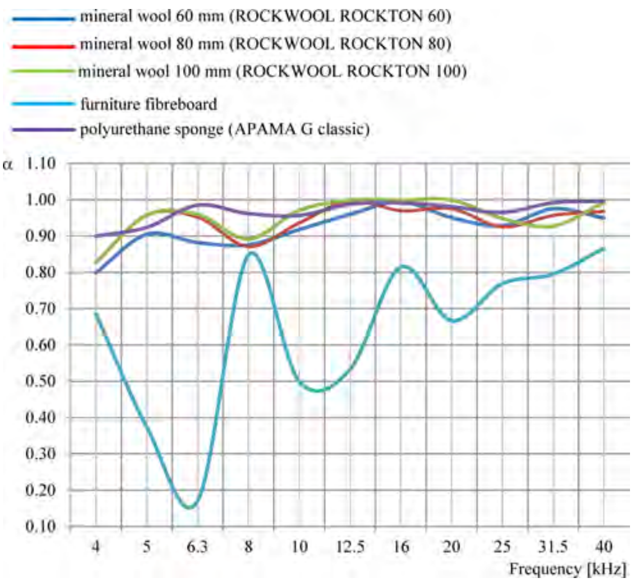


Fig. 5. Values of the directional sound absorption coefficients for tested materials for the sound wave incidence angle of 0°.

absorption coefficient values. Each of the tested mineral wool samples was characterized by high values of the sound absorption coefficient and for the incidence angle of 30°, they ranged from 0.88 to 0.99 and for frequencies above 10 kHz, the following relation can be observed: the larger thickness of mineral wool, the higher value of the sound absorption coefficient.

The latter of the above figures (Fig. 5) shows a comparison of the sound absorption coefficients of all tested samples for the sound wave incidence angle of 0° also known as the normal sound absorption coefficient. Except for the thin furniture panel which cannot be considered a good sound absorbing material (the sound absorption coefficient values for this sample vary from 0.37 to 0.86 and their distribution as a function of frequency reflects a resonance nature of this structure), the remaining materials possess very similar values of the sound absorption coefficients. The values are:

- from 0.79 to 0.99 for mineral wool with thickness of 60 mm (ROCKWOOL ROCKTON 60),
- from 0.82 to 1 for mineral wool with thickness of 80 mm (ROCKWOOL ROCKTON 80),
- from 0.83 to 1 for mineral wool with thickness of 100 mm (ROCKWOOL ROCKTON 100),
- from 0.9 to 1 for polyurethane open cell foam (APAMA G classic).

5. Conclusions

The knowledge of the sound absorbing material properties in the frequency range above 4 kHz enables proper selection of a design of collective equipment protecting from high-frequency noise (including ultrasonic noise) emitted by various machines and high speed devices as well as technological ultrasonic devices which are more and more commonly applied in modern manufacturing processes.

The developed impulse sound absorption coefficient measurement method for materials as a function of the sound wave incidence angle allows to determine the sound absorbing material properties in the frequency range from 4 kHz to 40 kHz.

The tests performed on mineral wool samples with different thickness (60 mm, 80 mm, and 100 mm) and polyurethane open-cell foam samples have shown:

- very good sound absorbing properties of mineral wool and polyurethane open-cell foam in the frequency range from 4 kHz to 40 kHz – in this frequency range, the sound absorption coefficient for the tested materials was close or equal to one,
- no significant effect of the mineral wool sample thickness on the values of the measured sound absorption coefficient, since thickness was larger than wave length of the incident signal,

- no significant relation between the values of the sound absorption coefficient for the tested materials and the sound wave incidence angle.

However, the results of the performed tests of the fibreboard in the rigid frame confirm not only a resonance nature of this structure which manifests itself in a large spread of the sound absorption coefficient values depending on the frequency and sound wave incidence angle, but the results also confirm worse sound absorbing properties of this sample in comparison with mineral wool and polyurethane open-cell foam.

Acknowledgments

This paper has been based on the results of a research task carried out within the scope of the second stage of the National Programme "Improvement of safety and working conditions" partly supported in 2011–2013 – within the scope of research and development – by the Ministry of Science and Higher Education/National Centre for Research and Development. The Central Institute for Labour Protection-National Research Institute is the Programme's main co-ordinator.

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Hammerstein Nonlinear Active Noise Control with the Filtered-Error LMS Algorithm

Krzysztof MAZUR, Marek PAWEŁCZYK

Institute of Automatic Control, Silesian University of Technology
Akademicka 16, 44-100 Gliwice, Poland; e-mail: {Krzysztof.Jan.Mazur, Marek.Pawelczyk}@polsl.pl

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Active Noise Control (ANC) of noise transmitted through a vibrating plate causes many problems not observed in classical ANC using loudspeakers. They are mainly due to vibrations of a not ideally clamped plate and use of nonlinear actuators, like MFC patches. In case of noise transmission though a plate, nonlinerities exist in both primary and secondary paths.

Existence of nonlinerities in the system may degrade performance of a linear feedforward control system usually used for ANC. The performance degradation is especially visible for simple deterministic noise, such as tonal noise, where very high reduction is expected. Linear feedforward systems in such cases are unable to cope with higher harmonics generated by the nonlinearities. Moreover, nonlinearities, if not properly tackled with, may cause divergence of an adaptive control system.

In this paper a feedforward ANC system reducing sound transmitted through a vibrating plate is presented. The ANC system uses nonlinear control filters to suppress negative effects of nonlinearies in the system. Filtered-error LMS algorithm, found more suitable than usually used Filtered-reference LMS algorithm, is employed for updating parameters of the nonlinear filters. The control system is experimentally verified and obtained results are discussed.

Keywords: active noise-vibration control, active structural acoustic control, adaptive algorithm, nonlinear system.

1. Introduction

Vibrating plates are very attractive for noise reduction systems. They can be used as secondary sources in ANC systems or as active acoustic barriers (Hansen, Snyder, 1997; Fahy, Gardonio, 2007). In the latter application the noise transmitted through a plate is reduced. Such active barriers can be much thinner than comparable passive barriers. Double panel systems with two plates separated by a cavity are even more beneficial, because they can provide improvement in transmission loss as compared to the single plate (Pietrzko, 2009).

The plate itself provides some passive noise reduction. The reduction can be improved by using shunt damping systems (Tawfik, Baz, 2006; Pietrzko, 2009). In such systems the vibration energy is converted to electrical energy, usually by piezoelectric patches, and then it is dissipated in appropriately designed RLC circuits. Noise reduction can be further improved by using semi-active shunt systems, where a control system modifies parameters of RLC circuits. This technique is very attractive because of a very low energy consumption of the control system.

The reduction of sound transmitted though a plate can also be improved by using active control. In such systems the plate vibrations are usually controlled by electromagnetic or piezoelectric actuators mounted on a plate. Such actuators can be used to reduce vibrations (active structural acoustic control) or to generated vibrations in order to reduce the sound pressure level at selected locations (active noise-vibration control).

For active control systems, the Filtered-reference FXLMS algorithm, which is especially popular in Active Noise Control systems, is commonly used. This algorithm, however, exhibits a slow convergence rate. Recursive Least Squares or other computationally exhausting algorithms are used to speed the system up (Leniowska, Kos, 2009; Leniowska, 2011).

In this paper reduction of sound pressure level at a single point, where the error microphone is located is investigated. However, presented algorithms can be easily extended to reduce sound pressure level or sound intensity in multiple points, and provide larger area of reduced sound. Also the location of the area can be shifted by using Virtual Microphone Control (Pawełczyk, 2003).

2. Filtered-reference LMS

For systems that should cope with possibly non-deterministic and wide-band noise, feedforward control is usually used. In case of noise reduction in rooms, lack of changes in acoustic paths cannot be usually assumed. When a vibrating plate is used, also temperature change may lead to changes in electroacoustic paths (Mazur, Pawełczyk, 2011a). Adaptive control is then the most appropriate technique. In such systems a signal correlated with the noise is acquired and used as the reference signal. The reference signal is then filtered by an adaptive linear (in terms of parameters) control filter to obtain the control signal and drive the secondary source. Filtered-reference LMS (FXLMS) algorithm is usually used for updating the control filter (Kuo, Morgan, 1996).

Figure 1 shows the block diagram of typical multichannel ANC system with the FXLMS algorithm (Kuo, Morgan, 1996; Elliott, 2001). This system is presented here in brief to give a reference for the remainder of the paper.

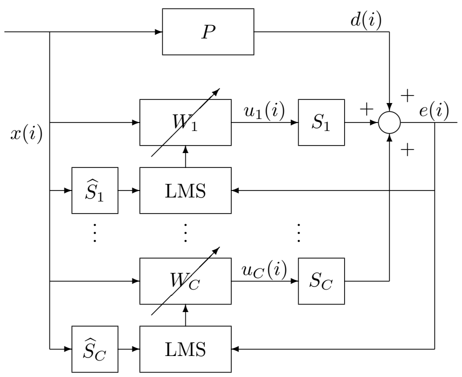

Fig. 1. Active Noise Control system diagram.

In Fig. 1 $x(i)$ is the reference signal, P is the primary path, $d(i)$ is the primary noise at the point of interest, $e(i)$ is the error signal, S_1–S_C are the secondary paths, the symbols with hats stand for models of respective paths and W_1–W_C are control filters, one for each secondary path.

The j-th control signal is obtained according to:

$$u_j(i+1) = \mathbf{w}_j(i)^{\mathrm{T}}\mathbf{x}_u(i), \tag{1}$$

where $\mathbf{w}_j(i) = [w_{j,0}(i), w_{j,1}(i), \dots, w_{j,N-1}(i)]^{\mathrm{T}}$ is a vector of parameters of the j-th control filter and $\mathbf{x}_u(i) = [x(i), x(i-1), \dots, x(i-(N-1))]^{\mathrm{T}}$ is a vector of recent N reference signal samples.

When Normalized FXLMS algorithm is used control filter parameters are updated using the following formula (Elliott, 2001):

$$\mathbf{w}_j(i+1) = \mathbf{w}_j(i) - \mu \frac{\mathbf{r}_j(i)}{\sum\limits_{k=0}^{C} \mathbf{r}_k^{\mathrm{T}}(i)\mathbf{r}_k(i) + \zeta} e(i), \tag{2}$$

where μ is the convergence coefficient, and ζ is a parameter protecting against division by zero in case of lack of excitation. In this equation $\mathbf{r}_j(i) = [r_j(i), r_j(i-1), \dots, r_j(i-(N-1))]^{\mathrm{T}}$ is a vector of N regressors of the filtered-reference signal, with elements obtained as:

$$r_j(i) = \widehat{\mathbf{s}}_j(i)^{\mathrm{T}}\mathbf{x}(i), \tag{3}$$

where $\widehat{\mathbf{s}}_j(i) = [\widehat{s}_{j,0}(i), \widehat{s}_{j,1}(i), \dots, \widehat{s}_{j,M-1}(i)]$ is a model of the j-th secondary path filter impulse response, $\mathbf{x}(i) = [x(i), x(i-1), \dots, x(i-(M-1))]^{\mathrm{T}}$ is a vector of regressors of the reference signal. Zero initial conditions, $\mathbf{w}_{j,k}(i) = 0$ for $k \in \mathbb{Z}$, $0 \le k \le (N-1)$, were used.

3. Nonlinear feedforward control

The FXLMS algorithm works satisfactorily for typical ANC systems, where primary and secondary paths are linear. Then, assuming that the primary source generates a tonal sound, tones of the same frequency, modified only in amplitude and phase arrive to the reference and error sensors, respectively. With classical loudspeakers used as secondary sources, the assumption concerning the secondary path is usually acceptable. However, in case of vibrating plates used as secondary sources, the secondary paths are nonlinear. Additionally, if sound transmission through the plates is concerned (what is the subject of this paper), the primary paths are also nonlinear. The nonlinearities can be caused due to vibrations of clamped plates (El Kadiri *et al.*, 1999; Saha *et al.*, 2005) and also by actuators (i.e. d33 effect of MFC patches) (Stuebner *et al.*, 2009).

Nonlinearity in the primary or/and the secondary path generates higher harmonics of the original signal and can degrade performance of such systems, because a linear control cannot generate frequencies that are not present in the reference signal. In the simplest case of reduction of tonal noise the nonlinearity in primary path will cause presence of additional harmonic frequencies at the point of interest. Introducing a nonlinearity in the secondary path will cause generation of additional harmonic frequencies of the control signal. In both cases, even when the fundamental tone were successfully reduced by the ANC system its harmonics would be present at the area, where noise reduction is demanded. The control system would not be able to reduce them because the linear control filter with sinusoidal input can only change phase and amplitude and cannot generate different frequencies. Feed-back systems have the potential to mitigate the effect of plant nonlinearity to some extent. However, they cannot be effectively used for non-deterministic wide-band disturbances. Also in case of nonlinearities in the system, the reduction of unwanted harmonics in linear feedback systems may be limited and worse than in nonlinear feedforward systems (Mazur, Pawełczyk, 2011b).

The output of general nonlinear adaptive finite impulse response filter can be written as:

$$u_j(i+1) = f(x(i), x(i-1), \ldots, x(x-N_B), \\ w_{j,0}, w_{j,1}, \ldots, w_{j,k}, \ldots, w_{j,K-1}), \tag{4}$$

where $u_j(i+1)$ is the value of the control signal in the $i+1$ sample, f is an arbitrary nonlinear function, x is the reference signal and $w_{j,k}$ is the k-th coefficient for filter for j-th control signal. In such general form, the optimal nonlinear function f and filter coefficients are hard to find.

Because of this, some structured filters, e.g. artificial neural networks can be used (Hansen, Snyder, 1997). Second large group of filters used in Nonlinear Active Noise Control (NANC) are filters, which are linear with respect to parameters:

$$u_j(i+1) = \sum_{k=0}^{K-1} w_{j,k} \\ f_k(x(i), x(i-1), \ldots, x(x-N_B)). \tag{5}$$

For such filters optimal coefficients can be more easily obtained. In case of adaptive control simple classical algorithms, like LMS or RLS, can be employed for adaptation. For ANC, where the secondary path is present, the algorithms are extended by filtering the reference signal through a model of that path. FXLMS has been found as an efficient algorithm for adaptation (Fig. 2). The past N_B+1 regressors of reference signal x are processed by a bank of K nonlinear f_k functions. The sum of results of each function multiplied by w_k coefficient gives the control signal.

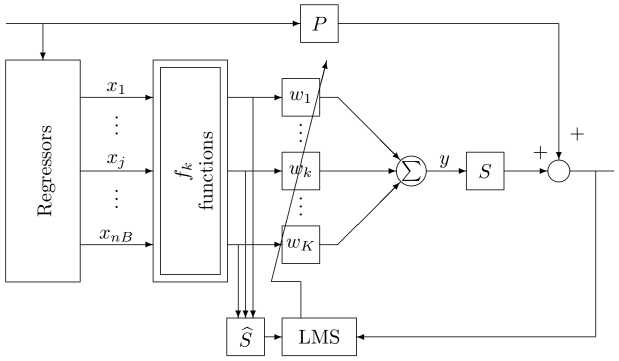

Fig. 2. Active Noise Control system with nonlinear filter linear with respect to parameters using FXLMS algorithm.

There are many possibilities for choosing f_k functions. They can be multivariable polynomials of a specified order with previous samples of reference signal x as independent variables. Such functions are used in the Volterra FXLMS algorithm (Tan, Jiang, 2001). Other common approach is to choose functional-link Artificial Neural Network (FLANN), what is behind the Filtered-s LMS algorithm (Das, Panda, 2004).

Also sum of Hammerstein models can be used as non-linear filter (Mazur, Pawełczyk, 2011b). The Hammerstein model combines nonlinear static function with linear dynamics:

$$u_j(i+1) = \sum_{k=0}^{K-1} W_{j,k}(z^{-1}) F_k(x(i)), \tag{6}$$

where $W_{j,k}(z^{-1})$ is the linear finite response filter for j-th control signal and k-th nonlinear function, z^{-1} is the one sample delay operator and F_k are functions.

Such model leads directly to a simpler and less computationally demanding implementation. This system can be seen as a linear K-channel ANC system of K reference inputs, generated by nonlinear F_k functions. Multichannel FXLMS algorithm (Tu, Fuller, 2000) can be used for adaptation of $W_{j,k}(z^{-1})$ filters (Fig. 3).

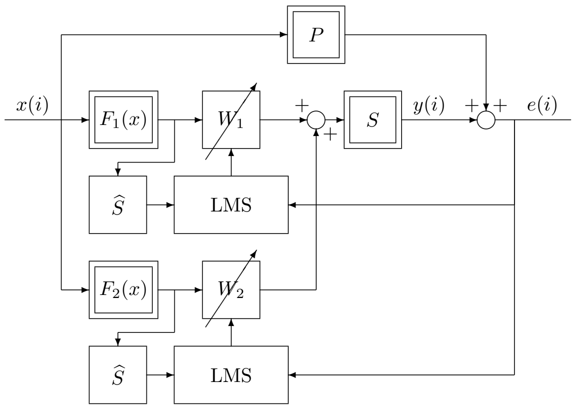

Fig. 3. ANC system with Hammerstein nonlinear control filters using FXLMS algorithm.

This model can be also extended by combining values of reference signal from different samples:

$$u_j(i+1) = \sum_{k=0}^{K-1} W_{j,k}(z^{-1}) \\ F_k(x(i), x(i-1), \ldots, x(x-R)). \tag{7}$$

4. Filtered-error LMS

For the application concerned, the FXLMS algorithm involves two significant problems. Firstly, each reference signal must be filtered by a secondary path model. Because multiple virtual reference signals generated from the single reference signal are used, a large number of operations is needed. The second problem is that the FXLMS algorithm assumes linearity of the secondary path. Nonlinear secondary path model cannot be simply used in this structure. Both problems can be solved by using the Filtered-error (FELMS) structure, which is presented for a linear filter, e.g. in Kuo, Morgan (1996). The number of filters in the Filtered-error LMS does not depend on the number of reference signals.

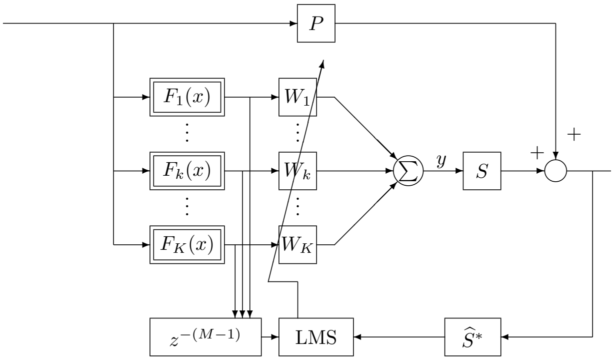

Fig. 4. ANC system with Hammerstein nonlinear control filters using FELMS algorithm.

For adaptation of filter coefficients the Normalized FELMS algorithm can be applied. Control filter parameters are updated using the following formula:

$$\mathbf{w}_j(i+1) = \mathbf{w}_j(i) - \mu \frac{\mathbf{x}_j^*(i)}{\sum\limits_{k=0}^{C} \mathbf{x}_k^{*\mathrm{T}}(i)\mathbf{x}_k^*(i) + \zeta} e^*(i), \quad (8)$$

where $\mathbf{x}^*(i) = \mathbf{x}(i+(M-1))$ is a vector of regressors of the delayed reference signal and $e_j^*(i)$ stands for the filtered error obtained as:

$$e_j^*(i) = \widehat{\mathbf{s}}_j(i)^{\mathrm{T}}\mathbf{e}(i), \quad (9)$$

where $\widehat{\mathbf{s}}_j(i) = [\widehat{s}_{j,M-1}(i), \widehat{s}_{j,M-2}(i), \ldots, \widehat{s}_{j,0}(i)]$ is a model of the j-th secondary path filter impulse response, $\mathbf{e}(i) = [e(i), e(i-1), \ldots, e(i-(M-1))]^{\mathrm{T}}$ is a vector of regressors of the error signal.

5. Experimental results

The noise transmitted through a fully clamped aluminum plate is considered (Fig. 5). The plate is 1 mm thick. The noise is generated by a loudspeaker in the enclosure on one side of the plate, and it is transmitted to laboratory room. The primary noise is monitored by a reference microphone. The sound transmitted from that enclosure through the plate is measured by an error microphone located 1.2 m away from the plate at the centre line in the laboratory room. The goal of the control system is to reduce sound pressure level at a given area, where the error microphone is located.

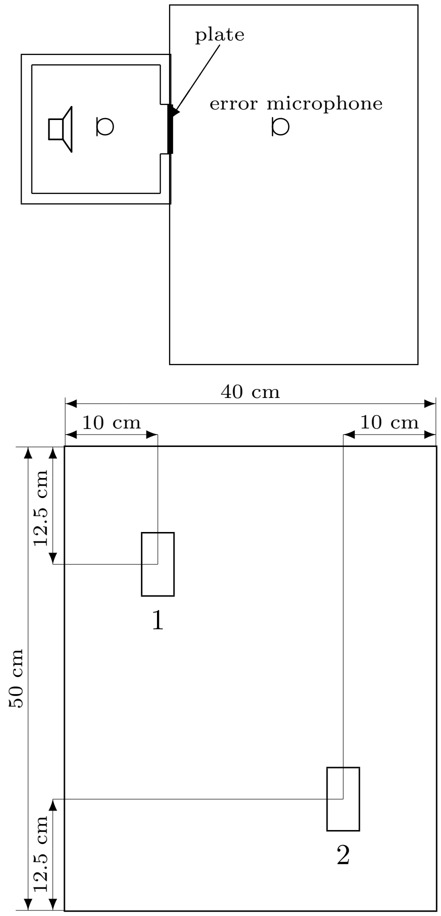

Fig. 5. Laboratory setup (top) and MFC patches on a plate (bottom).

Two d33-effect Macro-Fiber Composite (MFC) patches working in bending mode are used as actuators. MFC is a piezoelectric actuator. Such actuators are recently frequently used for active control of plates and other structures (Sodano *et al.*, 2004; Górski, Kozupa, 2012). They provide higher power-to-weight ratio than PZT patches. The positions of actuators have been chosen experimentally to maximize sound radiation from the plate for the selected frequency band. An alternative approach would be to perform optimization using numerical methods to solve the model as in (Bruant *et al.*, 2010; Górski, Kozupa, 2012; Kedziora, Muc, 2012) or to guarantee controllability of vibration modes by maximizing eigenvalues of appropriate grammian matrix (Wrona, Pawełczyk, 2013).

For all experiments the sampling frequency has been set to 4 kHz, and 8th order Butterworth low-pass analogue filters with 1200 Hz cut-off frequency have been used as antialiasing and reconstruction filters. The order of the FIR path models has been $M = 256$ for all experiments. This value has been chosen based on impulse response analysis. The order of the FIR control filters has been $N = 256$ for all experiments.

Filtered-error structure has been used. For nonlinear control, two functions $F_1 = x$ and $F_2 = x^3$ have been used.

For tests, two simple deterministic signals 382 Hz tone and sum of 382 Hz and 504 Hz tones have been selected due to high possible reduction of such noises by ANC system without causality problems. The frequencies for tonal signals have been roughly selected for the secondary path to yield a high gain. The exact choice has been dictated to have a high least common multiple with the other frequency and the sampling frequency, to avoid aliasing of harmonic frequencies. The third signal is a recorded real-world noise originating from ball-bearing pulverizers.

Figure 6 shows the PSD of A-weighted noise measured by the error microphone for 382 Hz tonal noise. The ANC system with linear control filter has been able to reduce the fundamental frequency to the noise floor level, however some clearly visible harmonic frequencies have been generated. The measured sound pressure level reduction is equal to 22.0 dB. However, the dominating third harmonic is in the band of a higher sensitivity of the human hearing system. With the A-weighting, the reduction level drops to 17.3 dB. The ANC system with nonlinear control filters has been able to reduce the third harmonic to the noise floor level and improve sound pressure level reduction to 28.7 dB, and to 27.9 dB with the A-weighting. It is in accordance with the design assumption, because it has been noticed that the highest noise reduction could be achieved by reducing the third harmonic, and hence the nonlinear function $F_2 = x^3$ has been selected. Further improvements can be obtained by adding more non-linear functions or, for simple signals, by using nonlinear functions, which would generate multiple harmonics.

Figure 7 shows the PSD of A-weighted noise measured by the error microphone for sum of two tones – 382 Hz and 504 Hz. Similarly to the single tone case, the third harmonic after reduction by the ANC system with linear control filter is dominant. By applying the ANC system with nonlinear control filters, the A-weighted noise reduction level was improved from 15.3 dB to 23.9 dB.

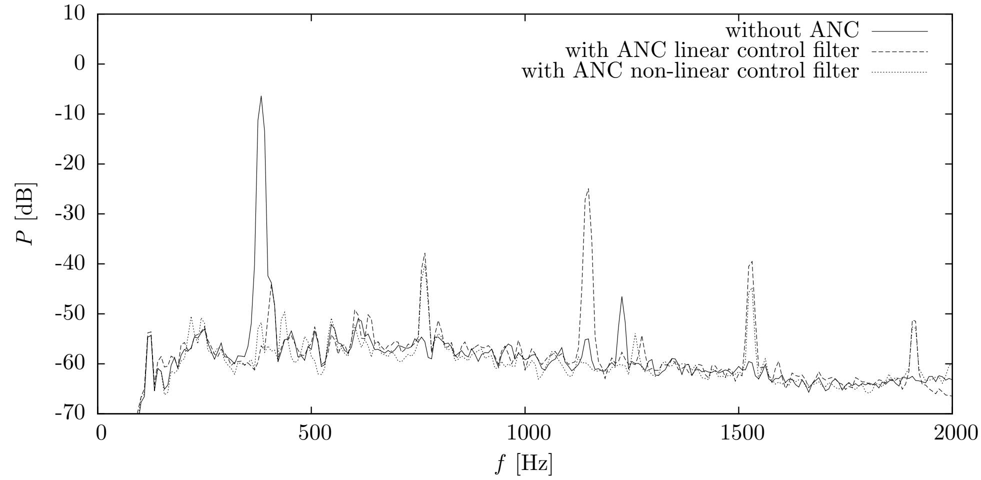

Fig. 6. PSD of A-weighted error microphone signal for different control strategies for 382 Hz tonal noise.

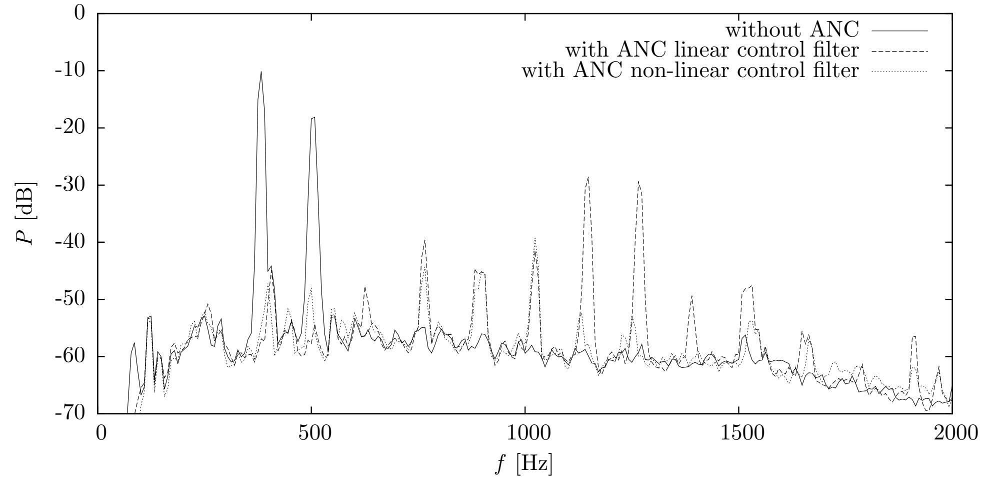

Fig. 7. PSD of A-weighted error microphone signal for different control strategies for sum of 382 Hz and 504 Hz tones.

For more complex noise signals such as recorded noise from ball-bearing pulverizers the improvement is much lower (see Table 1). In such case nonlinear distortions have lower power than residue from active reduction of primary noise.

Table 1. Noise Pressure Levels measured without active control and with different control systems operating (A-weighted).

Noise	without ANC [dB]	FXLMS [dB]	nonlinear FELMS [dB]
382 Hz tone	87.0	69.7	59.1
382 Hz + 504 Hz tones	82.8	67.5	58.9
ball-bearing pulverizers	74.7	64.6	64.1

6. Conclusions

In this paper the problem of Active Noise Control of sound transmitted though a vibrating plate has been considered. Nonlinearity of the vibrating plate significantly degrades performance of the ANC system. The human hearing system is more sensitive to higher harmonics than to fundamental frequencies of the noise usually tackled with by active means.

By using a nonlinear control filter the performance of ANC can be improved resulting in a high acoustic comfort. The nonlinear control filter, however, comes with the cost of huge increase of computational load. Application of the Filtered-error LMS algorithm instead of the Filtered-reference LMS algorithm is therefore beneficial, because the set of generated reference signals does not need filtering.

Significant improvements have been obtained only for simple signals where noise reduction level was high and nonlinear distortions were dominant. The idea needs further development for wide-band noises.

Acknowledgments

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Urban Noise Annoyance Between 2001 and 2013 – Study in a Romanian City

Diana Ioana POPESCU, Iuliana Fabiola MOHOLEA, Radu Mircea MORARIU-GLIGOR

Technical University of Cluj-Napoca, Faculty of Machine Building
B-dul Muncii 103-105, 400641 Cluj-Napoca, Romania; e-mail: Diana.Popescu@mep.utcluj.ro

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The paper presents results of three socio-acoustic surveys conducted in an interval of twelve years, between 2001 and 2013, in a large Romanian city, Cluj-Napoca. The purpose of the surveys was to assess the awareness of residents on urban noise and the extent to which the noise environment affects their everyday life, behavior and health. The surveys were conducted in 2001, 2009 and 2013. The questionnaire used in the first survey had 16 questions and it was verified prior to study through a pilot survey, being corrected and improved. For the second and the third study, the questionnaire was enriched with eight more questions, regarding essentially the description of the residential area, criteria for its selection and also awareness about the noise map of the city. The analysis of responses defines the main characteristics of the local pattern of annoyance and reaction of the urban population to the environmental noise.

Keywords: noise annoyance, urban noise, socio-acoustic survey.

1. Introduction

Most studies related to the noise annoyance in urban environment use two assessment methods, usually combined, depending on the specific situation and needs. The first method describes the existing noise situation by means of noise exposure indicators provided by a noise map of the area, with the possibility to model other different noise scenarios, characterizing the development or re-organization of the urban area (Sommerhoff *et al.*, 2004; Lee *et al.*, 2008). Noise maps are developed within specialized software, resulting in a computer visual model of the noise situation, with a precision which depends on the volume and accuracy of input numerical and graphical data. A map must be validated and corrected based on noise measurements values. With the entry into force of the EU Noise Directive, noise mapping methods were merged and unified, action which led to the obtaining of comparable results.

The second method aims to find out the population response to urban noise through a sociological study (Klæboe *et al.*, 2004). This approach is important for the assessment of exposure-effect relationship, described by quantifiable indicators of the presence and intensity of certain features. It is considering, in this case, the evaluation and interpretation of the subjective side of the issue, by taking into account both acoustic and non-acoustic factors, in their interaction, when characterizing the short-term and long–term effects of noise pollution on the population in different urban areas. Non-acoustic factors influencing noise nuisance are numerous and can be grouped into three main categories: situational factors (induced by the location of noise source and urban context), individual factors (socio-demographic and attitudinal, relatively stable over time but variable from person to person) and social factors (relevant in the context of social groups: lifestyle, perception of noise source and its time evolution, attitude of responsible persons and others). The purpose is to find what people think and feel about the noise in their residential area, how annoyed they are, how sensitive to noise, how informed and warned about its negative effect on health.

There are studies which combine measurement and survey methodology (Skinner, Grimwood, 2005; Lam *et al.*, 2009) and others developing new methods, models and theories for predicting effects of environmental noise on people and defining exposure-effect relationship (Batko, Pawlik, 2012; Kryter, 2009; Miedema, Oudshoorn, 2001; Maris *et al.*, 2007) or for improvement the urban acoustic environment (Kompala, 2011)

This paper presents parallel results of two socio-acoustic surveys undertaken in 2001 and 2009 in the city of Cluj-Napoca, Romania and partial results of a third survey which is in progress during the year 2013. They are related to studies which assess the noise environment of the city, in the context of noise mapping actions.

2. The area of study and the general noise context

The city of Cluj-Napoca is located in the North-Western region of Romania, being the capital of Cluj County and an important cultural, scientific and educational centre. According to a statistical study made in August 2000, the stable population of the city consisted of 316001 inhabitants. An estimation from July 2007 indicated 310243 inhabitants with registered residence in Cluj-Napoca and also more that 100000 students and 50000 non-resident employers. Population Census from 2011 showed that the stable population has decreased to 309136 inhabitants.

For the study in 2001, a distribution of population in ten districts was considered. In later years, besides the existing districts have been developed new ones, mainly due to enlargement of the residential area towards the limits of the city. Some of the new districts were formed by reorganizing existing ones. Thus the studies in 2009 and 2013 considered the population grouped in 19 districts. Ten of them are new districts, which concentrate in present about 28% of the city population.

Cluj-Napoca City is the third – in terms of number of inhabitants – of the nine Romanian cities that have made the noise map and action plans for reducing ambient noise, as required in the Directive 2002/49/EC and equivalent Romanian legislation GD nr. 321/14.04.2005. The noise mapping action was started in the second half of 2006, being coordinated by the local public administration. Specific information related to noise map, noise exposure and action plans was made available to the public on the website of the town hall, starting with 2007. According to this noise assessment, a total percentage of 6.67% of the stable population in Cluj-Napoca represents the estimated number of people exposed to excessive noise by road traffic, rail, aircraft and industrial activities.

3. Socialological surveys in 2001, 2009 and 2013

3.1. Methodology 2001

The purpose of the sociological investigation was to know the opinion of the inhabitants on the noise levels and sources of noise in Cluj-Napoca city, including the situation in districts, and to find if people have taken actions to reduce noise and to improve the acoustic comfort of their dwellings. Also, we aimed to find out the extent to which the environmental noise affects their daily activities, behavior and health. The questionnaire was developed after a preliminary study of the existing situation in the city, which included the collection of related data necessary to establish the sample volume and composition. A pilot study was conducted for field-testing and refinement of the questionnaire.

The number of questions was set at 16, so that the questionnaire was not boring and covered all stated subjects. Since the questionnaire was one of opinion, following aspects were taken into account: the questionnaire contained a series of open questions, to let the respondent to formulate his/her own opinion on the issue; the respondent had the possibility to motivate a specific answer; pre-coded questions were asked in order to measure the intensity of subjects' opinion. Among other items, the questionnaire asked about current occupation, field of activity, education, age, residential district. A number of 238 questionnaires were selected form the returned number and their answers were structured and analyzed in a database program and then compared with objective data collected on the preliminary documentation (Popescu, Morariu-Gligor, 2004).

3.2. Methodology 2009

The aim of the study was to determine the current reactions and response of residents related to the urban noise and changes in attitudes compared to 2001. An improved form of the questionnaire was developed, adapted to the intended purpose of establish references for: level of knowledge and awareness of environmental noise in urban areas, by population; information of citizens about the noise mapping action and its results; main negative effects and reaction of inhabitants to the noise pollution, specific forms of behavioral; hierarchy of different sources of urban noise, depending on the level of perception and disturbance of residents; involving of citizens in authorities effort to improve urban acoustic environment; citizens options on the most effective way of information that should be used by authorities.

The survey questionnaire contained 24 questions, being dimensioned to require no more that 20 minute attention and specifically design to reflect the three major classes of non-acoustic factors that influence noise annoyance: situation, individual and social factors. Questions were grouped in four categories: residential zone description in relation with traffic and environmental noise; annoyance due to different noise sources and effects on peoples' habit; information, trends and attitudes towards environmental noise; identification of respondent as occupation, sex, age and education.

The questionnaire was distributed in 19 districts of the city, during May-September 2009. A number of 325 questionnaires were processed, from 348 returned, after elimination of those containing improbable or inconsistent answers (Popescu, Moholea, 2010).

3.3. Methodology 2013

The same questionnaire was used for the study in 2013, which has started in February. Only partial results are available, from the processing of 135 returned valid questionnaires, grouped according to age, education and occupational state, as presented in Table 1.

Table 1. Responses by age, education and occupational state (2001; 2009; 2013 – partial).

		Year of the survey		
		2001	2009	2013
Age	18–30	98	122	33
	31–50	113	128	72
	51–70	21	70	25
	over 70	6	5	5
Education	≤10 classes	5	6	5
	High school	132	114	45
	University	101	205	85
Occupational state	Employed	207	222	94
	Retired	12	42	19
	Student	10	24	11
	Unemployed	4	6	9
	Other situation	5	31	2

4. Results and discussions

Results obtained from the two sociological studies in 2001 and 2009 are presented as follows in combined charts. They have been released as percentage, taking as basis the total number of valid responses – Fig. 1 to Fig. 6. Survey results form 2013 were not included in these charts, as they are currently only partial results, which represents about a quarter of the estimated total responses. Only the questions common to the both questionnaires were suited for a parallel presentation of results. Because there were some changes in the wording of the noise annoyance questions and quantification between the surveys, there were some situations in which it was necessary to re-group the answers on common criterions.

In describing the noise level of their residential area (Fig. 1), subjects of the study in 2001 and 2009 had similar opinion. A lot of them (41.6%, respectively 37.2%) characterized their noise environment as “Medium”, on a five point answer scale and the other answers are equilibrated on the left and right side of the scale. Responses recorded in 2013 indicate a decrease in the number of people who are disturbed by noise in their residential area: 6.7% “Very low”, 32.6% “Low”, 38.5% “Medium”, 19.3% “High”, 2.9% “Very high”.

At the question: “Indicate the main source of noise in the vicinity of your home” the percentage of answers: “Light vehicles” increased from 35.4% in 2001 to 42.0% in 2009 and 49.8% in 2013 (Fig. 2). The situation is explainable, considering the sharp increase of the road traffic in the last twelve years. Decreased percentage of responses: “Heavy vehicles” may be due to the fact that some mandatory routes were established for heavy traffic through the city in the recent years, in the absence of a ring road surrounding the city. To note that a significant number of responses indicated neighbors as the main noise source in all three studies. At this question subjects might choose one or more variants of answer, the reference being the total number of variants in each study.

The quantification of annoyance induced by the environmental noise was made on a four point scale (Fig. 3). In the first study 62.2% of respondents declared to be annoyed and very annoyed by the noise in their residential area, since in 2009 only 47.7% of the subjects indicated these two degrees of annoyance, in 2013 the percentage decreased to 35.5%.

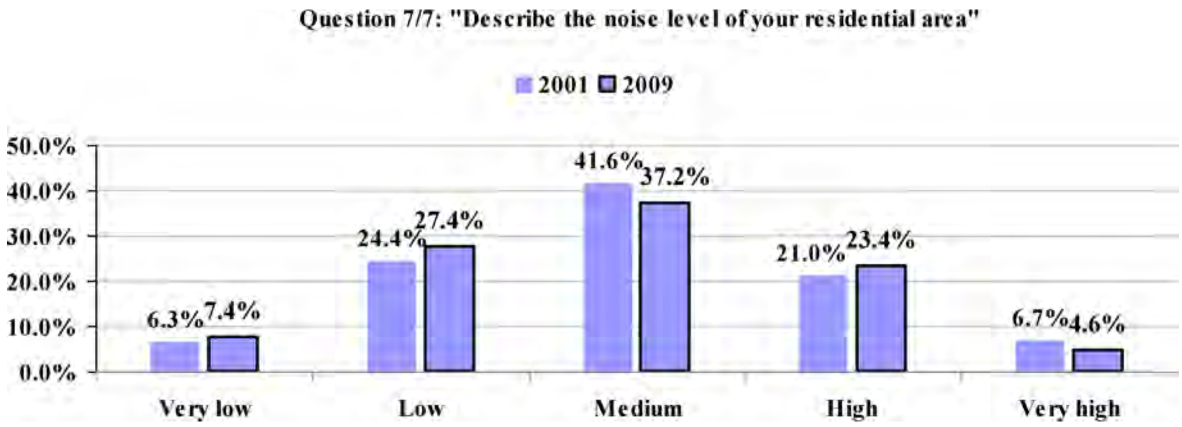

Fig. 1. Proportion of responses describing the noise level in the residential area (2001, 2009).

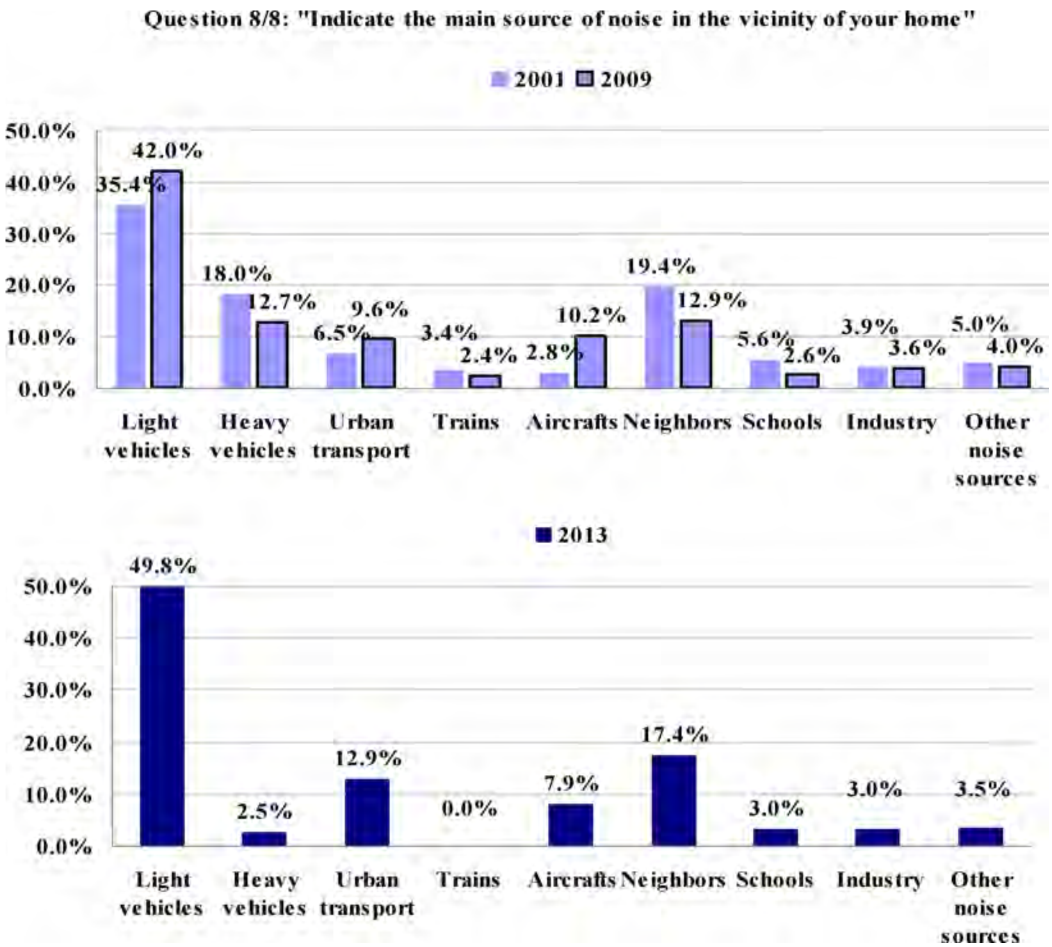

Fig. 2. Proportion of responses pointing the main source of noise in home vicinity.

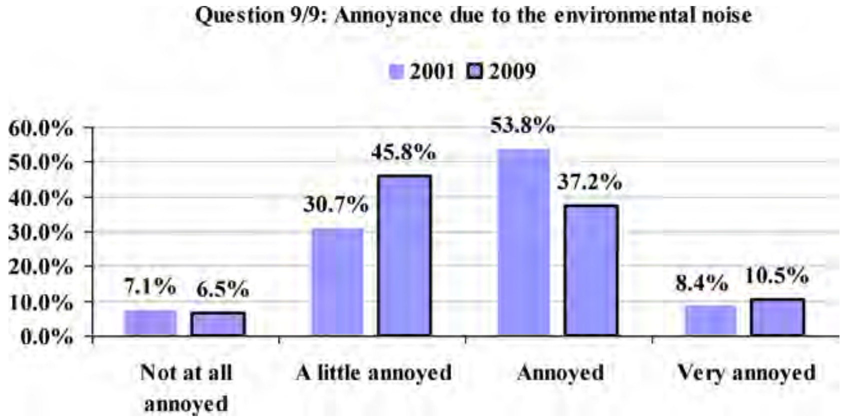

Fig. 3. Proportion of responses describing the annoyance due to the environmental noise.

For the time of the day most affected by the environmental noise, all three studies indicated mainly the time interval between the hours: 15^{00} (3^{00} PM) and 22^{00} (10^{00} PM). An explanation might be that for most of the subjects this is the afternoon rest time period, spent at home. Figure 4 presents responses from 2001 and 2009, grouped by respondents' age.

In all three studies subjects were asked to indicate experienced harmful effects produced by the environmental noise. The pre-defined answers measuring these items were more detailed in the questionnaire used in the last two studies. For the studies in 2009 (Popescu, Moholea, 2010) and 2013 (preliminary results) responses are indicated in Table 2. Fatigue and nervousness were mostly selected by subjects. The missing percent up to 100% indicates other possible effects. The answers were re-grouped to compare the studies in 2001 and 2009 (Fig. 5). Subjects could choose more

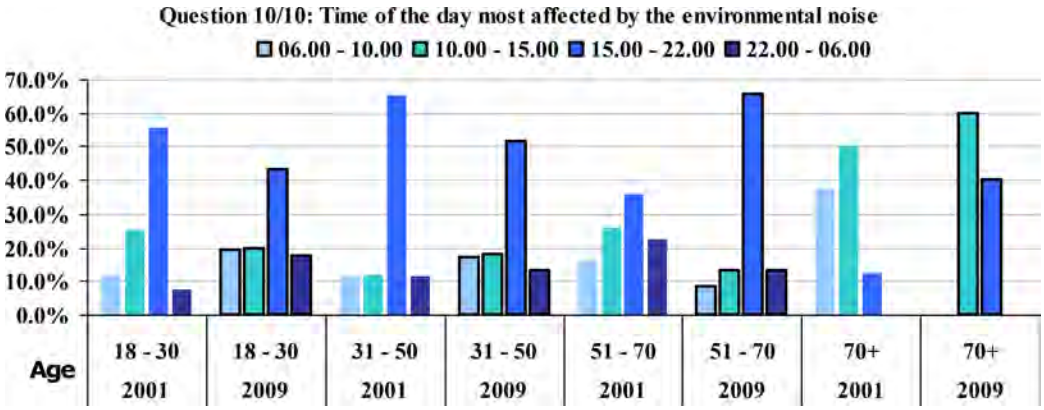

Fig. 4. Proportion of responses, sorted by age of the subjects, pointing the time of the day most affected by the environmental noise (2001, 2009).

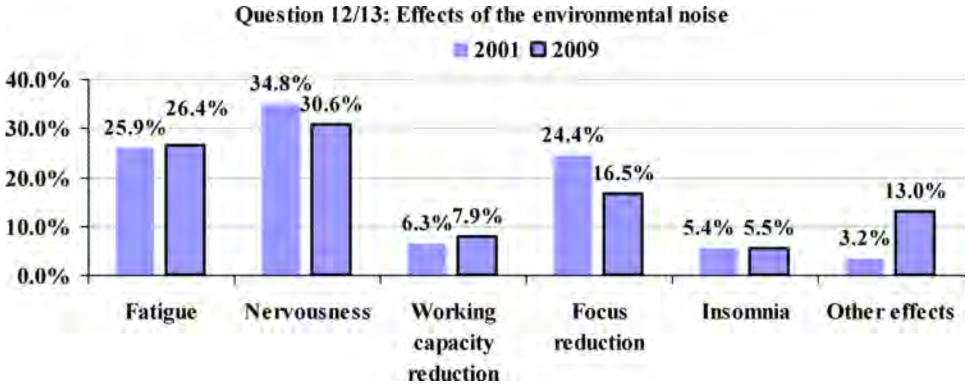

Fig. 5. Proportion of responses describing harmful effects of the environmental noise.

Table 2. Harmful effects of the environmental noise (2009 and 2013 – partial results).

Noise effects	Year of the survey	
	2009	2013
Fatigue	26.4%	24.4%
Nervousness	17.6%	24.4%
Anxiety and agitation	12.6%	14.8%
Depression	0.4%	2.4%
Reduction of working capacity	7.9%	2.9%
Focus reduction	16.5%	11.0%
Discomfort by masking other sounds	12.5%	12.4%
Insomnia	5.5%	3.8%

than one pre-defined answer and the percentage was calculated as report to the total number of answers selected by respondents.

In the end of the questionnaires subjects were asked if they have taken any action in order to improve the acoustic comfort of their dwelling. The number of "Yes" answers varied from 21% in 2001 to 51.4% in 2009 and 31.9% in 2013. Subjects have been asked then to indicate the actions they have done. Figure 6 shows that the mentality of inhabitants has changed between 2001 and 2009, many of them renouncing to write complains to responsible authorities but deciding to take measures for reducing the annoying noise in their home environment. The situation is similar in 2013, when responses are as follows: 5.3% "complains to authorities", 24.5% "acoustic isolation of dwelling", 5.3% "change of the residential area", 63.2% "change windows" and 1.7% took other noise reduction measures. This fact may also explain the decrease of the percentage of persons which have declared to be annoyed and very annoyed by the environmental noise from 62.2% in 2001 to 47.7% in 2009 (Fig. 3) and 35.5% in 2013.

One of the issues identified by the study in 2009 was related to the poor information of population about the noise map of the city and measures undertaken by local authorities to reduce noise pollution in the urban area and to frame the noise environment in admissible limits. The subjects were asked about urban noise studies performed in the last years and responses were as follows (Popescu, Moholea, 2010): 4.8% "Noise map of the city", 3.9% "Noise measurements", 0.9% "Noise questionnaires", 36.5% "No studies", 53.9% "Don't know". More than half of respondents (52.0%) didn't know if measures have been taken to reduce noise pollution in the city and 26.8% considered that no measure has been taken.

After four years the situation was not improved. The 2013 survey has recorded the following percentages of response to the same question: 2.8% "Noise

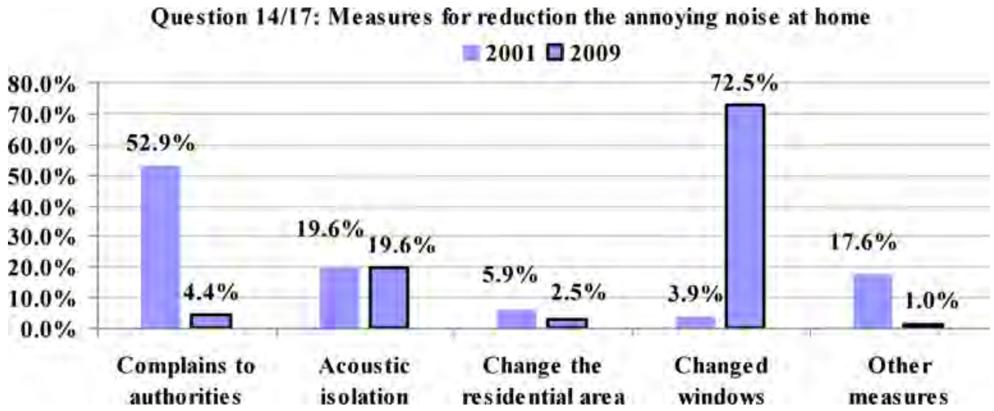

Fig. 6. Proportion of responses related to actions for reduction of annoying noise.

map of the city", 2.8% "Noise measurements", 4.2% "Noise questionnaires", 32.4% "No studies", 57.8% "Don't know". In terms of actions to reduce urban noise, 64.4% of responses were "Don't know" and 18.5% indicated "No measures".

5. Conclusions

Over the past twelve years the growing traffic in the city of Cluj-Napoca has produced important changes in urban noise situation. At the same time there has been a growing concern for reducing the effect of noise on inhabitants. EU Noise Directive requirements have led to the development of the first noise map of the city, followed by action plans to reduce noise. This paper aimed to observe how these changes were perceived by the citizens and also to provide a reference for the noise annoyance estimation for planning purpose in Romania.

The analysis defines the main characteristics of the local pattern of annoyance, reaction and response of the urban population to the environmental noise and gives information on the changes of noise perception over a time period of twelve years. From the point of view of noise annoyance the situation has improved in the last years, but the insufficient dissemination of information about noise as a hazard is still an issue and needs more emphasis.

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The paper will be presented during the 16th International Conference on Noise Control 2013.

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Experimental Acoustic Flow Analysis Inside a Section of an Acoustic Waveguide

Stefan WEYNA, Witold MICKIEWICZ, Michał PYŁA, Michał JABŁOŃSKI

West Pomeranian University of Technology
al. Piastów 17, 70-310 Szczecin, Poland; e-mail: weyna@zut.edu.pl

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Noise propagation within ducts is of practical concern in many areas of industrial processes where a fluid has to be transported in piping systems. The paper presents experimental data and visualization of flow in the vicinity of an abrupt change in cross-section of a circular duct and on obstacles inside where the acoustic wave generates nonlinear separated flow and vortex fields.

For noise produced by flow wave of low Mach number, laminar and turbulent flows are studied using experimental sound intensity (SI) and laser particle image velocimetry (PIV) technique adopted to acoustics (A-PIV). The emphasis is put on the development and application of these methods for better understanding of noise generation inside the acoustic ducts with different cross-sections. The intensity distribution inside duct is produced by the action of the sum of modal pressures on the sum of modal particle velocities. However, acoustic field is extremely complicated because pressures in non-propagating (cut-off) modes cooperate with particle velocities in propagating modes, and *vice versa*. The discrete frequency sound is strongly influenced by the transmission of higher order modes in the duct. By understanding the mechanism of energy in the sound channels and pipes we can find the best solution to noise abatement technology.

In the paper, numerous methods of visualization illustrate the vortex flow as an acoustic velocity or sound intensity stream which can be presented graphically. Diffraction and scattering phenomena occurring inside and around the open-end of the acoustic duct are shown.

Keywords: sound intensity, laser anemometry, acoustics flow, sound visualization.

1. Introduction

Much of theoretical research concerned with acoustics provides useful information about pressure fields, but none currently offers a full mapping of the acoustic energy flow (vector effects) in the front and back of any scattering system working in three-dimensional space. In real environmental conditions, interference, diffraction and scattering of waves mode in the real field are very complex and difficult in comparison with the theoretical modeling. This is one of the reasons why the experimental investigations of acoustic field using sound intensity (SI) (Weyna, 2010b) or acoustic particle image velocimetry (A-PIV) (Weyna, 2012; Raffel *et al.*, 2007) techniques are such effective and serviceable methods. Besides, SI and A-PIV investigation techniques are very useful in locating noise sources, and they also provide the advantage that the measurements can be made in almost any environment.

Visualization of acoustic energy flow in real-life acoustic three-dimensional space fields can explain many particular energetic effects (perturbations and vortex flow, effects of scattering in the direct and near field, etc.) concerning the areas in which it is difficult to make numerical modeling and analysis with numerical simulation methods. The SI and A-PIV image represents a more accurate and really efficient information as compared to the spatial pressure acoustic field modeled. Both measurement techniques expressing energetic quantity give a very useful information about the propagation paths and the amount of energy radiated into the flow field. From experimental point of view, the time-averaged acoustic intensity (*rms* values) is often more interesting than its instantaneous value.

The article presents mainly the application of SI and partly A-PIV techniques to graphically show a spatial distribution the acoustic energy flow over obstacles with different geometrical shapes located in a three-dimensional space inside acoustic waveguides with different cross-sections. As a results of the research, the graphic analysis of the acoustic wave flux in two- and three-dimensional space is shown. Visualization of the results is shown in the form of vectors or streamlines in space and as the shape of a flow wave or an isosurface in space. Numerous examples illustrate the application of the SI measurement for practical problems useful for vibroacoustical diagnostics and noise abatement.

2. Sound Intensity

Acoustic intensity is a very useful energetic quantity, since it gives information about the propagation paths and the amount of energy being transported or radiated. Sound intensity, as a vector variable, *inseparably* couples the acoustic particle velocity and acoustic pressure ($\mathbf{I}_a = p\mathbf{v}$) and represents a stream of acoustic energy flowing in the field. This vector parameter of acoustic wave can be measured (as *rms* value) with special sound intensity probe and can be easily shown in different graphical forms.

The acoustic particle velocity $\mathbf{v}$ and the mean pressure p satisfy the time-averaged equations of continuity and momentum. For linear acoustics, in the absence of external flow, $\langle \rho \mathbf{v} \rangle = \langle p' \mathbf{v} \rangle / c_0^2 = \mathbf{I}_a / c_0^2$, where p' is the acoustic pressure perturbation and $\mathbf{I}_a$ is the acoustic intensity. Sound intensity can be directly measured and recorded as an acoustical flow field divided into normalized octave frequency bands (normalized acoustic filters correspond to 1/1, 1/3, 1/12, 1/24 octave bands). In traditional acoustic metrology, the analysis of acoustic fields mainly focuses on the distribution of pressure levels (scalar variable). However, in a real acoustic field both scalar and vector (the acoustic particle velocity) effects are closely related as far as their phase and amplitude is concerned. The acoustic field may also be separately described as a spatial distribution of pressure and particle velocity, their amplitude p and $\mathbf{v}$ being proportional for plane traveling waves ($p = \rho c_0 v$), where ρ is the density and c_0 is the sound speed.

The application of the sound intensity technique together with numerical methods has improved the quality of acoustic diagnostics and has made it possible to visualize energy wave phenomena (vector distribution) in a vibrating structure or in an acoustic field around the structure. The visualization of acoustic energy flow in real-life acoustic 3D space fields can explain many peculiar energetic effects (scattering, vortex flow, shielding area, etc.) (Weyna, 2010a) concerning the areas in which it is difficult to make numerical modeling and analysis with the commonly used CFD-FSI-CAA methods.

3. Particle image velocimetry

The development of Particle Image Velocimetry (PIV), an optical measurement technique, which allows for capturing velocity information of whole flow fields in fractions of a second, has begun in the eighties of the last century. The time since then was again characterized by a rapid development of hard- and software for the PIV technique. Improved cameras, lasers, optics and software, led to a significant increase in performance. But also the range of possible applications increased drastically over the years.

PIV is nowadays used in very different areas from aerodynamics to biology, from fundamental turbulence research to applications in the turbo-machinery design, from combustion to two phase flows, and very intensively in micro devices and systems. Due to the variety of different applications of PIV and the large number of different possibilities to illuminate, record, and evaluate, many different technical modifications of the PIV technique have been developed (Raffel *et al.*, 2007; Tropea *et al.*, 2007; Lorenzoni *et al.*, 2012). Moreover, most publications (Siddiqui, Nabavi, 2008; Roch, Park, 2003) describe the problems from a specific point of view (e.g. in fluid mechanics). We therefore felt that it was the right time to compile the PIV knowledge and practice to the implementation in theoretical and applied acoustics.

The experimental setup of a PIV system typically consists of several subsystems (Fig. 1). In most applications, tracer particles have to be added to the flow to quantify the velocity field of fluid. These particles have to be to illuminated in plane of the flow at least twice within short time interval Δt between laser pulses (usually a double pulse Nd:YAG laser). The light scattered by the particles has to be recorded either as a single frame or a sequence of frames with special cross-resolution digital CCD or CMOS modern cameras.

The digital PIV recording area is divided in small subareas called "interrogation areas" (e.g. 32 × 32 pixels). The two-component local flow velocity vector v_x and v_y for the images of the tracer particles is

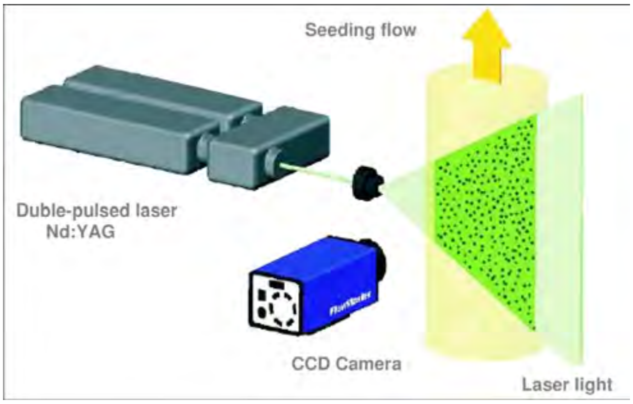

Fig. 1. The principle of operation of the PIV measurement.

determined and projected on the plane of the light sheet. High-speed recording with several thousand instantaneous velocity vectors is obtained within the period of the order of a second with standard computers. The processing algorithms are defined using the processing pipeline with a complete range of image processing tools. Innovative algorithm design and a comprehensive range of image pre-processing, processing, analysis, and display options are critical for accurate velocity measurements in the full range of potential applications.

4. Experimental research with SI and PIV techniques

Good understanding of the evolution process of acoustic wave motion in pipes and ducts is critical to development of engineering designs with the most attractive operating properties to achieve an optimized low-noise design of duct systems and low-noise emission characteristic. The detailed flow acoustic evaluation process of the in-duct flow structure has recently attracted attention of investigators (Ingard, Ising, 1967; Dalmond *et al.*, 2001).

The research presented in this paper also refers to studies of acoustic waveguides (denoted as number 1 and 2). In Fig. 2 we show a model of circular acoustic waveguide no. 1 where investigations with sound intensity measurement were made. The 6-m long open-end duct with internal radius 0.474 m was used as a model for an acoustic waveguide. At one end it was connected to a loudspeaker, a source of broadband acoustic signals. The duct was excited with acoustic pink noise, so the sound power along the duct was sent without mean flow. Initial measurement were made on a circular duct without any obstacles present in the duct. Afterwards, a tested obstacle in the form of conical baffle with a 127-mm hole was placed at a distance of about 2.2 m from the end of the duct.

The space inside the duct was scanned with sound intensity probe measuring the x, y and z components of sound intensity vectors. Measurements were made in the frequency band 50–6800 Hz and analyzed in 1/3 and 1/12 octave frequency bands. The image of the dipolar and quadrupolar sound generated by a flow inside a duct was obtained using a SI three-dimensional *USP Microflown* probe and our graphical post-processing *SIWin* software.

Another series of tests was carried out on a different model of the waveguide (number 2). For this model (Fig. 3), the study was carried out by two techniques – SI and laser A-PIV. Applying the method of SI, we can see that this method has one disadvantage: the field can not be measured very closely to the sound source (e.g. at a distance of roughly < 1 mm). In this region called the *hydrodynamic acoustics near field* the sound is born and radiated to the environment. Since SI is the size of vector, to describe the stream intensity we need to know the value of the *particle acoustic velocity v*.

The work in this part of the article is concerned with the measurement of acoustic particle velocity fields at the open-ended 750-mm long 150 mm × 150 mm square tube (Fig. 4). This part of the waveguide was connected with a pipe with diameter of 150 mm and length of 730 mm. At the end of this section there was the source of acoustic signals. The study was conducted in the area inside the square waveguide no. 2 and partly outside at the waveguide outlet.

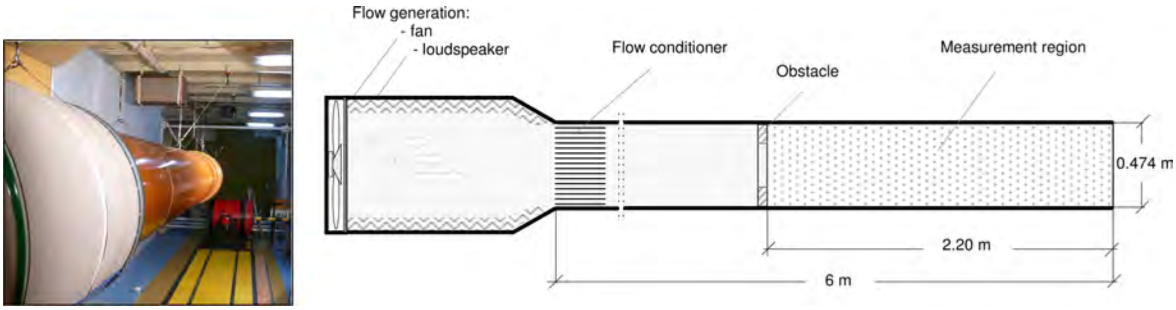

Fig. 2. Sound incident and scattered at an obstacle acoustic waveguide no. 1 of circular cross-section.

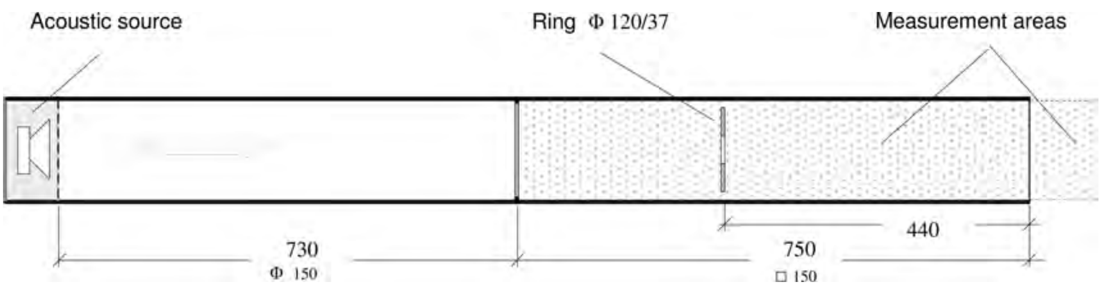

Fig. 3. Acoustic waveguide no. 2 with variable cross-section (partly round and partly square) used in the studies by SI and A-PIV measurement methods.

5. Sound intensity measurement results

In our investigation using SI technique we can see that the intensity distribution inside a circular duct produced by the action of the axial and radial modes is extremely complicated because this propagating modes influence each other.

In Fig. 4 we show some results of this investigations for 1/12 octave frequency bands where the sound intensity streamlines and the velocity vectors show the dynamic shape of the acoustics flow. Direct measurement of the acoustic power flow around outlet of an obstacle in the form of perpendicular diaphragm and a conical baffle with a 127 mm hole can explain a diffraction

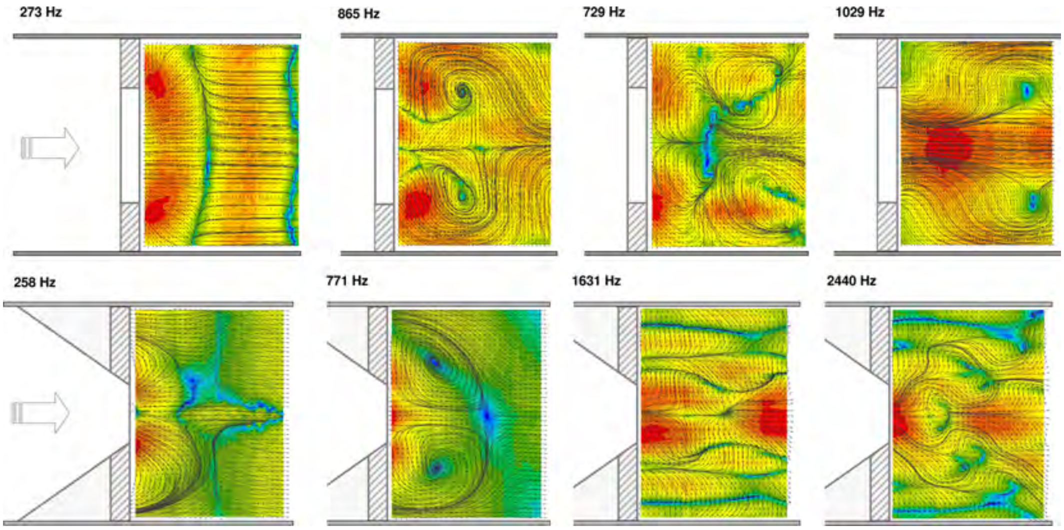

Fig. 4. Acoustic flow field close to obstacles – diaphragm and conical baffle – placed inside the circular waveguide no. 1.

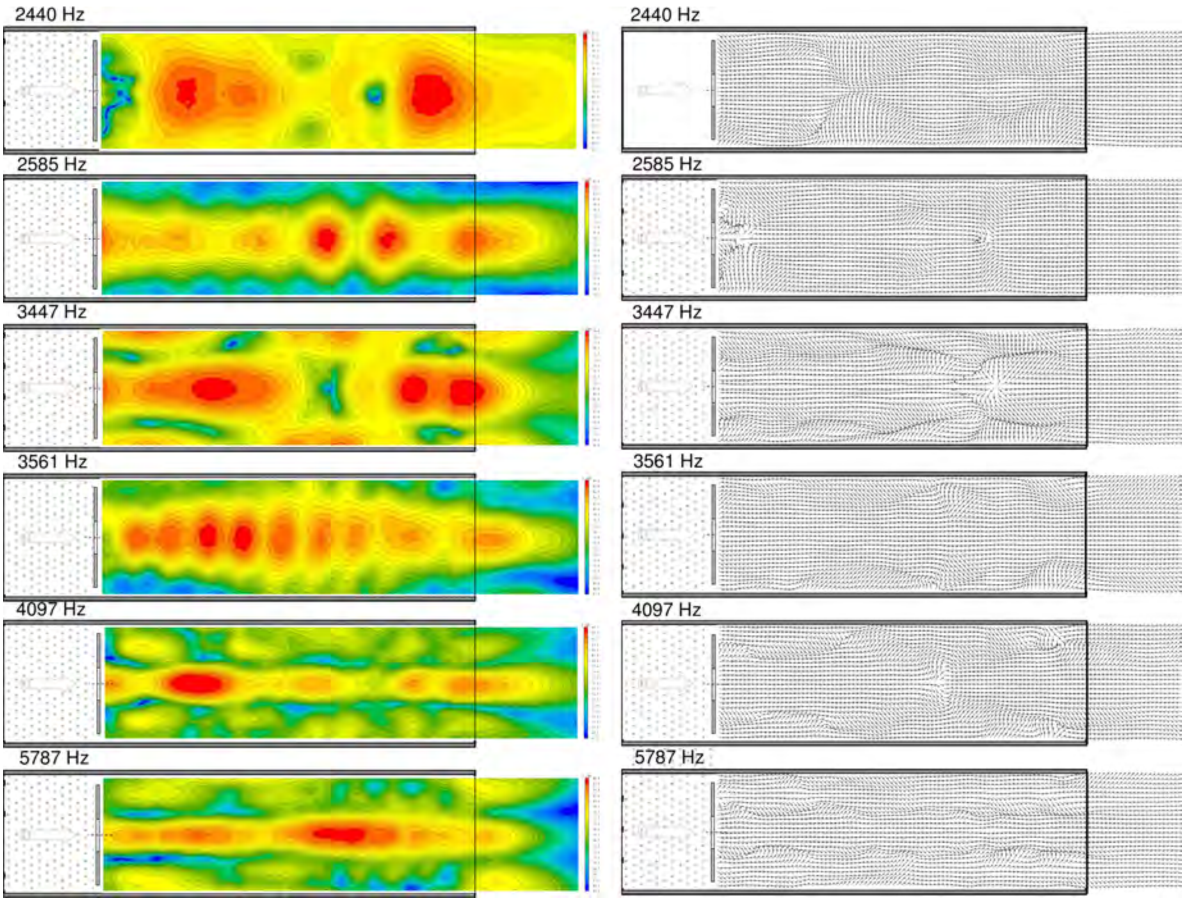

Fig. 5. Sound intensity field outside the ring-shaped barrier in a square acoustic waveguide – map of intensity and sound intensity streamlines (frequency 1/12 octave band).

and scattering phenomena occurring in the region close to the obstacles. The space behind the obstacles was studied in consideration of deformation of the acoustic field due to presence of the obstacles. Experimental results show the map of intensity traveling along the duct no. 1 and distribution of sound intensity streamlines of the generated flow.

In Fig. 5 we show one of examples of our research with sound intensity measurement made inside the square waveguide no. 2. With graphical form we can see the evolution process of flows in the measurement plane located 0.44 m from the end of the duct and partly outside the channel. In Fig. 5 we show some results of these investigations for 1/12 octave frequency bands where the sectional streamlines and the velocity vectors show the topological multi-cell structure of the flow for high-order modes.

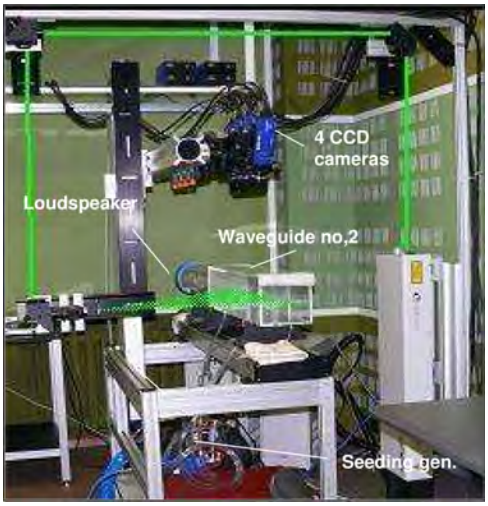

Fig. 6. Experimental setup – acoustic square waveguide model investigated with PIV technique.

6. Laser method measurement results

Laser methods can also be adapted to provide an instantaneous flow and acoustic particle velocity with the minimum disturbance of the source sound field. The non-invasive nature combined with the small measuring volume of the PIV system makes the technique ideally suited to measuring the acoustic particle velocity flow in the boundary layer and wave interactions on the obstacles placed in the sound field. The particle image velocimetry (PIV) is obviously used in fluid mechanics (Raffel *et al.*, 2007). The proposed adaptation of the noninvasive laser methods for acoustical purposes (A-PIV) gives us the opportunity to explain many vibroacoustical phenomena and allows to complete missing knowledge about disturbed acoustic flows in real systems (Henning *et al.*, 2008).

Figure 6 shows the experimental acoustic square waveguide model investigated with the PIV technique. In our measurement with laser PIV technique a fluid in square duct is seeded with tiny 1-μm DEHS synthetic oil particles which faithfully follow the motion of the flow and are illuminated in plane by a Nd:YAG, 325 mJ double pulsed laser with green light source. The 14 f/s CCD camera (Imager ProX-LaVision) was used to acquire raw PIV image for the study. This camera can take separate images at resolution of 2048 × 2048 pixels with minimum of 200 ns between images. It possible to program the delay, relative to an input trigger signal, and the exposure time of the first image. The second exposure continues for the time depending on how long the computer processes the first image. In this study, the time was 143 ms. These images were phase-locked with respect to the acoustic cycle by using a timing circuit. The interrogation area size was 32 × 32 pixels with a 50% overlap between adjacent interrogation windows. Up to 100 samples were used to determine the mean velocities of the flow fields examined. The CCD camera was positioned perpendicularly to the light sheet and focused on the illuminated fog particles. The observation window corresponded to a section of the volume with dimensions 120 × 120 mm. Figure 6 shows the experimental setup — acoustic square waveguide model no. 2 investigated with the PIV technique. A part of measurement results is shown in Fig. 7. For low Mach-number isother-

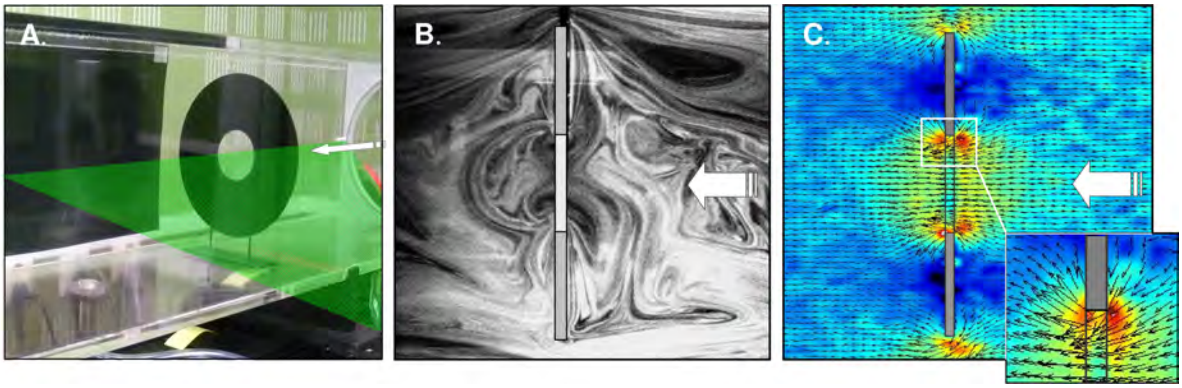

Fig. 7. Acoustics wave motion around a ring recorded using laser PIV method: A – acoustic square waveguide with obstacle to be lighted by laser sheet, B – cloud of seeding particle DEHS around obstacle, C – acoustic flow effects on the edge of an obstacle.

mal flow we can see that additional aeroacoustic sound production by the flow around the ring is entirely due to mean flow velocity fluctuations, which may be described in terms of the underlying vortex dynamics. The use of PIV technique can allow to see these vector properties of acoustic wave in a large-scale. Acoustic flow effects on the edge of an obstacle can be analyzed with great precision.

7. Conclusions

We can conclude that by the direct measurement of acoustic power flow and graphical description of the results, we can explain a diffraction and scattering phenomena occurring in the real acoustic flow field. The analysis of acoustic field with floating wave in space show that the sound intensity technique together with a particle image velocimetry techniques are very useful in visualization of vector acoustic phenomena.

If the laser methods for assessing the dynamics of the aero-acoustic fields turn out to be justified, we gain an effective tool for non-invasive research of acoustic flows in broad range of acoustic particle velocity. The big advantage of the research is also the fact that with PIV measurements all the changes in dynamics of flow structure can be recorded and visualized as a function of time. Evaluation of space-time correlation of fluctuating velocity and vorticity fields explain the mechanism of formation of turbulence in the wake region of flow. Studying the interaction of vortices with the structure of the test may be advisable when modifying numerical models of the flow acoustics.

The proposed adaptation of the non-invasive laser method for acoustical purposes offers the opportunity to explain many vibroacoustical phenomena and allows to complete missing knowledge about disturbed acoustic flows in real systems. We shall attempt to complete elementary knowledge about acoustic wave flows and reactions at the obstacles generating nonlinear refraction, diffraction, and diffusion effects in waves propagating in viscoelastic environment.

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The Study of Behavior of Vibrating Systems Controllable by Devices with Rheological Fluid

Marek L. SZARY, Peter WEBER

Department of Mechanical Engineering and Energy Processes, Southern Illinois University
1230 Lincoln Drive, Carbondale Ill 62901-6603 USA; e-mail: szary@engr.siu.edu

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The nonlinear mathematical model of behavior of controllable viscosity fluid (CVF) under applied external field is presented. A large family of these fluids is commonly used to control responding forces of dampers in vibration control applications. The responding force of a damper with CVF has two components. The first one – uncontrollable – is proportional to the viscosity of a base fluid and velocity of its motion, the second one, which is controllable, depends on the strength of the applied external field. Both are involved in the process of dissipation of unwanted energy from the vibrating systems. An equivalent damping factor based on the principle of energy dissipated during one cycle of damper work under a constant strength external field was calculated. When mass or stiffness is variable the equivalent damping factor can be set accordingly by adjusting the strength of external field to have vibrating damped system purposely/continuously working in the critical or other chosen state. This paper also presents cases of applying periodically changing strengths of an external field synchronized with cycles of periodical motion of the vibrating system to continuously control the damping force within each cycle.

Keywords: noise control, vibration control, smart materials, rheological fluids.

1. Introduction

Magnetorheological (MR) fluids are suspensions consisting of ferromagnetic particles in a low permeability base liquid, usually oil (in some cases water) with surfactants to prevent sedimentation. Electrorheological (ER) fluids are suspensions of electrostatically polarizable particles. Very fast reversible changes (usually in milliseconds) of rheological properties, especially apparent viscosity and elasticity are caused by the polarization induced in the suspended particles under applied external magnetic flux or electrical field. The particle chain formation and later changes from chains to columns are observed. This is known as the rheological effect. Thus MR or ER fluids behave as a Newtonian liquid (if base fluid has this property) without the presence of polarizing magnetic flux or electrical field and as a semi-solid when exposed to the field. This phenomenon is associated with changes of yield stress of the suspension. In effect, fluid strength changes according to applied external field. This fluid (or suspension) under an external field behaves as a Bingham semi-plastic until the shear stress becomes equal to the yield stress, which begins the onset of flow. The ER fluid behaves in the same manner as the MR fluid when an external electrical field is applied. The known applications of MR fluids are in brake/clutch design (Choi *et al.*, 1999), valves (Yoo, Wereley, 2002), engine mounts (Choi *et al.*, 2008) and in vibration dampers (Carlson *et al.*, 1996; Kamath *et al.*, 1999; Pang *et al.*, 1997; Spencer *et al.*, 1997).

Early investigations of sound transmission loss (STL) in the stiffness controlled space between two barriers with electrorheological fluid between them under DC and AC voltage (Szary 2002; 2004) shows, that due to increased mechanical coupling strength, the STL decreases. The STL was investigated for various kinds of ER suspensions in the frequency range from 100 Hz up to 2 kHz. Laboratory results showed that the normal stress developed in ER fluid has a significant influence on the magnitude of STL. The tangentional (shear) stress had a negligible effect on the STL.

As an example, in Fig. 5, the vibration of a two degree of freedom system with a MR damper is used to illustrate the separation of the vibrating excitation source from the system to reduce the negative effect from the unwanted vibrations. This is a very common example of an airplane taxiing over a wavy surface of a runway or a vehicle driving over a wavy road surface. The MRF damper in this suspension design is used to separate, to some extent, motion of mass m_1 which represents wheel with attached masses, from m_2, which is an airplane or vehicle body mass. This RF damper, with a controlled value for its damping factor by associated control system, allows optimizing for minimization of the amplitude of motion or force transmitted to the airplane or vehicle body. The passive, the most common design, vibration suspension works in optimal conditions only when the mass of the system varies in a narrow range and in a certain frequency space. To improve/expand suspension performance over a wide range of payloads and frequencies, the active vibration control technique can be used, however, associated with this design, complexity, cost and power requirements limits its applications. With some compromise in control effectiveness, the active vibration control system can be replaced by a semi-active vibration control system. In many practical applications semi-active vibration control systems can be nearly as effective as active vibration control systems, for example, the semi-active suspension system used in some passenger vehicles. The positive characteristics of this system are: 1. The semi-active system/suspension still works in a passive regime even when the control system and/or power supply fails. 2. The power requirements to control the damping force of the damper with rheological fluid (RF) are relatively low. 3. By using MR fluid in a damper, a common passenger vehicle 12V DC electrical system is sufficient to create effective the damping force. The force controlling the electrical current usually does not exceed a few amperes.

In this paper the nonlinear mathematical model of the behavior of a MR fluid in a damper under an applied external magnetic flux density is presented. The equivalent apparent variable damping factor, related to the apparent viscosity, based on the equivalent energy dissipated principle was calculated.

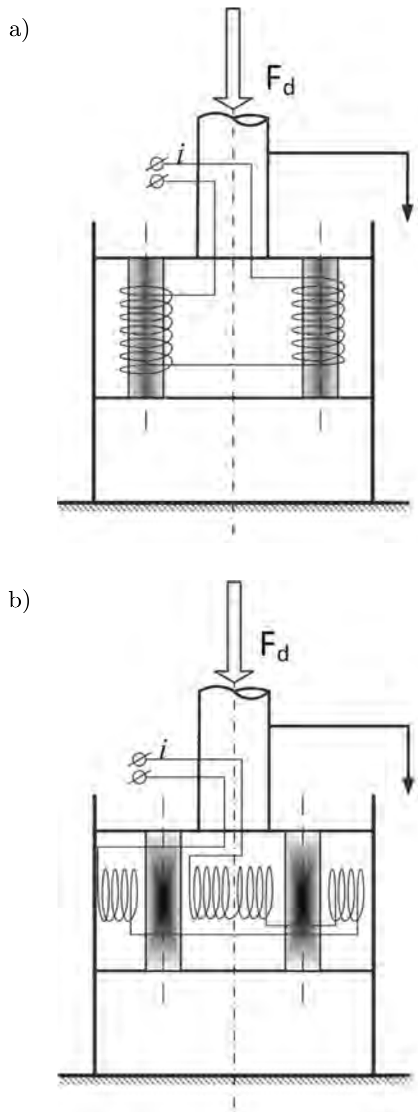

Fig. 1. The principle to control damping force F_d by applying variable electrical current i to change the apparent viscosity of the MRF in the orifices: a) tangential stress control, b) normal stress control.

2. Response of rheological fluid to the external field

The principle of application of a magnetorheological fluid in damper design to control the magnitude of a damping force F_d by applying electromagnetic field resulted from electrical current i flowing in coils around piston's orifices is shown in Fig. 1. The response of the damper under an applied external field in this example results from the changes in apparent viscosity of the MRF suspension.

The damping force F_d is proportional to the apparent viscosity of the RF in the orifices and its velocity ($\dot{x}$). The viscosity (after I. Newton) is described as a relationship between shear stress in a fluid (τ) and observed velocity gradient ($\partial\dot{x}/\partial h$) in a fluid subjected to motion. Characteristics $\tau_{\mathrm{RF}} = f(\dot{x})$ of a typical MRF are shown in Fig. 2. In the absence of an applied external field the RF often exhibits Newtonian-like behavior associated mostly with the base fluid physical properties. An applied external field changes this behavior and the rheological fluid in the piston's orifices shows a variable yield stress which depends on the strength of that field. The apparent shear stress of the RF depends on two components. One of them is Newtonian, proportional to the viscosity of the base fluid and velocity gradient. The second is controllable by the applied external field. The controllable external field stress shown in Fig. 1b is significantly higher in amplitude than in the design shown in Fig. 1a.

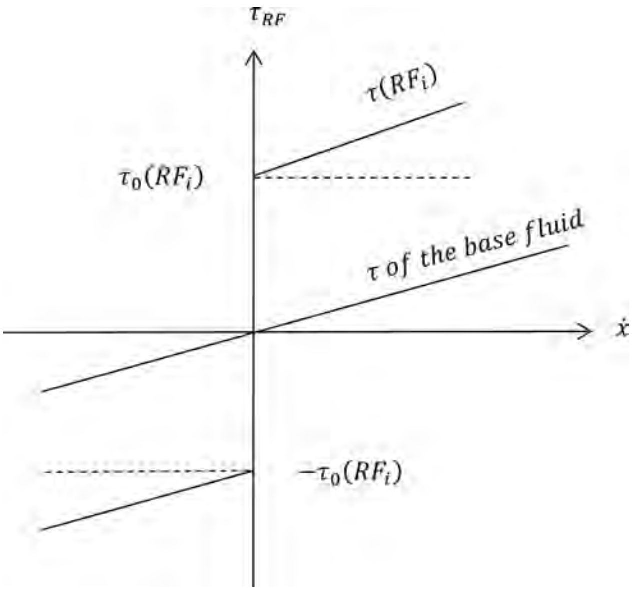

Fig. 2. The shear stress *versus* velocity of a MRF under applied electromagnetic field represented by current i.

Equation (1) describes the property of apparent shear stress observed in the piston's orifices when an external field is applied.

$$\tau(\mathrm{RF}_i) = \tau_0(\mathrm{RF}_i) + \eta(\partial\dot{x}/\partial h), \tag{1}$$

where yield stress $\tau_0(\mathrm{RF}_i)$ as a function of the external field caused by the magnetic flux density for $\dot{x} = 0$ and Newtonian shear stress $\eta(\partial\dot{x}/\partial h)$ proportional to dynamic viscosity of the base fluid η and velocity gradient $\partial\dot{x}/\partial h$.

In the absence of an external field, the shear stress $\tau(\mathrm{RF}_i)$ of the rheological fluid behaves viscoelastically. Figure 2 shows the behavior of the apparent shear stress of a rheological fluid in a damper under an applied external electrical or electromagnetic field. The electromagnetic field can also be represented by the electrical current i flowing in coils placed around piston's orifices.

According to Fig. 2 the shear stress of a RF can be expressed as:

$$\tau(\mathrm{RF}_i) = \tau_0(\mathrm{RF}_i) + \frac{\partial\tau_{\mathrm{RF}_i}}{\partial\dot{x}}\,\dot{x}\,. \tag{2}$$

The equivalent damping factor C_{RF_i} is:

$$C_{\mathrm{RF}_i} = \left[\left\{\tau_0(\mathrm{RF}_i) + \frac{\partial\tau_{\mathrm{RF}_i}}{\partial\dot{x}_i}\,\dot{x}\right\} A\right]\frac{1}{\dot{x}}\,, \tag{3}$$

where A is chosen oblique area.

The damping force F_{di} at point of work is:

$$F_{di} = \tau(\mathrm{RF}_i)A\,. \tag{4}$$

The ratio of:

$$\frac{\partial\tau_{\mathrm{RF}i}}{\partial\dot{x}} = f\left[\tau_0(\mathrm{RF}_i)\right] \tag{5}$$

need to be established experimentally.

3. RF damper model

The balance of internal damper forces in equilibrium with an external force (free body diagram) of a RF damper is shown in Fig. 3. The complex damping force F_{di} (which is also a response force from the damper in motion) has two components, $F_{d\eta}$, which depends on a damping constant C_η (related to the piston's orifice design and physical properties of the base fluid) and velocity $\dot{x}$, and F_{doi}, which depends only on the external, in this case electromagnetic field, represented by electrical current i. In the absence of an external electromagnetic field and/or current i, the internal force F_{doi} becomes zero and the damping force becomes $F_{di} = F_{d\eta}$.

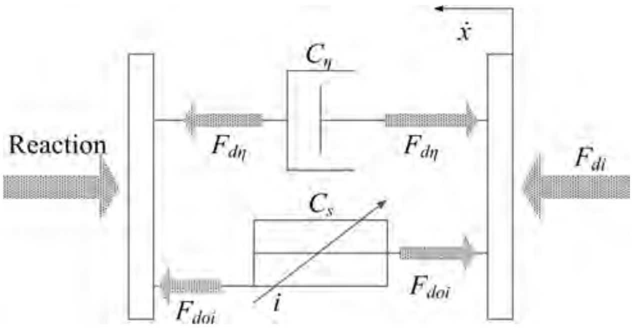

Fig. 3. Model of the rheological fluid damper, where viscous damping force is $F_{d\eta} = C_\eta\dot{x}$ and damping force controlled by external field is $F_{doi} = F_{do}(\mathrm{RF})\,\mathrm{sgn}(\dot{x})$. The C_s represents the apparent damping coefficient of the RF under an external field and F_{do} represents the offset damping force when $\dot{x} = 0$.

The relationship between force, shear stress and velocity is called the Rheological Fluid Model and can be expressed in the general form as:

$$F_{di} = \begin{cases} \tau_0(\mathrm{RF}_i)A + \dfrac{\partial_{iRF}}{\partial\dot{x}}A\dot{x} & \dot{x} > 0, \\ 0 & \dot{x} = 0, \\ -\tau_0(\mathrm{RF}_i)A + \dfrac{\partial_{iRF}}{\partial\dot{x}}A\dot{x} & \dot{x} < 0. \end{cases} \tag{6}$$

Considering that:

$$\tau_0(\mathrm{RF})A = F_{do}(\mathrm{RF}) \tag{7}$$

represents damping force controlled by an external field and:

$$\frac{\partial\tau_{\mathrm{RF}}}{\partial\dot{x}}A\dot{x} = F_{d\eta} \tag{8}$$

which represents damping force proportional to the velocity $\dot{x}$ (see Fig. 3) and is:

$$F_{di} = F_{doi} + F_{d\eta} \tag{9}$$

represents the complex damping force.

4. Response of the vibrating system with RF damper

4.1. One degree of freedom system with RF damper

The free body diagram of a one degree of freedom (1 DOF) vibrating system with a RF damper is shown in Fig. 4.

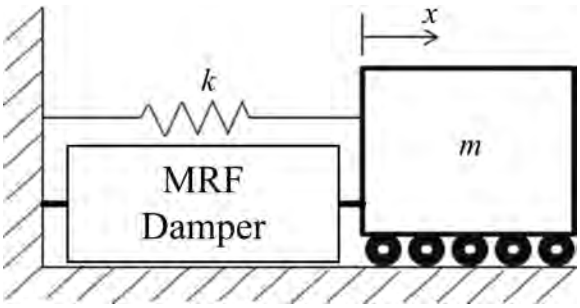

Fig. 4. Model of a 1 DOF of vibrating system with a RF damper, where m is mass and k is stiffness.

In this model the instantaneous equilibrium of forces is:

$$m\ddot{x} + C_\eta \dot{x} + F_{do}(\mathrm{RF})\,\mathrm{sgn}\,(\dot{x}) + xk = 0, \tag{10}$$

where

$$C_\eta \dot{x} + F_{do}(\mathrm{RF})\,\mathrm{sgn}\,(\dot{x}) = F_d \tag{11}$$

is the complex damping force.

This can be expressed as a product of equivalent damping C_{eq} and velocity $\dot{x}$:

$$F_d = C_{eq}\dot{x}\,. \tag{12}$$

4.2. Two degree of freedom system with base excitation and RF damper

This model represents two degree of freedom (2 DOF) with a base excitation system, having stiffness k_1 and mass m_1 in the first stage and connected by a spring with stiffness k_2 and a parallel attached controllable MR damper to the second mass m_2.

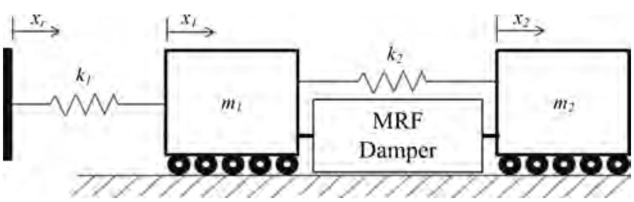

Fig. 5. The model of two degree of freedom vibrating system with base excitation.

Behavior of this two degree of freedom system can be described by a set of two equations which are the instantaneous equilibrium of the acting forces:

$$\begin{aligned} m_2\ddot{x}_2 &= (x_1 - x_2)k_2 + (\dot{x}_1 - \dot{x}_2)C_{\mathrm{RF}}\,, \\ m_1\ddot{x}_1 &= (x_2 - x_1)k_2 + (\dot{x}_2 - \dot{x}_1)C_{\mathrm{RF}} \\ &\quad + (x_r - x_1)k_1\,, \end{aligned} \tag{13}$$

where

$$(\dot{x}_2 - \dot{x}_1)C_{\mathrm{RF}} = F_d \tag{14}$$

represents the magneto-rheological damping force.

The rheological complex damping coefficient (C_{RF}) depends on the mechanical and electrical design of the damper and rheological fluid used.

5. Equivalent damping

The response of the 1 DOF vibrating system with a RF damper presented in Fig. 4 under harmonic excitation force $F_0 \sin(\omega t)$ applied to mass m is:

$$m\ddot{x} + F_{do}(\mathrm{RF})\,\mathrm{sgn}\,(\dot{x}) + C_\eta \dot{x} + kx = F_0 \sin(\omega t). \tag{15}$$

In this equation the damping force has two components. One of them is a Newtonian type and is proportional to the velocity $\dot{x}$, and a second, a semi Bingham one, which depends on the strength of the external field and direction of motion expressed by $\mathrm{sgn}\,(\dot{x})$.

The energy dissipated, ΔE_η in the viscously damped system per one cycle with viscous damping coefficient C_η is:

$$\begin{aligned} \Delta E_\eta &= \oint F_{d\eta}\,\mathrm{d}x = \int\limits_0^{2\pi/\omega} C_\eta \dot{x}\frac{\mathrm{d}x}{\mathrm{d}t}\,\mathrm{d}t \\ &= \int\limits_0^{2\pi/\omega} C_\eta \dot{x}^2\,\mathrm{d}t. \end{aligned} \tag{16}$$

Substituting $x = X\sin(\omega t)$ and $\dot{x} = \omega X \cos(\omega t)$ into above equation,

$$\Delta E_\eta = C_\eta \int\limits_0^{2\pi/\omega} \left[\omega^2 X^2 \cos^2(\omega t)\right]\,\mathrm{d}t \tag{17}$$

then integrating, results in:

$$\Delta E_\eta = C_\eta \pi \omega X^2. \tag{18}$$

The second damping component represented by force, $F_{do}(\mathrm{RF})$ in Eq. (9) yields the following expression for dissipated energy:

$$\Delta E(\mathrm{RF}) = F_{do}(\mathrm{RF}) \int\limits_0^{2\pi/\omega} \left[\mathrm{sgn}\,(\dot{x})\dot{x}\right]\,\mathrm{d}t. \tag{19}$$

Then dissipated energy in one cycle of the damper becomes:

$$\Delta E(\mathrm{RF}) = F_{do}(\mathrm{RF})X\left[\int_0^{\pi/2}\cos(\omega t)\,\mathrm{d}(\omega t) - \int_{\pi/2}^{3\pi/2}\cos(\omega t)\,\mathrm{d}(\omega t) + \int_{3\pi/2}^{2\pi}\cos(\omega t)\,\mathrm{d}(\omega t)\right]. \quad (20)$$

Solving the integration yields that the energy dissipated by a controllable damping force $F_{do}(\mathrm{RF})$ is:

$$\Delta E(\mathrm{RF}) = 4F_{do}(\mathrm{RF})X. \quad (21)$$

To create a viscously damped system of equivalent energy loss, we obtain:

$$\pi C_{eq}\omega X^2 = 4F_{do}(\mathrm{RF})X + C_\eta \pi\omega X^2. \quad (22)$$

Thus the equivalent damping coefficient C_{eq} yields:

$$C_{eq} = \frac{4F_{do}(\mathrm{RF})X + C_\eta\pi\omega X^2}{\pi\omega X^2}. \quad (23)$$

In terms of equivalent damping ratio ξ_{eq}:

$$C_{eq} = 2\xi_{eq}\omega_n m \quad (24)$$

and

$$\xi_{eq} = \frac{4F_{do}(\mathrm{RF})X + C_\eta\pi\omega X^2}{2\pi\omega\omega_n X^2}. \quad (25)$$

The 1 DOF system with equivalent damping C_{eq} which will dissipate as much energy as the system described by Eq. (10) is:

$$\ddot{x} + 2\xi_{eq}\omega\dot{x} + \omega_n^2 x = f_0\sin(\omega t) \quad (26)$$

where $f_0 = F_0/m$ and $\omega_n = \sqrt{k/m}$.

This is also an approximation of the Eq. (15).

6. Conclusions

In this paper the analytical model of rheological fluid was formulated and the equivalent coefficient of damping of the damper with a magneto-rheological (MR) fluid based on the dissipated energy principle was calculated. The major parameter in these calculations is apparent viscosity associated with shear stress of the MR fluid under an applied external field. This equivalent coefficient of damping allows the performance of vibration calculations and the design of mechanical systems to control unwanted vibrations in wider payload and frequency ranges than the system with uncontrollable damping. In addition, when a variable strength external field synchronized with the period of system's oscillations is applied an almost unlimited characteristic of a damping force can be obtained. The rheological phenomenon can also be used to control sound transmission loss of a multi-barrier system with rheological fluid placed between them. The increasing mechanical strength of the fluid between barriers increases apparent/equivalent stiffness of the system, thus the control of sound transmission loss in a stiffness control space is achievable.

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Noise-Induced Hearing Loss in Professional Orchestral Musicians

Małgorzata PAWLACZYK-ŁUSZCZYŃSKA, Małgorzata ZAMOJSKA, Adam DUDAREWICZ, Kamil ZABOROWSKI

Department of Physical Hazards, Nofer Institute of Occupational Medicine
Św. Teresy 8, 91-348, Łódź, Poland; e-mail: mpawlusz@imp.lodz.pl

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The overall purpose of this study was to assess hearing status in professional orchestral musicians. Standard pure-tone audiometry (PTA) and transient-evoked otoacoustic emissions (TEOAEs) were performed in 126 orchestral musicians. Occupational and non-occupational risk factors for noise-induced hearing loss (NIHL) were identified in questionnaire inquiry. Data on sound pressure levels produced by various groups of instruments were also collected and analyzed. Measured hearing threshold levels (HTLs) were compared with the theoretical predictions calculated according to ISO 1999 (1990).

Musicians were exposed to excessive sound at weekly noise exposure levels of for 81–100 dB (mean: 86.6±4.0 dB) for 5–48 years (mean: 24.0±10.7 years). Most of them (95%) had hearing corresponds to grade 0 of hearing impairment (mean hearing threshold level at 500, 1000, 2000 and 4000 Hz lower than 25 dB). However, high frequency notched audiograms typical for noise-induced hearing loss were found in 35% of cases. Simultaneously, about 35% of audiograms showed typical for NIHL high frequency notches (mainly occurring at 6000 Hz). When analyzing the impact of age, gender and noise exposure on hearing test results both PTA and TEOAE consistently showed better hearing in females vs. males, younger vs. older musicians. But higher exposure to orchestral noise was not associated with poorer hearing tests results.

The musician's audiometric hearing threshold levels were poorer than equivalent non-noise-exposed population and better (at 3000 and 4000 Hz) than expected for noise-exposed population according to ISO 1999 (1990). Thus, music impairs hearing of orchestral musicians, but less than expected from noise exposure.

Keywords: orchestral musicians, exposure to orchestral noise, hearing, risk of noise-induced hearing loss.

1. Introduction

The associations between exposure to noise and occupational hearing loss has been recognized for over 150 years. However, studies looking at the effects of music on hearing began more recently in the 1960.

It has been shown that musicians, in particular professional orchestral musicians, are often exposed to sounds at levels exceeding the upper exposure action values from Directive 2003/10/EC (Royster *et al.*, 1991; Obeling, Poulsen, 1999; Laitinen *et al.*, 2003; O'Brien *et al.*, 2008; Toppila *et al.*, 2011). Furthermore, they can also develop noise-induced hearing loss (NIHL) and suffer from other hearing symptoms such as tinnitus, hyperacusis, which can influence their work abilities more severely than hearing loss (Royster *et al.*, 1991; Jansson, Karlsson *et al.*, 1983; Teie, 1998; Kähäri *et al.*, 2001; Laitinen, 2005; Emmerich *et al.*, 2008; Jansen *et al.*, 2009).

However, because of insufficient audiometric evidence of hearing loss caused purely by music exposure, there is still disagreement and speculation about risk of hearing loss from music exposure alone (Royster *et al.*, 1991; Obeling, Poulsen, 1999; Karlsson *et al.*, 1983; Teie, 1998; Kähäri *et al.*, 2001; Emmerich *et al.*, 2008; Jansen *et al.*, 2009; Axelsson, Lindgren, 1981; Zhao *et al.*, 2010. There are studies that conclude that classical musicians have NIHL due to music exposure (Royster *et al.*, 1999; Axelsson, Lindgren, 1981; Ostri *et al.*, 1989) and studies that conclude just opposite (Karlsson *et al.*, 1983; Obeling, Poulsen, 1999; Kähäri *et al.*, 2001).

Nevertheless, when Directive 2003/10/EC was introduced to protect workers from harmful effects of noise, it recognized the needs of the music and entertainment sectors, including orchestral musicians (2003/10/EC). All member states were required to develop a code of conduct to provide practical guidelines which would help workers and employers in those sectors to attain the levels of protection established by that directive. Such regulations are still missing in Poland.

The purpose of this study was to assess hearing status in professional orchestral musicians and its relation with self-reported hearing ability as well as to compare the observed audiometric hearing threshold levels to the theoretical predictions according to ISO 1999 (1990) (PN-ISO 1999 (2000)).

2. Materials and methods

2.1. Study group

Participants were 126 professional musicians (58 females and 68 males), aged 24–67 years (mean ±SD: 43.0±10.7 years, median: 43.5 years) from two opera and four symphony orchestras. The study group comprised musicians playing violin (37), viola (13), cello (10), oboe (10), flute (8), horn (8), trombone (7), bassoon (7), clarinet (6), trumpet (5), double bass (4), percussion (3), tuba (2) and other instruments (4).

They were recruited by advertisement and did not receive any financial compensation for their participation in the experiment. The local Ethics Committee approved the study design.

2.2. Questionnaire inquiries

All musicians filled a questionnaire developed to enable identification of occupational and non-occupational risk factors for NIHL. The questionnaire consisted of items on: a) age and gender; b) education; c) professional experience; d) medical history (past middle-ear diseases, and surgery, etc.); e) physical features (body weight, height, skin pigmentation); f) lifestyle (smoking, noisy hobbies, etc.); g) self-assessment of hearing status and h) use of hearing protective devices. A special attention was paid to professional experience, i.e. the time of employment in orchestra/musical career or comparable experience, various work activities and instruments in use, time of daily and/or weekly practice, including individual rehearsals.

In addition, musicians' hearing ability was assessed using the (modified) Amsterdam Inventory for Auditory Disability and Handicap ((m)AIADH) (Meijer *et al.*, 2003). This inventory consists of 30 items and includes five basic disability factors dealing with a variety of everyday listening situations: a) distinction of sounds (subscale I), b) auditory localization (subscale II), c) intelligibility in noise (subscale III), d) intelligibility in quiet (subscale IV), and e) detection of sounds (subscale V).

The respondents were asked to report how often they were able to hear effectively in the mentioned situation. The four answer categories were as follows: almost never, occasionally, frequently, and almost always. Responses to each question were coded on a scale from 0 to 3; the higher the score, the smaller the perceived hearing difficulties. The total score per subject was obtained by adding the scores for 28 questions. Maximum total score of the questionnaire was 84. Additionally, the answers for each subscale were summed up (maximum score for subscale I was 24, while for the other subscale it was 15).

2.3. Hearing examinations

Conventional pure-tone audiometry (PTA) was performed in all study subjects ($n = 126$). In addition, transient-evoked otoacoustic emission (TEOAE) determinations were made in 92,9% ($n = 117$) of musicians. Before the exact examinations, otoscopy was performed in order to screen for conditions that would exclude examined subject from the study.

PTA was performed using an Audio Traveller Audiometer type 222 (Interacoustics) with TDH 39 headphones. Hearing threshold levels (HTLs) for air conduction were determined using an ascending–descending technique in 5-dB steps.

A Scout Otoacoustic Emission System ver. 3.45.00 (Bio-logic System Corp.) was applied for recording and analyzing of otoacoustic emissions. TEOAE recordings of 260 averages each were collected for every subject at stimuli levels of about 80 dB, using standard clicks. The artefact rejection level was set at 20 mPa. Each response was windowed from 3.5 to 16.6 ms post stimulus and band-pass filtered from 0 to 6000 Hz. The total TEOAE amplitude level and the TEOAE amplitude levels for frequency bands with central frequencies 1, 1.5, 2, 3 and 4 kHz were examined.

Hearing examinations were performed in quiet rooms located in concert halls and opera buildings where the A-weighted equivalent-continuous sound pressure level of background noise did not exceed 35 dB.

2.4. Evaluation of exposure to orchestral noise

Musicians' exposures to orchestral noise were evaluated based on data concerning sound pressure levels produced by various groups of instruments in orchestra. These data were collected during measurements performed with the measuring equipments placed in various instrument groups during collective and individual rehearsals, concerts and performances comprising diverse repertoire and various venues. Noise measurements were carried out according to Standards

No. PN-N-01307 (1994) and ISO 9612 (2009) (for details see (Pawlaczyk-Łuszczyńska *et al.*, 2011; Dudarewicz *et al.*, 2013).

For various groups of players the weekly noise exposure levels ($L_{EX,wi}$) were calculated from the values of the A-weighted equivalent-continuous sound pressure levels produced by the respective instrument (e.g. violins or trumpets) and time of weekly practice gathered from the questionnaire, using the following equation:

$$L_{EX,wi} = 10 \cdot \log\left[\frac{1}{T_0}(T_1 \cdot 10^{0.1 \cdot L_{Aeq,T_1}} + T_2 \cdot 10^{0.1 \cdot L_{Aeq,T2}})\right], \tag{1}$$

where: L_{Aeq,T_1} – is the A-weighted equivalent-continuous sound pressure level during group playing (i.e. collective rehearsals, concerts and performances), in dB; L_{Aeq,T_2} – is the A-weighted equivalent-continuous sound pressure level during solo rehearsals, in dB, T_1, T_2 – is the declared time of group and individual practice per week, in hours, T_0 – is the reference duration, $T_0 = 40$ h.

The data on noise exposure levels in college music students were also collected (Zamojska *et al.*, 2013). Subsequently, for each study subject weekly noise exposure level averaged over total time of musical career (including academic music education) was determined using the following equation:

$$L_{EX,w} = 10 \cdot \log\left[(t_1 \cdot 10^{0.1 \cdot L_{EX,w1}} + t_2 \cdot 10^{0.1 \cdot L_{EX,w2}}/(t_1 + t_2)\right], \tag{2}$$

where: $L_{EX,w1}/L_{EX,w2}$ – is the weekly noise exposure level assigned to orchestra musicians/ college music students playing respective instrument, in dB; t_1 – is the duration of music college education (over eighteen years of age), in years; t_2 – is the declared time of employment in orchestra (musical career), in years.

2.5. Prediction of noise-induced hearing loss

The musicians' actual hearing threshold levels were compared with the theoretical predictions calculated according to ISO 1999 (1990). The aforesaid standard specifies the method for determining a statistical distribution of hearing threshold levels in adult populations after given exposure to noise based on four parameters: age, gender, noise exposure level and duration of noise exposure (in years).

In order to compare predictions obtained for musicians of different gender, age, time and exposure, so-called standardized hearing threshold levels (STHLs) were determined using the following formulas (Śliwińska-Kowalska *et al.*, 2006):

$$\mathrm{SHTL} = 1.282 \cdot \frac{\mathrm{HTL} - \mathrm{PHTL_{Q50}}}{\mathrm{PHTL_{Q10}} - \mathrm{PHTL_{Q50}}} \quad \text{for } \mathrm{HTL} \geq \mathrm{PHTL_{Q50}}, \tag{3}$$

$$\mathrm{SHTL} = 1.282 \cdot \frac{\mathrm{HTL} - \mathrm{PHTL_{Q50}}}{\mathrm{PHTL_{Q90}} - \mathrm{PHTL_{Q50}}} \quad \text{for } \mathrm{HTL} < \mathrm{PHTL_{Q50}}, \tag{4}$$

where HTL – is the actual hearing threshold level, in dB, $\mathrm{PHTL_{Q50}}$ – is the median value of predicted hearing threshold level, in dB; $\mathrm{PHTL_{Q10/Q90}}$ – is the fractile Q10/Q90 of predicted hearing threshold level, in dB.

These calculations were applied to the audiograms twice, i.e. the musicians' hearing was compared to the hearing of the non-noise-exposed population and noise-exposed population.

2.6. Statistical analysis

A three-way analysis of variance (ANOVA) for independent data was performed to analyze the impact of gender, age and exposure on PTA and TEOAE results as well as the (m)AIAHD scores. For this purpose, the study group was divided into subgroups according to gender (females and males), age (younger and older subjects) and exposure (lower- and higher-exposed to noise subjects). Musicians were categorized as higher-exposed or lower-exposed on the basis of their assigned values of the weekly noise exposure level ($L_{EX,w}$). Subjects with the $L_{EX,w}$ levels above median value were classified as higher-exposed, while the others as lower-exposed. Similarly, the median value of age was used as the basis for classification of subjects as younger and older ones.

Answers to the questionnaire were presented as the proportions with 95% confidence intervals The relations between variables, e.g. results of PTA or TEOAE and musicians' self-reported hearing ability expressed in terms of the (m)AIADH scores were evaluated using Pearson's correlation coefficient. The standardized hearing threshold levels were analyzed using t-test.

All statistical tests were done with an assumed level of significance $p < 0.05$. The STATISTICA (version 9.0) software package was employed for the statistical analysis of the data.

3. Results

3.1. Noise exposure evaluation and additional NIHL risk factors

Table 1 summarizes sound pressure levels measured in various groups of instruments during group and solo playing in orchestra (i.e. collective and individual rehearsals, concerts and performances) as well as during academic music education (i.e. solo and group practicing, lessons with teacher, concerts, etc.).

According to the responses to the questionnaire, musicians under study were employed in orchestras from 5 to 48 years (mean ±SD: 24.0±10.7 years, median: 24.5 years). They were playing instruments on average 30 hours a week, including 7.5 and 22.5 hours

Table 1. Results of sound pressure levels measurements performed in orchestral musicians and college music students during solo and group practicing, lessons with teacher, concerts, etc. (Pawlaczyk-Łuszczyńska *et al.*, 2011; Dudarewicz *et al.*, 2013; Zamojska *et al.*, 2013).

	Individual rehearsals in orchestra			Group playing in orchestra			Academic music education		
	A-weighted equivalent-continuous SPL [dB] Mean ±SD (10th/50th/90th percentile)								
Violin	14*	85.1±2.0 [85.5]**	(82/86/87)	77	84.0±2.4 [84.6]	(82/84/87)	32	85.5±3.9 [87.0]	(80/86/91)
Viola	9	87.0±1.0 [87.1]	(86/87/89)	34	83.7±3.3 [84.7]	(79/84/88)	6	85.9±2.3 [86.5]	(84/85/89)
Cello	14	81.9±4.7 [84.0]	(76/82/88)	33	81.5±3.2 [82.6]	(77/82/85)	12	81.0±3.7 [82.5]	(78/80/86)
Double bass	10	80.4±4.1 [82.7]	(76/80/87)	27	82.4±4.7 [84.6]	(75/84/87)	5	80.5±3.4 [81.5]	(77/80/84)
Clarinet	11	89.1±3.7 [90.6]	(85/88/94)	28	86.2±3.4 [87.6]	(81/86/90)	8	89.7±1.2 [89.8]	(88/90/91)
Oboe	7	87.4±4.5 [89.2]	(82/86/92)	23	87.0±3.0 [88.1]	(83/87/92)	6	86.9±1.8 [87.3]	(85/87/89)
Bassoon	11	87.4±3.9 [88.4]	(84/88/91)	39	85.4±3.3 [86.4]	(81/86/90)	2	94.9±0.8 [94.9]	(94/95/95)
Flute	17	91.0±4.6 [92.9]	(83/91/97)	32	86.7±3.1 [87.8]	(84/87/91)	14	91.2±5.7 [94.2]	(83/91/98)
Horn	8	92.4±2.6 [92.9]	(87/93/95)	48	88.0±3.1 [89.3]	(85/88/92)	6	93.8±3.0 [94.4]	(91/95/96)
Trumpet	11	89.1±8.7 [100.9]	(84/86/97)	38	88.1±2.8 [88.9]	(84/89/92)	14	97.2±3.2 [98.3]	(94/98/101)
Trombone	14	94.8±2.9 [95.7]	(90/95/99)	31	88.0±4.0 [90.1]	(84/87/94)	14	95.1±4.8 [97.3]	(89/95/101)
Tuba	12	91.2±3.7 [92.5]	(86/91/95)	17	85.9±5.1 [87.9]	(79/87/91)	8	94.3±1.8 [94.7]	(93/94/96)
Percussion	3	89.6±3.2 [90.3]	(86/90/93)	25	85.2±4.5 [87.1]	(80/86/91)	21	95.9±7.6 [105.7]	(89/94/104)
Harp	2	81.4±6.5 [83.5]	(77/81/86)	12	82.0±3.4 [83.3]	(78/82/85)	4	85.5±0.6 [85.5]	(85/85/86)
Total	148	88.1±5.7 [93.2]	(80/88/95)	465	85.4±4.0 [87.2]	(81/86/90)	199	89.9±7.2 [97.9]	(81/90/99)

* Number of noise samples; ** An energy average of the number of measured *A*-weighted equivalent-continuous SPLs.

of solo practicing and group playing. The weekly noise exposure levels calculated from this data ranged between 81–95 dB (mean ±SD: 85.7.0±3.2 dB, median: 84.2 dB) (Fig. 1).

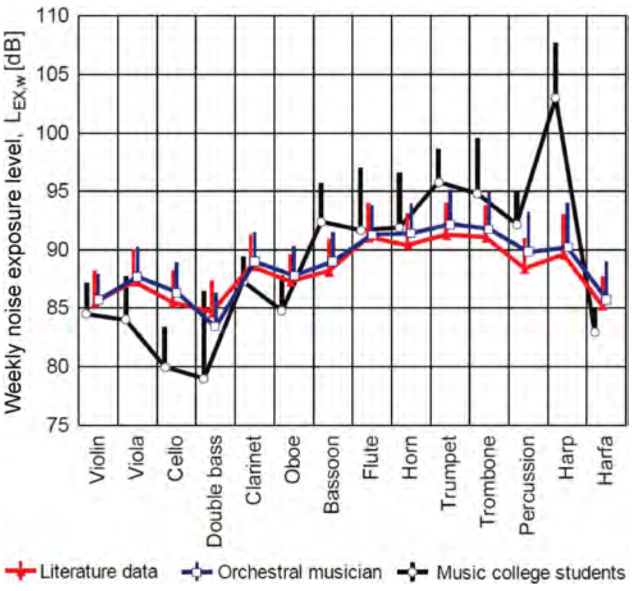

Fig. 1. Results of noise exposure evaluation for various groups of players among orchestral musicians and college music students together with evaluations based on literature data (Dudarewicz *et al.*, 2013; Zamojska *et al.*, 2013). (Weekly noise exposure levels $L_{EX,w}$ are specified with one-side 95% CI).

Figure 1 illustrates the aforesaid data together with our noise exposure determination for college music students and evaluations based on literature data (Pawlaczyk-Łuszczyńska *et al.*, 2011; Dudarewicz *et al.*, 2013; Zamojska *et al.*, 2013). As can be seen there are differences in exposure condition between professional and college music students; the highest difference was noted for percussion instruments players. However, there is a good agreement between literature data and our assessment of noise exposure in orchestral musicians. Thus, these results seem to be a reliable basis for assessing risk of NIHL in orchestral musician.

Subsequently, weekly noise exposure level averaged over total time of musical career (including academic music education) varied from 81–100 dB (mean ± SD: 86.6±4.0 dB, median: 84.3 dB). Please note that nearly half (47.0%) of study subjects were exposed to the $L_{EX,w}$ levels exceeding the Polish maximum admissible intensity values ($L_{EX,w} = 85$ dB), while 47.0% – the exposure limit value according to the noise directive ($L_{EX,w} = 87$ dB) (Fig. 2).

As to other NIHL risk factors, 7.1% (95%CI: 2.5–11.2%) of musician reported elevated blood pressure. Moreover, 5.6% (95%CI: 3.6–13.2%) of them were current smokers, while 17.5% (95%CI: 11.8–25.1%) smoked in the past. 12.7% (95%CI: 7.9–19.7%) of musicians had used regularly painkillers. The presence of white-finger syndrome was reported by only 7.1% (95%CI: 3.6–13.2%) of them, while overweight (BMI > 25) by 17.5% (95%CI: 11.8–25.1%).

Furthermore, 15.1% (95%CI: 9.8–22.4%) of musicians often used noisy tools and 25.4% (95%CI: 18.6–33.7%), listened often to music through headphones.

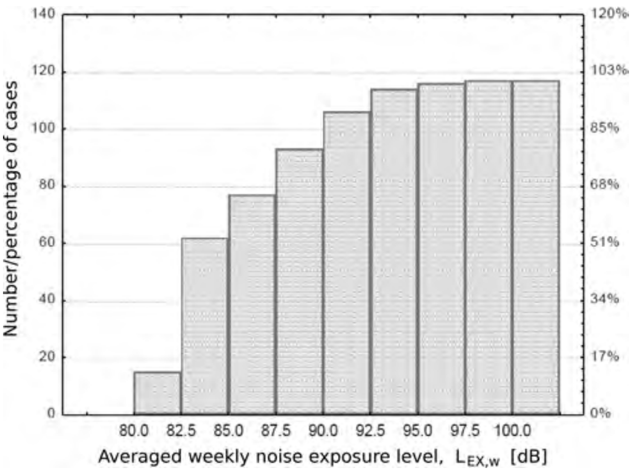

Fig. 2. Cumulative distribution of the weekly noise exposure level averaged over total time of musical career (including academic music education) in study group.

On the other hand, only 11.1% (95%CI: 6.6–17.9%) of them declared using hearing protective devices (HPDs) at present or in the past, while 31.0% (95%CI: 23.5–39.5%) players intended to use HPDs in the future.

3.2. Results of hearing tests

In the majority (95.6%) of cases a mean value of the hearing threshold level for 500, 1000, 2000 and 4000 Hz was lower than 25 dB, which corresponds to grade 0 of hearing impairment according to the World Health Classification (WHO). Only 3.8% and 0,8% of the measured audiograms corresponded to grade 1 and 2 of hearing impairment, respectively. Moreover, almost all of them (88.9%) were found in the older musicians. Table 2.

Typical NIHL notches at 4000 or 6000 Hz of at least 15 dB depth relative to the best preceding threshold (from 1000 Hz) were observed in 35.1% of audiograms, including 61.4% for left ear. Most of them (73,9%) occurring at 6000 Hz. The portion of total population with bilateral notching at any frequency was 19.2%.

Audiometric hearing threshold levels determined in 126 professional orchestral musicians (251 ears) are shown in Fig. 3. A significant main effect of age on the HTLs was observed in the frequency range from 1000 to 8000 Hz (Fig. 3a, Table 2).

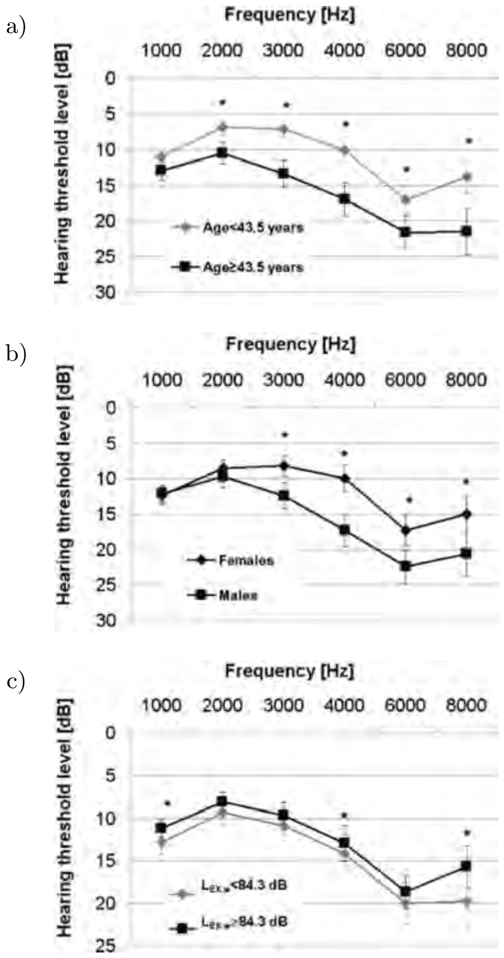

Fig. 3. Audiometric hearing threshold levels (mean ±95% CI) in various subgroups of musicians, i.e. females and males (a), younger and older subjects (b), and lower- and higher-exposed subjects (c). Significant differences ($p < 0.05$) between subgroups are marked (*).

Generally, older subjects showed higher reduction of hearing threshold level than younger ones. Similar relation was observed between males and females

Table 2. Summary results of the three-way ANOVA – influence of gender, age and noise exposure on audiometric hearing threshold levels in orchestral musicians. Significant main effects or interactions are given in bold ($p < 0.05$).

Frequency [Hz]	Main effect			Interaction			
	Age (A)	Exposure (E)	Gender (G)	E × A	A × G	E × G	A × E × G
	Statistical significance, p						
1000	0.110	**0.042**	0.664	**0.001**	0.221	0.488	0.587
2000	**0.007**	0.096	0.454	**0.006**	0.435	0.188	0.969
3000	**0.000**	0.067	**0.000**	0.177	**0.048**	**0.039**	0.773
4000	**0.000**	**0.028**	**0.000**	0.481	0.098	0.368	0.489
6000	**0.002**	0.083	**0.000**	**0.031**	0.074	**0.031**	0.122
8000	**0.000**	**0.012**	**0.001**	**0.023**	0.108	0.072	**0.049**

in the high frequency region from 3000 to 8000 Hz (Fig. 3b). There was also a significant main effect of noise exposure on the HTLs at frequencies of 1000, 4000 and 8000 Hz. However, contrary to our expectations, higher-exposed subjects ($L_{EX,w}$ > 84.3 dB) had lower (better) audiometric hearing levels compared to lower-exposed individuals ($L_{EX,w} \leq$ 84.3 dB) (Fig. 3c). Moreover, significant two-way interactions between noise exposure and age (for the HTLs at 1000, 2000, 6000 and 8000 Hz) as well as between noise exposure and gender (for the HTLs at 3000 Hz) were noted (Table 2).

As can be seen in Fig. 4a, among older subjects, those lower-exposed had higher (poorer) hearing level (at 6000 Hz) compared to higher-exposed individuals, while in younger musicians there were no differences due to noise exposure. (Similar, relations were observed for other frequencies, i.e. 1000, 2000 and 8000 Hz). On the other hand, when analysing lower-exposed musicians, females had better hearing than males, while there were no differences in case of higher-exposed subjects.

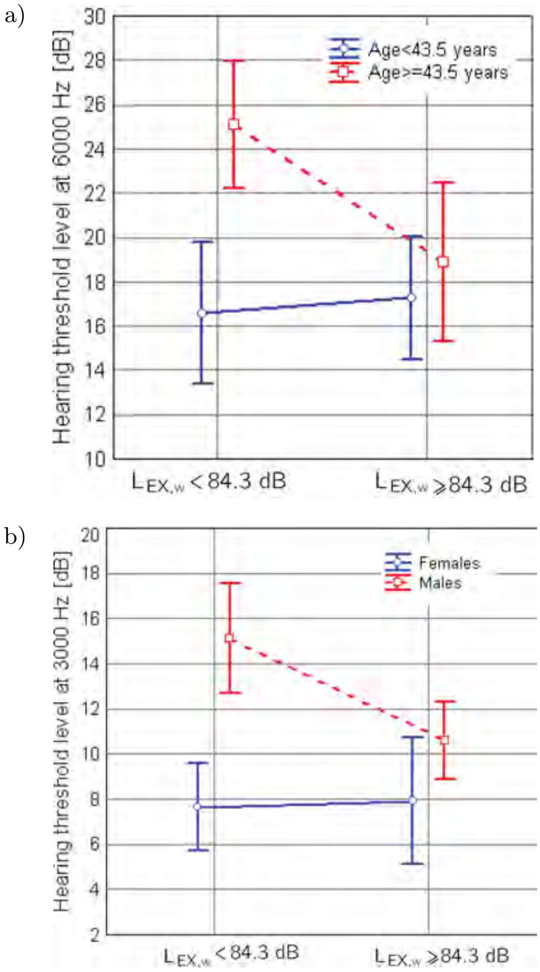

Fig. 4. A two-way interaction between: a) noise exposure and age for the HTLs at 6000 Hz ($F(1, 225)$ = 4.732, p = 0.031), b) noise exposure and gender for the HTLs at 3000 Hz ($F(1, 225) = 4.305$, $p = 0.039$).

In almost all cases (94.4% of ears) the reproducibility of the TEOAE above 70% for the total response was noted. On the other hand, higher than 6 dB signal to noise ratio (SNR) was observed in the 72.1% of cases. Both higher values of reproducibility and SNR were more frequently noted in the females than males.

Results of TEOAE testing are summarized in Fig. 5. Significant main effects of gender and age on TEOAE amplitude, SNR as well reproducibility was noted (Table 3, Figs. 5b, 5e and 5h).

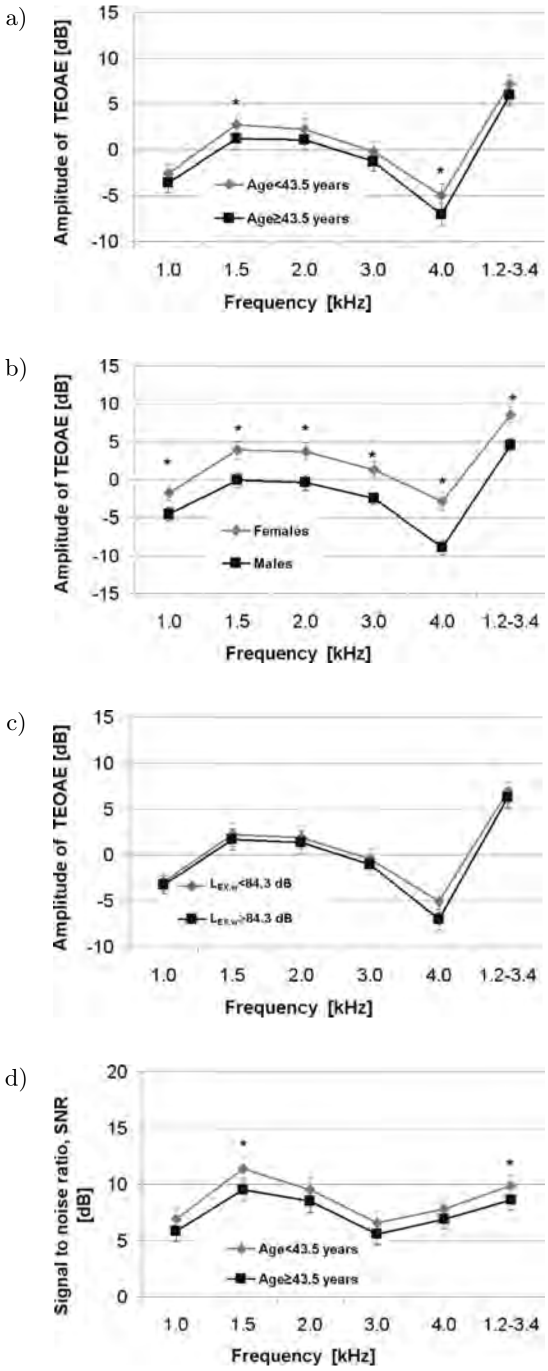

Fig. 5 a–d

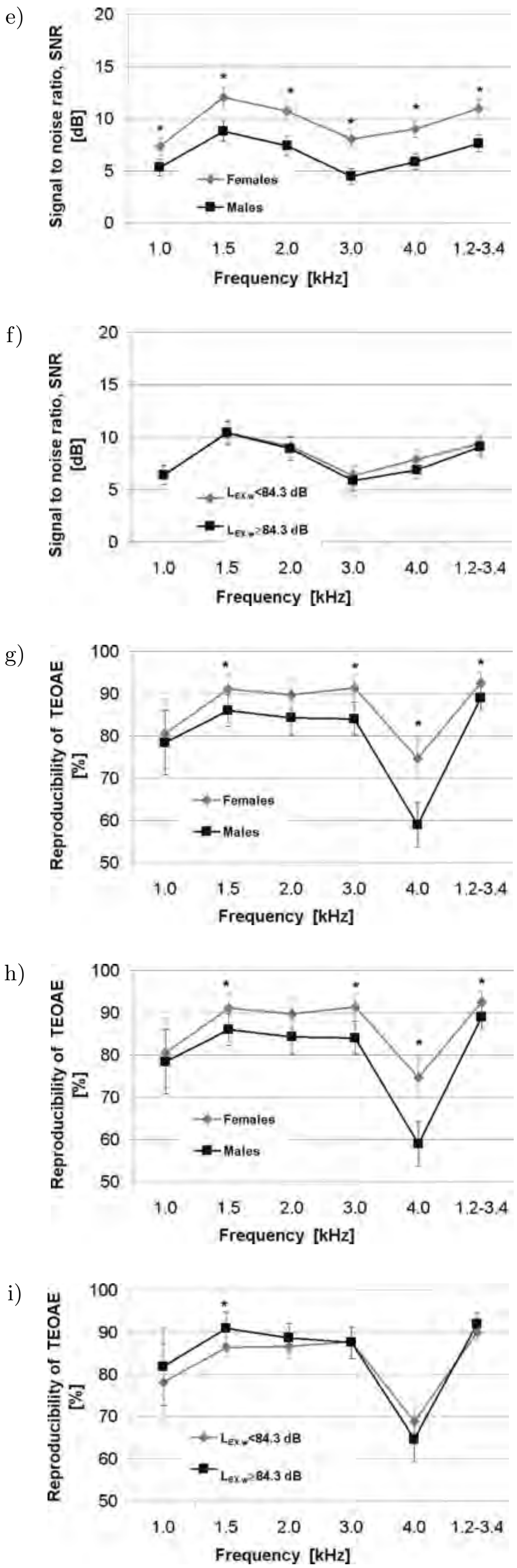

Fig. 5. TEOAEs (mean ±95% CI) in various subgroups of musicians, i.e. females and males (a, d, g), younger and older subjects (b, e, h), and lower- and higher-exposed subjects (c, f, i). Significant differences between subgroups were marked (*) (ANOVA, $p < 0.05$).

Generally, females showed better results of TEOAE testing compared to males. Similar relation was observed when analysing younger and older musicians. On the other hand, noise exposure was only found to significantly affect the reproducibility of TEOAE in the frequency bands of 1.5 kHz (Fig. 5i). Similar to PTA, higher-exposed musicians had better results (i.e. greater reproducibility) than lower-exposed ones.

Furthermore, a significant two-way interaction between exposure and gender was observed for the signal to noise ratio and reproducibility of TEOAE in the frequency band of 4 kHz (Figs. 6a and 6b, $p < 0.05$). Among lower-exposed musicians, females showed better reproducibility compared to males, while among higher-exposed subjects there were no differences caused by gender. On the other hand, the opposite relations was observed when analyzing SNR at 4 kHz. Higher-exposed females had better results than higher-exposed males, while there was no gender-related difference in the lower-exposed musicians.

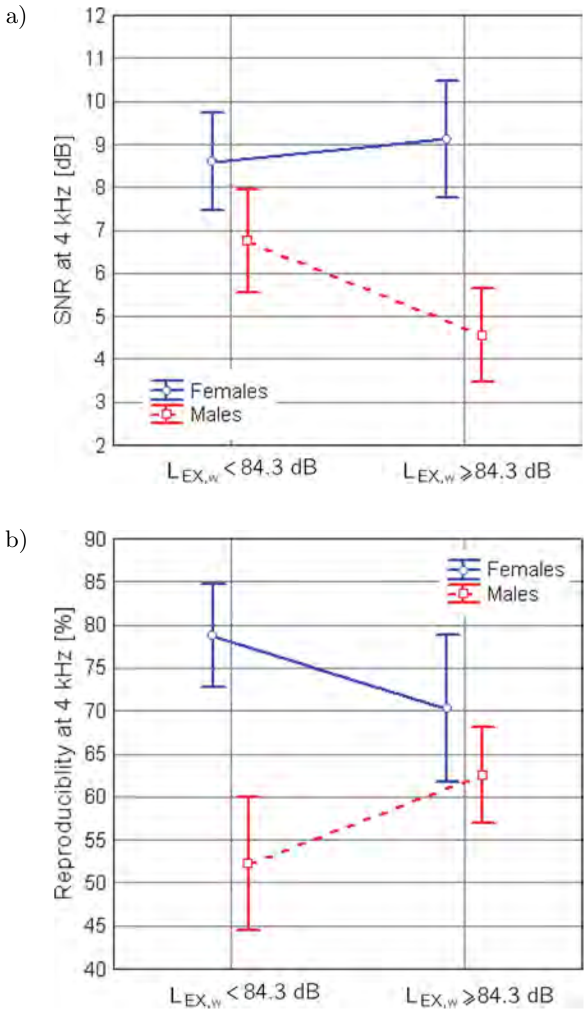

Fig. 6. A two-way interaction between noise exposure and gender for a) the signal to noise ratio ($F(1, 207) = 5.501$, $p = 0.020$), and b) reproducibility of TEOAE in the frequency band of 4 kHz ($F(1, 207) = 6.867$, $p = 0.009$).

Table 3. Summary results of the three-way ANOVA – influence of gender, age and noise exposure on TEOAE in orchestral musicians. Significant main effects or interactions are given in bold.

Frequency [Hz]	Main effect			Interaction			
	Age (A)	Exposure (E)	Gender (G)	E × A	A × G	E × G	A × E × G
	Statistical significance, p						
TEOAE amplitude							
1	0.078	0.737	**0.000**	0.606	0.474	0.705	0.101
1.5	**0.034**	0.781	**0.000**	0.802	0.856	0.692	0.072
2	0.109	0.668	**0.000**	0.944	0.820	0.867	0.069
3	0.126	0.706	**0.000**	0.101	0.334	0.663	0.426
4	**0.009**	0.538	**0.000**	0.324	0.566	0.228	0.342
Total response (1.2–3.4)	0.057	0.810	**0.000**	0.676	0.869	0.581	0.087
Signal to noise ratio							
1	0.073	0.490	**0.002**	0.885	0.545	0.880	0.184
1.5	**0.012**	0.493	**0.000**	0.639	0.779	0.862	0.100
2	0.125	0.500	**0.000**	0.568	0.948	0.901	0.092
3	0.141	0.593	**0.000**	0.096	0.312	0.696	0.479
4	0.173	0.872	**0.000**	0.870	**0.028**	**0.020**	0.916
Total response (1.2–3.4)	**0.044**	0.594	**0.000**	0.877	0.979	0.735	0.116
TEOAE reproducibility							
1	**0.029**	0.203	0.422	0.254	0.079	0.249	0.604
1.5	**0.001**	**0.021**	**0.034**	0.092	**0.014**	0.339	**0.012**
2	0.310	0.200	0.059	0.068	**0.023**	0.333	0.058
3	0.500	0.407	**0.002**	0.354	0.184	0.247	0.709
4	0.276	0.796	**0.000**	0.735	**0.027**	**0.009**	0.691
Total response (1.2–3.4)	**0.006**	0.104	**0.040**	0.116	**0.013**	0.266	**0.034**

3.3. Comparison of actual and predicted hearing threshold levels

Figure 7 shows standardized hearing threshold levels in musicians under study. It is worth noting that the closer to zero value of SHTL, the better the prediction of hearing loss according to ISO 1999 (1990). On the other hand, the positive values of SHTLs indicate that actual hearing threshold levels are higher than predicted.

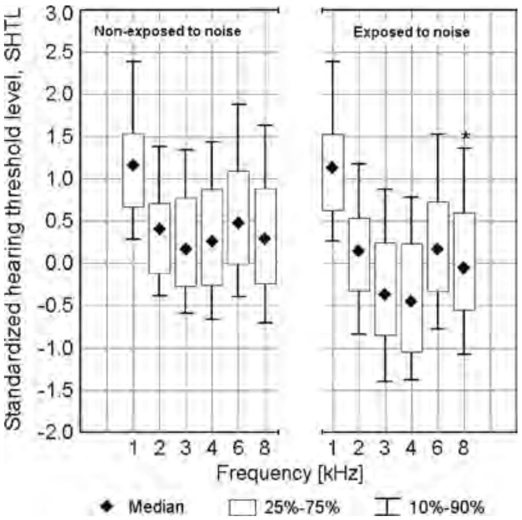

Fig. 7. Comparison of the musicians' hearing loss to that of non-noise-exposed and noise-exposed populations. All SHTL values, excluding those marked (*) significantly differ from 0 (t-test, $p < 0.05$).

Comparing the musicians to non-noise-exposed population (database A from ISO 1999 (1990)) revealed that their hearing losses (in the frequency range 1000–8000 Hz) were higher than predicted ($p > 0.05$). On the other hand, the actual hearing threshold levels were lower (better) than expected for 3000 and 4000 ($p < 0.05$) with an expected value at 8000 Hz ($p > 0.05$), when compared to equivalent population exposed to industrial noise. Furthermore, the observed audiometric hearing losses were higher than predicted for 1000, 2000 and 6000 Hz.

3.4. Self-assessment of hearing status

Over half of musicians (54.4%, 95%CI: 45.3–63.4%) assessed their hearing as very good, while 17.5% (95%CI: 11.8–25.1%) of them noticed hearing impairment. In majority cases (90.9%) hearing deficit developed gradually. Moreover, it was associated with difficulty in speech intelligibility in noisy environment 27.0% (95%CI: 20.0–35.4%) and hearing whisper 12.7% (95%CI: 7.9–19.7%). 20.6% (95%CI: 14.4–28.6%) of musician complained of hyperacusis, while 11.9% (95%CI: 7.2–18.8%) of them reported tinnitus.

Musicians examined using the (m)AIADH obtained mean total score of 89.9±11.0% of maximum value, which suggests no substantial hearing difficulties in subjects under study (Table 4). Relatively low scores were frequent only in the subscale (III) evaluating intelligibility in noise (23.0% of subjects scored below 70% of maximum value). No significant main effects of age, gender and noise exposure on the (m)AIAHD scores were noted. There were no significant interactions between of age, gender and exposure, either (ANOVA, $p < 0.05$).

However, weak but statistically significant linear relationships were noted between PTA results and the total score of (m)AIAHD and scores of the individual subscales (Table 5). In particular, relatively high values of correlation coefficients were observed for subscale evaluating intelligibility in noise (subscale III) (up to −0.36, $p < 0.05$). The linear relationships were also noted between musicians' self-assessment of hear-

Table 4. Musicians' self-assessment of hearing ability in the (m)AIAHD scores.

(m)AIAHD scores Mean ±SD (10th/50th/90th percentiles)					
Total	Subscale I	Subscale II	Subscale III	Subscale IV	Subscale V
75.5±9.2 (64/78/84)	22.8±2.4 (21/24/24)	13.4±2.0 (10/14/15)	12.0±2.6 (8/12/15)	13.3±2.1 (9/14/15)	13.8±1.8 (11/15/15)

Table 5. Relationships between results of hearing tests (PTA and TEOAE) and the (m)AIAHD scores and Pearson's correlation coefficient r. Statistically significant Pearson's correlation coefficient r values are given in bold ($p < 0.05$).

	Pearson's correlation coefficient r					
	Total score	Subscale I	Subscale II	Subscale III	Subscale IV	Subscale V
Audiometric hearing threshold level/Frequency [kHz]						
1	**−0.19**	−0.02	−0.14	**−0.31**	**−0.22**	−0.13
1.5	**−0.21**	−0.04	**−0.16**	**−0.31**	**−0.28**	**−0.20**
2	**−0.23**	−0.05	**−0.15**	**−0.32**	**−0.31**	**−0.21**
3	**−0.29**	**−0.15**	**−0.21**	**−0.36**	**−0.33**	**−0.24**
4	**−0.22**	−0.13	**−0.15**	**−0.27**	**−0.16**	−0.14
6	**−0.22**	−0.09	**−0.16**	**−0.33**	**−0.23**	−0.10
Total response	**−0.24**	−0.12	−0.13	**−0.33**	**−0.20**	−0.12
Amplitude of TEOAE/Frequency [kHz]						
1	−0.08	−0.08	−0.11	−0.04	−0.06	−0.05
1.5	−0.02	−0.07	−0.11	0.06	−0.05	−0.03
2	0.09	0.02	−0.02	**0.18**	0.10	0.03
3	0.12	0.10	0.00	**0.17**	0.08	0.07
4	**0.22**	**0.16**	0.12	**0.28**	0.12	0.13
Total response	0.03	−0.02	−0.06	0.12	0.02	0.00
Signal to noise ratio/Frequency [kHz]						
1	−0.11	−0.08	−0.12	−0.07	−0.08	−0.06
1.5	−0.05	−0.08	−0.13	0.04	−0.07	−0.05
2	0.08	0.01	−0.01	**0.17**	0.09	0.03
3	0.12	0.10	0.00	**0.17**	0.08	0.07
4	**0.25**	**0.21**	**0.18**	**0.29**	**0.15**	**0.16**
Total response	0.02	−0.02	−0.06	0.11	0.00	−0.01
Reproducibility of TEOAE/Frequency [kHz]						
1	0.04	0.04	−0.03	0.02	0.03	0.08
1.5	0.06	−0.02	−0.07	**0.17**	0.05	0.00
2	0.12	0.05	0.02	**0.21**	0.13	0.01
3	**0.19**	0.14	0.10	**0.22**	**0.16**	0.09
4	**0.26**	**0.23**	**0.20**	**0.29**	**0.15**	**0.16**
Total response	0.10	0.02	0.00	**0.19**	0.08	0.02

ing ability in the (m)AIAHD scores and the TEOAE results ($0.15 \leq r \leq 0.29$, $p < 0.05$). In the latter case, the highest values of correlation coefficient were noted between score of subscale III and amplitude, SNR and reproducibility of TEOAE in the frequency band of 4 kHz (up to 0.29, $p < 0.05$).

4. Discussion

Although hazardous aspects of music have been extensively studied for several decades, there is still lack of unanimous opinion on music exposure causing hearing loss. Nevertheless, studies on orchestral musicians have been relatively consistent that hearing threshold levels in this staff group are higher (worse) when compared to age-related reference data from otologically normal persons, that is ISO 7029 (Royster *et al.*, 1991; Jansson, Karlsson, 1983; Axelsson, Lindgren, 1981; Ostri, 1989).

For example, Royster *et al.*, (1991) analyzed audiometric hearing threshold levels in 59 musicians from the Chicago Symphony Orchestra exposed to orchestral noise at A-weighted daily noise exposure levels of 75–95 dB. Although musicians' HTLs were better than those of unscreened non-industrial population, typical NIHL notches were observed in over half (52.5%) of them.

Recently, Emmerich *et al.* (2008) measured the noise exposure and assessed the audiologic status of 109 professional musicians aged 30–69 years from three major German orchestras. They observed hearing loss ($\geq$ 15 dB) in over half of musicians. The highest losses were found among the string and the brass players. Moreover, among string players a dominant hearing deficit was observed in the left ear.

On the other hand, Jansen *et al.* (2009) have performed an audiological test battery (PTA and otoacoustic emissions (OAEs)) in 241 professional musicians aged between 23 and 64. Most of them had normal hearing, but their audiograms showed notches at 6 kHz. They often complained about tinnitus and hyperacousis, while diplacusis was generally not reported as a problem. The OAEs were more intense with better PTA thresholds. Moreover, the musicians showed worse HTLs than it could be expected on the basis of age and gender.

Our results are in line with the aforesaid findings. Almost all musicians under study had normal hearing (mean hearing threshold level for 0.5, 1, 2 and 4 Hz up to 25 dB) corresponding to grade 0 of hearing impairment according to the classification of the WHO, while only a few of them had hearing loss corresponding to grade 1 or 2. It is worth noting that according to the aforesaid classification in the case of grade 0 ("no impairment") no or very slight hearing problems can occur, and one is able to hear whispers, while in grade 1 ("slight impairment") one is able to hear and repeat words spoken in normal voice at a distance of 1 meter, but hearing aids may be needed (WHO).

Nevertheless, 35.1% of audiograms showed high frequency notches (mainly at 6 kHz). Furthermore, over half of them (61.4) were noted in case of left ear. Nearly every fifth musician had bilateral notching at any frequency (4 or 6 kHz).

Moreover, both PTA and TEOAE consistently showed better hearing in females vs. males and younger vs. older subjects. These findings confirmed some earlier observations. For example, Emmerich *et al.* (2008) in the quoted above study also observed lower hearing loss (at 4 and 6 kHz) in younger musicians (aged 30–39 years) when compared to older ones (aged over 60 years). On the other hand, Kähäri *et al.* (2001) analyzing audiometric HTLs in 140 classical orchestral musicians employed at the Gothenburg Symphony Orchestra and the Gothenburg Opera, found that female musicians had significantly better hearing thresholds in the high-frequency area (above 2 kHz) than did male musicians.

However, contrary to our expectations higher noise exposure levels ($L_{EX,w}$) were not associated with higher (worse) audiometric HTLs and worse results of TEOAE. In our study, higher-exposed musicians ($L_{EX,w} >$ 84.3 dB) had better hearing thresholds (at 1, 4 and 8 kHz) than the lower-exposed individuals ($L_{EX,w} \leq$ 84.3 dB). Furthermore, among older subjects, those lower-exposed had higher hearing level (at 1, 2, 6 and 8 kHz) compared to higher-exposed individuals, while in younger musicians (as expected) there were no differences due to noise exposure.

The impact of noise exposure on TEOAE was less pronounced than was in case of PTA. Higher-exposed musicians had only greater reproducibility (in the frequency band of 1.5 kHz) than lower-exposed ones. Furthermore, among lower-exposed musicians, females showed better results (higher reproducibility of TEOAE at 4 kHz) compared to males, while among higher-exposed subjects there were no differences caused by gender. Among lower-exposed musicians, females showed better reproducibility (at 4 kHz) compared to males, while among higher-exposed subjects there were no differences caused by gender. On the other hand, higher-exposed females had higher SNR (at 4 kHz) than higher-exposed males, while there was no gender-related difference in the lower-exposed musicians.

Generally, the latter results might be explained by high-resistance to NIHL in musicians, in particular those higher-exposed to orchestral noise. It has been shown that individual susceptibility to hearing loss is very diversified (Śliwińska *et al.*, 2006). It is worth to underline that the study group comprised only volunteers. It is obvious that professional musicians which had any hearing problems did not responded positively to the invitation to participate in the study. Nevertheless, the results of hearing tests are consistent with musicians' self-reported hearing ability assessed by the (m)AIAHD showing some hearing difficulties in relation to intelligibility in noisy environment in 29.0% players.

Please note that the (m)AIAHD has been used for various purposes. For example, attempts were made to apply this questionnaire for measuring the effect of middle ear surgery with the aim of improving hearing, as well as for evaluation of the relation between the audiometric and psychometric measures of hearing after tympanoplasty (WHO). The results of the latter investigation indicated that the (m)AIADH scores were almost independent of hearing loss for postoperative hearing levels in the range of 25–40 dB. For the permanent threshold shifts (PTS) higher than 40 dB, the (m)AIAHD scores clearly decreased with an increasing PTS. However, even small residual hearing losses (less than 25 dB) led, on average, to (m)AIADH scores which were substantially lower than scores for normal hearing. Thus, the (modified) Amsterdam Inventory for Auditory Disability and Handicap seems to be a useful tool for a hearing conservation programme.

In this study, the observed audiometric hearing threshold levels were compared with the theoretical predictions according to ISO 1999 (1990). It is worth to underline that aforesaid standard specifies the method for prediction of NIHL after given exposure to noise based on four parameters: age, gender, noise exposure level and duration of noise exposure (in years). However, it does not take into consideration risk factors other than occupational noise, such as exposure to noise beyond workplace (e.g., leisure noise, noise exposure during compulsory military service), co-exposure to certain chemicals (organic solvents and heavy metals), vibrations, and several individual factors and NIHL, including smoking, elevated blood pressure, cholesterol and skin pigmentation (Toppila *et al.*, 2001, Pyykko *et al.*, 2007; Dudarewicz *et al.*, 2010). It does not discuss the protective effects of hearing protective devices, either.

Since in musicians' working conditions there are no ototoxic chemicals or vibrations, to assess the incidence of additional NIHL risk factors, the study subjects filled in a questionnaire. According to the responses, risk factors (such as exposure to noise beyond workplace, smoking, elevated blood pressure, cholesterol and white-finger syndrome) were rather seldom. Moreover, only 11.1% of musicians declared using hearing protective devices at present or in the past. Hence, their protective effect was negligible.

It has been shown that musicians' hearing threshold levels were higher (worse) than equivalent (in terms of age and gender) non-noise-exposed population. When compared to the equivalent population exposed to industrial noise, the actual hearing threshold levels were lower (better) than expected for 3000 and 4000 Hz, while there was no significant difference for 8000 Hz. Furthermore, the observed audiometric hearing losses were higher than predicted for 6000 Hz as well as for 1000 and 2000 Hz.

The latter results (i.e. a relatively high permanent threshold shift at lower frequencies) might be dependent on the testing procedure. Relatively low hearing threshold levels were determined with 5 dB accuracy. Moreover, PTA was performed in quiet rooms (with background noise up to 35 dB) located in concert halls and opera building instead of sound-proof cabins, which is especially important when determining HTLs in the low frequency range. Nevertheless, our findings confirm earlier observations that orchestral noise deteriorate hearing less than expected from noise exposure (Obeling, Polusen, 1999; Toppila *et al.*, 2011).

Recently, Toppila *et al.* (2011) compared audiograms of 63 musicians from four Helsinki orchestras with the theoretical predictions calculated according to ISO 1999 (1990) and analyzed the role of individual susceptibility factors in the onset of hearing loss among this staff group. Number of individual NIHL risk factors was small in their study group. No age dependency was found. The musicians' hearing loss distribution corresponded to that of the general population. However, the highly-exposed players had greater (poorer) permanent threshold shift at the frequencies over 3000 Hz than the lower-exposed individuals. Moreover, the musicians' hearing loss was smaller than expected for the frequencies of 2000, 3000 and 4000 Hz, with an expected value for 6000 Hz, when compared to an industrial population with the same lifetime exposure (Toppila *et al.*, 2011).

Earlier, Obeling and Poulsen (1999) compared audiograms of 57 symphony orchestras to expected (basing on noise exposure) hearing threshold levels from ISO 1999 (1990). They also found out that musicians' actual hearing threshold levels were better than expected from noise exposure and concluded that exposure of musicians cannot be expected to result in pronounced audiometric hearing losses from playing in a symphony orchestra.

To sum up, music impairs hearing of orchestral musicians, but less than expected from noise exposure. Nevertheless, a special hearing conservation program should be developed for the professional group of orchestral musicians.

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Creating Dynamic Maps of Noise Threat Using PL-Grid Infrastructure

Maciej SZCZODRAK[(1), (2)], Józef KOTUS[(1), (2)], Bożena KOSTEK[(1), (3)], Andrzej CZYŻEWSKI[(2)]

[(1)] *Academic Computer Center – TASK, Gdansk University of Technology*

[(2)] *Multimedia Systems Department, Gdansk University of Technology*
e-mail: grid@sound.eti.pg.gda.pl

[(3)] *Audio Acoustics Laboratory, Gdansk University of Technology*
Narutowicza 11/12, 80-233 Gdańsk, Poland

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The paper presents functionality and operation results of a system for creating dynamic maps of acoustic noise employing the PL-Grid infrastructure extended with a distributed sensor network. The work presented provides a demonstration of the services being prepared within the PLGrid Plus project for measuring, modeling and rendering data related to noise level distribution in city agglomerations. Specific computational environments, the so-called domain grids, are developed in the mentioned project. For particular domain grids, specialized IT solutions are prepared, i.e. software implementation and hardware (infrastructure adaptation), dedicated for particular researcher groups demands, including acoustics (the domain grid "Acoustics"). The infrastructure and the software developed can be utilized mainly for research and education purposes, however it can also help in urban planning. The engineered software is intended for creating maps of noise threat for road, railways and industrial sources. Integration of the software services with the distributed sensor network enables automatic updating noise maps for a specific time period. The unique feature of the developed software is a possibility of evaluating auditory effects which are caused by the exposure to excessive noise. The estimation of auditory effects is based on calculated noise levels in a given exposure period. The outcomes of this research study are presented in a form of the cumulative noise dose and the characteristics of the temporary threshold shift.

Keywords: noise, dynamic noise map, reverse engineering, grid computing.

1. Introduction

Environmental noise that occurs in the urban areas is known to impose a threat to human health (Engel, 2004; Kompala, Lipowczan, 2007; Kucharski, 2007; Popescu, Moholea, 2010). The effects of this harmful factor can be observed in various aspects of human life. In 2002, in order to assess the noise pollution threat, the European Parliament along with the Council of the European Union issued the legal foundation for undertaking urban noise monitoring in all Member States, i.e. "*European Directive 2002/49/EC*" (2002) on assessment and management of environmental noise. The main aim of this Directive is to provide a common basis for assessing the noise problem across the EU. It commits the EC-member states to evaluate the noise impact for all agglomerations, for all major roads and major railways and for all major airports within their territories and to present in the form of strategic noise maps. Until 30 June 2007 noise maps had to be prepared for all cities, or more precise, for agglomerations with more than 250,000 inhabitants. Subsequently, noise maps of municipalities of over 100 000 inhabitants should have to be drawn up by 30 June 2012.

The release of the guidelines have raised numerous initiatives in order to asses an acoustic climate in European cities. Technical implementations are based on two main methods, namely noise measurements and noise pollution prediction. The first approach utilizes a grid of noise measuring devices which are registering sound pressure level values and associated data. Such systems have been deployed in several European cities, for example in Lille, France (Chopard *et al.*, 2007) where over 80 acoustic monitoring stations cover the urban area. In the second approach noise distribution is estimated based on noise source and propagation model. Systems based on this concept are implemented in most of large European cities. For instance the city of Gdansk, Poland developed strategic noise maps for road traffic, railway, tram and air traffic noise calculated according to the L_{DEN} and L_N noise indexes (2013). Developed acoustic disturbance maps are utilized to assess the threat citizens are exposed to, and introduce noise reduction strategies in critical locations of the urban area.

Computation of noise map for large city areas would result in high calculation time. To solve that problem the software for calculating road and railway noise on supercomputer platform was proposed and developed (Szczodrak, Czyzewski, 2009; Czyzewski *et al.*, 2011; 2012). The procedure of preparing the noise map requires knowledge of source data and propagation environment. Considering source models, we need to note that road and railway noise are the most frequent sources of disturbance that people are exposed to. The achievements of European Harmonoise and Imagine projects, providing a description of road and railway models (Jonasson, 2007; Salomons *et al.*, 2011), were utilized during the implementation of the software devoted to work on supercomputers (Szczodrak, Czyzewski, 2009; Czyzewski *et al.*, 2011; 2012; Kotus *et al.*, 2012). The Harmonoise model was intended to unify all the methods prepared and utilized by European Union state members.

In this paper we propose to combine the short-term noise measurement data together with model-based calculations in order to provide an accurate up to date noise map. Recently, an installation of acoustic sensors which measure noise level was conducted in Gdansk. These devices provide information that can be projected to the source model and update it by finding the inverse transform.

The calculations were conducted on the supercomputer platform which is a part of the Polish Grid Infrastructure. The infrastructure was prepared within the PLGrid Plus project in which the most important task is to identify and establish specific computing environments, the so-called domain grids. This includes solutions, services and extended infrastructure (including software), tailored to the needs of various groups of scientists. The Polish Grid Infrastructure has been built to provide the Polish scientific community with an IT platform based on computer clusters, enabling research in various domains of e-Science. The infrastructure supports scientific investigations by integrating experimental data and results of advanced computer simulations carried out by geographically distributed research teams.

The work study presented in this paper was realized within the Acoustics domain grid. The aim of this domain grid is to provide efficient computational tools for the community of acousticians engaged in the noise threat reduction. Moreover, knowledge of noise and its influence on human health is popularized, since the outcome is presented in the form of noise map in the Internet accessible for wide spectrum of recipients.

2. Concept and Setup (location of sensors, map, measured quantities)

2.1. Location

For the experiments we have chosen an area where practically only road noise occurs as a source. Within the area of about 4 square kilometers, four sensors are deployed. Each sensor is continuously measuring sound

Fig. 1. Experiment localization, numbers denote measurement stations.

levels in the close vicinity of one road, which has the predominant influence on the obtained acoustic pressure values. There are three roads of a relatively high traffic flow (separate lane in each direction) and one road on which low traffic occurs. The map showing experimental setup is presented in Fig. 1. Roads encompassed by measurement stations are marked with colors.

2.2. Measurement system

The measurement data originates from the microphone setup built by Gdansk authorities. The network of acoustic pressure sensors have been deployed in the city area (Mioduszewski *et al.*, 2011). Sensors are installed on building facades. The measurement of the sound level is based on the "Backing Board" method developed by Fégeant (Fegeant, 1998). The principle of the method is to position a microphone flush to the totally reflecting surface. Such an approach allows for measuring sound pressure at any site with reflecting conditions similar to those produced by urban building facades. The measurement station is presented in Fig. 2.

Fig. 2. Measurement station.

For a source located on the same side of the microphone, Fégeant considered the total sound pressure level at the microphone as the sum of the incident, reflected and diffracted fields. On the hard surface, the incident and reflected fields can be considered as equal. In that case, the sound pressure level is doubled on the plate. This corresponds to the sound pressure increase of +6 dB (Berengier, 2012). Fégeant in his theoretical study determined a position of the microphone in the plate in such a way that the effect of diffraction can be minimized. The detailed discussion of results of measurements with this type of microphone including diffraction influence can be found in the literature (Memoli *et al.*, 2008). Due to fact that in our case the surface of the plate is much smaller than the surface of the façade we decided to neglect this effect.

Noise maps were calculated employing the supercomputer optimized software which uses Harmonoise source model and ray tracing method in propagation model (Szczodrak, Czyzewski, 2009; Czyzewski *et al.*, 2011; 2012). The process of creating dynamic noise map was performed in two stages. First, the propagation paths were obtained and attenuation on each propagation path was calculated. Assuming that geometry of the urban infrastructure does not change such attenuation data can be used for fast calculation of noise level in the designated city area. In the second step, the traffic data were united with the source model and total noise level in a grid of points was calculated based on previously obtained attenuation data. The traffic data were prepared for roads which have the main influence on the noise level measured by the monitoring stations.

Attenuations are calculated only once, but the second step can be repeated many times. The propagation model does not include a feature for calculating noise on building facades. The considered minimum distance to the building façade is 1 meter. The setup of the microphone is such that it measures sound level affected by the "façade" effect. Therefore, in order to maintain conformity with the model which calculates sound level in the free field, we obtain sound level according to Eq. (1) (Memoli *et al.*, 2008):

$$L_{\text{free}} = L_{\text{near}} - 3 = L_{\text{facade}} - 6. \tag{1}$$

2.3. Measurements results

In the presented study the functionality of the dynamic noise mapping procedure was shown on the basis of one day measurement results (25.07.2011). The update time was set to one hour. For this purpose the A-weighted equivalent sound pressure levels calculated in one hour time periods were taking into consideration. The measurements results obtained in selected points are presented in Fig. 3.

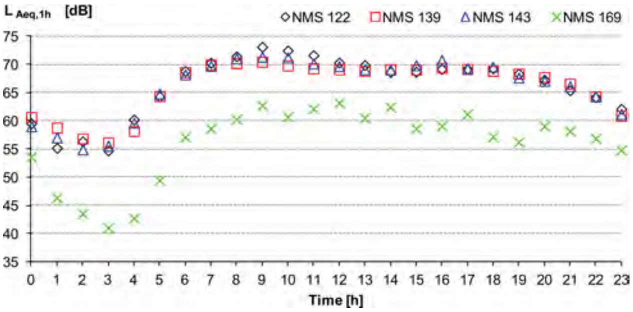

Fig. 3. Selected noise measurement results obtained by noise monitoring stations.

Noise levels in points 122, 139 and 143 were congruous. The essential differences were noticed for hours between 0 – 3 and 9 – 11 AM. Noise levels indicated by NMS 169 were relatively lower because the traffic flow on the nearest road was also relatively low. The presented real measurement data were used in the calculation of the reverse function. This procedure was described in detail in the next section.

3. Algorithm description

Typically, if we want to calculate the noise map for a given area, we need the input data for the noise source model. In the considered case, only road noise sources were taken into account. In consequence, we need information about: the number of vehicles per hour, type of road surface, type of vehicle, vehicle speed.

The employed noise monitoring stations did not deliver data about the road noise parameters. The missing data are calculated on the basis of the measured noise level. The reverse engineering technique is applied for this purpose. We assume that monitoring stations measure noise the main source which derives from the nearest road. To get the input data for the noise source model we need to calculate the number of vehicles on the basis of the measured noise level. Other factors of road noise source remain constant. The block diagram of the proposed methodology of the dynamic noise map calculation is presented in Fig. 4.

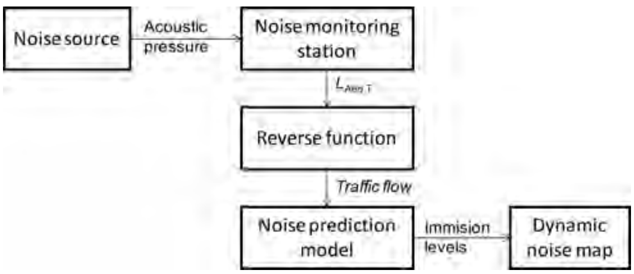

Fig. 4. Block diagram and data flow of the proposed methodology of the dynamic noise map calculation.

First, noise levels as a function of the number of vehicle per hour were calculated independently for all measurements points. Next, on the basis of these results the reverse function (RF) which can be used to determine the number of vehicles for a given noise level was calculated. The initial traffic volume on each road was adopted from the data obtained from the pre-existing noise map of the city of Gdansk representing long-term averaged values. For monitoring stations impacted by noise originating from more than one road (or carriageway), the following methodology of evaluation of RF (reverse function) parameters was applied. A division of the traffic flow between each road was calculated. An assumption was made, that this division is generally stable. The noise level was calculated in the point where the monitoring station was located for diverse values of the traffic flow, taking into account the above given assumption. Consequently, the noise level measured by the monitoring station can be expressed as a sum of noise levels generated by each road. Based on obtained data, parameters of reverse functions were calculated. The traffic volume value varied maintaining the proportion of its intensity on each road. For example, according to the values shown in Table 1, row 5, the ratio of the traffic flow between roads 186 and 189 is 1.12.

It is important to emphasize that the noise level calculated in the first step include all propagation factors between the noise source and the measurement point, such as: distance, ground reflections, other buildings, sound attenuation in the atmosphere, type of the ground. It means that the reverse function also includes such factors during the computation of number of vehicles (traffic flow – TF) derived from the noise level. The model of the reverse function is given by Eq. (2):

$$TF = a \cdot (L_{Aeq,1\,\mathrm{h}} - K_{\mathrm{facade}})^b, \tag{2}$$

where a and b – constants depending on the type of road and position of the measuring microphone, $L_{Aeq,1\,\mathrm{h}}$ – A-weighted sound equivalent level for one hour time period, K_{facade} – correction of pressure doubling conditions, in considered cases the measuring microphones were mounted directly on the facade surface (equal to 6 dB).

Constants a and b are obtained for all measurement points. The constants values were determined using the method of least squares. Figures 5 and 6 present the process of selection of the RF parameters for a chosen road. The left charts in Figs. 5 and 6 show the results of calculation of the noise level in the localization of the measurement microphone. This result is obtained by the road noise source model integrated with the propagation model. A typical relation of the noise level change as function of the road traffic flow was obtained, this way. All other parameters of the source model have the following default values: speed 70 km/h (50 km/h

Table 1. Constants values of the reverse function for traffic flow calculation computed for all roads. The number of NMS and the average traffic flow were also presented.

NMS No.	122		139		143		169
Road No.	186	189	676	675	68	73	422
a	9.30E-23	8.25E-23	2.15E-23	2.30E-23	2.73E-24	2.73E-24	4.98E-18
b	1.37E+01	1.37E+01	1.41E+01	1.41E+01	1.45E+01	1.45E+01	1.12E+01
Avg. TF	398	353	731	784	780	780	85

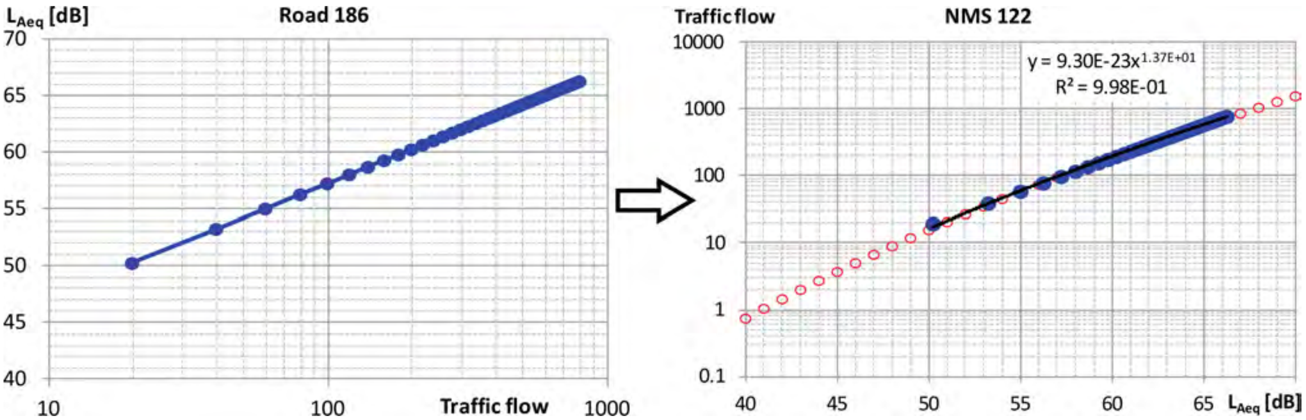

Fig. 5. Reverse function calculation for road no. 186 (Noise Monitoring Station no. 122).

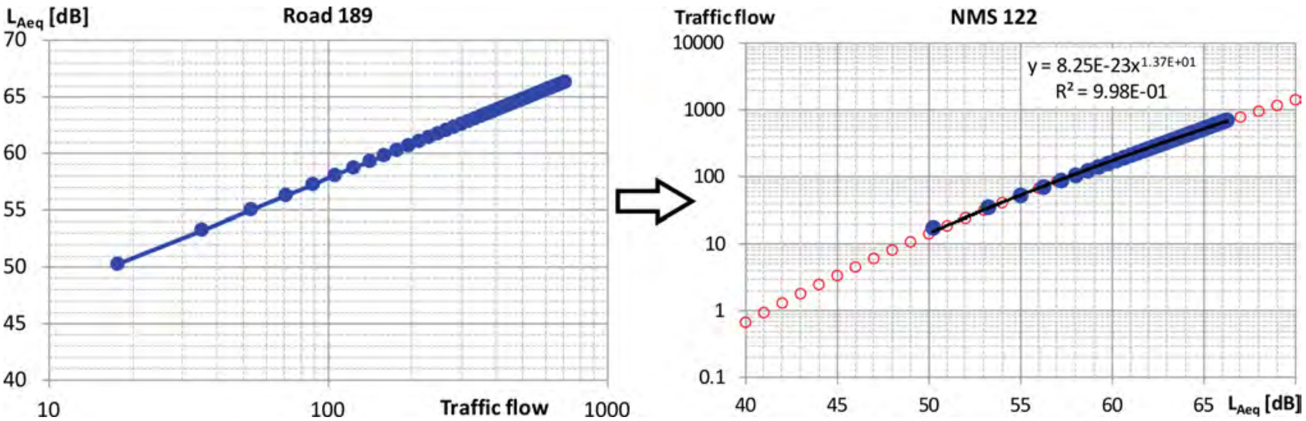

Fig. 6. Reverse function calculation for road no. 189 (Noise Monitoring Station no. 122).

for point 169), percentage of heavy vehicles – 2, 3, 4, 5 respectively for points 169, 122, 139, 143. During the experiments these values remained constant. Calculation of the reverse function requires exchange of function argument and value. The right side of Figs. 5 and 6 shows the resultant reverse function representing traffic flow dependency of the noise level. The use of the function type given by Eq. (2) and the least squares method allow for deriving constants a and b. In the considered case the values are respectively: $9.3{\cdot}10^{-23}$ and 13.7. Blue points in charts presented at the right side of Figs. 5 and 6 were calculated based on the measured noise level. Points marked with red circles denote values extrapolated with the obtained RF. The continuous line represents the graphical form of the function RF. Determination of model parameters was done for each monitoring station and all roads that affect measured noise level. In case of streets that consist of separated carriageways, the model parameters were determined for both carriageways, as both have influence on the noise measurement result. A series of simulations was done in order to calculate the noise level in the location of each monitoring station. Initial value of traffic flow was modified according to the scale factor α, which varied between 0 and 2. Table 1 presents calculated constants a and b for particular roads and carriageways and corresponding monitoring stations. Traffic flow data for roads not encompassed by noise monitoring stations were calculated separately for every time period. The calculation method relied on scaling the long-term averaged value of traffic flow for each road by global scale factor. This factor was obtained by computing proportions of traffic flow obtained by the reverse function to the long-term averaged traffic flow, for each road encompassed by the monitoring station, and then taking the mean value.

4. Experiments and results

The proposed methodology and the developed algorithm were used to prepare noise maps for the considered area in one hour time intervals. Maps for the area of 1650×1610 meters were calculated. The noise level was calculated in a grid of points spaced equally by 10×10 meters, what resulted in 26982 points. The following main parameters of the propagation model were set as follows: reflections of the 1st order, search ray 2 000 meters, reflected ray 100 m, the distance between following rays 2 degrees, and the building sound reflection coefficient 0.8. The ground type for the whole area was set to 10 000 kNsm^{-4} (representing hard ground) (Taraldsen, Jonasson, 2011). In the first stage (see Sec. 2.2), calculation was performed on 432 cores and took 2847 seconds. On the basis of the proposed reverse function and measured noise levels the workday traffic flow profile can be calculated. Several characteristics of the traffic flow for selected roads are presented in Fig. 7.

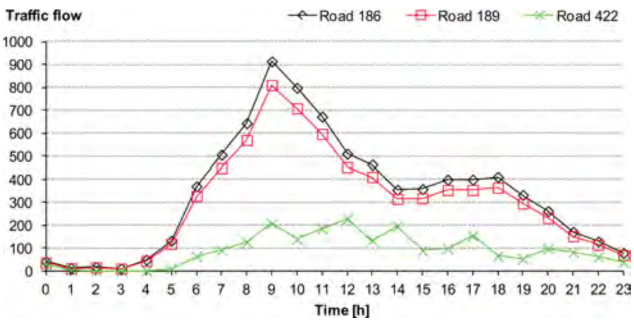

Fig. 7. Traffic flow calculated for selected roads.

As shown in Fig. 7, the traffic flow is relatively high on roads no. 186 and 189 (based on noise levels obtained by NMS 122). The road no. 422 has lower throughput because it has one lane in each direction (based on noise levels obtained by NMS 169). This is the reason of large difference in the traffic flow volume. The traffic flow data calculated for all considered roads were used to compute dynamic noise maps. The update time was one hour. The noise maps calculation can be time-synchronized with real noise measurement results. The final maps obtained for a various hours are presented in Figs. 8, 9 and 10. The range of noise pollution impact can be observed in detail.

Fig. 8. Noise maps for 2011.07.25 (Monday), hours: 3 AM, 4 AM, 5 AM (from left).

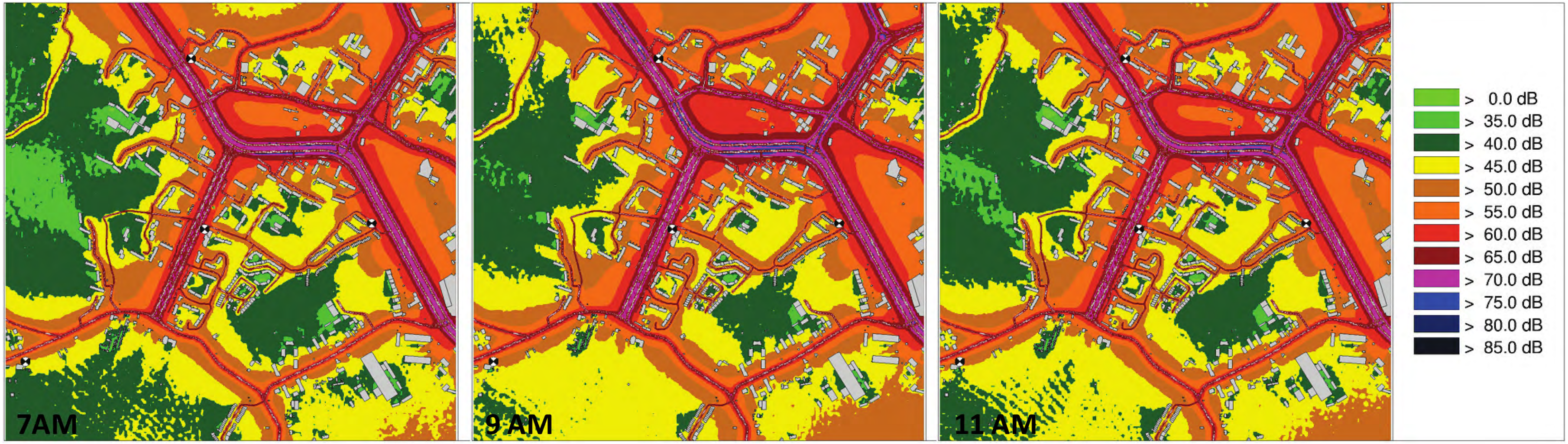

Fig. 9. Noise maps for 2011.07.25 (Monday), hours: 7 AM, 9 AM, 11 AM (from left).

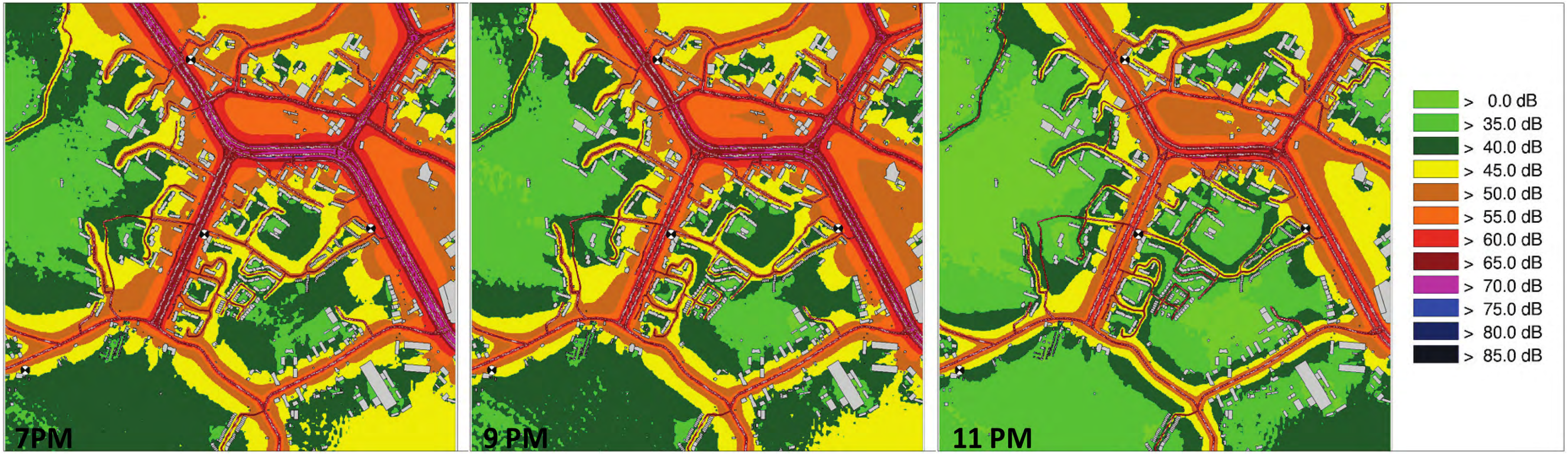

Fig. 10. Noise maps for 2011.07.25 (Monday), hours: 7 PM, 9 PM, 11 PM (from left).

5. Conclusions

As a result of the described work, the system for dynamic noise maps calculation employing supercomputing grid and sensor network was practically implemented, and tested. Implementation of the software for the traffic flow determination on the basis of acoustic climate measurements was performed. The calculated traffic flow data were used to automatically update noise source model. It was optimized towards working on the computer cluster, and thus accelerating noise maps generation process. Through a unique approach to the map generation process, dynamic noise maps may be presented to the public in a convenient and attractive manner.

The utilization of measured data allows for achieving unprecedented accuracy of short-term and long-term sound level distribution visualization. The achievement of the proper results of the model is conditioned by providing exact data of the traffic parameters, even though it cannot be guaranteed that computed levels are always reflect the real ones. Local sound events may have an influence on the total instantaneous noise level. The verification of sound levels based on a series of real measurements increases credibility of the simulation results. Employing the supercomputer allows for creating such maps in a reasonable time.

Future work could be aimed at applying sound recognition algorithms in order to identify sound events not related to the traffic noise. Moreover, the use of hardware devices for traffic flow measurements, which are currently being installed in the city, would help to achieve precise source model parameters.

Acknowledgments

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Assessment of Ultrasonic Noise Hazard in Workplaces Environment

Antoni ŚLIWIŃSKI

Institute of Experimental Physics, University of Gdańsk
Wita Stwosza 57, 80-952 Gdańsk, Poland; e-mail: fizas@univ.gda.pl

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The hazard assessment of ultrasonic noise impact on human body at workplaces presents an open problem; it is not satisfactorily solved comparing the fund of knowledge and standard regulations established for the case of audible noise. Some research carried on in the Central Institute of Labour Protection – National Research Institute, Poland, are essential for elaboration reliable procedures for the assessment of ultrasonic noise hazard and they have to bring to modernization and creation the corresponding standards in this field. In the presentation, some problems related to measurement procedures applied as well as to the interpretation of results essential for hazard assessment of ultrasonic noise impact on human body will be considered; in particular such cases where some procedures elaborated for audible noise assessment are being transferred to apply in the ultrasonic range without taking fully into account some specific aspects of the high frequency components of the noise.

Keywords: ultrasonic noise hazard assessment, maximal acoustic level values distribution, technological ultrasonic devices.

1. Introduction

Due to industrial technological progress there appear more and more of the ultrasonic noise sources at the workplaces producing high frequency noise in the range of one third octave bands of central frequencies: 10, 12.5, ..., 40 kHz, conventionally called the ultrasonic noise, though the components of the two lowest bands are practically audible. The convention comes from the fact that usually the hazard assessment for the audible noise, with regard to the speech intelligibility and hearing losses, is performed up to the one third octave band of 8 kHz. In spite of relatively wide knowledge on the subject of ultrasonic noise sources and the ultrasonic noise itself appearing at the workplaces as well as of general conviction about its harmful interaction on the human body, the activity in the field of the assessment of the ultrasonic noise hazard on the working people is still not sufficient. The problems of ultrasonic noise are a subject of scientific and normalization interest in different places in the world (Grigoriewa, 1965; Acton, 1974; 1975; Holmberg, Landstrom., 1995; Schust, 1996; Lawton, 2001; Howard *et al.*, 2005; Ashihara *et al.*, 2006), also in Poland (Puzyna,1981; Puzyna, Pasterczuk, 1982; Grzesik, Pluta, 1978; 1983; 1986; Koton, 1986; 1988; 1999; 2004) and among others, there in CIOP-PIB (Central Institute of Labour Protection – National Research Institute, Poland) procedures of hazard assessment and methods for evaluation of the ultrasonic noise on human body were performed (Pawlaczyk-Łuszczyńska *et al.*, 2001a; 2001b) as well as some normative establishments were elaborated (Polish Norms, 1986); Recently, however, they were not taken into account in the norm (Polish & ISO Norms, 2011) and formally they stopped to be in operation. Further and recent works continued in CIOP-PIB are important for elaboration of reliable procedures of ultrasonic noise hazard at workplaces and they should lead to current interest and to establish the adequate standards for the matter (Radosz, 2012a; 2012b; Smagowska, 2012).

In the paper some topics are presented in relation as to measurement procedure as well as to interpretation of results being essential for the assessment of the effect of ultrasonic noise on working people; particularly, some problems are discussed relating to cases when some procedures, usually applied in the case of audible noise, are used to apply for the ultrasonic noise and often the very specific aspects of high frequency components of that noise (different as of audible noise) are not taken into account.

Also, some considerations on the approach for determination of maximal acoustic level values of random noise signals are discussed and a proposal to apply the Rice statistical distribution for signal peak values using the Broch's procedure (originally applied for audible frequency signals, Broch, 1963) for ultrasonic noise case is presented and exampled.

2. Equivalent noise level L_{eq} and maximal noise level $L_{\max}$ as quantities for ultrasonic noise hazard assessment

2.1. Historical reflection in relation to audible noise

In the procedure applied to the ultrasonic noise hazard assessment (Pawlaczyk-Łuszczyńska *et al.*, 2001a, 2001b; Koton, 1986; 1999) described in similar way as for audible noise, there are predicted for workplaces the equivalent noise pressure level L_{eq} related to the 8-hour day (or to a week) and the maximal noise pressure level $L_{\max}$ determined in one third octave bands.

In Fig. 1, for a comparison few curves are shown presenting permissible acoustic pressure levels determined in standards: L_{eq} and $L_{\max}$ for audible noise in dB A, maximal values in dB C and in noise rating numbers N as well as the corresponding curves for the ultrasonic noise range; the lowest curve is the total curve used for evaluation when the noise spectrum contains both the audible as well as the ultrasonic components. In the figure, the "intermediate" range is marked (Śliwiński, 2010) as the range of a great part as audible one and 20 kHz corresponds to the upper hearing threshold frequency. The range 10–20 kHz is often called the high frequency sound range and presents a special interest of audiometry for

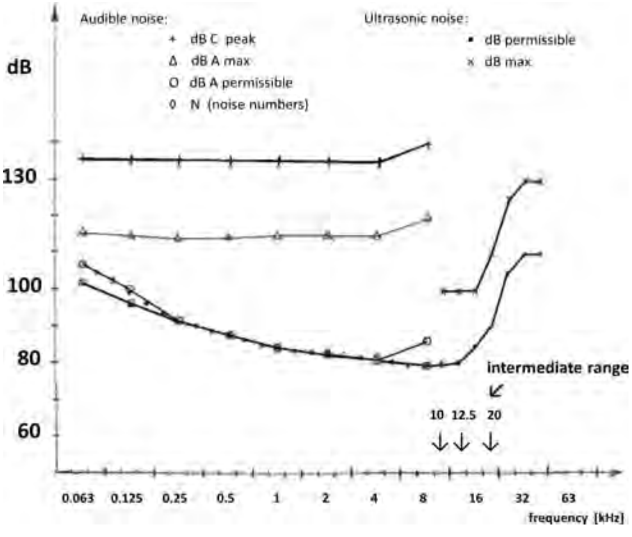

Fig. 1. A comparison of the curves for evaluation of permissible values for audible noise and for ultrasonic noise at work places L_{eq} and $L_{\max}$, respectively.

examination of harmfulness and annoyance of noise in that range of frequency (Przeklasa *et al.*, 2008; Mehrparvar *et al.*, 2011). In many previous papers (Smagowska, Mikulski, 2007; 2008; 2009; Mikulski, 2008; Mikulski, Radosz, 2009; Smagowska, 2009) and also in recent ones (Radosz, 2011; 2012a; 2012b; Smagowska, 2012; Kirpluk, 2013) related to examination of various types of ultrasonic sources one can notice that in cases when the noise presented a character very variable in time, the interpretation of results has been to some extent difficult and uncertainties of measurements have increased. In the discussion related to the assessment of noise hazard a question appears whether, how much, and when measured values of $L_{\max}$ can deliver additional information about the noise hazard, particularly, when determined values of L_{eq} are charged of greater uncertainty for example in the case of impulsive noise sources. In very radical opinions some voices appear that there could be possible to turn over measuring $L_{\max}$ values and to settle for L_{eq} as sufficient to assess the professional hazard. The author's opinion is that such voices are baseless and resigning from determination the $L_{\max}$ and in consequence not using $L_{\max}$ levels to hazard assessment would be a situation of reduced circumstances. Therefore, it seems reasonable to turn back to some historical elements when some fundamentals later used for normative purposes were developed. Let us consider some facts related to maximum values of noise signals looking for arguments why they are useful for characterization of the noise properties. In particular, how the matter looks like for the ultrasonic noise.

There have been many examinations performed for the audible noise related to the influence of noise impulses on the hearing apparatus (Hassall, Zaveri, 1979). In general, for sounds shorter than 200 ms the loudness decreases versus shortening of the impulse time duration and a break-point is the value of the effective averaging time of the ear. The drop of impulse loudness is such that for its compensation one needs roughly increasing of the acoustic pressure level by 3 dB (a doubling of impulse intensity) to obtain the same loudness when the impulse time duration has decreased by one half. The product of the intensity and time it is the energy; so the ear works as an energy sensitive device (in respect to the loudness detection, not taking into account other specific human reactions to the impulse noise). Impulse characteristics of acoustic measuring devices are standardized to follow variations of loudness of single impulses. So, requirements for acoustic instruments (e.g. precision sound level meters) to evaluate the loudness properly have appeared; it means that the meter should be able to detect and keep the peak value of the impulse with the rise time of less than 50 microseconds. For assessment of hazard of the impulse noise, the following characteristics are taken into account: a shape of the pulse, its peak sound level, duration time, its rise time, and, in the case of pulse repetition, the frequency of their repetition; also, the reverberation field in the place of measurements should be determined. Impulsive and random variable variations of noise levels appearing in many practical cases have been taken into account in norms elaborated for protection against the audible noise and further on also adapted in procedures for the case of the ultrasonic noise (in one third octave bands 10–40 kHz). The elaboration of norms and measurement procedures was preceded by many years of research activities on physical nature of the noise as the acoustical signal and results of those examinations have been adopted as a base for standardization. Therefore, it will be useful to remind some facts.

A historically important contribution were developments of the sixties of the last century. Among others, Robinson D. W. (1969) has introduced (for rating a noise of random variable character containing many extremes) the quantity called the noise pollution level L($_{\mathrm{NP}}$),

$$L_{\mathrm{NP}} = L_{eq} + K\sigma, \tag{1}$$

representing two terms, where the first one (L_{eq}) is a measure corresponding to the equivalent continuous sound level during the measured period, and the second one corresponding to an increase of annoyance caused by fluctuations of that level proportional to the standard deviation of the instantaneous level during the same period. (*The coefficient K appearing in the formula was originally evaluated by Robinson as equaling 2.56 based on data at that time available for a communication noise*).

Many other later publications related to the industrial noise have found its reflection in norms, where conditions for determination of L_{eq} and definition for noise exposure time of 8 hour day and 5 day week were introduced, however the second term of the formula (1) was in the norms replaced by the procedure of maximal level detection with weighting A (in dB A) and peak level values with weighting C (in dB C) as well as accepting the standard deviation σ being the measure of the noise level fluctuations. Also in norms the procedures of uncertainties evaluation of noise level measurement results were determined.

For noises of random variable character the statistical distribution of maximal values was described using the Rice's distribution (Rice, 1944). An example of application of such distribution to the statistical analysis of real acoustical signals was presented by Broch J. T. (1963). As Broch noticed, Rice has shown that signals, which exhibit Gaussian (normal) instantaneous value distribution can be represented by a combination of an infinite number of sine components with random phases independent on spectrum shape. However, the peak values to a great extent depend on the shape of the spectrum. Rice has found a general formula (2) for the distribution of peak values as a function of the spectrum shape (provided the main part of the signal instantaneous components is described by Gaussian distribution). In the Rice distribution there appears a parameter α the values of which range from 0 to 1. When $\alpha = 0$, the formula represents a normal distribution, and when $\alpha = 1$, the distribution is a Rayleigh distribution. Intermediate values of α correspond to mixed distributions which always lie between the Gaussian and the Rayleigh ones. The departure from a normal distribution, a measure of which is α parameter, delivers information about a change of a shape of the spectrum related to participation and character of signal maxima (also impulse peak values). Figure 2 presents a set of curves of theoretical statistical peak probability density distributions of random variable signals with α as a parameter (Broch, 1963) described by the Rice formula (2) (Rice, 1944):

$$\begin{aligned} p(x) = {} & \frac{\sqrt{1-\alpha}}{\sigma\sqrt{2\pi}} \exp\left[-\frac{x^2}{2\sigma^2(1-\alpha)}\right] \\ & + \frac{\sqrt{\alpha}}{2\sigma}\,\frac{x}{\sigma}\left[1+\mathrm{erf}\left(\frac{x}{\alpha}\sqrt{\frac{\alpha}{2(1-\alpha)}}\right)\right] \\ & \cdot \exp\left[-\frac{x^2}{2\sigma^2}\right], \end{aligned} \tag{2}$$

where x – peak values of a signal, σ – root mean square value (RMS) of a signal (a standard deviation), α – parameter of a distribution variation, erf – error function, $p(x)$ – probability density of variable x.

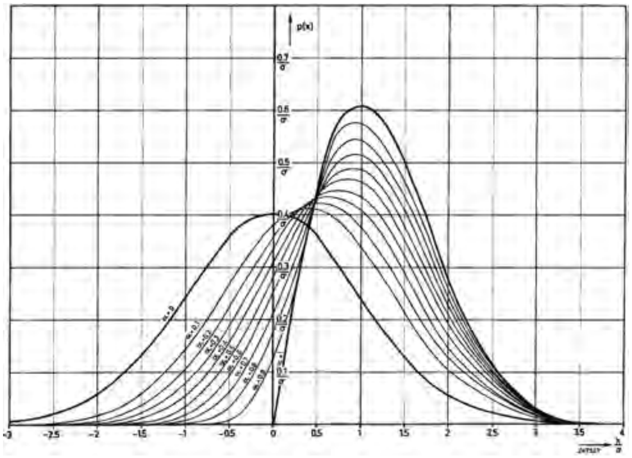

Fig. 2. Set of curves of probability density function of peak values of signal $p(x)$ against random variable x/σ; (σ – standard deviation) for the Rice distribution as variation of the α parameter from 0 to 1 (Broch, 1963).

Parameter α depends on the shape of a spectrum. When to assume a theoretical shape of a power density noise spectrum in a given pass-band as having a regular slope between two limiting frequencies in the form

$$w(f) = cf^n, \tag{3}$$

where c is a constant, f is the frequency, and n is an exponent which can be positive, zero, or negative, then one can assign various theoretical noise spectra to various power spectrum densities versus frequency as shown in Fig. 3.

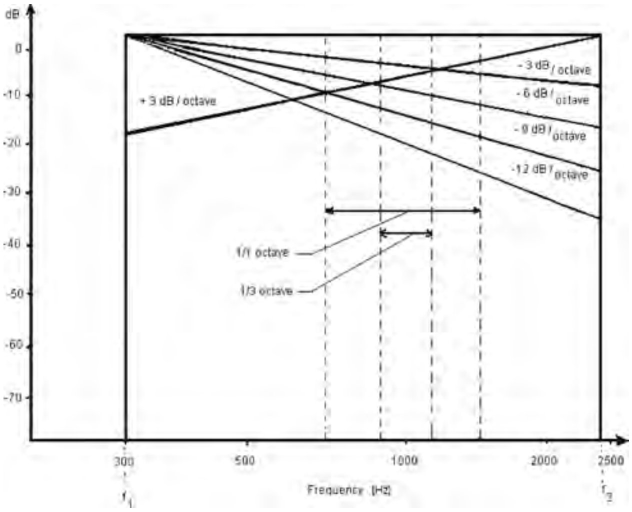

Fig. 3. Plots of power spectral density for various "theoretical" noise spectra, (Broch, 1963).

In Fig 3 the two limiting frequencies are marked as f_1 and f_2. Also, the 1/1 and 1/3 octave bands (of the central frequency $f_0 = 1000$ Hz) are shown. This original figure of Broch refers to an audible range of frequency and the ratio of the frequencies f_2/f_1 is equal to about 8. Broch in his paper has presented additional plots and discussed in details the relation between the exponent n and the ratio f_2/f_1 as a parameter. In his considerations he concluded that for the ratios f_2/f_1 less than 2 (an octave band) and the more so for narrower bands, the lowest values of α are obtained between $n = 0$ and $n = 6$ and in that range α is roughly constant having the value a bit less than 1 which corresponds to the Rayleigh distribution of peak values greater than 1.25σ. That allowed Broch to conclude (Broch, 1963) that a shape of a filter characteristic narrower than 1/1 octave did not change inside the band the distribution of the signal peak values important for its evaluation. It has such consequences in practice that the filter band is approximated by means of a "box" containing roughly the same amount of energy, i.e. having the same RMS value σ as the original noise. However, if the width of the band considered is greater than one octave ($f_2/f_1 \gg 2$), the slope of the spectrum will considerably influence the peak values distribution; for instance, for $f_2/f_1 = 25$ and the slope – 9 dB/octave ($n = 3$), the theoretical distribution appears to be nearly Gaussian one ($\alpha = 0$).

The two limit cases considered above ($\alpha = 1$ and $\alpha = 0$) physically represent two quite distinctly different statistical situation. In the first case of the Rayleigh distribution of maxima, the signal represents a narrow band noise, but in the second case of the Gaussian distribution, the signal is a wide band noise.

According to the Rice's interpretation (Rice, 1944; Broch, 1963), $\alpha = [z/(2m)]^2$ where z is the total number of zero crossings and m is the total number of noise maxima per second. For the Rayleigh distribution ($\alpha = 1$) one has exactly two zero crossings per peak (modulated sine wave) and for the Gaussian one ($\alpha = 0$) there fall (theoretically) infinitely many peaks per zero crossing.

The considerations discussed above brought from (Broch, 1963) were verified by Broch in experiments and by analysis of acoustical spectra of signals which corresponded to analogs of vibration systems with one, two, and more degrees of freedom. The Broch's conclusions have been such that in practice Rice distributions can be in a good approximation modified using calculations based on the evaluation of energy in spectral bands (containing resonance maxima) as "boxes" being a product of the top of a maximum and the width of the "box" i.e. $\pi/2$ times the -3 dB band-width of the resonance peak (Broch, 1963). If the consecutive maxima appearing in a spectrum have frequencies f_1, f_2, ... f_n and the energies corresponding to them in bands are ψ_1, ψ_2, ..., ψ_n, then one can, for the above determined quantity α, create a family of curves representing its dependence on the ratios f_n/f_1 for various ratios of ψ_n/ψ_1 as a parameter $\beta_n = \psi_n/\psi_1$ and finally find the following formula for calculating α (Broch, 1963):

$$\alpha = \frac{\left[1 + \sum\limits_n \left(\frac{f_n}{f_1}\right)^2 \beta_n\right]^2}{\left(1 + \sum\limits_n \beta_n\right)\left[1 + \sum\limits_n \left(\frac{f_n}{f_1}\right)^4 \beta_n\right]}, \tag{4}$$

where the parameters $\beta_n = \psi_n/\psi_1$ expressing the energy ratios in bands in the above-mentioned "box" approximation can be calculated as the ratios of "heights" of boxes c_n/c_1 times the ratios of bandwidths $\Delta f_n/\Delta f_1$; in turn, what was mentioned above, the energy ratios are equal to the square of the ratios of RMS signal values σ_n/σ_1, respectively. So, one has a useful formula for calculating β_n:

$$\beta_n = \frac{\psi_n}{\psi_1} = \frac{c_n}{c_1}\frac{\Delta f_n}{\Delta f_1} = \left(\frac{\sigma_n}{\sigma_1}\right)^2. \tag{5}$$

All considerations and dependencies presented above were determined and verified by Broch in the range of rather low audible acoustic frequencies; however, from the theoretical point of view they have been so general that would be true for the noise of random variable character in any range of frequency. So, it seems reasonable to try to apply the procedure described above for the assessment of an ultrasonic noise.

In the following, some examples of such trial of applying the Broch's procedure (calculating α parameters) are given for assessment of maximal level values distributions of noise produced by ultrasonic devices (ultrasonic washer, ultrasonic driller, ultrasonic welder) used in industry at workplaces.

2.2. Assessment of maximal level values in ultrasonic noise spectra

As the first example of application of the procedure described above we can calculate the quantity α for a spectrum of a typical ultrasonic washing device (Koton, 1999) presented in Fig. 4.

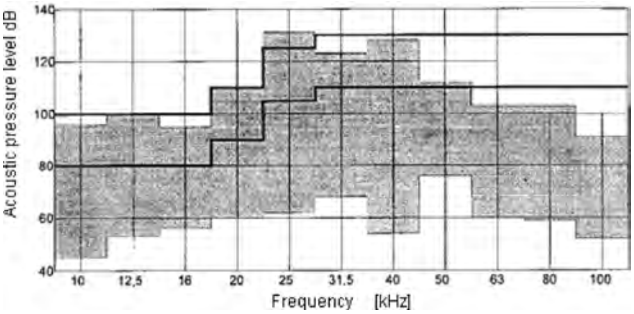

Fig. 4. The 1/3 octave spectrum of an ultrasonic noise level of a typical ultrasonic washing device, (Koton, 1999); the solid lines represent the permissible values for L_{eq} and $L_{\max}$ (upper line), respectively.

Let us remark that for 1/3 octave frequency bands one can write the following relations: $f_g - f_d = f_0 \times 23.1\%$, where f_g and f_d are the upper and lower limit frequencies of a band, respectively, and f_0 is the central frequency of the band. So, one can write

$$\beta_n = \frac{c_n}{c_1}\frac{\Delta f_n}{\Delta f_1} = \frac{c_n}{c_1}\frac{(f_g - f_d)_n}{(f_g - f_d)_1} = \frac{c_n f_{0n} \cdot 23.1}{c_1 f_{01} \cdot 23.1} = \frac{c_n f_{0n}}{c_1 f_{01}}. \qquad (6)$$

To calculate α from the formula (4), one can read out the needed values from the spectrum (Fig. 4) finding out energy ratios of the consecutive values of the maxima (after conversion of level values in dB) in relation to the first chosen reference band f_{01} and next from the formula (6) to calculate β_n. Starting from the band $f_{01} = 10$ kHz as the reference one and finding out appropriate relative values for the next bands: $f_{02} = 12.5$, ..., $f_{0n} = f_{07} = 40$ kHz, one gets values gathered in Table 1 (40 kHz is the central frequency of the last 1/3 octave band in which we are interested according to the arbitrary upper frequency limit of the ultrasonic noise range).

After calculations one gets from the formula (4) the value $\alpha = 0.06$. Comparing the result with an adequate curve of the Fig. 2, we see that the probability density

Table 1. Acoustical energy ratios c_n/c_1 of the consecutive values of maxima read out from the 1/3 octave spectrum of ultrasonic noise level maxima of a typical ultrasonic washing device (Fig. 4), relative central frequencies f_{0n}/f_{01} and calculated β_n values for determination of α from formula (6).

$\frac{c_2}{c_1}$	$\frac{c_3}{c_1}$	$\frac{c_4}{c_1}$	$\frac{c_5}{c_1}$	$\frac{c_6}{c_1}$	$\frac{c_7}{c_1}$
2.0	0.63	20	2000	502	1580
100 dB;	95 dB;	110 dB;	132 dB;	124 dB;	129 dB;
97 dB	97 dB	97 dB	97 dB	97 dB	97 dB

$\frac{f_{02}}{f_{01}}$	$\frac{f_{03}}{f_{01}}$	$\frac{f_{04}}{f_{01}}$	$\frac{f_{05}}{f_{01}}$	$\frac{f_{06}}{f_{01}}$	$\frac{f_{07}}{f_{01}}$
1.25	1.60	2.0	2.50	3.15	4.0

β_2	β_3	β_4	β_5	β_6	β_7
2.5	1.0	80	500	1581	6320

distribution of maximal values in the noise of the ultrasonic washer is closer to the Gaussian distribution than to the Rayleigh one. One can conclude that the maximal values appearing in the noise influence on random variable character of the noise generated by the ultrasonic washer in not a great extent but noticeably.

As a second example we used the noise spectrum of an ultrasonic drilling device presented in Fig. 5 (for a type BDB1o – the upper curve). This time the maximal component of frequency $f_{04} = 20$ kHz corresponds to the working frequency of the device. Again the $f_{01} = 10$ kHz is the reference frequency and the consecutive bands for central frequencies are 12.5 kHz to 40 kHz. The needed values are collected in Table 2.

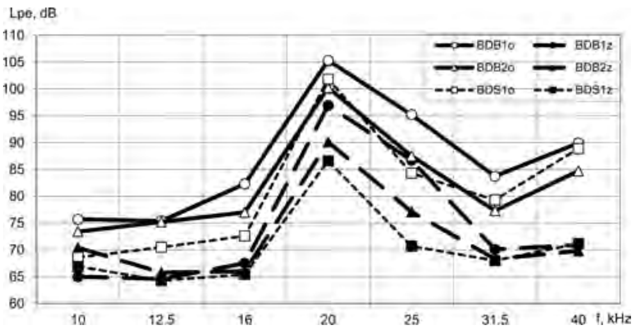

Fig. 5. Acoustic pressure emission levels in 1/3 octave bands of ultrasonic drilling devices (types BDB and BDS) noise, (Smagowska, Mikulski, 2008).

The value for α calculated on the grounds of data of Table 2 is $\alpha = 0.953$. Comparing the result with the curves in Fig. 2 leads to the conclusion that the influence of maximal values in the spectrum in the case of drilling devices is much more evident than in the first case of the ultrasonic washer and the distribution for

Table 2. Acoustical energy ratios c_n/c_1 of the consecutive values of maxima read out from the 1/3 octave spectrum of ultrasonic noise level maxima of the ultrasonic drilling device – type BDB1o (Fig. 5), relative central frequencies f_{0n}/f_{01} and calculated β_n values for determination of α from formula (6).

$\frac{c_2}{c_1}$	$\frac{c_3}{c_1}$	$\frac{c_4}{c_1}$	$\frac{c_5}{c_1}$	$\frac{c_6}{c_1}$	$\frac{c_7}{c_1}$
1.0	5.0	1000	100	7.8	0.3
75 dB;	82 dB;	105 dB;	95 dB;	84 dB;	90 dB;
75 dB	75 dB	75 dB	75 dB	75 dB	75 dB

$\frac{f_{02}}{f_{01}}$	$\frac{f_{03}}{f_{01}}$	$\frac{f_{04}}{f_{01}}$	$\frac{f_{05}}{f_{01}}$	$\frac{f_{06}}{f_{01}}$	$\frac{f_{07}}{f_{01}}$
1.25	1.6	2.0	2.5	3.15	4.0

β_2	β_3	β_4	β_5	β_6	β_7
1.25	8.0	2000	2500	24.6	1.2

this noise tends to be almost fully shifted towards the Rayleigh distribution.

The third example represents results of calculations for the noise measured at the workplaces of ultrasonic welding machine. A set of maximal values (selected from 440 measured samples*) for 1/3 octave bands in the range of central frequencies from 10–40 kHz as well as the data needed to calculate α are given in Table 3. In this example, the limits of the total range of frequency lie below and above the working frequency of the welder (20 kHz) and again the band of 10 kHz was taken as the reference band.

Using the data of Table 3 and formula (4) after calculations yields $\alpha = 0.776$. The comparison of the value with the curves of probability density in Fig. 2 gives us the distribution more close to the Rayleigh distribution. It evidently shows a dominant role of maximal values contained in the noise generated by ultrasonic welding machine resulting in shifting the character of statistical distribution towards the Rayleigh one.

All the considerations above and the examples considered showed that in the case of randomly variable and impulsive noises, as for audible as well as for ultrasonic ones, the role of maxima for statistical distribution shape is essential. One can conclude that measurements and determination of $L_{\max}$ values and using them in assessment of noise hazard is well-grounded and useful. So, it would be not reasonable to abandon the procedure of determination $L_{\max}$ levels at workplaces, particularly when in the majority of cases of industrial conditions, noises have random and impulsive character.

3. Impulsive noise and a role of directivity pattern of ultrasonic noise sources

In the case of the ultrasonic noise at workplaces there are two kinds of sources distinguished (Smagowska, Mikulski, 2007): the first kind represents the so-called technological sources which are machines and devices working at a given ultrasonic frequency at which a maximum of energy is radiated (usually above 20 kHz). Examples of such technological sources are washing devices (Fig. 4), drilling devices (Fig. 5), or welding devices (Radosz, 2012A). The second kind represents sources (called non-technological ones) generating noise of a wide spectrum containing simultaneously audible and ultrasonic (non-audible) components (for instance, the noise of spindle textile machines, air compressors, etc. (Smagowska, 2011; 2012) in high-frequency range).

Sources of the first kind can work as continuous ones (e.g. washing devices) or as impulsive ones (e.g.

Table 3. Acoustical energy ratios c_n/c_1 of the consecutive values of maxima for the 1/3 octave spectrum of ultrasonic noise level maxima of a typical ultrasonic welder, relative central frequencies f_{0n}/f_{01} and calculated β_n values for determination of α from formula (6).

ultrasonic welder*)	Central frequency of 1/3 octave bands f_0 [kHz]						
	$f_{01} = 10$	$f_{02} = 12.5$	$f_{03} = 16$	$f_{04} = 20$	$f_{05} = 25$	$f_{06} = 31.5$	$f_{07} = 40$
$L_{\max}$ [dB]	94.3	88	87.3	108.7	88.9	89.1	92.9

*) courtesy of B. Smagowska CIOP – PIB

$\frac{c_2}{c_1}$	$\frac{c_3}{c_1}$	$\frac{c_4}{c_1}$	$\frac{c_5}{c_1}$	$\frac{c_6}{c_1}$	$\frac{c_7}{c_1}$
0.234	0.200	27.6	0.288	0.302	0.725
88; 94.3 dB	87.3; 94.3 dB	108.7; 94.3 dB	88.9; 94.3 dB	89.1; 94.3 dB	92.9; 94.3 dB

$\frac{f_{02}}{f_{01}}$	$\frac{f_{03}}{f_{01}}$	$\frac{f_{04}}{f_{01}}$	$\frac{f_{05}}{f_{01}}$	$\frac{f_{06}}{f_{01}}$	$\frac{f_{07}}{f_{01}}$	β_2	β_3	β_4	β_5	β_6	β_7
1.25	1.6	2	2.5	3.15	4	0.293	0.320	55.1	0.720	0.951	2.90

drilling or welding devices). In the case of the second kind sources which in general work in a continuous way, the so-called "intermediate" range of frequencies (see Fig. 1) is of special interest; within that range there appears the overlapped exposure to both audible and ultrasonic (non-audible) noise but effects are not the same in these both cases. In the literature, the matter of ultrasonic noise hazard for these non-technological sources is not efficiently described yet and requires more studies.

A particular kind of a risk is the noise of technological sources of impulsive working regime. For a proper assessment of hazard of such noise, similarly as have been said above for the case of audible noise, its measurement should deliver information about peak values and maximal acoustic pressure levels of impulses as well as about a character of its statistical distributions (see Subsec. 2.2), about the rise time, duration time, decay time, and repetition frequency. In measuring practice, determination of these quantities and evaluation of a real hazard at a workplace may cause some difficulties. They are for instance connected with uncertainties of evaluation of real (reliable) exposure time in the procedure of determination of equivalent noise levels of the ultrasonic noise at workplaces (Radosz, 2012a, 2012b) and also with uncertainties connected with instrumentation and measuring conditions (e.g. position of a microphone (Radosz, 2011), and other factors) or with a character of acoustic field depending on the source directivity pattern and reverberation conditions at the measuring site.

In measuring practice of the ultrasonic noise, the radiation directivity of ultrasonic sources plays a very essential role in such cases when in enclosures the existing acoustic field appears far from a diffusive one required for the proper evaluation of absorption coefficient often used for projecting and constructing of isolation casings for ultrasonic noise sources. The role of directivity is also important in a case of acoustic power determination of ultrasonic sources. Irregularities of the acoustic field around the ultrasonic source having sometimes very space varied directivity pattern cause difficulties in determination of acoustic power with required accuracy for that kind of sources. For getting the required accuracy, some methods of determination of optimal number of measuring points located upon the measuring surface were elaborated (Mikulski, 2008; Mikulski, Radosz, 2009). The higher the frequency of the ultrasonic noise source, the greater number of required measuring points. The research activities in this direction being performed in CIOP-PIB are important to recognize conditions of the ultrasonic noise impact on persons working at ultrasonic device stands.

All factors and physical aspects mentioned above are taken into account during measurements performed for assessment of the ultrasonic noise hazard on human body. Often some procedures used typically for audible noise are also adapted for noise of the ultrasonic range. One example for that may be the procedure of determining and using correction coefficients K_1 and K_2 (introduced for audible noise) also to the ultrasonic noise assessment case. Often in ultrasonic noise measurement practice, determination of those coefficients leads to obtaining zero values. This fact in the light of the directivity properties discussed above and due to the high attenuation properties of ultrasonic waves is not strange; however, because these zero values result from the fact that the reverberation acoustic field distributions for the ultrasonic noise are different than for audible sound, therefore, perhaps, it would be reasonable to abandon determination of these correction coefficients in the ultrasonic noise assessment procedure and replace the determination of them by the requirement to measure and to order directivity patterns of a given ultrasonic device at a given workplace and to assess the influence of the directivity of radiation on a working person. It is a matter for discussion, of course.

4. Assessment of the influence of the ultrasonic noise on a human body

As it was already said, the matter of assessment of the real influence of the ultrasonic noise on human body has been not yet fully investigated. The problem lies mainly in the fact that within the arbitrary frequency range (10–40 kHz) there is not possible to separate two contributions operating simultaneously, i.e. the direct influence of ultrasonic components on the hearing apparatus (they act though they are not detected by the ear, however they cause disturbances in the inner ear, disorders in the vegetative system and others (Pawlaczyk-Łuszczyńska *et al.*, 2007; Koton, 2004)) from the influence of audible components accompanying them nearly always. Therefore, very important are examinations carried on in CIOP-PIB on laboratory stands (Smagowska, Mikulski, 2009; Smagowska, 2009) and also using psychological tests for annoyance evaluation of the ultrasonic noise. It is important to recognize physical conditions determining acoustical field radiated by ultrasonic sources of the examinations in details. There is a proposal for methodology of psychological tests to apply ultrasonic doses of the ultrasonic noise for observers in each 1/3 octave band and to collect statistical results of observers' annoyance assessment. In perspective, the investigations could lead to a set of ultrasonic noise annoyance contours analogous to ones existing for the audible noise (called equal noisiness counters). It would have essential advantage leading to establishment of ultrasonic noise noxiousness acoustic pressure level values and also making the established ultrasonic noise permissible values the basis for assessment of hazard of that noise at workplaces.

It is worth to note that important for recognizing the harmfulness and hazard of the ultrasonic noise are papers (Przeklasa *et al.*, 2008; Mehrparvar *et al.*, 2011) related to the high-frequency audiometry (which covers frequencies 8–20 kHz). The subject of interest of that audiometry is determination of hearing losses appearing due to exposure to noise containing components in this range (such components exist in non-technological ultrasonic noise sources mentioned above). The high-frequency audiometry results have shown that the hearing losses appearing in persons working in industrial environment with noise containing high frequency components chronologically are much in advance than those appearing in persons working only in audible noise.

Coming back to the Fig. 1 and to the author's suggestion expressed in his lecture presented at the previous Noise Control Conference in 2010 (Śliwiński, 2010) relating the "intermediate" range marked in the Fig. 1 as 10–20 kHz (partly overlapping with the high-frequency audiometry range) to treat that range as exclusively sectioned off on the whole noise frequency scale as having its own characteristics and to name as intermediate audible-ultrasonic range, one can remind that it would have a practical advantage. Then, for instance, the results of high-frequency audiometry domain could be used to elaborate its own procedure for assessment of noise in this intermediate range. So, if such proposal was accepted, then it would be necessary to have different procedures for noise assessment in three frequency ranges (expressed in 1/3 octave band central frequencies): audible one (up to 8 kHz), intermediate audible-ultrasonic one (10–20 kHz), and purely ultrasonic one (above 20 kHz). Similar suggestion was already stated many years ago (Grzesik, Pluta, 1978). Of course, to accept such proposal much more research on noise impact on human body is required, mainly in these two higher ranges because the matter is evidently better recognized for the audible noise range.

5. Summary and conclusions

A possibility of using Rice statistical distribution of acoustic signal maxima (peak values) appearing in the spectrum of noise of random variable character for the purpose of description of the ultrasonic noise case has been presented. The procedure for calculation of the parameter α (characterizing variations of the Rice distribution) applied by Broch (for the case of low frequency noise) was used in the paper as a trial for calculations of α to characterize ultrasonic random variable impulse noise. The calculations were illustrated in three examples of noise radiated by technological ultrasonic devices (ultrasonic washer, ultrasonic driller, and ultrasonic welder).

The calculated values of α parameter for noise of ultrasonic devices considered fall within the range from 0 to 1. The values of α characterize a tendency of shifting the noise maxima statistical distributions from the Gaussian (normal) to the Rayleigh ones. The α could be treated as a measure of contents of maximal value components in the noise of the ultrasonic devices and to some extent its value reflects a role of the maxima in variability of the noise signal. The results have shown that the presented approach could be interesting and it looks promising as an additional way to assess the nature of variability of ultrasonic noises.

The above considerations allow to conclude that in the case of impulsive and random variable noises, determination of $L_{\max}$ levels is entirely justified and it would be not wise abandon the procedure of measuring them at workplaces in particular at industrial conditions where in many cases noises have random and impulsive nature.

In measuring practice it is important to assess the real hazard resulting from impulsive character of the ultrasonic noise and often one encounters some difficulties with doing that. They are for instance connected with uncertainties of the duration time of exposure defining when equivalent levels of the 8 h exposure to ultrasonic noise are determined as well as with uncertainties connected with instrumentation and measuring conditions; like for instance with the microphone position or with the character of acoustic field created and being dependent on the directivity characteristic of a source and reverberation conditions at the measuring place. These reverberation conditions due the directivity of radiation are different for ultrasonic than for audible noise and therefore the suggestion has been presented that it could be possible for the ultrasonic noise to resign from calculation of correction coefficients K_1 and K_2 and replace the requirement of calculation them by a requirement to measure and to use characteristics of radiation directivity of a given ultrasonic device at a given workplace as an additional factor in the noise hazard assessment for a person operating the device.

In laboratory investigations carried out in parallel with psychological tests performed for evaluation of annoyance induced by the ultrasonic noise, the noise doses applied in experiments should present samples of a given 1/3 octave band acoustic pressure levels. The data of results collected in such experiments could conduce in perspective to create a set of ultrasonic noise annoyance contours analogous to the equal noisiness contours existing for audible noises.

A proposal has been suggested to treat the intermediate range of frequencies 10–20 kHz (partly overlapped with the range of high-frequency audiometry) as exclusively sectioned off and to name it the intermediate audible-ultrasonic range. Then, it would be necessary to differentiate procedures for noise hazard assessment in three frequency ranges: audible one (up to 8 kHz), intermediate audible-ultrasonic one (10–20 kHz), and purely ultrasonic one (above 20 kHz) where the figures represent 1/3 octave band central frequencies.

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A Perception-Based Method for the Noise Control of Construction Machines

Eleonora CARLETTI

IMAMOTER-National Research Council of Italy
Ferrara, Italy; e-mail: e.carletti@imamoter.cnr.it

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During operation, construction machines generate high noise levels which can adversely affect the health and the job performance of operators. The noise control techniques currently applied to reduce the noise transmitted into the operator cab are all based on the decrease of the sound pressure level. Merely reducing this noise parameter may be suitable for the compliance with the legislative requirements but, unfortunately, it is not sufficient to improve the subjective human response to noise. The absolute necessity to guarantee comfortable and safe conditions for workers, requires a change of perspective and the identification of *different* noise control criteria able to combine the reduction of noise levels with that of psychophysical descriptors representing those noise attributes related to the subjective acoustical discomfort.

This paper presents the results of a study concerning the "customization" of a methodology based on Sound Quality for the noise control of construction machines. The purpose is to define new hearing-related criteria for the noise control able to guarantee not only reduced noise levels at the operator position but also a reduced annoyance perception.

Keywords: noise control, acoustic design, sound quality, annoyance, psychoacoustics, construction machines.

1. Introduction

The noise generated by construction machines is very high; it has a negative impact on people in the surrounding areas and, even more, on the machine operators. At present, the sound power levels generated by these machines range from 93 to 116 dBA, depending on the engine net installed power. On the other hand, noise levels at the operator position are generally in the range 78–85 dBA, even if levels higher than 85 dBA are not uncommon. Many studies have shown that long exposures to moderate or high levels of noise can cause permanent damage to the hearing mechanisms of the inner ear, resulting in an increase of the hearing threshold level at certain frequencies. Prolonged exposure to high noise levels can have other physiological and psychological effects, including hypertension, heart trouble, fatigue, reduced motor efficiency and annoyance. All these effects greatly increase the possibility for operators to make mistakes during their job. In addition, the noise at the operator station can also have masking effects on other acoustical signals which could be very important for the worker in order to properly operate. For all the above reasons the noise control at the operator station is a key issue for these machines.

The noise control methodologies currently applied to make construction machines quieter and comfortable have been addressed to identify the main noise sources and the related noise transmission paths. As a result, nowadays the generated sound power levels and the sound pressure levels at the operator position generally meet the current legislative requirements. Despite this compliance, however, the noise condition at the operator station is still unsafe.

This paper summarises the main results of a study aimed at overcoming the above limitation. A methodology based on Sound Quality was developed in order to identify new hearing-related criteria for the noise control able to guarantee not only reduced noise levels but also reduced annoyance conditions.

2. Noise control at the operator position: the current situation

Nowadays, the noise control of construction machines is usually considered only when these machines are already in production rather than at their design stage. In particular, the noise reduction at the operator station is obtained by passive noise control strategies, based on the application of more than one methodology to ensure great confidence in the identification of the major noise sources and the relevant transmission paths.

Sound intensity technique is often used for this purpose. Figure 1 shows some results of a study performed by the author with the purpose to reduce the noise level inside the cab of a loader already in production (Carletti, 2006).

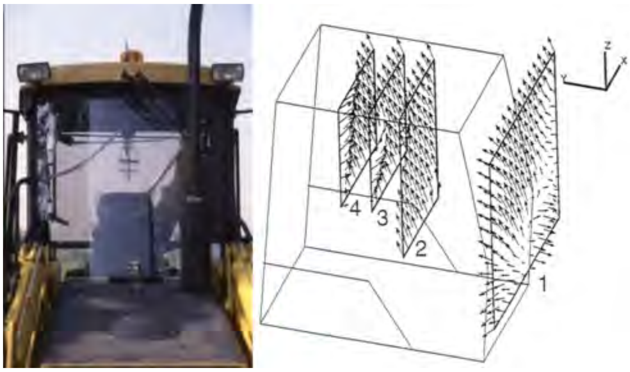

Fig. 1. Sound intensity tests on grids of points inside and outside the cab of a loader.

The vector sound intensity method was successfully used to map the sound path from the engine power group to the operator cab. Tests were performed on grids of points inside and outside the cab while the machine was operating in stationary conditions. The overall sound intensity maps in this figure give a visual representation of the sound energy flux from the engine compartment. They clearly show that the noise enters into the cab mainly from the rear window (window seals were not effective) and the floor, especially in the areas around the levers.

Also the order tracking technique is often applied to these machines in order to identify the major noise sources and their relative contributions to the overall noise inside the cab. Its suitability is due to the fact that in these machines all the noise components from the main noise sources (engine cooling system, hydraulic system) are strictly related to the engine rotational speed value (Willemsena *et al.*, 2009).

Besides the several studies concerning noise control strategies on machines already in production, methodologies and tools integrating vibroacoustic modelling and experimental analyses are nowadays widely applied in order to simulate the dynamic behaviour of different machine components, such as hydraulic pumps, cooling system fans and air conveyors, exhaust mufflers (Kim *et al.*, 2007; Mucchi, 2007). The purpose of vibroacoustic modelling is to predict the effects of each design modification on the emitted noise as well as to reduce the number of experiments required for developing the prototype. Figure 2 shows some results of a study aimed at developing a vibroacoustic model

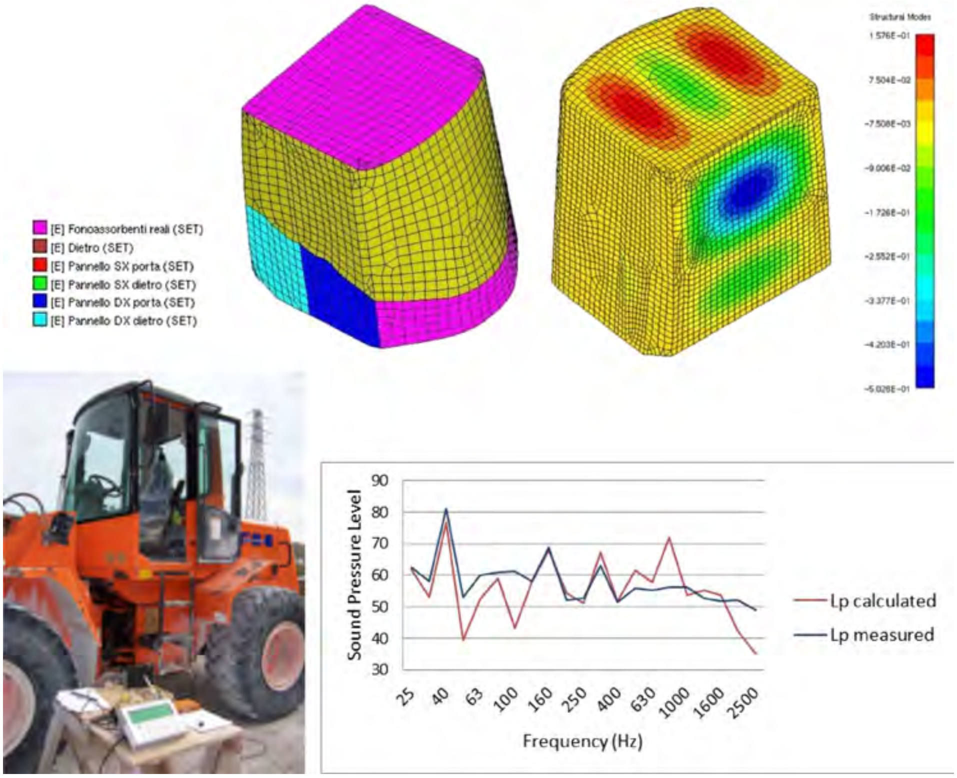

Fig. 2. Vibroacoustic model of a loader cab: comparison between numerical and experimental sound pressure levels at the operator position (left ear).

of a loader cab for the simulation of the acoustic inner field and the prediction of the influence of the different design options on its dynamic behaviour (Bregant *et al.*, 2006).

The active noise control (ANC) approach seems particularly suitable to reduce the noise at the operator position of these machines, as the dominant noise components are all included in the middle-low frequency range and the volume to be controlled is rather limited. However, only a limited bibliography exists dealing with the use of this technique inside the machine cabs and most of the available papers describe only the simulation of the ANC process.

A study was undertaken by the author on the application of an ANC device to reduce the noise level at the operator station of a skid steer loader, with the constrain that the implemented scheme had to avoid any significant modification in the standard layout of the cabin, in order to minimize the economic impact (Carletti, Pedrielli, 2009).

A commercially-available ANC device, following a single channel adaptive feed-forward scheme, was then used for tests. Figure 3 shows the machine object of this study and the layout of the active noise control system used for experiments.

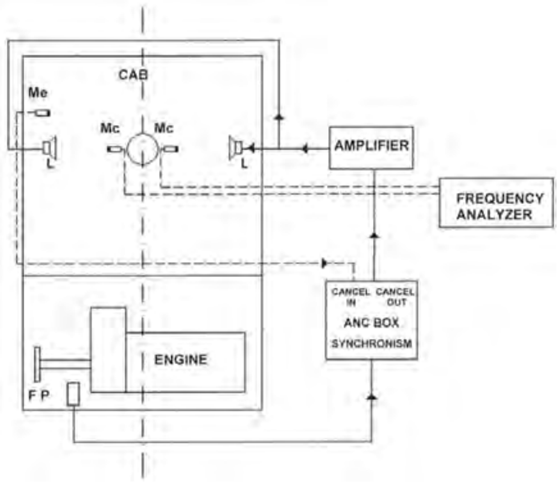

Fig. 3. Skid steer loaders and layout of the active noise control system. L – loudspeakers, Me – error microphone, Mc – monitoring microphones, FP – photoelectric probe.

Results confirmed the capability of such a cheap ANC system to significantly reduce the dominant engine periodic noise components and the overall sound pressure level within the space where the operator's head is located during his/her work. On the contrary, its efficiency in reducing the A-weighted sound pressure level turned out to be quite limited.

3. Noise control at the operator position: new perspectives

All the above examples show that the reduction of the energy-oriented noise parameters is the main target nowadays driving the noise control of construction machines. Noise control solutions have to lead to lower A-weighted sound power levels (noise emission in environment) and lower A-weighted sound pressure levels (operator ear position) in order to comply with the current regulations. Unfortunately, the reduction of these parameters has proved to be the right solution for the above purpose but absolutely ineffective to guarantee an improvement of the subjective human response to noise, especially for sounds exceeding 60 dB, which is a common condition inside these machine cabs (Genuit, 1999).

Consequently, a different noise control perspective turns out to be necessary to overcome this limitation. With this purpose, an approach based on Sound Quality (SQ) was developed in order to improve the noise conditions at the operator station of loaders. Figure 4 shows the layout of the developed procedure.

The starting point of this SQ-based approach was the establishment of the target. Taking into account the peculiarity of this "working environment" (machine cab), the noise control target included two main *expectations*. On the one hand, the simultaneous reduction of noise levels and perceived annoyance. On the other hand, the guarantee that the reduced noise signal maintained its original inherent function of carrier of information about the state of operation of the machine.

The next key point was the collection of a significant amount of noise signals at the working station of different loaders, all recorded in the same way as they would be heard by an operator in the same position. These recordings had to be representative of the noise at the operator ear position for all the possible operating conditions. For this purpose, a huge amount of binaural recordings were taken at the operator station of many different loaders in stationary and dynamic conditions. The recordings were performed while the machine was repeating the same typical work cycle, with the use of two different usual materials (gravel and loam) and in stationary conditions, with the engine running at a fixed speed. Figure 5 shows the different setup used for binaural measurements, both in stationary and dynamic conditions.

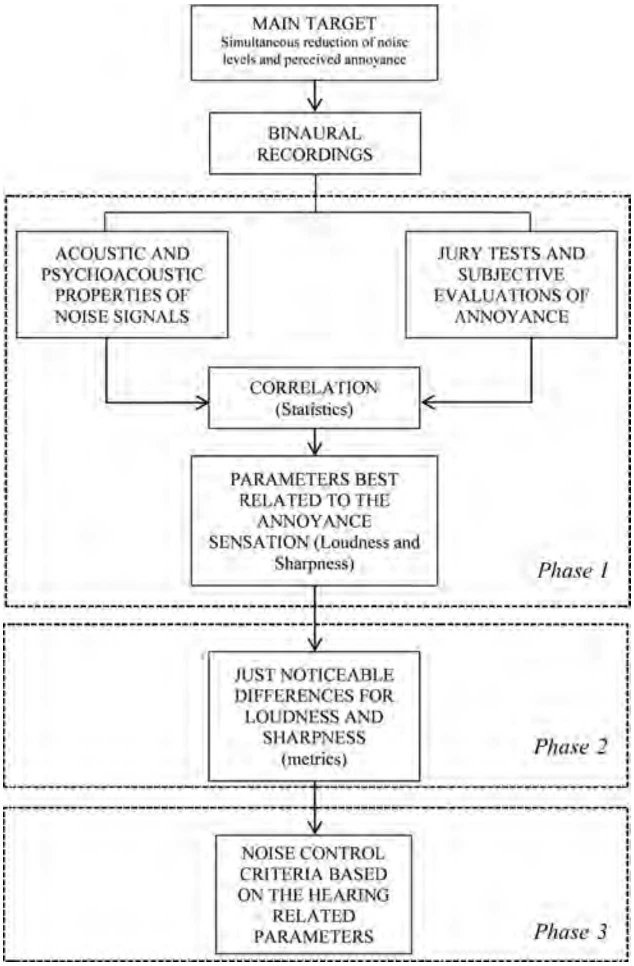

Fig. 4. Development process of the SQ approach applied to loaders.

This hearing-related methodology includes three main phases (see diagram in Fig. 4).

Phase 1 was aimed at obtaining a deeper knowledge of the relationship between the multidimensional characteristics of the noise signals at the operator position (frequency content, time structure, modulations, …) and the relevant auditory perception of annoyance. The target was the identification of hearing-related parameters mainly affecting the auditory perception of annoyance. This purpose required the following two main tasks.

a. Listening tests, based on the paired-comparison procedure. These tests were performed in laboratory, under stable, controlled boundary conditions (in order to guarantee a high reproducibility of the test results) and involved many juries of subjects. The main objective of these investigations was the assessment of a subjective scale of annoyance values for the several noise recorded signals. A ranking of subjective judgements of annoyance related to all the different machines and operating conditions was so established.

a)
b)

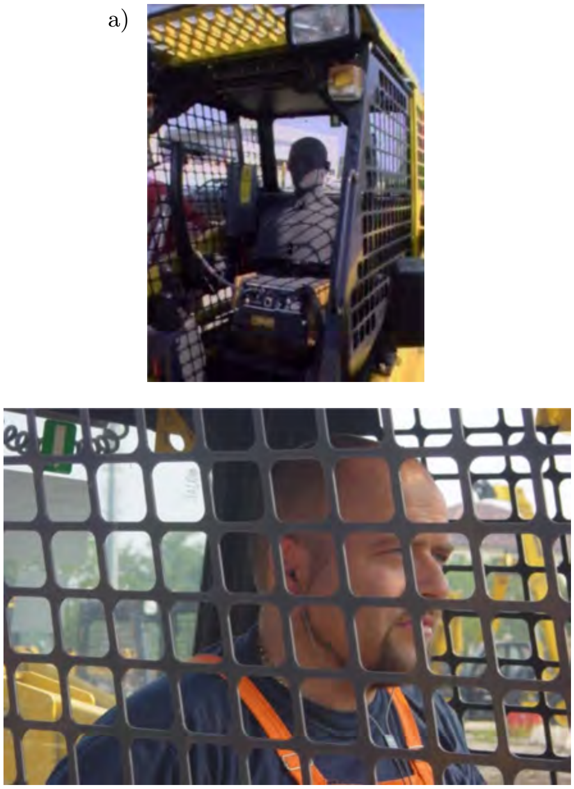

Fig. 5. Binaural recording setup: a) stationary conditions, b) dynamic conditions.

b. Noise signal objective analyses. Based on the results of a previous study concerning the sound quality evaluation of wheel loaders (Khan, Dickson, 2002), several acoustic and psychoacoustic parameters were calculated for the left and the right signals, separately. This set included: the overall sound pressure levels Leq and LAeq (in dB and dBA), the mean values of loudness (in sone), sharpness (in acum), fluctuation strength (in vacil) and roughness (in asper). Referring to the psychoacoustic parameters, they were all calculated according to the models proposed by Fastl and Zwicker.

On the basis of the Pearson correlation coefficients obtained between the subjective annoyance ratings and the objective parameters, the hearing-related parameters mainly affecting the auditory perception of annoyance were finally identified. Loudness and sharpness are the objective parameters better describing the auditory perception of annoyance at the operator station of loaders. Moreover, in the case of time-varying noise signals, the value of the fifth percentile of sharpness (S_5) turns out to be the parameter better describing the effects of time-variability on annoyance.

Phase 2 was aimed at developing a specific metrics for loudness and sharpness. The knowledge of the parameters best correlated to the annoyance sensation, indeed, is insufficient to develop a methodology able to identify the basic criteria for noise control. Tiny variations in stimulus magnitude may not lead to a variation in sensation magnitude. Then, it was necessary to determine the minimum variation in these parameters which led to a variation in the sensation (*Just Noticeable Differences* (JNDs)) (Pedrielli, Carletti, 2008). For this investigation a binaural noise signal recorded at the operator station of the loader in stationary conditions was used as reference signal. This signal was post-processed to create two sets of sound stimuli with different loudness or sharpness values, respectively. Subjective listening tests were performed following the classical Method of Limits in order to detect the step size of each psychoacoustic parameter that leads to a difference in the hearing sensation. In the experiments, a total number of six runs (three ascending alternated to three descending runs) were planned for each loudness and sharpness subjective test. Three test sessions, different from each other as far as the sound pressure levels of the reference stimulus were undertaken (65 dB, 73 dB, 82 dB). The step size of these parameters that leads to a difference in the hearing sensation of a group of people was described following a statistical approach. Cumulative distributions rather than unique values of just noticeable differences, indeed, make it possible to choose the just noticeable difference value depending on the specific target. Figure 6 shows the loudness and sharpness cumulative distributions for the three loudness/sharpness tests, having the reference stimulus with different sound pressure levels. The 75° percentile was considered appropriate to guarantee that the improvement of the operator comfort conditions was extensively appreciated. For loaders, where the sound pressure levels at the operator position is around 82 dB, the cumulative distribution for a similar presentation level must be considered. Therefore, the just noticeable difference in loudness and sharpness resulting from the test with the highest sound pressure level of the reference stimulus, were assessed as 0.8 sone and 0.04 acum, respectively.

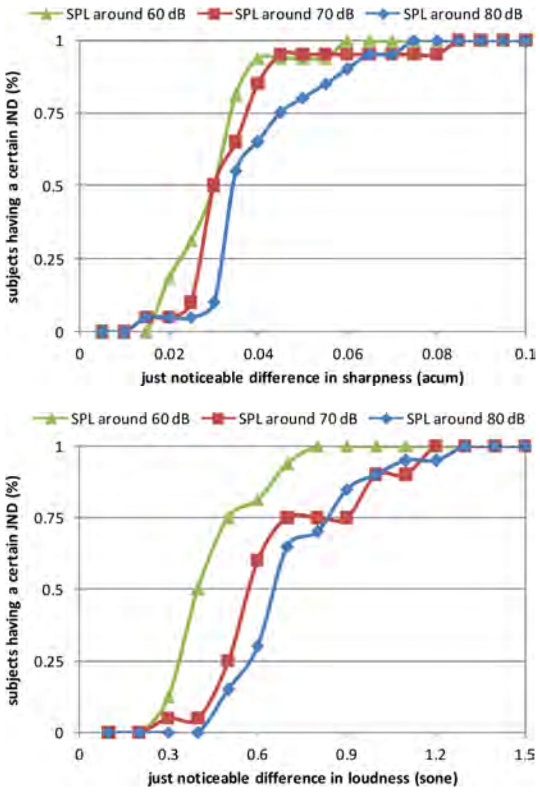

Fig. 6. Loudness and sharpness cumulative distributions for the three loudness/sharpness tests.

Phase 3, still in progress, is aimed at the exploitation of the above results in new criteria for the noise control based on the identified parameters which are well related to the annoyance sensation.

In this respect, a preliminary investigation was undertaken in order to verify whether the simultaneous reduction of loudness and sharpness could be a promising target for the noise control of these machines. A numerical optimisation procedure, based on a multi-objective genetic algorithm, was applied to some noise signals recorded at the operator station in stationary condition in order to analytically identify the noise spectrum modifications which led to the simultaneous reduction of these parameters (Carletti, Pedrielli, 2010). Then the same procedure was "adapted" to be suitable for time-varying noise signals, typical of real working conditions. New input variables describing the time variant characteristics of the system were identified and a numerical module for the correct calculation of loudness for time-variant sounds was developed according to the DIN-45631/A1 procedure. In this case the target was the simultaneous minimisation of the loudness and sharpness percentile values N_{50} and S_5 (Carletti, Pedrielli, 2011).

Very interesting results were obtained. Among the several solutions of the numerical process, some of the optimized noise spectra showed important reductions of the noise contributions due to the hydraulic system, confirming the relevance of this source in producing bad noise conditions. On the other hand, listening tests using optimized and original noise signals confirmed the subjective relevance of the simultaneous reduction of loudness and sharpness in reducing the annoyance sensation.

4. Conclusions

Sound quality targets were developed for the noise control of loaders in order to really combine the requirement of reduced noise levels with that of safe and comfortable conditions for the operators of these machines. A hearing-related approach was developed in order to relate the physical characteristics of the noise signals in typical working conditions with other noise features affecting the auditory perception of annoyance. A ranking of subjective judgements of annoyance related to the different binaural noise signals was assessed by performing jury tests. In parallel, the most relevant acoustic and psychoacoustic parameters characterising these signals were calculated. On the basis of the Pearson correlation coefficients obtained between the subjective ratings and the computed metrics, the hearing-related parameters mainly affecting the auditory perception of annoyance were finally identified (loudness and sharpness). The detection of the minimum difference in these parameters which leads to a difference in the hearing sensation were then obtained by subjective listening tests following the Method of Limits. The availability of these new hearing-related parameters and the knowledge of their relevant JNDs could really open new possibilities to the noise control of these machines, towards effective and efficient vibro-acoustic solutions able to guarantee safe conditions and comfort.

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Noise Exposure of School Teachers – Exposure Levels and Health Effects

Marija HADZI-NIKOLOVA[(1)], Dejan MIRAKOVSKI[(1)], Milka ZDRAVKOVSKA[(2)], Bistra ANGELOVSKA[(2)], Nikolinka DONEVA[(1)]

[(1)] *Faculty of Natural and Technical Sciences, Goce Delcev University*
Mail Box 201, 2000 Stip, Republic of Macedonia; e-mail: marija.hadzi-nikolova@ugd.edu.mk

[(2)] *Faculty of Medical Sciences, Goce Delcev University*
Mail Box 201, 2000 Stip, Republic of Macedonia

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Faculty of Natural and Technical Sciences and Faculty of Medical Sciences starting from December 2012, launched joint study in order to investigate personal noise exposure and associated health effects in general school teachers population, starting from kindergartens up to high schools in Stip, Macedonia.

In order to determine workplace associated noise exposure and associated health effects in this specific profession, a full shift noise exposure of 40 teachers from 1 kindergarten, 2 primary and 2 high schools were measured in real conditions using noise dosimeters.

A-weighted equivalent-continuous sound pressure levels (L_{Aeq}) of each teacher were recorded during single activities (classes). Normalized 8-hours exposure, termed the noise exposure level ($L_{ex,8\,\mathrm{h}}$) was also computed. Daily noise dose is another descriptor for noise exposure that was determined as a measure of the total sound energy to which workers have been exposed, as a result of working in the varying noise levels.

Health effects were assessed trough a full scale epidemiological study which included 231 teachers from the same schools. Specific questionnaire was used to extract information about subject's perception on occupational noise exposure, as well as theirs occupational and medical history.

Keywords: teachers, school, noise, exposure, health effects.

1. Introduction

Noise, one of the most widespread occupational hazardous agents, contributes to 16% mortality and morbidity due to the global burden of occupational diseases and injuries (Alberti, 1998). Noise in schools is also a harmful factor that affects the hearing organs of the pupils and teachers and disturb the speech reception and comprehension (Bradley, Sato, 2008; EN ISO 9921 (European Committee for Standardization [CEN], 2003, p. 18; Kreisman *et al.*, 2010). This may cause some irritation of both the teachers and pupils, tiredness, lack of concentration and consequently a deterioration of the teaching and learning processes (Augustynska, Radosz, 2009a; 2009b; Koszarny, 1992; Koszarny, Gorynski, 1990).

According to the report of the European Agency for Safety and Health at Work (2009) a safe and healthy school, which ensures a secure environment for the pupils as well as the safety and health of the teachers, is one of the main aims of membership countries of the European Union. Also the World Health Organization [WHO] report, Guidelines for Community Noise, (WHO,1999, p. 21) clearly indicate that noise-induced hearing loss (NIHL) is the most prevalent irreversible occupational hazard.

Exposure to excessive noise is one major cause of hearing disorders. It has been estimated that worldwide as many as 500 million individuals might be at risk of developing noise-induced hearing loss (Nelson *et al.*, 2005). Prolonged exposure to noise at high intensity is associated with damage to the sensory hear cells of the inner ear and development of permanent hearing threshold shift, as well as poor speech in noise intelligibility (Mikulski, Radosz, 2011; IEC 60268-16 (International Electrotechnical Commission [IEC], 2003, p. 15). There is also evidence that noise exposure frequently leads to tinnitus which might be due to alterations in the central auditory function (Nelson *et al.*, 2005). In the adult population it may significantly influence quality of life, and constitute a major limitation in relation to hearing-critical jobs, decreasing the potential worker's chance of employment. Thus, NIHL not only affects health, but is also a major social problem.

2. Aim of the paper

The objective of this study was to determine noise exposure and associated health effects in school teachers from kindergartens, primary and high schools in Republic of Macedonia.

3. Methods and materials

This paper presents cross-sectional study conducted from 01 of December 2012 until 31 of January, 2013. Full-day measurements of noise exposure were performed during 40 working days, in winter period when most of the children stay inside even on breaks. Health effects were assessed trough a full scale epidemiological study which included 231 teachers from the same schools.

In order to assess workplace noise exposure and associated health effects (irreversible hearing damage, psychological and physiological adverse effects) in this specific profession, a full shift noise exposure of 40 teachers from 1 kindergarten, 2 primary and 2 high schools were measured in real condition using, ER-200D Personal Noise Dosimeter (Fig. 1a) and Extech Sound Level Dataloger (Fig. 1b).

a) b)

Fig. 1. a) ER-200D Personal Noise Dosimeter, b) Extech Sound Level Dataloger.

The default settings used by the ER-200D for calculation of noise dose are consistent with ANSI S1.25–1991 (R2002), ISO-1999 Specification for Personal Noise Dosimeters, and NIOSH Criteria for a Recommended Standard (NIOSH, 1998).

Default settings are:

- Exchange rate: 3 dB,
- Criterion level: 85 dB,
- Threshold level: 75 dB.

Dynamic range of dosimeter is 60 dB (70–130) dB. Dose values are obtained every 220 msec, summed over a 3.75 minute interval and saved in non-volatile memory every 3.75 minutes (16 times during one hour). At the end of measurement, equivalent noise exposure level for measurement period in dB(A), dose value in % and graphical display of dose exposure for the measurement period are received.

The A-weighted equivalent-continuous sound pressure level (L_{Aeq}) measured in dB of each teacher was recorded in classrooms, during various courses and lessons, in corridors (during pauses) and at the sports halls. A-weighted equivalent-continuous sound pressure level was measured following the procedures stated in the International Standard ISO 9612:2009, Acoustics – Determination of occupational noise exposure – engineering method (full-day measurement), sound pressure level was measured continuously over complete working days.

Normalized 8-hours exposure, termed the noise exposure level ($L_{ex,8\,\mathrm{h}}$) was also computed by the equation according to ISO 9612-2009:

$$L_{ex,8\,\mathrm{h}} = L_{Aeq,T_e} + 10\log_{10}\frac{T_e}{T_0} \quad \mathrm{dB(A)}, \tag{1}$$

where L_{Aeq,T_e} is the A-weighted equivalent continuous sound pressure level for T_e; T_e is the effective duration, in hours, of the working day; T_0 is the reference duration, $T_0 = 8$ h.

Daily noise dose was determined as a measure of the total sound energy to which a workers have been exposed, as a result of working in the varying noise levels.

Health effects were assessed trough a full scale epidemiological study which included 231 teachers from the same schools. Specific questionnaire was used to extract information about subject's perception on occupational noise exposure, as well as theirs occupational and medical history.

The epidemiological study of teachers has been conducted with questionnaires which contained questions about personal (demographic) data, characteristic of working conditions (general assessment of the working conditions, consequences and noticeable ailments arising from noise, subjective assessment of noise annoyance and the general assessment of the healthy state (subjective feelings and ailments and how often they appear). The examinations have been performed anonymously and in accordance with all the rules concerning the protection of personal data.

Both descriptive and analytical epidemiological methods were applied in the analysis of the parameters.

4. Results and discusion

Table 1 summarize the results of teachers' personal noise exposure in the examined schools (1 kindergarten, 2 primary and 2 high schools), recorded by Personal Noise Dosimeters, providing the mean value of the measured L_{Aeq}, mean value of calculated $L_{ex,8\,\mathrm{h}}$, exposure time of teachers and dose per type of school. Mean, standard deviation and range were calculated for the activities of each school. Results in Table 1 shows that the daily personal noise level exposure of teachers in examined schools does not exceed the limits in accordance with the Macedonian Occupational Health and Safety Regulations for employees exposed at noise risk (Official Gazette of Republic of Macedonia, No. 21/08), but still quite close to them (especially the exposure of teachers in the kindergarten). Macedonian Occupational Health and Safety Regulations for employees exposed at noise risk specifies that the maximum daily 8-hour exposure level should not exceed 85 dB(A) assuming that for the rest of the day the teacher is not exposed to loud noise (Patricia, Niquette, 2009). This criterion is also used by the National Institute for Occupational Safety and Health [NIOSH], American Conference of Governmental Industrial Hygienists [ACGIH] and the International Organization for Standardization [ISO].

Table 1. Results of teachers' Personal Noise Exposure in examined schools.

Type of school	Exposure time (hours)	Mean L_{Aeq} [dB]	Mean $L_{ex,8\,\mathrm{h}}$ dB(A)	Standard deviation	Range	Dose [%]
Kindergarten	7	80.4	78.8	2.5	77–85	23
Primary	6	79.8	78.6	3.1	75–84	22
High	6	78.7	77.5	2.8	74–83	19

Recorded results by Extech Sound Level Dataloger shows high noise levels present in classrooms during classes, corridors during pauses, sport halls in primary and high schools, as much as during almost all activities in kindergarten. A-weighted equivalent continuous noise levels are in wide range from 53.5 to 100.3 dB, depending of activities. In primary schools, A-weighted equivalent continuous noise levels are slightly higher in integrated teaching classes (grade I–IV) than in higher grades. A-weighted equivalent continuous noise levels in classes are defined as equivalent teacher's speech level and background noise, i.e. noise transmitted into classrooms from all external sources or interactive teaching (Augustyńska *et al.*, 2010). Two years noise monitoring and noise measurements outside of examined school buildings show exterior A-weighted equivalent continuous noise levels of 58.3 – 62.5 dB(A). Exterior noise can also affect background noise in classrooms with opened windows and therefore teachers use raised voice (Bronder, 2003). According to EN ISO 9921 (European Committee for Standardization [CEN], 2003, p. 20], teacher's voice effort is considered normal if the voice A-weighted sound pressure level, measured from a distance of 1 meter from the mouth of the speaker, equals 60 dB; voice is considered raised if that level has a value of 66 dB.

Measurements have shown that corridors in primary and high schools during pauses and lunch rooms during the lunch break in kindergartens are the loudest places. A-weighted equivalent continuous noise levels are 83.3 dB and 84.7 dB, respectively, and the peak level is 107.9 dB. Teachers supervising children during pauses and in lunch rooms during the lunch break in kindergartens are especially exposed to such noise levels. During lessons, the noise in all schools' corridors is significantly lower. The A-weighted equivalent continuous noise level ranges from 50.4 to 64.3 dB.

Sports halls during physical education classes are also considered as loud places. A-weighted equivalent continuous noise levels measured on these places are 79.2–81.7 dB.

Teachers' rooms are considered relatively quiet during classes. In teachers' rooms, the A-weighted equivalent continuous noise levels during pauses range from 63.9 to 75.2 dB. During classes, they are adequately lower at 46.3 dB and 48.9 dB.

In order to estimate presence of subjective and objective health problems that occur as a consequence of workplace noise exposure, 231 teachers were surveyed. 29 (N1) of the teachers were from kindergartens, 118 (N2) were from primary schools and 84 (N3) from high schools. In order to see if there are any statistically significant differences between the three examined groups according to numerical variables of interest (age / years, length of service/years and working hours), it is implemented one-way ANOVA (F). If ANOVA shows that there are significant differences, the differences between the three examined groups have been tested separately with post hoc – Tukey HSD Test. For testing the significance of differences between the three examined groups according to the attributive variable of interest (gender, hearing problems, headaches, dizziness, anxiety / tension, diagnosed hearing impairment and elevated blood pressure) it is applied Kruskal–Wallis Test (H), and the differences between the three examined groups have been tested separately with Mann–Whitney U Test.

Table 2 shows distribution of the examinees according to curtain demographic variables. Regarding to the gender, there are significant differences be-

Table 2. Distribution of examinees according to demographic variables.

Variables	Kindergartens ($N = 29$)	Primary schools ($N = 118$)	High schools ($N = 84$)	ANOVA
Gender	$m = 1$ (3.4%) $f = 28$ (96.6%)	$m = 38$ (32.2%) $f = 80$ (67.8%)	$m = 14$ (16.7%) $f = 70$ (83.3%)	$H = 13.59$ $p = 0.0011$
Age / years	47.1±10.4	55.6±8.9	44.0±10.9	$F = 1.22$ $p = 0.2971$
Length of service / years	20.6±14.7	18.7±10.2	170±11.1	$F = 1.24$ $p = 0.2892$
Working hours	6.93±0.75	6.21±1.05	6.05±1.12	$F = 8.029$ $p = 0.0004$

tween the three examined groups (Kruskal–Wallis Test: $H = 13.59$, $p = 0.0011$). Expectedly, women are considerably more represented compared to men, especially in kindergartens and in high schools. Teachers in the kindergartens were in an average age of 47.1±10.4 years, in the primary schools the average age was 55.6±8.9 years, while in the high schools 44±10.9 years. According to the age, there are no significant differences between the three examined groups (one-way ANOVA: $F = 1.22$, $p = 0.2971$). According to the average years of work experience there is also insignificant statistical difference between the teachers (one-way ANOVA: $F = 1.24$, $p = 0.2892$). Regarding to the daily working hours between the three examined groups were noticed meaningful differences (one-way ANOVA: $F = 8.029$, $p = 0.0004$). Kindergarten teachers are working noticeably longer then primary school teachers (post hoc – Tukey HSD Test: $p = 0.017$) and high school teachers (post hoc – Tukey HSD Test: $p = 0.0002$). Primary and high school teachers have same working time which means they are exposed in a workplace noise at the same time ($p = 0.5851$).

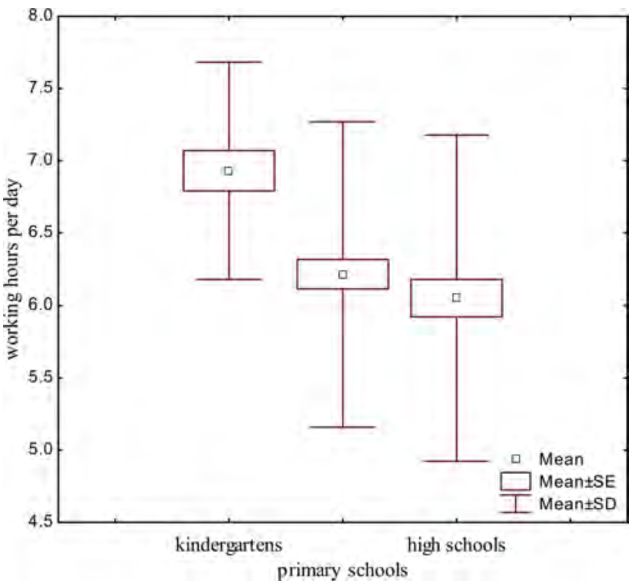

Fig. 2. Mean values of working hours per day.

Anamnestically hearing impairment (hearing loss, tinnitus, clogged ears) was confirmed by 6 (20.7%) of kindergarten teachers, 22 (18.6%) of primary school teachers and 9 (10.7%) of teachers from high schools – the differences are not statistically significant (Kruskal–Wallis Test: $H = 3.108$, $p = 0.2113$). According to the appearance of headache, there are statistically significant differences between the three examined groups (Kruskal–Wallis Test: $H = 7.422$, $p = 0.0245$). Primary school teachers complain about headache more often than high school teachers (Mann–Whitney U Test: $Z = 2.195$, $p = 0.0280$). Differences between kindergarten and primary school teachers ($p = 0.3102$) and differences between kindergarten and high school teachers ($p = 0.6142$) are not meaningful.

Temporary dizziness was confirmed by 9 (31%) of kindergarten teachers, 26 (22%) of primary and 12 (14.3%) of the high school teachers and the differences are not significant (Kruskal–Wallis Test: $H = 3.737$, $p = 0.1543$).

The biggest percent of the primary school teachers (52%) showed anxiety and tension after work. However, the differences according to this parameter are not meaningful ($H = 5.809$, $p = 0.0584$).

Medical documentation for objective hearing impairment and hearing loss was registered in 10.3% of the kindergarten teachers, 7.6% primary school teachers and in 3.6% of the high school teachers. The differences are not statistically significant ($H = 3.102$, $p = 0.2120$).

Higher blood pressure was registered in 34,5% of the kindergarten teachers, 20.3% of the primary school teachers and 19% of the high school teachers. The differences are not significant ($H = 2.757$, $p = 0.2519$).

Of the total number of examinees ($N = 231$), subjective and objective hearing impairment were noticed in 4 cases among people up to the age of 45 and in 33 cases among people over the age of 45. There is a strong correlation between the age of the teachers, i.e. the duration of the workplace noise exposure and the occurrence of the hearing impairment (Fisher exact test: $p = 0.00001$).

Table 3. Distribution of examinees according to subjective (anamnestic) health problems.

Variables	Kindergartens ($N = 29$)	Primary schools ($N = 118$)	High schools ($N = 84$)	ANOVA
Hearing problems	yes = 6 (20.7%) no = 23 (79.3%)	yes = 22 (18.6%) no = 96 (81.4%)	yes = 9 (10.7%) no = 75 (89.3%)	$H = 3.108$ $p = 0.2113$
Headaches	yes = 8 (27.6%) no = 21 (72.4%)	yes = 50 (42.4%) no = 68 (57.6%)	yes = 22 (26.2%) no = 62 (73.8%)	$H = 7.422$ $p = 0.0245$
Dizziness	yes = 9 (31.0%) no = 20 (69.0%)	yes = 26 (22.0%) no = 92 (78.0%)	yes = 12 (14.3%) no = 72 (85.7%)	$H = 3.737$ $p = 0.1543$
Anxiety / tension	yes = 12 (41.4%) no = 17 (58.6%)	yes = 64 (54.2%) no = 54 (45.8%)	yes = 33(39.3%) no = 51 (60.7%)	$H = 5.809$ $p = 0.0584$

Table 4. Distribution of examinees according to objective health problems.

Variables	Kindergartens ($N = 29$)	Primary schools ($N = 118$)	High schools ($N = 84$)	ANOVA
Diagnosed hearing impairment	yes = 3 (10.3%) no = 26 (89.7%)	yes = 9 (7.6%) no = 109 (92.4%)	yes = 3 (3.6%) no = 81 (96.4%)	$H = 3.102$ $p = 0.2120$
Elevated blood pressure	yes = 10 (34.5%) no = 19 (65.5%)	yes = 24 (20.3%) no = 94 (79.7%)	yes = 16(19.0%) no = 68 (81.0%)	$H = 2.757$ $p = 0.2519$

5. Conclusion

A-weighted equivalent continuous noise levels measured in classrooms, teacher rooms, corridors and sport halls are in the range of 58–88 dB and they exceed guideline values for community noise in specific environments, Guidelines for Community Noise (WHO, 1999, p. 47). High noise levels caused by the children activities especially in the corridors during pauses and in sports halls of primary and high schools often leads A-weighted equivalent noise level to exceed 80–90 dB.

High exterior noise levels (55–65 dB) in schools surrounding, also contribute to noise level in classrooms which often exceed 40 dB established as limit of the environmental noise level in Regulations for limits of the environmental noise levels (Official Gazette of Republic of Macedonia, No. 147/08) for a correct speech reception, thus forcing teachers to raise their voice. It can lead to the development of an occupational disease – chronic voice disorders due to excessive vocal effort (Bronder, 2003). The noise levels in classrooms during classes are within the limits of 53–79 dB, depending on the type of classes and activities performed.

Health consequences caused by workplace noise exposure between the teachers from the three examined groups are evidential and serious. Noise actually is causing not only medical, but socio-economical problems as well. Hearing impairment / hearing loss, dizziness, elevated blood pressure, headache and anxiety affects the social life of the teachers, their families and the people in their surrounding.

Data collected clearly indicate the need of immediate protective actions, as much as further investigations of this problem.

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Low Frequency Noise and Its Assessment and Evaluation

Stanislav ŽIARAN

Faculty of Mechanical Engineering, Slovak University of Technology in Bratislava
Nam. slobody 17, 812 31 Bratislava, Slovak Republic; e-mail: stanislav.ziaran@stuba.sk

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The main aim of this paper is to present recent knowledge about the assessment and evaluation of low frequency noise and infrasound close to the threshold of hearing and the potential effects on human health. Low frequency noise generated by air flowing over a moving car with the open window is chosen as a source of noise. The noise within the interior of the car and its effects on a driver's comfort at different velocities is analyzed. An open window at high velocity behaves as a source of specifically strong tonal low frequency noise which is annoying. The interior noise of a passenger car was measured under different conditions; while driving on normal highway and roadways. First, an octave-band analysis was used to assess the noise level and its impact on the driver's comfort. Second, a *Fast Fourier Transform* (FFT) analysis was used for the detection of tonal low frequency noise. Finally, the paper suggests possibilities for scientifically assessing and evaluating low frequency noise but not only for the presented source of the sound.

Keywords: low frequency sound, human being, health, evaluation.

1. Introduction

To be of practical use, any method of description, measurement and assessment of outdoor and indoor noise sources acting in enclosed spaces must be related in some way to what is known about the human response to noise. Many adverse consequences of outdoor and indoor noise sources grow with increasing noise, but the precise dose-response relationships involved continue to be the subject of scientific debate. In addition, it is important that all methods used should be practicable within the social, economic and political climate in which they are used. For these reasons, there is a very large range of different methods currently in use around the world for different types of noise, and this creates considerable difficulties for international comparison and understanding.

The methods and procedures described in this paper are intended to be applicable to low frequency noise from various sources, individually or in combination, which contribute to the total exposure at a site. At the present stage of technology, the evaluation of low frequency noise annoyance seems to be best met by adopting the adjusted Z-weighted equivalent continuous sound pressure level or minimal C-weighted one as shown the experiments (Darula, Ziaran 2010; Ziaran *et al.*, 2012, Ziaran, 2012).

The goal of this study is to contribute to the international harmonization of methods for the description, measurement, assessment and evaluation of low frequency noise (sound) from all external and internal sources in enclosed spaces and to provide some background for public professional discussion on how to describe, assess and evaluate low frequency noise in enclosed spaces. Based on the principles described in this paper, the background can be set for further research in this area.

Relatively little research has been carried out in order to establish which effects are specifically caused by low frequency noise emitted e.g. from an open window in a moving car, vibration of pipes, standing waves which are created by traffic noise (especially from Diesel engine vehicles such as lorries, buses, and trains) or by sound which is generated by sources inside of the enclosed space (vibration of building equipment, heating and ventilating air-condition – HVAC, music noise pollution, etc.), and, how to assess and evaluate this low frequency noise in enclosed spaces. This problem was discussed in (Broner, Leventhal, 1983; 1985, Gottlob, 1998; Jakobsen, 1998, Piorr, Wietlake, 1990; Vercammen 1992; Mirowska, 1995) and the standards (ISO 1996-1:2003, ISO 7196:1995) shows the possibilities correctly to asses and evaluate the low frequency sound (noise). Sound with a very long wavelength may be heard as noise (primary noise), caused by the rattling of windows, doors or furniture (secondary noise), and they may be difficult to distinguish from structural vibration.

Both forms of noise can cause disturbance, particularly during mental work, when driving, relaxation, etc. Low frequency noise can be more noticeable indoors, which is why it is often associated with attention reduction, sleep disturbance, adverse effects on health etc. Another problem is that low frequency noise travels farther than higher frequencies, so the source is often difficult to trace. A large proportion of sound is generated by the mechanical vibration of a solid component of the buildings structure and/or by the equipment in the buildings as was experimentally proved in (Ziaran, 2011). The mechanical energy involved has often been transmitted from remote mechanical or acoustical sources by means of audio-frequency vibrational waves propagating in connected structures, which is typical structure-born sound. The subject of structure-borne sound is far more complex than that of air-born sound in otherwise quiescent air. Whereas air can support only longitudinal acoustic waves, two fundamental forms of vibrational waves can exist in unbounded elastic solids because they can support shear stress. This paper will focus, in detail, on low frequency noise generated by open windows of a moving car. This type of noise is very strong and is a good example of why it is necessary to assess and evaluate by different methods as was used up-to-now.

2. Investigation and measurement methods

Noise generated by an open window of a moving car was investigated as a good representative source of strong low frequency noise. The air circulation in a car can be influenced by a variety of possibilities. Either the built-in air-conditioning can be used, or the air can be exchanged by opening the windows. Many drivers prefer the second option, due to some reported effects of air-conditioning on health. However opening the windows, and so exchanging the air, leads to a reduction of acoustic comfort for the driver and passengers, especially due to the introduction of low frequency noise. This effect was observed especially on highways, or roads out of the city. In a city the effect of air flow induced noise is insignificant due to low car speeds. Under certain conditions, this specific noise can have a negative impact on the health of the driver and/or passengers (Ziaran, 2008).

To analyze the noise exposition at the lower frequency limit of sound perception, i.e. around 16 Hz, which is generated when opening the car windows, the sound level meter analyser BRUEL & KJAER 2250 was used. To identify the energy dominant tonal noise more precisely, the FFT analyzed BRUEL & KJAER PULSE was applied. The methodology presented in the article can be applied also for other sources of very low frequency acoustical vibration, such as air-conditioning systems, boiler systems, large low frequency Diesel engines, etc. and more detail is described in (Ziaran, 2005).

The noise level was measured inside of the passenger car NISSAN TIIDA. During the measurements the car was driven on Slovak highways with minimal traffic, i.e. the aim was to minimize the influence of other sources of noise from passing cars. The measurements were done at various car speeds ranging from 70 km/h to 140 km/h. The measurements were done on roads chosen to be as homogeneous as possible. Another variable parameter in the analysis is the window opening, where three cases were compared:

- all windows closed;
- window partially open (approximatelly 5 cm);
- window fully open.

It was concluded that neither engine nor rolling noise from tyres influence the strong low frequency acoustic vibration (noise) induced by opening the window. The noise was measured at the head level of the driver, i.e. the microphone was positioned close to the head, in order to analyze the effect of the noise on the driver while driving the car, as shown in Fig. 1.

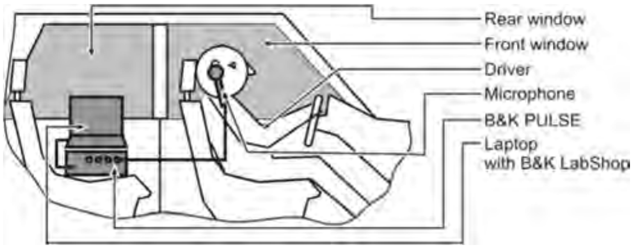


Fig. 1. Schematic of the measurement setup inside of a passenger car while driving.

2.1. Repeatability and reproducibility of measurements

The FFT measurements show that the measured data are consistent and that the dispersion of peak values was maximally 3 dB, as presented in Fig. 2. This difference can be caused by the speed variation of car or variation of the air flow speed around the car. Similarly the frequency variation up to 1 Hz, at approximately the same car speed can be caused especially by the real conditions of the air stream during measurements.

From the FFT analysis it is obvious that when the window is open, strong tonal very low frequency acoustic vibration is generated in the lower limits of human sound perception. The non-weighted values (so-called Z-weighting) exceeded 115 dB, depending on car speed. These levels of sound pressure are close to the threshold of pain.

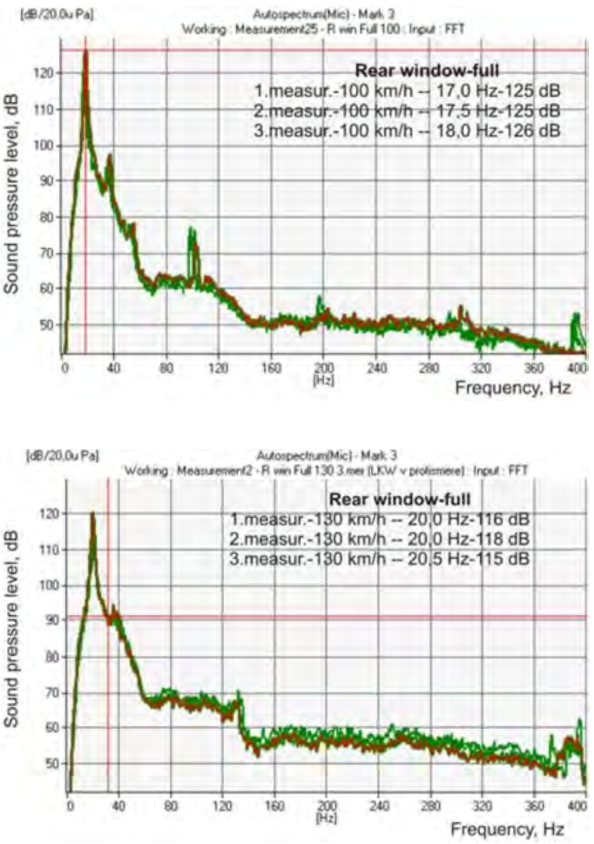
a)
b)


Fig. 2. FFT analysis of the generated noise in the car interior – three measurements with two different car speeds: a) 100 km/h; b) 130 km/h.

2.2. Weighting functions

The utilization of Z-weighting (i.e. no weighting) shows the exposition of the human being directly to this noise, regardless of the sensitivity of his/her ears.

Currently there is a discussion about the evaluation of low frequency noise at high sound pressure levels, since the A-filters, which are used most often, do not reflect the correct influences on health and comfort of human beings as is introduced in (Broner, Leventhal, 1983; 1985; Gottlob, 1998; Jakobsen, 1998; Piorr, Wietlake, 1990; Vercammen, 1992; Mirowska, 1995). Therefore, in analyzing the measured spectra in the article, the A-, C- and Z-weightings are to be presented.

Frequency analysis of the investigated low frequency region with application of these weightings is presented in Fig. 3, where Fig. 3a shows the results for constant speed and Fig. 3b for different speeds.

The sensitivity of the human ear at low frequencies is much lower, therefore also the measured results, weighted using the A- as well as C- or Z-weightings, differ significantly.

The energy difference between the C- and A-weighting is approximately 32 000-fold, between Z- and A-weighting up to 160 000-fold. Even keeping in mind

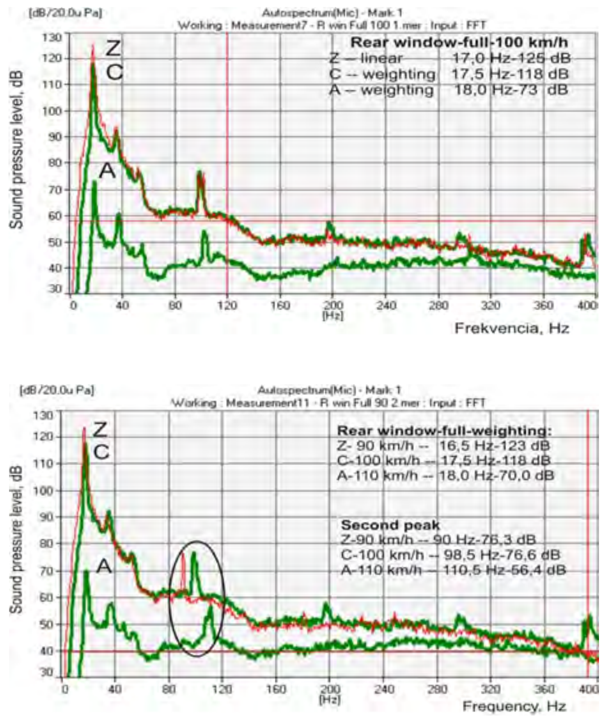
a)
b)


Fig. 3. Comparison of energies using Z-, C- and A-weighting of the same acoustic signal at different car speeds: a) 100 km/h; b) different speeds.

that the acoustic energy is negligible compared to other sources of energy, the presented differences in acoustical weighting should not be ignored in evaluating the influence of low frequency acoustic vibration on human beings. From a health point of view, each type of energy has the ability to do work – either negative or positive. However, there exists a limit of the positive and negative influences on human organisms, and so this limit should be set exactly or should be estimated in the most precise way.

2.3. Influence of an open car window

The behaviour of A- and C-weighting of the analysed, strong, very low frequency acoustic vibration is presented in Fig. 4a. Again, there are significant differences between the A- and C-weighting compared to measured cases with fully and partially open rear (driver's side) car window (the same window used) within the frequency band of interest (11.2 Hz – 22.4 Hz).

The reduction of acoustic level, applying C- and A-weighting, with the same maximal window opening is up to 46 dB, whereas with a partially open rear window, the maximal noise levels are shifted to higher frequency for the A-weighting used. Even though the low frequency content of acoustic energy is significantly higher than background noise (i.e. all windows closed), as shown in Fig. 4b. It is important to notice that the subjective perception of the driver and operator on the

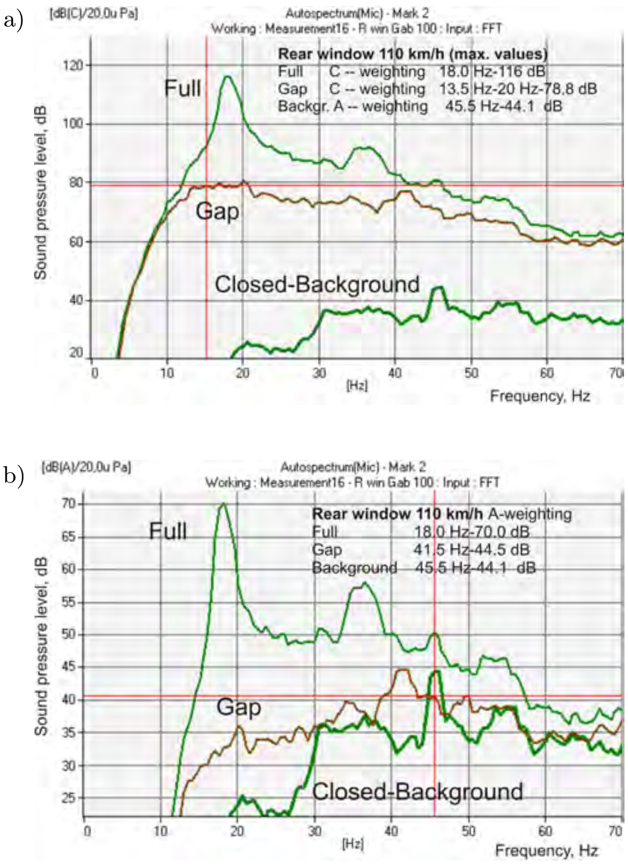


Fig. 4. Comparison of energies using A- and C-weighting of the same acoustic signal with constant car speed (110 km/h).

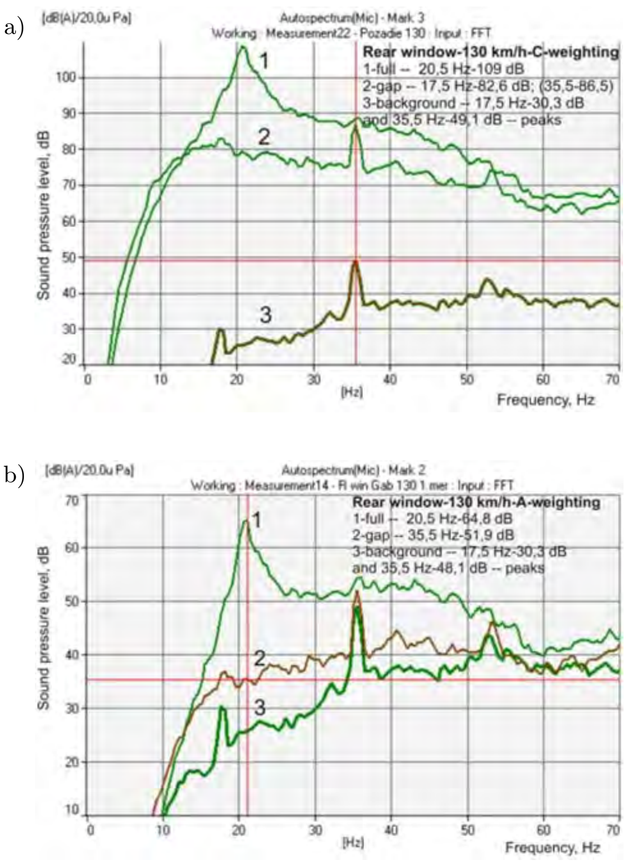


Fig. 5. Comparison of energies using A- and C-weighting of the same acoustic signal at constant car speed (130 km/h).

noise was significantly higher than the measured A-weighted sound pressure, and this perception reflected the acoustic C-weighting more.

2.4. Influence of car speed

A similar behaviour of the frequency spectra was analyzed at higher car speeds, where the difference between C- and A-weighting was just 2 dB lower, i.e. 44 dB and also for this set of measurements, with partial window opening, the characteristic amplitudes of tonal frequencies were shifted to higher frequencies (Fig. 5a, b). At higher car speeds, two specific tonal frequencies of a mechanical nature were identified. With open windows (or window), these tonal frequencies are masked by the source of strong aerodynamic low frequency noise.

Variation of A-weighted sound pressure level (SPLA), variation of C-weighted sound pressure level (SPLC), variation of Z-weighted sound pressure level (SPLZ), and also frequency variation as a function of analyzed car speeds is presented in Fig. 6. From this figure, it is obvious that the highest energy values of the tonal low frequency acoustic vibration with fully opened windows occur at car speeds from 80 km/h to 130 km/h. The measured levels are close to the threshold of pain. Non-negligible energy values are present at both lower and higher car speeds. A significant difference in energy values is observed when an acoustic weighting is used, i.e. an artificial correction of human exposure with the exception of different sound perception at the defined frequency bandwidth. From this, the question can be raised whether it is not more correct to use C- or Z-weighting in the evaluation of energy from powerful acoustic vibration at very low frequency bands.

In Fig. 6 it can be seen that a variation of the speed and the corresponding characteristic frequency of the tonal noise is shifted from the region of infrasound into the range of audible sound.

Again it needs to be emphasized that the perception of strong, low frequency noise was much more significant than at the A-weighted level. The perception corresponded more to the C-weighted level, probably also because of the fact that C-weighting is close to the threshold of pain. Furthermore, the analyzed low frequency, energy rich, acoustical vibration is close to the threshold of pain. Increasing the cars speed above 130 km/h, the specific tonal low frequency acoustic vibration generated by air entering the interior of the

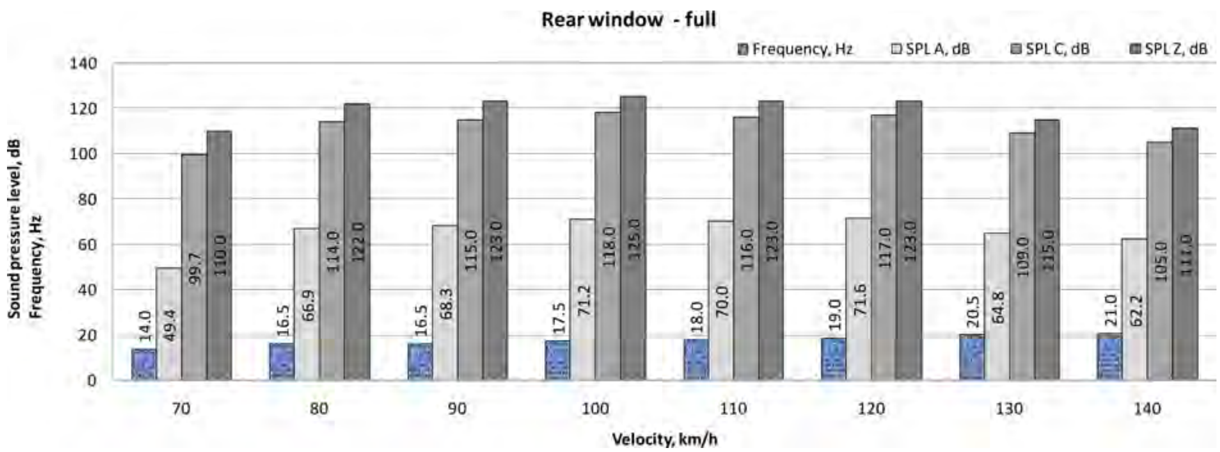


Fig. 6. The levels of A-, C- and Z-weighted sound pressure and variation of the frequency as a function of the car speed.

car is decreased and the noise induced from tyre and aerodynamic effects became dominant as shown the measurements in (Ziaran, 2012).

3. Assessment and evaluation of noise with strong low frequency content

The influence of noise on blood pressure is generally known and the consequent origination or even deterioration of hypertension. In the assessment of risk factors of noise on blood pressure, noise effect blood pressure at levels higher than $L_{Aeq} > 85$ dB. Based on the results presented by professor Issing (cited in Ziaran, 2008) the relative risk of infarct at the sound level pressure $L_{Aeq} = (62-65)$ dB is between 1.05 and 1.3 and at the levels $L_{Aeq} > 66$ dB between 1.1 and 1.6, which corresponds to an increased risk of harm by 10% to 60%. It must be kept in mind that low frequency noise has essentially higher energy severity than a noise of middle and higher frequencies. In the measurements, the investigated strong low frequency noise on the boundary of hearing is characterized by an unpleasant, pulsating pressure on the ear drum. The long-term exposition of the energy rich low frequency noise can lead to harm to human health, and not only the hearing organ but also functionality of other organs such as the central nervous system. Therefore it is important to improve the criteria of energy rich, low frequency, noise assessment so that the influences of energy on human health and comfort are assessed correctly. From the experiment, it can be concluded that for energy rich, low frequency noise (sound), the following is valid:

a) the frequency range of interest appears to be from 10 Hz to approximately 25 Hz;
b) the strong low frequency content of acoustic vibration often contains tonal components, and therefore it is more suitable to use CPB analysis or a more suitable FFT analysis in the frequency range from 10 Hz to 25 Hz;
c) for the assessment of acoustic vibration, with strong low frequency content, in the frequency range from 10 Hz to 25 Hz, it is more logical to use C- or Z-weighting rather than A-weighting;
d) in the assessment criteria of low frequency noise, it is important to consider measurements inside of the protected space rather than outside the environment, namely due to the presence of standing waves in that protected space.

In generally, at the assessment and evaluation of the low frequency noise (sound) the frequency range can be taken account up to 100 Hz.

4. Conclusion

From the experiments, and even from personal participation participating in the experiments, the energy from strong acoustic vibration of low frequency content cannot be correctly evaluated using A-weighting. The main reason is that this filter attenuates the energy severity of the acoustic vibration acting on human beings. The strong energy exposition requires more application of C- or Z-weighting, in which the sound pressure levels are in closer agreement with the threshold of pain. The results and analysis show that the executed experiments are closer to the evaluation methodology used in other, more developed countries. It can be concluded that energy from weaker, low frequency, acoustic waves can also cause the generation of standing waves and so amplify the energy exposure on human beings. The presented recommendations for the evaluation of low frequency acoustic waves in protected spaces should be taken as a contribution to the current knowledge about noise evaluation, as well as a stimulus for the technical community, since the correct evaluation of this type of noise can help reduce adverse health effects and reduction the comfort of human beings. Of course, the aforementioned assessment and evaluation of strong low frequency noise is up for further scientific debate and frequency range could be wide-spread up to approximatelly 100 Hz.

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Technical Note

The "NOMAD" Project – A Survey of Instructions Supplied with Machinery with Respect to Noise

Jacques CHÂTILLON[1], Marian SZYSZKO[2]

[1] *Institut National de Recherche et de Sécurité (INRS)*
Rue du Morvan CS 60027 54519 Vandoeuvre-lès-Nancy Cedex, France; e-mail: jacques.chatillon@inrs.fr

[2] *National Labour Inspection, District Labour Inspectorate – Szczecin*
Pszczelna 7, 71-663 Szczecin, Poland; e-mail: marian.szyszko@szczecin.pip.gov.pl

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The NOMAD project was a survey to examine the noise-related content of instructions supplied with machinery offered for purchase in Europe. The project collected more than 1 500 instructions from machines covering 40 broad machine-families and from 800 different manufacturing companies. These instructions were analyzed to determine compliance with the requirements of the Machinery Directive, and assess the quality of information.

The general state of compliance of machinery instructions with the noise-related requirements of the Machinery Directive was found to be very poor: 80% of instructions did not meet legal requirements. Some required numerical values relating to noise emissions were often missing. Where values were given, they were often not traceable to machine operating conditions or measurement methods, and not credible either against stated conditions/methods or as warnings of likely risk in real use.

As a consequence, it is considered highly likely that, in making a machinery procurement decision, employers are prevented from taking noise emissions into account, and understanding what is necessary to manage the risks from noise relating to equipment that is procured.

Recommendations are made for actions aimed at bringing about a global improvement to the current situation. Targeted actions are now proposed by "ADCO Machinery Group" aimed at raising awareness of the legal requirements, responsibilities and actions required among the various groups who have parts to play in the system – machine manufacturers, machine users, occupational safety and health professionals, and standards-makers. Recommendations are also made aimed at providing, or improving, tools and resources for all these actors.

Keywords: noisy machine, machinery directive, legal requirements, survey.

1. Introduction

1.1. Noise control at source and "buy quiet" strategy

Reducing workers noise exposure is, as for the other risks, ever more efficient when acting at the source. Acting at the noisy machinery, and at the design stage, must be the chosen solution as said by the European so-called "Machinery Directive" (Directive 98, Directive 2006) in which "*essential health and safety requirements in relation to design and manufacture in order to improve the safety of machinery placed on the market*" are detailed.

Manufacturers (or importers) of machinery sold in the European Economic Area must provide values of sound emission of the machinery in the instructions. Then, users of noisy equipment should be able to compare the different products available for purchase and really reduce the risks at source by "buying quiet" (Kurtz, Jacques, 2011).

Furthermore, risk evaluation by the employer, as required by legislation (Directive 2003) can be based also on the "*information on noise emission provided by manufacturers of work equipment* (...)". Quality of information on noise emission is then a key element allowing regulation to work for improving the prevention of risks.

In this context, NOMAD ("Noise Machinery Directive") aimed at assessing the quality of information on noise emission provided in the machinery instructions.

1.2. Legal requirements relating to noise in the Machinery Directive

The European Machinery Directive (89/392/EEC, 98/37/EC and 2006/42/EC) was introduced to enable free trade and consistent standards of safety across Member States and European Free Trade Agreement (EFTA) countries. The Directive contains essential health and safety requirements (EHSR) relating to a range of health and safety risks arising from the use of machinery at work.

In relation to noise, the Machinery Directive (2006/42/EC) places an explicit duty on machine manufacturers and suppliers to:

- design and construct products in such a way that the "*risks resulting from the emission of airborne noise are reduced to the lowest level taking account of technical progress and the availability of techniques for reducing noise, particularly at source*" (EHSR 1.5.8);

with further explicit requirements that the instructions accompanying machinery must contain:

- information on noise emissions (numerical values) (EHSR 1.7.4.2u); and
- instructions on installation and assembly for reducing noise and vibration (EHSR1.7.4.2j).

The Machinery Directive has other requirements relating to the content of instructions that apply to all hazards, including noise. The main requirements that can be applied to noise in relation to instructions are that they must contain:

- instructions for safe use and necessary training of operators (EHSR 1.7.4.2k);
- information on residual risks (EHSR 1.7.4.2l); and
- instructions on protective measures for the user, including appropriate Personal Protective Equipment to be provided (EHSR 1.7.4.2m).

The main purpose of NOMAD was to assess the information provided in machinery instructions (relevant to noise as a hazard) against these legal requirements.

The purpose of providing warnings, risk information and noise emission information is to allow manufacturers to demonstrate low-noise designs; and to allow purchasers and users of machinery to make informed choices regarding the safety of a potential purchase and to understand what measures will be necessary to mitigate the risk in real use.

1.3. NOMAD survey objectives and steering

NOMAD project involved the collection of machinery instructions, extraction and storage of relevant data from these instructions, and systematic analysis (qualitative and quantitative) of the data to determine legal compliance and quality of information. The work was supported by the Administrative Co-operation Group for Market Surveillance under the Machinery Directive ("Machinery ADCO") and involved contributions from 14 European Union (EU) and European Free Trade Association (EFTA) Member States.

The project was overseen by a Steering Committee, with practical contributions being managed by representatives of individual Member States. The Steering Committee included members from Finland, France, Germany, Poland, Spain, The Netherlands and the United Kingdom.

2. Survey methodology

2.1. Data collection

Several sources were used for obtaining the machinery instructions. The main sources were:

- Manufacturers/Importers (directly or via web sites);
- Final users;
- Existing databases built up for other purposes.

Depending on the individual contributing Member State, instructions were either collected for specific types of machine, or without any specific machine-type in mind. As a matter of policy, only instructions from machines first put on the market from 2000 onwards were collected.

The total sample of instructions included in the final analysis (i.e. excluding those assessed as unusable for analysis) was 1 530. This covered 40 broad categories of machinery, and several hundred different manufacturers.

2.2. Data analysis

Two types of information were extracted:

- Those allowing the identification of the machinery (type, family, model, manufacturer, country, does the machinery fall within the scope of Annex IV of the Directive? Does the machinery fall also within the scope of Directive 2000/14/CE? (Directive 2000), etc.),
- Those connected to noise emission and associated risks: Table 1 displays the main information which must be clearly provided in conformity with the Machinery Directive.

The methodology for deciding whether a piece of instructions conformed to legal requirements is described in the full NOMAD Report (NOMAD Report, 2012). From replies to a set of key questions, instructions were categorized as shown in Table 2.

Table 1. Information on noise mandatory in the instructions.

Information on noise	Role in prevention and risk management
1. Emission sound pressure level at workstation (continuous sounds) L_{pA} dB(A) if > 70 dB(A)	Allows assessment of noise exposure of the worker knowing work duration and other environmental parameters (place, other sources, ...)
2. If emission sound pressure level $\leqslant 70$ dB(A) this fact must be indicated	In this case, manufacturer guarantees that the machinery is "not really noisy"
3. Maximal emission sound pressure level (impulsive sounds) at workstation $L_{pC,\text{peak}}$ if > 130 dB(C)	The same as 1 but for impulsive noise (shocks)
4. Emission sound power level L_{WA} if $L_{pA} > 80$ dB(A) *Previous Directive 98/37/CE – less severe – indicated > 85 dB(A)* Always mandatory if machinery falls in the scope of Directive 2000/14/CE (Directive 2000)	In this case, the machinery is rather very noisy. Manufacturer is required to measure all the acoustical energy emitted (in the total space around and not only to the workstation). This number allows easy comparison between the emission levels of different machinery. It allows also to calculate noise levels in the environment where the machinery operates
5. Uncertainties in measurement of L_{pA} et L_{WA} *Not mandatory in Directive 98/37/CE*	Relative to 1 and 4, they show the measurement quality
6. Type-B standard or manufacturer's own general method of measurement	Relative to 1 and 4, this information insures traceability of noise emission values to general measurement methods. It shows also quality and credibility of declared values
7. Noise test code used or manufacturer's own particular method of measurement	Relative to 1 and 4, this information insures traceability of noise emission values to a noise test code specific to the machinery. It shows also quality and credibility of declared values and allows: • the user to know what are the working conditions of the machinery when the measurements are carried out • declared values to be verified, if needed
8. Warnings about risks that have not been eliminated and which the user will need to manage, i.e. residual risks 9. Instructions for safe use and necessary training of operators 10. Information on residual risks 11. Instructions on protective measures for the user, including appropriate Personal Protective Equipment to be provided 12. Description of adjustment, maintenance and preventive maintenance requirements	Qualitative information required for the user who must operate the machinery with reduced risks

Table 2. Categorization of instructions.

Conformity	Final assessment	Meaning
COMPLIANT WITH THE DIRECTIVE	A Correct	Correct information, very clear and useful for final user
	B Good enough	Some correct information, some lacks or missing information not too risky for final user
NOT COMPLIANT WITH THE DIRECTIVE	C Inadequate	Some correct information but one or several reasons for non compliance
	D Very poor	No information or unusable information

3. Results

Results show that the content of the instructions analyzed is incomplete or wrong relatively to the essential requirements on noise of the Directive: 80% of them do not meet these legal requirements (cf. Fig. 1).

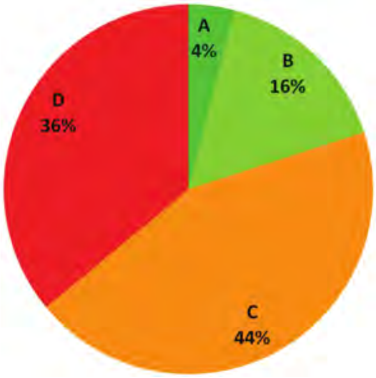

Fig. 1. Distribution of instructions in the 4 categories (A – correct; B – good enough; C – inadequate; D – very poor).

Some of the numerical values, or all of them, can be missing. Furthermore, when values are given, they cannot always be linked to operating conditions of the machinery or to measurement methods.

There is not one reason for non-compliance which is more important than others: instructions were often found to be not compliant for a combination of reasons. Lack of traceability and lack of credibility of the declared numerical values are often present in most of non-compliances. Lack of information on residual risks or safe use of the machinery appears very often for the instructions classified in the worst category (D).

Other results are, among other things:

- 12% of the instructions analyzed do not display any piece of information on noise.
- 27% display some information about noise but no required numerical values.
- 4 instructions out of 10 displaying numerical values are not compliant.
- 75% of instructions displaying numerical values do not allow the traceability of these values.
- When credibility (relative to operating conditions and/or measurement methods and/or real conditions of use) of the numerical values could be assessed, 64% of the non-compliant instructions were found not to be credible.
- Where instructions for safe use or residual risk information were assessed, 51% of non-compliant instructions lacked information about residual risks.
- 32% of non-compliant instructions where quantitative values were given contained incorrect noise terminology.
- Instructions were often found to be not compliant for a combination of reasons. Of the 1 244 non-compliant instructions, 22% show only one single reason for failure.

The situation is not significantly better for machinery covered by Annex IV of the Machinery Directive. This suggests that the involvement of Notified Bodies in the compliance procedure has negligible effect on noise declaration.

No significant difference was noticed for machines also covered by the Outdoor noise directive 2000/14/CE. This result suggests that the requirement for a manufacturer to consider an additional Directive specifically relating to noise has negligible effect on his approach to the provision of information on noise in relation to the Machinery Directive.

4. Discussion

Reasons that are likely to explain this situation are: (i) lack of knowledge among machine manufacturers about legal requirements, machinery safety standards or noise test codes, technical issues around noise or technical know-how in applying noise test codes, and (ii) lack of care among machine manufacturers, caused by the lack of commercial incentive to comply (quieter machines or those with better instructions not gaining market share), no fear of enforcement action and/or reputational harm, or simply that noise and damage to hearing is not considered a significant risk.

A large proportion of users/purchasers of machinery are likely to take quantitative noise emission information at face value; they are unlikely to check the traceability details, and may not have the knowledge to judge credibility. Therefore it is considered that the manufacturer has a significant responsibility to ensure that the emission values either can be taken at face value as a means to compare machines and describe likely risks, or are accompanied by clear warnings if either of these is not the case.

As a consequence of the survey results, it is considered highly likely that, in making a machinery procurement decision, employers are prevented from taking noise emissions into account, and are prevented from understanding what is necessary to manage the risks from noise relating to equipment that is procured.

5. How to improve the situation?

To improve the situation, targeted actions (that are achievable on a large scale, can be carried out within existing frameworks and are expected to have measureable outcomes) are foreseen.

Actions aimed at manufacturers: large campaign of information, promotion and enforcement to raise manufacturers' awareness of the noise aspects of European regulations (both directives 2006/42/CE and 2000/14/CE), their responsibilities and the resources that are available to support them.

Actions aimed at final users and purchasers: large campaign of information to raise final users' awareness of their responsibilities and the available resources to support them and to promote a "buy quiet" strategy highlighting the advantages, for employers, to purchase less noisy machinery.

Actions aimed at public authorities: targeted market surveillance, in a few sectors, aimed at technical sales literature. The latter, easier to get than the instructions, have to display, since December 2009, the same noise information as instructions.

Actions aimed at standardization organizations: to make them more aware of the basic role of noise test codes regarding traceability of noise emission values.

Actions aimed at Notified Bodies: to clarify their duties regarding noise and to make sure that competences required are present.

Actions aimed at occupational safety and health organizations: to ensure that they play efficiently their key role of technical risk reduction interface between the various actors.

6. Conclusion

NOMAD survey has shown that instructions are, for the largest part, not in compliance with current noise legislation. As a consequence, final users and purchasers of machinery do not have the information necessary to manage the noise risk from the data that should be provided by these instructions.

The improvement of this situation requires a variety of actions aimed at all major actors who all bear some responsibility for this situation. NOMAD survey reveals the knowledge gap between experts in acoustics and machinery manufacturers. To bring the two parties together, there are two not mutually exclusive solutions i.e. to increase the knowledge of machine manufacturers and to simplify the noise risk display. Joint efforts of those who know too much (acousticians) and those who should know more (all other actors contributing to noise reduction at the workplace) are necessary to make the "Buy Quiet" attitude a reality. Progress requires innovative tools to be designed such as simple and easy-to-understand noise indices, color scales as it is currently done in the environmental field (Mietlicki, 2012).

Acknowledgments

The authors thank all contributors to the NOMAD project, particularly the Steering Committee members and among them Jean Jacques and Genevieve Jeanjean who are the main French actors of the project. Fatma Sinha-Dellagi from INRS computer department is also thanked for her technical contribution.

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Abstracts

Selected Issues of Vibroacoustic Protections in Rail Transport

ADAMCZYK Jan, adamczyk@agh.edu.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland;

AGH University of Science and Technology
Departament of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

The article presents selected, now available in rail transport vibroacoustic protections. In the study the relationships between noise and vibration in certain frequency bands, generated due to speed of a train were discussed. The analysis of the different types of solutions for vibroacoustic protections for railways was presented, as well as the dynamic effects generated by the passing train on the commonly used noise protection equipment were examined.

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The Vibroacoustic Optimization Process of the Off-Road Machines

BARANSKI Filip[1], f.baranski@kfb-polska.pl
SCHOLTEN Jan[2], j.scholten@ibaf-bochum.de

[1] CEO, KFB Polska Sp. z o.o.
Elementarzowa 15a, 51-173 Wrocław, Poland;

[2] CEO, IBAF GmbH
Heinrichstrasse 67, D-44805 Bochum, Germany

In spite of the manufacturers' extensive efforts to reduce noise emission of the off-road machines especially those with intensive operating process noise, they have not succeeded. The empirical optimization process manufacturers exploit is not responding to desired limit of noise emission values. Furthermore the necessary optimization loops increase both time and costs of acoustic product development.

The effective identification of potential reduction requires sophisticated knowledge of vibroacoustic system which includes not only the noise emission but also the sound excitation and transmission. The vibroacoustic optimization process is based on three elements: designing the virtual prototypes, validation of virtual prototypes by extensive measurements, adapting and transferring the results of simulation into a real model.

The article introduces a hybrid approach developed by the KFB Polska Sp. z o.o. and IBAF Engineering GmbH, in order to obtain vibroacoustically optimised product. To illustrate that approach the article exemplarily describes the acoustic optimisation of some types of off-road machines.

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Low Cost System for Vibration Sensor Checking

BARAŃSKI Robert, robertb@agh.edu.pl

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Department of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

To build close systems dedicated only for one application is unfavorable from few point of view. The main of them are collection of unnecessary (duplicate) equipment and of course financial cost.

Base on this assumptions, we try to build system based on easily accessible and inexpensive components. Our system is dedicated for checking vibration sensors and rather should be used for education application. The main reason is accuracy. Our system consist of own production exciter, National Instruments data acquisition card (DAQ) and PC class computer.

Dedicated software provides us to DAQ card full control. We just select frequency band width and start test. All next steps are controlled by software. At the end of test we obtain information about each of third octave frequency in table or graph.

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Verification of the Calculation Assumptions Applied to Solutions of the Acoustic Measurements Uncertainty

BATKO Wojciech[1], batko@agh.edu.pl
BAL Renata, renbal@pwsz.krosno.pl

[1] AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Departament of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

[2]State Higher Vocational School
Politechnical Institute
Rynek 1, 38-400 Krosno, Poland

The assessment of the uncertainty of measurement results, an essential problem in environmental acoustic investigations, is undertaken in the paper. An attention is drawn to the – usually omitted – problem of the verification of assumptions related to using the classic methods of the confidence intervals estimation, for the controlled measuring quantity.

Especially the paper directs attention to the need of the verification of the assumption of the normal distribution of the measuring quantity set, being the base for the existing and binding procedures of the acoustic measurements assessment uncertainty. The essence of the undertaken problem concerns the binding legal and standard acts related to acoustic measurements and recommended in: "*Guide to the expression of uncertainty in measurement*" (GUM) (OIML, 1993), developed under the aegis of the International Bureau of Measures (BIPM). The model legitimacy of the hypothesis of the normal distribution of the measuring quantity set in acoustic measurements is discussed and supplemented by testing its likelihood on the environment acoustic results.

The Jarque-Bery test based on skewness and flattening (curtosis) distribution measures was used for the analysis of results verifying the assumption. This test allows for the simultaneous analysis of the deviation from the normal distribution caused both by its skewness and flattening.

The performed experiments concerned analyses of the distribution of sound levels: L_D, L_E, L_N, L_{DEN}, being the basic noise indicators in assessments of the environment acoustic hazards.
Keywords: acoustic monitoring of environment, estimation of long-term noise indicators, statistical analysis results.

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Improvements of the Uncertainty Determination of the Noise Sources Identification Process

Batko Wojciech, batko@agh.edu.pl
Pawlik Paweł

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Departament of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

The new method of the uncertainty calculation of the process of the noise sources identification, realised according to the method of disconnecting successive sources, was proposed in the paper. The situation, in which we are dealing with the diffuse sound field – formed by the background noise emission and the noise sources being identified – was assumed in these considerations.

In the identification algorithm were applied the mathematical formalism of the interval arithmetic, related to the measurement results of the noise level relevant to disconnecting successive sources of emission L_{s-i} [dB/A], and the noise level generated by influences of all sound sources.

The properties of the indicated solution were referred to the uncertainty calculation methods usually applied in various metrological solutions. The proposed approach was illustrated by the example realised under laboratory conditions.

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Type a Standard Uncertainty of Long-Term Noise Indicators

Batko Wojciech, batko@agh.edu.pl
Stępień Bartłomiej, Bartlomiej.Stepien@agh.edu.pl

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Departament of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

The problem of estimation of the long-term environmental noise hazard indicators and their uncertainty is presentedi n the hereby paper. The type A standard uncertainty is defined by the standard deviation of the mean. The rules given in the ISO/IEC Guide 98 are used in the calculations. It is usually determined by means of the classic variance estimators, under the following assumptions: the normality of measurements results, adequate sample size, lack of correlation between elements of the sample and observation equivalence. However, such assumptions in relation to the acoustic measurements are rather questionable. This is the reason why the authors indicated the necessity of implementation of non-classical statistical solutions. There is formulated the estimation idea of seeking density function of long-term noise indicators distribution by the kernel density estimation, bootstrap method, and Bayesian inference. These methods do not generate limitations for form and properties of analyzed statistics. The theoretical basis of the proposed methods is presented in this paper as well as the example of calculation process of expected value and variance of long-term noise indicators L_{DEN} and L_N. The illustration for indicated solutions and usefulness analysis were constant monitoring results of traffic noise recorded in Cracow, Poland.

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Soundscape of Polish National Parks

Bernat Sebastian, sebastian.bernat@poczta.umcs.lublin.pl

Maria Curie-Skłodowska University
Faculty of Earth Sciences and Land Management
Department of Environmental Protection
al. Kraśnicka 2cd, 20-718 Lublin, Poland

The aim of the research, which has been taken up in Polish national parks is to identify threats connected with noise, recognize soundscape resources, indicate opportunities of their protection. Studies were carried out with the use of surveys which help to diagnose awareness of threats and values of soundscapes among service of parks. Additionally, method of semantic differential was applied, just to learn opinion of students, concerning quality of soundscape in Polish national parks. Except for empirical studies experience in protection of soundscapes in national parks of the US were presented. Finally, possibilities of future research on soundscape in areas of high natural values were pointed out.
Keywords: landscape perception, soundscape, quiet zone, national parks.

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Evaluation of Influence of Work Analysis Data on Determination of Occupational Noise Exposure in Accordance with Standard PN-EN ISO 9612:2011 for Mechanic – Welder Workstation

Blasiak Krzysztof, k.blasiak@kfb-polska.pl
Chmielewski Bartosz, b.chmielewski@kfb-polska.pl
Baranski Filip, f.baranski@kfb-polska.pl

KFB Polska Sp. z o.o.
Elementarzowa 15a, 51-173 Wrocław, Poland

In article authors present results of determination of occupational noise exposure (performed in accordance with standard PN-EN ISO 9612:2011) for mechanics – welders working in one of manufacturing plant in Poland. Main goal was to verify previous results obtained using task-based measurements (strategy 1). For this purpose an additional measurement session with full-day measurement (strategy 3) was performed, extended by highly detailed recording of work activities and their duration. Emphasis was placed on matter of determination and identification of tasks and tools usage. Analysis of collected results led to evaluation of influence of work analysis data on determination of occupational noise indicators. Finally, for both strategies, the comparison of the contribution from each identified task to daily noise exposure level was made.

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The Use of GIS Data in the Acoustic Models – Processing of Data Obtained or Prepared to Adapt Them to the Local Law Requirements which Performers of an Acoustic Projects Have to Fill

Byrdy Dawid, Dawid.Byrdy@sgs.com
Polak Wiesław

SGS EKO-PROJEKT Sp. z o.o.
Muchoborska 18, 54-424 Wrocław, Poland

The paper initially describes the purpose of the use of GIS data used in the models created for the purpose of acoustic noise maps for cities with a population of over 100 thousand inhabitants performed on the basis of Directive 2002/40/EC and the most popular data formats.

It then provides necessary format conversion and commonly used for this purpose methods to the minimum loss of data. While describing the format conversions most frequently used computer programs were mentioned.

The first step in describing the work of the GIS data is to prepare the data obtained to import them into the acoustic software, and therefore presents the computational requirements of

the models as to the scope of GIS data, file formats and structure of tabular attributes of individual thematic layers together with a description of the process of data processing. The paper also includes data fusion capabilities of GIS with the results of acoustic measurement collected in such a way as to permit the implementation of direct importation into acoustic programs such as CadnaA or IMMI.

Then the need to verify the data entered was identified and different ways to carry out the process were suggested. At the stage of verifying the description of GIS data the most common mistakes and ways to exclude them were indicated.

The paper also describes ways to export the acoustic data to the most common file formats and the most common deficiencies which can occur during this process in relation to the layer attributes associated with sources of industrial noise, road and rail – deficiencies in most commercially available applications for modeling environmental noise were indicated.

There also have been described frequent requirements asked by the government about the data both for reporting on the implementation of noise map for internal use, along with the methods of processing the results of acoustic analysis in such a way that all the requirements are met.

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The "NOMAD" Project – A Survey of Instructions Supplied with Machinery with Respect to Noise

Châtillon Jacques(1), jacques.chatillon@inrs.fr
Szyszko Marian(2), marian.szyszko@szczecin.pip.gov.pl

(1) Institut National de Recherche et de Sécurité (INRS)
Rue du Morvan CS 60027
54519 Vandoeuvre-lès-Nancy Cedex, France;

(2) National Labour Inspection
District Labour Inspectorate – Szczecin
Pszczelna 7, 71-663 Szczecin, Poland

The NOMAD project was a survey to examine the noise-related content of instructions supplied with machinery offered for purchase in Europe. The project collected more than 1 500 instructions from machines covering 40 broad machine-families and from 800 different manufacturing companies. These instructions were analyzed to determine compliance with the requirements of the Machinery Directive, and assess the quality of information.

The general state of compliance of machinery instructions with the noise-related requirements of the Machinery Directive was found to be very poor: 80% of instructions did not meet legal requirements. Some required numerical values relating to noise emissions were often missing. Where values were given, they were often not traceable to machine operating conditions or measurement methods, and not credible either against stated conditions/methods or as warnings of likely risk in real use.

As a consequence, it is considered highly likely that, in making a machinery procurement decision, employers are prevented from taking noise emissions into account, and understanding what is necessary to manage the risks from noise relating to equipment that is procured.

Recommendations are made for actions aimed at bringing about a global improvement to the current situation. Targeted actions are now proposed by "ADCO Machinery Group" aimed at raising awareness of the legal requirements, responsibilities and actions required among the various groups who have parts to play in the system – machine manufacturers, machine users, occupational safety and health professionals, and standards-makers. Recommendations are also made aimed at providing, or improving, tools and resources for all these actors.

Keywords: noisy machine, machinery directive, legal requirements, survey.

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Selection of Sound Insulating Elements in Hydraulic Excavators – on the Basis of the Identification of Vibroacoustic Energy Propagation Paths

Dąbrowski Zbigniew, zdabrow@simr.pw.edu.pl
Dziurdź Jacek, Pakowski Radosław

Warsaw University of Technology
The Institute of Machine Design Fundamentals
Narbutta 84, 02-524 Warsaw, Poland

In spite of the fact that standardising operations and increased awareness of hazards led to a significant improvement of vibroacoustic climate of operator's stands of new machines, their long-term exploitation – often under difficult conditions – leads to a fast degradation of acoustic qualities of machines. Temporary operations, performed during surveys and periodical overhauls are rarely effective, due to the lack of any guidelines. In this situation the authors propose the algorithm – of selection of eventual screens or sound absorbing and sound insulating partitions – utilizing the measuring procedure of an identification at the operator's stand, of main noise components originated from various sources. On the basis of this procedure the vibroacoustic energy propagation path in the machine was estimated.

Keywords: noise and vibration, propagation path, coherence function.

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The Apparatus Intended for Measurement of Ultrasonic Noise and the Capabilities of Its Traceable Calibration

Dobrowolska Danuta, akustyka@gum.gov.pl

Central Office of Measures
Laboratory of Acoustics and Vibration
Elektoralna 2, 00-139 Warszawa, Poland

Measurements of airborne ultrasounds still encounter a lot of unsolved problems concerning the apparatus and measurement traceability. The lack of measurement standards and standardised primary methods of reproduction of sound pressure unit in ultrasound frequency range is essential. Another important problem is the lack of the internationally agreed requirements for the apparatus intended for the measurement of ultrasonic noise. In this paper the results of the review and analysis of the characteristics of the instruments available on the market, crucial for ultrasonic noise measurement are presented as well as the current capabilities of ensuring the measurement traceability. Temporary recommendations regarding the apparatus and the methods and programme of its periodic calibration are also presented.

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The Influence of Apparatus Parameters on the Uncertainty of Ultrasonic Noise Measurement

Dobrowolska Danuta(1)
Radosz Jan(2), jarad@ciop.pl

(1) Central Office of Measures
Laboratory of Acoustics and Vibration
Elektoralna 2, 00-139 Warszawa, Poland

(2) Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

Ultrasonic noise is a harmful factor to health in a working environment. For that reason it is necessary to asses risk arising from ultrasonic noise. However, for the frequency range above 20 kHz, there is no clear and complete information on the factors influencing the result of a measurement of the sound pressure level. What is more, there are no current international standards for performing measurements of ultrasonic noise in working environment. This paper presents the methodology for estimating combined uncertainty related to the apparatus used for measurements of ultrasonic noise at work places. The methodology comprises the identification of main quantities influencing the uncertainty, the detailed methods for evaluating standard uncertainties of these quantities, collation of the significant sources of uncertainty in the form of the uncertainty budget and the calculation of combined standard uncertainties.

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Preliminary Study on the Influence of Headphones for Listening to the Music on Hearing Loss of Young People

Dobrucki Andrzej B., andrzej.dobrucki@pwr.wroc.pl
Kin Maurycy J., maurycy.kin@pwr.wroc.pl
Kruk Bartłomiej, bartlomiej.kruk@pwr.wroc.pl

Wrocław University of Technology
Faculty of Electronics, Chair of Acoustics
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The paper presents results of hearing loss measurement provided for over than 80 young people (from 16 to 25 years old). The main aim of the work was to find an influence of type of used headphones (closed, semi-open, open and in-ear) on the hearing losses. The first part of the research was to answer questions of: time of listening, loudness of the music, the other noise exposures as well as the type of used headphones. It turned out that all factors mentioned above influence thresholds of hearing but the found dependencies are not explicit. The greatest hearing losses were observed for the people who work as sound reinforcement engineers and, moreover, no influence of headphones type was found for them. It turned out that the use of in-ear headphones causes the greatest hearing losses for some subjects (thresholds shifted up to about 20 dB at 4 kHz). The daily time of a listening also affected hearing thresholds and it was found that for users of in-ear and close headphones, an average time of musical exposure was of three hours and it causes the hearing loss of 10–15 dB at higher frequencies. The use of open as well as semi-open headphones has no influence on hearing damage and it would be stated that these kinds are safety in use. Almost 15% of investigated young people have their thresholds shifted up at higher frequencies, particularly at 4 kHz what means that they have the first symptoms of the permanent hearing damage.
Keywords: hearing threshold, headphones.

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Does Exposure to Sounds During Individual Rehearsals Increase the Risk of the Hearing Loss in the Orchestral Musicians?

Dudarewicz Adam, adudar@imp.lodz.pl
Pawlaczyk-Łuszczyńska Małgorzata,
Zamojska Małgorzata, Zaborowski Kamil

Nofer Institute of Occupational Medicine
Department of Physical Hazards
Św. Teresy 8, 91-348 Łódź, Poland

In order to evaluate musicians' exposure to orchestral noise during solo and group rehearsals, the field studies were carried out in three symphony orchestras.

The load of musicians playing instruments was evaluated using a questionnaire survey. The survey was performed in the group of 57 musicians to identify a typical playing times of individual and collective rehearsals or concerts. Weekly time of playing instruments is divided between performances, team and individual rehearsals 2.5, 20, and 7.5 hours, respectively.

The noise exposure of various groups of instruments was measured during preparations to perform diversified repertoire. The measurements were performed during the individual playing and collective playing. Equivalent sound pressure levels recorded during individual practicing were higher than in the case of team play in the woodwind and brass instruments, while similar levels were recorded for the string instruments.

Majority musicians, excluding stringed instruments players, were exposed to excessive sounds exceeding Polish maximum admissible intensity value (85 dB).

Exposure during both individual and group rehearsals should be taken into account in the hearing conservation program for this staff group.
Keywords: noise measurement, noise exposure, orchestral musicians.

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Exposure to Excessive Sounds During Orchestra Rehearsals and Temporary Hearing Changes in Hearing Among Musicians

Dudarewicz Adam, adudar@imp.lodz.pl
Pawlaczyk-Łuszczyńska Małgorzata
Zamojska Małgorzata, Zaborowski Kamil

Nofer Institute of Occupational Medicine
Department of Physical Hazards
Św. Teresy 8, 91-348 Łódź, Poland

The harmful effects of exposure to orchestral noise may include the prevalence of temporary changes in hearing.

The temporary changes in hearing after group rehearsals were determined in musicians using transient-evoked otoacoustic emissions (TEOAEs). The study group comprised 19 orchestral musicians, aged 30–58 years (mean 40 years) having from 12 to 40 years (mean 22 years) of professional experience.

Musicians' hearing threshold levels were higher than expected for the non-noise-exposed population. Moreover, the high frequency notched audiograms were observed in some of them.

No significant differences between pre- and post-exposure reproducibility of TEOAE and signal to noise ratio were found. However, the significant post-exposure reductions of TEOAE amplitudes (approx. 0.7 dB) both for the total response and frequency bands of 2 000 and 3 000 Hz were noted.
Keywords: orchestral musicians, temporary changes in hearing, transient evoked otoacoustic emission.

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Two Stage Vibration Isolation on Example of a Vibratory Conveyor

Fiebig Wiesław, wieslaw.fiebig@pwr.wroc.pl

Wrocław University of Technology
Institute of Machine Design
Łukasiewicza 7/9, 51-370 Wrocław, Poland

In this paper the effectivity of two stage vibration on example of the vibratory conveyor has been shown. Vibratory conveyors are used i.e. for coal transportation in power stations. In the considered case the conveyor has been supported on the ceiling in 1st floor of the building and caused vibrations. For identification of dynamical behavior of the conveyor, vibrations measurements and simulation have been carried out. To reduce the transmission from the conveyor to the ceiling two stage vibration isolation has been performed and significant reduction of vibrations in the building has been achieved.

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Model of Interactive System for Training in the Proper Use of Hearing Protection Devices

Górski Paweł, pawel@ciop.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

In 2011, over 520 thousand persons worked in hazardous conditions (according to the GUS). Among hazardous factors related to working environment, noise was found to be the most common threat, which threatened 199,6 thousand persons (52.9% threats-cum-persons related to working environment). The prevalence of workplace noise and increasing awareness of effects of its impact on the human body causes increase of the demand for knowledge of the methods of noise reduction. Due to the lack of knowledge concerning the proper use of hearing

protectors, effective noise exposure in the real world may be about a dozen dB higher than the declared assumed protection value. For this reason, in Central Institute for Labour Protection – NRI "The interactive system to learn the correct use of hearing protectors" had been developed. The system includes the multimedia guide on hearing protectors supplemented by video tutorials, training materials with training hearing protectors, and software for evaluation of the activities of the trainee.
Keywords: active noise reduction, hearing protestors.

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Noise Exposure of School Teachers – Exposure Levels and Health Effects

Hadzi-Nikolova Marija[(1)], marija.hadzi-nikolova@ugd.edu.mk
Mirakovski Dejan[(1)], Zdravkovska Milka[(2)],
Angelovska Bistra[(2)], Doneva Nikolinka[(1)]

[(1)] Goce Delcev University
Faculty of Natural and Technical Sciences
Mail Box 201, 2000 Stip, Republic of Macedonia

[(2)] Goce Delcev University
Faculty of Medical Sciences
Mail Box 201, 2000 Stip, Republic of Macedonia

Faculty of Natural and Technical Sciences and Faculty of Medical Sciences starting from December 2012, launched joint study in order to investigate personal noise exposure and associated health effects in general school teachers population, starting from kindergartens up to high schools in Stip, Macedonia.

In order to determine workplace associated noise exposure and associated health effects in this specific profession, a full shift noise exposure of 40 teachers from 1 kindergarten, 2 primary and 2 high schools were measured in real conditions using noise dosimeters.

A-weighted equivalent-continuous sound pressure levels (L_{Aeq}) of each teacher were recorded during single activities (classes). Normalized 8-hours exposure, termed the noise exposure level ($L_{ex,8\,\mathrm{h}}$) was also computed. Daily noise dose is another descriptor for noise exposure that was determined as a measure of the total sound energy to which workers have been exposed, as a result of working in the varying noise levels.

Health effects were assessed trough a full scale epidemiological study which included 231 teachers from the same schools. Specific questionnaire was used to extract information about subject's perception on occupational noise exposure, as well as theirs occupational and medical history.
Keywords: teachers, school, noise, exposure, health effects.

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Influence of Infrasound Noise of Wind Turbines on EEG Signal

Kasprzak Cezary, cekasp@agh.edu.pl

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
Departament of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

The purpose of this paper is to determine the effect of infrasound noise of wind turbines (up to 20 Hz) on the changes in the morphology of the EEG signal. 35 subjects had undergone 20 minute exposure infrasound noise in the cabin pressure. The acoustic signal recorded at a distance of 750 meters from a wind turbine, then filtered frequency components above 20 Hz. So processed audio signal of the test were presented. The parameters of the presented signal SPL = 91.6 dB(LIN), SPL = 39.2 dB(A).

The study proceeded in three stages. Step one – five minutes without exposure of the acoustic signal. Step two – twenty-minute exposure of infrasound noise. Step three – ten minutes without exposure of the acoustic signal. The study was conducted in cabin pressure during the whole study was recorded EEG signal. Uses 19 electrodes placed on the head of the test system by 10–20.

The results of the initial EEG was analyzed in order to remove artifacts. Then the calculated power spectral density functions, uses 8-second window, overlapping 50%, and the window Haninge. The results were averaged for subsequent phases of the study. An analysis of the EEG signal changes in morphology between the three successive stages of the study.

The obtained results allowed to demonstrate changes in the morphology of the EEG signal during exposure of infrasound noise from wind turbines. Found changes in specific frequency ranges of the EEG signal.

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New Look at Management of Noise in Natural Environment

Kompała Janusz, j.kompala@gig.eu
Kozerska Katarzyna, Passia Henryk

Central Mining Institute
Department of Technical Acoustics
Laser Technology and Radiometry Technology
pl. Gwarków 1, 40-166 Katowice, Poland

It is recently observed that the sound layer is more and more polluted with noise, in particular in the urbanized areas. This hazard is being generated, to a large extent, by road transport. The investigations currently conducted at the road tests sites provide a basis for a trial to take actions imortant for a proper shaping of the acoustic climate in inhabited areas. Making an effort to meet this hazard, acoustic barriers are constructed to the greatest extent exposed to road traffic noise. However, it should be added that this is only a beginning of a certain process in which urban development, architectural and building methods, and legal- administrative actions should also be taken into account. But, in the course of designing acoustic screens, only their effectveness is considered, omitting the aesthetic attributes and harmony in the landscape.

Making a reference to the statements of the European Landscape Convention on protection of lanscapes, which includes the protection of views, one should conclude that it is necessary to take into account such things as their acoustic effectiveness in the area, and composition and aesthetics in the landscape. These actions are considered to be found at the border line between art (when taking care of aesthetic quality of sound environment), and science (including, among the other things, acoustics, landscape architecture, urban development, musicology, and psychology).

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Proposals for Noise Control Measures in Opencast Mineral Mines

Kosała Krzysztof[(1), (2)]
Zawieska Wiktor M.[(2)]

[(1)] AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

[(2)] Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

Exploitation of open-pit mines of minerals constitutes vibroacoustic hazards for their workers and inhabitants living near such establishments. Noise, being one of the main harmful factors in work environment, is a threat to the external environment, particularly when mining works are carried out near residential areas or reserves.

The quarry industry is connected with many noisy activities. There are: drilling, blasting works, crushing of rocks and aggregate screening and transport of mineral materials. The operators of mining and transport machines as well as servicing and technical inspection workers are the most endangered to noise. Exceeding level of noise is the reason of occupational diseases, distortions of speech intelligibility among workers and accidents at work.

General technical solutions, concern noise level reduction in open-pit mines of mineral raw materials, are given in the paper.

Some propositions of conceptions of noise protections, connected with operating of machines, which are mobile crushers, are also shown.

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A Dedicated Preamplifier for Vibration Transducer Made of PVDF Film

Kowalski Piotr[(1)], pikow@ciop.pl
Makarewicz Grzegorz[(2)], trioda@trioda.com

[(1)] Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

[(2)] Trioda

PVDF film transducers belonging to smart materials group are increasingly applied to the measurement of the mechanical vibration. The article presents the concepts and sample of laboratory test results of preamplifier intended for measuring of vibration at workstations using PVDF film. Developed preamplifier based on instrumental amplifier and on charge buffer. Regardless of the value of the transducer's capacity the charge buffer provides the constant transmission at lower frequency in the measuring system. The use of the reference transducer can effectively minimize the disturbance of the desirable signal. Preliminary laboratory measurements have confirmed the proper operation of the preamplifier.

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Acoustic Maps Before and After Change of Levels Permitted Noise

Kozakiewicz Andrzej
Franz Maria, biuro@bmtargoss.pl

BMT ARGOSS Sp. z o.o.
Kościerska 7, 80-328 Gdańsk, Poland

Acoustic maps of towns are developed in accordance with the Directive 2002/49/EC. The directive says that each Member State of the European Union determines limit values of noise indicators for different noise sources as well as different surroundings. The limit values in Poland for road- and rail-noise determined in 2007 were relatively low compared to other countries. These values have been significantly increased in October 2012 for two basic noise indicators, Lden (L_{DWN}) and L_{night} (L_N), by 5–10 dB, depending on the surroundings. The impact of these changes on estimated town areas and numbers of inhabitants exposed to the road- and rail-noise in seven Polish towns (3 towns with more than 250 000 inhabitants and four towns with more than 100 000 inhabitants) has been investigated based on results of acoustic maps. Non-dimensional results (standardization with regard to the total town area and total number of inhabitants) for the former (more restrictive) and the recent values of limits were compared using the same methodology. Analysis revealed that on average, the estimated number of inhabitants exposed to noise levels exceeding the limit values decreased by 90%.

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Effects of Acoustic Treatment on Music Teachers' Exposure to Sound

Kozłowski Emil, emkoz@ciop.pl
Młyński Rafał

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

In this study, music teachers' exposure to sound was tested by measuring the A-weighted equivalent sound pressure level (SPL), the A-weighted maximum SPL and the C-weighted peak SPL. Measurements were taken prior to and after acoustic treatment in four rooms during classes of trumpet, saxophone, French horn, trombone and percussion instruments. Results showed that acoustic treatment affects the exposure of music teachers to sound. Daily noise exposure levels ($L_{EX,\,8\,\text{h}}$) for all teachers exceeded a limit of 85 dB while teaching music lessons prior to room treatment. It was found that the $L_{EX,\,8\,\text{h}}$ values ranged from 85.8 to 91.6 dB. The highest A-weighted maximum SPL and C-weighted peak SPL that music teachers were exposed to were observed with percussion instruments ($L_{A\,\max} = 110.4$ dB and $L_{C\text{peak}} = 138.0$ dB). After the treatments, daily noise exposure level decreased by an average of 5.8, 3.2, 3.0, 4.2 and 4.5 dB, respectively, for the classes of trumpet, saxophone, French horn, trombone and drums, and did not exceed 85 dB in any case.

Keywords: music teachers, sound pressure levels, acoustic treatment.

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Temporary Threshold Shift and Hearing Loss for Recording Engineers

Kruk Bartłomiej, bartlomiej.kruk@pwr.wroc.pl
Kin Maurycy J., maurycy.kin@pwr.wroc.pl
Kamińska Magdalena, magdalena.kaminska@student.pwr.wroc.pl

Wrocław University of Technology
Faculty of Electronics, Chair of Acoustics
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The paper presents results of Temporary threshold shift measurement provided for over than 30 recording engineers. The main aim of this article is to provide information and explanation of these phenomena to understand basic principles and to help understand how to work more effectively and efficiently in the recording studio.

Noise exposure and intense sounds can cause two main types of hearing loss, temporary threshold shift and permanent threshold shift. This protection mechanism is responsible for sensitivity reduction, causing the hearing threshold to shift upward. Permanent threshold shift occurs during regular exposure to excessive noise for long periods of time.

Listening to loud music, which is an integral part of working in the recording studio, can cause a temporary loss of hearing in the mid frequency region. In one study, a group of 30 recording engineers were exposed to near-field sound at LEQ 93.6 dB, MAX 102.6 dB for 90 minutes. For all the people who attended in the tests was observed hearing threshold shift. The biggest changes were measured for frequency 4000 Hz and reached up to 10–20 dB. More than a half of the people also experienced 5–10 dB changes for 2000 and 8000 Hz. None showed a loss above the guideline at 1000 Hz or 8000 Hz, so the shifts are concentrated in the maximum sensitivity range of human hearing.

To ensure the comfort of working in a recording studio it is necessary to take regular breaks and thus avoid continuous exposure to loud sounds. This is the key to keep fresh ears and a fresh perspective in your music.

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Active Noise and Vibration Control System Based on a TMS320C6747 Floating Point Digital Signal Processor

Krukowicz Tomasz, tokru@ciop.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

In this paper an early stage of the design of an active noise control system based on the TMS320C6747 is presented. Aim of the article is to introduce capabilities of the system and its limitations. Purpose of the system are in-situ situations, where the system can applied immediately without measurements and system/signal analysis using PC and special software. Results of example laboratory tests of active noise control process using genetic algorithm and neural network are also presented.

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Land-Use Planning Methods in Environmental Acoustics. Towards to "Quiet zones"

Kucharski Radosław, kuchar@ios.edu.pl
Chacińska Patrycja

Institute of Environmental Protection
– National Research Institute
Krucza 5/11 D, 00-548 Warszawa, Poland

One of the most effective methods in environmental noise control is the adequate land-use technique. In fact, this method comes into effects rather in medium or even long-term perspective. The results of the noise mitigation activity using land-use process require the common indexes, classifications, assessment methods of different impacts (non-acoustic too) etc.

The paper orders the background relations between noise control and land-use techniques (main, but chosen examples) with the special emphasis laid down on the basic descriptors (indexes). The relations will be developed in the quantitative form (if possible) as well as in qualitative (descriptive) forms.

One of the most important issue on the field of environmental control is the prevention. This activity is indirectly connected with the so called "quiet areas" (zones). Present definition of the "Quiet zone" (in agglomeration) is enclosed in the Directive 2002/49/EU (DEN) (art. 3, point "l"):
"*quiet area in an agglomeration" shall mean an area, delimited by the competent authority, for instance which is not exposed to a value of Lden or of another appropriate noise indicator greater than a certain value set by the Member State, from any noise source*".

The paper includes the preliminary short proposition of the "quiet zone" creation, of course by adoption of the land-use techniques.

At the end the conception of the "quiet zones" recovering technology is presented.

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Railway Noise Measurements an Assessments in Poland. The State-of-Art Before Railways Lines Upgrading

Kucharski Radosław, kuchar@ios.edu.pl
Chacińska Patrycja

Institute of Environmental Protection
– National Research Institute
Krucza 5/11 D, 00-548 Warszawa, Poland

Railway noise is one of components of the environmental soundscape of Poland. The field measurements of the railway noise exposition were carried out during last 10 years. The results of them (few hundred's pieces) were used in different studies and analyses, especially in Environmental Impact Assessments as well as in noise mapping process.

DEN requirements point out that the appropriate method for the railway noise assessments is the SRMII (Dutch method). The methods include the reference library of the acoustic parameters of different kinds of trains. These data is not suitable for polish trains vs. polish rail-tracks.

In the paper the state-of art of railway noise exposition arise from the results of field measurements is presented. The measurements were mostly done around the present railways, aged few dozen years (tracks and rolling stocks). The results were compared with the noise calculations (SRMII).

On the base of comparisons the analysis of differences will be done taking into consideration expected upgrading (fulfill international conditions) many of railway's lines in Poland. Some examples between noise exposition before and after upgrading of the tracks added to the presentation.

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Active Noise Control Using a Fuzzy Inference System Without Secondary Path Modeling

Kurczyk Sebastian, Sebastian.Kurczyk@polsl.pl
Pawełczyk Marek, Marek.Pawelczyk@polsl.pl

Silesian University of Technology
Institute of Automatic Control
Akademicka 16, 44-100 Gliwice, Poland

For many adaptive noise control systems the Filtered-Reference LMS, known as FXLMS algorithm is used to update parameters of the control filter. Appropriate adjustment of the step size is then important to guarantee convergence of the algorithm, obtain small excess mean square error, and react with required rate to variation of plant properties or noise nonstationarity. There are several recipes presented in the literature, theoretically derived or of heuristic origin.

This paper focuses on developing a modification of the FXLMS algorithm, were convergence is guaranteed by changing sign of the algorithm steps size, instead of using a model of the secondary path. The Takagi-Sugeno-Kang fuzzy system is used to evaluate both the sign and the magnitude of the step size. The proposed approach is compared with the classical FXLMS algorithm by means of simulation experiments in terms of convergence and noise reduction.

Keywords: index terms, active noise control, adaptive control, fuzzy inference system, FXLMS, sign-varying step size.

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Latest Developments in International Standardization of Whole-Body and Hand-Arm Vibration

Liedtke Martin, martin.liedtke@dguv.de
Rissler Jörg, Kaulbars Uwe

Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) Alte Heerstraße 111, 53757 Sankt Augustin, Germany

New developments in international standardization of whole-body and hand-arm vibration are presented.

Two German projects are addressing both subjects at the same time: one is concerned with the uncertainty in vibration measurement, the other is dealing with the qualification of personnel responsible for the exposure measurement and risk assessment at work places.

In the field of whole-body vibration, the measurement standard ISO 2631-1 is currently under revision. The main activities are concerned with comfort effects. In addition, ISO/TR 10687 has been published recently which describes posture variables that should be reported when a combined exposure of whole-body vibration and awkward posture is investigated. The effect of shocks as described in ISO 2631-5 is also under revision, where two procedures are proposed. One of them is already available as DIN SPEC 45697.

As fas as hand-arm vibration is concerned, one can find the effect of coupling forces in the recently published CEN/TR 16391. Also DIN 45679 for the same subject has been revised in 2013, including also information available in ISO 15230. In addition, the frequency weighting for hand-arm vibration regarding vascular disorders is under discussion in an ISO working group. Finally, the standards for the assessment of vibrational emission of handheld power tools has been revised under EN ISO 28927 and replaces ISO 8662.

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Economic Aspects of Using Acoustic Maps

Lipowczan Adam, alipowczan@gig.katowice

Central Mining Institute
pl. Gwarków 1, 40-166 Katowice, Poland

The main project in the domain of environmental acoustics, executed over the last decade, were the activities related to working out the strategic acoustic maps for the cities with population exceeding 100 thousand, as well as those for main roads and railways The works conducted for the cities with a number of inhabitants over 250 thousand, and international-importance roads and railways have been completed, while the acoustic maps for the cities with population of 100–250 thousand are still under preparation. These documents have been gradually sent to the EU Central Office in Brussels. The expenditures on elaboration of the maps for the first groups of cities were about 24 million Polish zloty. It is estimated that a total cost of the entire project, as a consequence of the provisions of the UE Directive No. 49 and Polish Environmental Act, will be higher than 100 million zloty. The acoustic maps are considered to provide a basis for preparing programmes of protection against excessive environmental noise. Do they really serve this, and are they able to do this? The paper presents the author's reflection relative to economic consequences of programming the actions to reduce the environmental noise on the background of such actions being taken in other EU countries.

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Measurements of Ultrasonic and Audiable Noise During Ultrasonic Welding of Metals

Matusiak Jolanta[(1)], jolanta.matusiak@is.gliwice.pl
Szłapa Piotr[(2)], p.szlapa@imp.sosnowiec.pl
Wyciślik Joanna[(1)], joanna.wycislik@is.gliwice.pl

[(1)] Welding Institute
Błogosławionego Czesława 16-18, 44-100 Gliwice, Poland

[(2)] Institute of Occupational Medicine
and Environmental Health
Kościelna 13, 41-200 Sosnowiec, Poland

This article presents the results of measurements of sound pressure level in 1/3 octave bands of ultrasonic noise and audiable noise during ultrasonic welding of different metals. Research was carried out on the experimental work station in Welding Institute during ultrasonic welding of mononomial joints like copper + copper, aluminium alloy + aluminium alloy and heteronymous joints like copper + aluminium alloy. The research was conducted during ultrasonic welding in 2 options: with and without housing. The article also presents the results of simulation of 8-hour working day exposure on ultrasonic and audiable noise at hypothetical work station. Simulation was conducted by random sampling MonteCarlo method using Crystal Ball 2000 software.

The measurements' results showed that sound pressure level in 1/3 octave bands of ultrasonic noise during ultrasonic welding of metals depends on type of welded materials: the highest equivalent sound pressure level in dominant 1/3 octave band of ultrasonic noise with the center frequency 20 kHz occurs during ultrasonic welding of mononomial joints Al + Al type and the lowest during ultrasonic welding of heteronymous joints Cu + Al type. During ultrasonic welding without housing the highest equivalent sound pressure level in dominant 1/3 octave band of ultrasonic noise with the center frequency 20 kHz occurs in the place of operator's work in front and back of welding device. Working places located on both sides of welding device were characterized by lower sound pressure levels.

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Active Noise Control with a Single Nonlinear Control Filter for a Vibrating Plate with Multiple Actuators

Mazur Krzysztof, Krzysztof.Jan.Mazur@polsl.pl
Pawełczyk Marek, Marek.Pawelczyk@polsl.pl

Silesian University of Technology
Institute of Automatic Control
Akademicka 16, 44-100 Gliwice, Poland

Vibrating plates can be used in Active Noise Control (ANC) applications as active barriers or as secondary sources replacing classical loudspeakers. The system with vibrating plates, especially when nonlinear MFC actuators are used, is nonlinear. The nonlinearity in the system reduces performance of classical feed-forward ANC with linear control filters systems, because they cannot cope with harmonics generated by the nonlinearity. The performance of the ANC system can be improved by using nonlinear control filters, such as Artificial Neural Networks or Volterra filters.

However, when multiple actuators are mounted on a single plate, which is a common practice to provide effective control of more vibration modes, each actuator should be driven by a dedicated nonlinear control filter. This significantly increases computational complexity of the control algorithm, because adaptation of nonlinear control filters is much more computationally demanding than adaptation of linear FIR filters.

This paper presents an ANC system with multiple actuators, which are driven with a single nonlinear filter. To avoid destructive interference of vibrations generated by different actuators the control signal is filtered by appropriate separate linear filters. The control system is experimentally verified and obtained results are reported.

Keywords: active noise-vibration control, active structural acoustic control, adaptive control, nonlinear-control.

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A Two-Layer Adaptive Active Structural Noise Control System

Mazur Krzysztof, Krzysztof.Jan.Mazur@polsl.pl
Pawełczyk Marek, Marek.Pawelczyk@polsl.pl

Silesian University of Technology
Institute of Automatic Control
Akademicka 16, 44-100 Gliwice, Poland

Vibrating plates have been gaining increasing interest for active noise reduction or isolation systems. Unfortunately, they are much harder to control than loudspeakers. Plates have multimodal response with high variations of amplitude response. To effectively excite multiple vibration modes multiple actuators are usually needed. Using multiple actuators mounted on a single plate significantly increases the number of control signals to be worked out. This could be a severe problem for active control systems with multiple vibrating plates. Such system would have a large number of secondary paths and necessity to adapt many control filters. However, secondary paths for the same vibrating plate are not fully independent. In this paper a lower-layer single-input multiple-output controller is designed first for the vibrating plate to be seen as a single-input single-output plant of equalized frequency response. Then, a higher-layer active controller is designed to reduce noise. The control system is experimentally verified and obtained results are reported.

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Influence of Electrical and Magnetic Field at 50 Hz on Values Indicated by Noise Measure Instruments

Mikulski Witold, wimik@ciop.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

To assess of occupational risk at workplaces as a result of exposition of noise, it is necessary to perform credible measurements of noise. One of the elements of reassurance reliability of measure instruments' indications is using them in specific operation's conditions.

In the article shows the results of the effect of 50 Hz electromagnetic fields of high intensity on noise measure instruments' indications. Research was conducted on two noise measure instruments: noise dosimeter with microphone in ear canal and sound level meter. Both instruments were situated in magnetic and then electric field of 50 Hz frequency. Research was conducted for intensity fields from 0 to value higher than NDN on workplaces. It was certified in the research's results that both instrument were sensitive to both fields. It was also certified that essential difference of indications A-weighted sound pressure level, from the reliability of the research's results point of

view is 3 dB. Electrical field, on which employees could be exposed on workplaces, was not higher than this value. Magnetic field for sound level meter was also not higher than this value as well as for noise dosimeter, but only for field value up to 800 A/m. According to regulations employers could abide in field up to 2000 A/m for short periods of time, because of this fact in the areas where intensity of magnetic field is between 800 and 2000 A/m the research's results contain unacceptable errors. Taking range and form of the experiment into account, it is advisable to treat obtained results as indication of significance heretofore omitted factor, that affects reliability of noise measure and as foothold for further research in this matter.

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Influence of Classrooms' Acoustic Treatment on Background Noise Level and Teachers Voice Intensity

Mikulski Witold[1], wimik@ciop.pl
Jakubowska Izabela[2]

[1] Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

[2] The Main School of Fire Service – student
Słowackiego 52/54, 01-629 Warszawa, Poland

Noise is one of the indirect reasons of teachers' voice illnesses. It is the result of unintentional speaker's tendency to augment "voice intensity" to improve audibility in noisy surrounds. This effect is called Étienne Lombard's effect. It follows that decreasing the background noise can indirectly affect to teachers to reduce voice intensity. Decreasing the background noise can have positive influence on reducing teacher's voice occupational disease. The article verified that thesis. Sound-absorbing materials have been used as an element to decrease background noise (coming mostly from students).

Main conclusion from the studies is the fact, that acoustic treatment of classrooms (ceiling and parts of side walls) can decrease background noise and decrease teachers' voice intensity at 5-10dB, which consequently contribute to decrease excessive strain of teachers voices – main cause of most popular occupational disease in this occupational group.

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Assessment of Impulse Noise Hazard and the Use of Hearing Protection Devices in Workplaces where Forging Hammers are Used

Młyński Rafał[1], rmlynski@ciop.pl
Kozłowski Emil[1], emkoz@ciop.pl
Adamczyk Jan[1], [2],

[1] Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

[2] AGH University of Science and Technology
Departament of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

The impulse noise is agent harmful to health not only in the case of shots from firearms and the explosions of explosive materials. This kind of noise is also present in many workplaces in the industry. The paper presents the results of noise parameters measurements in workplaces where four different die forging hammers were used. The measured values of the C-weighted peak sound pressure level, the A-weighted maximum sound pressure level and A-weighted noise exposure level normalized to an 8 h working day (daily noise exposure level) exceeded the exposure limit values. For example, the highest measured value of the Cweighted peak sound pressure level was 148.9 dB. Due to the lack of possibility to use other methods for reduction the impact of impulse noise, workers present at considered workplaces have to wear hearing protection devices. In this study possibility of the protection of hearing with the use of earplugs or earmuffs was assessed. The measurement method for the measurements of noise parameters under hearing protection devices using an acoustical test fixture instead of testing with the participation of subjects was used. The results of these measurements allows for assessment which of two tested earplugs and two tested earmuffs sufficiently protect hearing of workers in workplaces where forging hammers are used.

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Internet Service BEZPIECZNIEJ Dedicated to Noise, Vibration and Other Physical Agents of Working Environment

Morzyński Leszek, lmorzyns@ciop.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

According to statistical data, a few hundred thousand of workers in Poland works in hazardous conditions caused by physical agents, like for example noise, vibration, electromagnetic fields or optical radiation (ultraviolet, visible and infrared). Working in hazardous conditions can lead to occupational diseases of workers, as well as cause industrial accidents. As one of the most important method of hazards prevention is education, it requires easy accessible educational materials, suitable for persons of different skills and degrees of education. An internet service BEZPIECZNIEJ (in English: SAFER) was developed as an system for supporting prevention of occupational hazards caused by physical agents. Service BEZPIECZNIEJ, available from main web portal of the Central Institute for Labour Protection – National Research Institute, consists of information and educational materials prepared by panel of experts and related to particular physical agents. In this article the structure and the contents of the service will be presented based on examples of noise and vibration hazards.

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Acoustical Quality Assessment of Sports Facilities

Nowicka Elżbieta, E.Nowicka@itb.pl

Building Research Institute, Acoustic Department
Ksawerów 21, 02-793 Warszawa, Poland

The aim of this paper is to present a method for the assessment of the acoustical quality index of sports enclosures in the design stage, which takes into consideration the selection of the architectural and acoustical parameters. The paper describes the proposed method for assessing the acoustical quality indicator of sports enclosures. The method consists of compiling and analyzing the proper selection of architectural and acoustical parameters (including reverberation time, and decay regimes of the absorption or scattering of sound). The result is a single number – sports facilities sound quality evaluation index, which can be used during the design of sports facilities. The method attempts to develop a rapid and simple procedure for estimating the initial acoustical conditions in such rooms in order to ensure the sound quality and the intelligibility of speech in the rooms.

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Assessment of Annoyance Due to Wind Turbine Noise

Pawlaczyk-Łuszczyńska Małgorzata, mpawlusz@imp.lodz.pl
Dudarewicz Adam, Zaborowski Kamil
Zamojska Małgorzata, Waszkowska Małgorzata

Nofer Institute of Occupational Medicine
Department of Physical Hazards
Św. Teresy 8, 91-348 Łódź, Poland

The overall aim of this study was to evaluate the perception and annoyance of noise from wind turbines in populated areas of Poland.

A questionnaire inquiry on response to wind turbine noise was carried in 363 subjects living in the vicinity of wind farms.

In addition, current mental health status of respondents was assessed using Goldberg General Health Questionnaire GHQ-12. For areas where respondents lived, A-weighted sound pressure levels (SPLs) were calculated as the sum of the contributions from the wind power plants in the specific area. Noise conditions outside the dwellings were verified by *in situ* measurements.

It has been shown that the wind turbine noise at the calculated A-weighted SPL of 27–49 dB was perceived as annoying outdoors by 32.8% of respondents. while indoors by 20.5% of them. The odds ratio of being annoyed outdoors by wind turbine noise increased with increasing SPLs (OR = 2.1; 95%CI: 1.22–3.62). Subjects' attitude to wind turbines in general and sensitivity to landscape littering was found to have significant impact on the perceived annoyance. About 52% of variance in annoyance assessment outdoors might be explained by the aforesaid subjective factors. Further studies are needed before firm conclusions can be drawn.

Keywords: wind turbines, noise, annoyance

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A Questionnaire for Assessment of Annoyance Due to Wind Turbines

Pawlaczyk-Łuszczyńska Małgorzata, mpawlusz@imp.lodz.pl
Zaborowski Kamil, Dudarewicz Adam
Zamojska Małgorzata

Nofer Institute of Occupational Medicine
Department of Physical Hazards
Św. Teresy 8, 91-348 Łódź, Poland

A special questionnaire was developed in order to evaluate the subjective response to noise from the wind turbines in people living in their neighborhood. This questionnaire was aimed at evaluation of respondents' living conditions, including prevalence of annoyance due to wind turbine noise, and the self-assessment of physical health and wellbeing.

The questionnaire consists of two parts. The first one comprised inquiries concerning: a) housing and satisfaction with the living environment, including questions on occurrence and the degree of annoyance experienced outdoors and indoors from various nuisances, b) sensitivity to odors and air pollution, landscape littering, c) general opinion on wind turbine and on the visual impact of wind turbines, d) different visual and auditory aspects of wind turbines, such as noise, shadows and reflections from rotor blades, during various subjects' activities and weather conditions. The second part of the questionnaire was aimed at self-assessment of subjects' physical health, including hearing status. It also comprised questions on chronic illnesses and general well-being, as well as quality of sleep and normal sleep habits.

Statistical analysis of results of questionnaire inquiry in study group of 156 subjects living in the vicinity of wind farms confirmed a high internal consistency of different questions evaluating response to wind turbines by Cronbach's α coefficient of 0.93.

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Evaluation of Efficiency of Personal Hearing Protective Devices in Case of Exposure to Ultrasonic Noise

Pawlaczyk-Łuszczyńska Małgorzata, mpawlusz@imp.lodz.pl
Zaborowski Kamil, Zamojska Małgorzata
Dudarewicz Adam

Nofer Institute of Occupational Medicine
Department of Physical Hazards
Św. Teresy 8, 91-348 Łódź, Poland

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Noise-Induced Hearing Loss in Professional Orchestral Musicians

Pawlaczyk-Łuszczyńska Małgorzata, mpawlusz@imp.lodz.pl
Zamojska Małgorzata, Dudarewicz Adam
Zaborowski Kamil

Nofer Institute of Occupational Medicine
Department of Physical Hazards
Św. Teresy 8, 91-348 Łódź, Poland

The overall purpose of this study was to assess hearing status in professional orchestral musicians. Standard pure-tone audiometry (PTA) and transient-evoked otoacoustic emissions (TEOAEs) were performed in 126 orchestral musicians. Occupational and non-occupational risk factors for noise-induced hearing loss (NIHL) were identified in questionnaire inquiry. Data on sound pressure levels produced by various groups of instruments were also collected and analyzed. Measured hearing threshold levels (HTLs) were compared with the theoretical predictions calculated according to ISO 1999 (1990).

Musicians were exposed to excessive sound at weekly noise exposure levels of for 81–100 dB (mean: 86.6±4.0 dB) for 5–48 years (mean: 24.0±10.7 years). Most of them (95%) had hearing corresponds to grade 0 of hearing impairment (mean hearing threshold level at 500, 1000, 2000 and 4000 Hz lower than 25 dB). However, high frequency notched audiograms typical for noise-induced hearing loss were found in 35% of cases. Simultaneously, about 35% of audiograms showed typical for NIHL high frequency notches (mainly occurring at 6000 Hz). When analyzing the impact of age, gender and noise exposure on hearing test results both PTA and TEOAE consistently showed better hearing in females vs. males, younger vs. older musicians. But higher exposure to orchestral noise was not associated with poorer hearing tests results.

The musician's audiometric hearing threshold levels were poorer than equivalent non-noise-exposed population and better (at 3000 and 4000 Hz) than expected for noise-exposed population according to ISO 1999 (1990). Thus, music impairs hearing of orchestral musicians, but less than expected from noise exposure.

Keywords: orchestral musicians, exposure to orchestral noise, hearing, risk of noise-induced hearing loss.

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Comparative Study of the Effects of Occupational Exposure to Infrasound and Low Frequency Noise with Those of Audible Noise

Pawlas Krystyna, k.pawlas@imp.sosnowiec.pl
Boron Marta, Pawlas Natalia, Szłapa Piotr
Zachara Jolanta, Kozłowska Agnieszka

Institute of Occupational Medicine and Environmental Health
Kościelna 13, 41-200 Sosnowiec, Poland

Long-term effects of moderate levels generated in working environment are very scarce. The study aimed to compare effects of occupational exposure n low frequency noise (LFN) in comparison with those of audible noise (AN). Three groups of 309 workers (I – exposed to LFN, II – exposed to audible noise and III – controls) were examined. Questionnaire, Blood pressure, subjective and objective hearing tests (conventional audiometry, impedance audiometry, TEOAEs, BERA), posturography, and biochemical parameters were performed for each subject. Levels of exposure in dB-A, dB-C, dB-G, octave analysis were determined.

Daily noise dose of LFN was trice higher in comparison with those of audible noise. More than 80% of energy was cumulated in 2–500 Hz range of octaves. In case of audible noise more than 75% of energy was cumulated middle and high frequency range. Blood pressure and other biochemical parameters were worse in AN group. LFN group assessed its exposure as irritating and annoying and An group as tiring and disturbing to hear. All parameters of hearing were worse in AN group in comparison with LFN one in whole range of frequency. The same trends were found in posturography. Contrary to results of Bourdone test. They were worse in LFN group.

The results of the study showed that audible noise is more hazardous than LFN, but LFN annoyed more. The results did not support thesis on vibroacoustic disease.

The study was founded by the National Center of Research and Development project II.B.09.

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Room Sound Field Analysis Using Integrated Multichannel Measurement System

Piechowicz Janusz, piechowi@agh.edu.pl
Pawlik Paweł, pawlik@agh.edu.pl

AGH University od Science and Technology
Department of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

A number of research or diagnostic problems of the vibroacoustics puts requirements for many synchronous acquisition of measurement data resulting from the distribution of sound field parameters studied objects around or inside, in the investigated objects. The authors have built an integrated multichannel measuring system that allows synchronous recording of acoustic signals. Analysis of the sound field was performed from data recorded by microphone line in order to extract some information about the parameters of the sound field in the room. The results were processed further calculations, can be used to visualize the distribution of sound pressure in a enclosed area.

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Urban Noise Annoyance Between 2001 and 2013 – Study in a Romanian City

Popescu Diana Ioana, Diana.Popescu@mep.utcluj.ro
Moholea Iuliana Fabiola, Morariu-Gligor Radu Mircea

Technical University of Cluj-Napoca
Faculty of Machine Building
B-dul Muncii 103-105, 400641 Cluj–Napoca, Romania

The paper presents results of three socio-acoustical surveys conducted in an interval of twelve years, between 2001 and 2013, in a large Romanian city, Cluj-Napoca. The purpose of the surveys was to assess the awareness of residents on urban noise and the extent to which the noise environment affects their everyday life, behavior and health. The surveys were conducted in 2001, 2009 and 2013. The questionnaire used in the first survey had 16 questions and it was verified prior to study through a pilot survey, being corrected and improved. For the second and the third study, the questionnaire was enriched with eight more questions, regarding essentially the description of the residential area, criteria for its selection and also awareness about the noise map of the city. The analysis of responses defines the main characteristics of the local pattern of annoyance and reaction of the urban population to the environmental noise.

Keywords: noise annoyance, urban noise, socio-acoustic survey.

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The Calculation Model for Predicting Unknown Values of Partial Indices in the Index Method for Acoustic Evaluation of Classrooms

Radosz Jan, jarad@ciop.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

One of the possibilities to make a comprehensive assessment of the acoustic quality of classrooms is the index method. It involves the determination of global index based on partial indices, which take into account in assessing the speech comprehension, external noise (including background noise during classes), voice effort of teachers and the comfort of teaching and learning. Due to the complexity and cost of measurement instrumentation it is a difficult task to take into account in assessment all the parameters of the index method. For this reason, it was necessary to develop methods for assessing the classroom acoustic quality at incomplete information. The paper presents calculation model based on the use of the most informative singular values taken from SVD (Singular Value Decomposition) decomposition and Repeated Matrix Reconstruction algorithm. Relative prediction errors of global indices do not exceed 4.7% for individual rooms. The developed calculation model was compared with the regression model. The simulation results show more accurate prediction using the presented calculation model.

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Aircraft Noise Evaluation Criteria for Determining Airborn Sound Insulation of External Walls of Buildings

Rudno-Rudzińska Barbara, barbara.rudno-rudzinska@pwr.wroc.pl

Wrocław University of Technology
Institute of Telecommunication and Acoustics
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The paper presents the results of research carried out in connection with the revision of standard PN-B-02151-3:1999 "Building acoustics. Protection against noise in buildings", in its part devoted to the way of determining the required sound insulation of the external walls against aircraft noise. A survey of the standards effective in selected European countries, the legal acts and regulations being in force in the EU and the state of knowledge concerning the adverse effects of night-time aircraft noise was carried out. The results of all the studies indicate a need for the use of a complementary noise index such as maximum noise level $L_{A\,\max}$. The recommended values of LAmax can be found in the WHO reports. The permissible number of aircrfat events with permissible $L_{A\,\max}$ remains an open question.

In order to determine the domestic conditions the data from the noise monitoring at two domestic airports were analyzed. The aim of the analysis was to determine the relationship between aicraft noise events parameters L_{AE} and $L_{A\,\max}$, as well as the the range of the values.

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Localization of Areas of Increased Vibroactivity by Means of the Inverse Method

Smagowska Bożena, bosma@ciop.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

The paper consists of study results of exposure to high frequency noise at metalworking workplaces. The study was carried out using objective methods (measurements of parameters characterizing noise) and subjective studies (questionnaire survey). Metalworking workplaces were located in a steel structure (e.g. deck gratings) manufacturing plant. The results of equivalent sound pressure level in 1/3 octave frequency bands with the

center frequencies from 10 kHz to 40 kHz, in reference to an 8-hour workday equal to approximately 81–105 dB on most of the tested workplaces and exceed permissible values. Questionnaire survey of annoyance high frequency noise (i.e. in the audible frequency range and low ultrasound) was conducted among 52 operators of machines. Most of the workers describe the noise as: buzzing, insistent, whistling and high-pitched squeaky. Respondents specific the noise levels occurring at workplaces as: loud, impeding communication, highly strenuous and tiring.

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Diminuation of the Reverberation Time in a Multi-Purpose Hall

Stan Mariana Cristina[(1)], sonobel_ms3@yahoo.co.uk
Anghel Luminita[(2)], luminitanghel@gmail.com

[(1)] Spiru Haret University Bucharest
Faculty of Architecture
13, Ion Ghica str, Bucharest, Romania

[(2)] Technical University of Civil Engineering
122-124, Lacul Tei av., Bucharest, Romania

The hall is part of a residential center for children and adolescents.

Although it was designed for sports, hall is also used for theater, concerts etc.

Because the architectural design not included acoustic treatments, it was necessary to further the development of measures to reduce the reverberation time.

Acoustic treatments were chosen so that their sound absorption coefficients allow obtaining more uniform reverberation time in the frequency range 125 ... 4000 Hz.

On the other hand, absorbing treatments lead to noise reduction through sound absorption.

This paper presents various solutions to reduce the reverberation time and results obtained by their application.

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The Study of Behavior of Vibrating Systems Controllable by Devices with Rheological Fluid

Szary Marek L., szary@engr.siu.edu
Weber Peter

Southern Illinois University
Department of Mechanical Engineering and Energy Processes
1230 Lincoln Drive, Carbondale Illinois 62901-6603 USA

The nonlinear mathematical model of behavior of controllable viscosity fluid (CVF) under applied external field is presented. A large family of these fluids is commonly used to control responding forces of dampers in vibration control applications. The responding force of a damper with CVF has two components. The first one – uncontrollable – is proportional to the viscosity of a base fluid and velocity of its motion, the second one, which is controllable, depends on the strength of the applied external field. Both are involved in the process of dissipation of unwanted energy from the vibrating systems. An equivalent damping factor based on the principle of energy dissipated during one cycle of damper work under a constant strength external field was calculated. When mass or stiffness is variable the equivalent damping factor can be set accordingly by adjusting the strength of external field to have vibrating damped system purposely/continuously working in the critical or other chosen state. This paper also presents cases of applying periodically changing strengths of an external field synchronized with cycles of periodical motion of the vibrating system to continuously control the damping force within each cycle.

Keywords: noise control, vibration control, smart materials, rheological fluids.

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Creating Dynamic Maps of Noise Threat Using PL-Grid Infrastructure

Szczodrak Maciej[(1), (2)], grid@sound.eti.pg.gda.pl
Kotus Józef[(1), (2)], Kostek Bożena[(1), (3)]
Czyżewski Andrzej[(2)]

[(1)] Academic Computer Center – TASK
Gdansk University of Technology

[(2)] Multimedia Systems Department
Gdansk University of Technology

[(3)] Audio Acoustics Laboratory
Gdansk University of Technology
Narutowicza 11/12, 80-233 Gdańsk, Poland

The paper presents functionality and operation results of a system for creating dynamic maps of acoustic noise employing the PL-Grid infrastructure extended with a distributed sensor network. The work presented provides a demonstration of the services being prepared within the PLGrid Plus project for measuring, modeling and rendering data related to noise level distribution in city agglomerations. Specific computational environments, the so-called domain grids, are developed in the mentioned project. For particular domain grids, specialized IT solutions are prepared, i.e. software implementation and hardware (infrastructure adaptation), dedicated for particular researcher groups demands, including acoustics (the domain grid "Acoustics"). The infrastructure and the software developed can be utilized mainly for research and education purposes, however it can also help in urban planning. The engineered software is intended for creating maps of noise threat for road, railways and industrial sources. Integration of the software services with the distributed sensor network enables automatic updating noise maps for a specific time period. The unique feature of the developed software is a possibility of evaluating auditory effects which are caused by the exposure to excessive noise. The estimation of auditory effects is based on calculated noise levels in a given exposure period. The outcomes of this research study are presented in a form of the cumulative noise dose and the characteristics of the temporary threshold shift.

Keywords: noise, dynamic noise map, reverse engineering, grid computing.

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Road Traffic Noise Attenuation by Vegetation Belts at Some Sites in the Tarai Region of India

Tyagi Vikrant[(1)]
Kumar Krishan[(2)], krishan_kumar@mail.jnu.ac.in
Jain Kumar Vinod[(2)]

[(1)] Ethiopian Civil Service College
P.Box No. 5648, Addis Ababa, Ethiopia

[(2)] Jawaharlal Nehru University
School of Environmental Sciences, New Delhi, India

Noise measurements have been carried out at eleven different sites located in three prominent cities of the Tarai region of India to evaluate the effectiveness of vegetation belts in reducing traffic noise along the roadsides. Attenuation per doubling of distance has been computed for each site and excess attenuation at different 1/3 octave frequencies has been estimated. The average excess attenuation is found to be approximately 15 dB over the over the low frequencies (200 Hz to 500 Hz) and between 15 dB to 20 dB over high frequencies (8 kHz to 12.5 kHz). Over the critical middle frequencies (1 kHz–4 kHz), the average excess attenuation (between 10 dB–15 dB) though not as high, is still significant with a number of sites showing an excess attenuation of 15 dB or more at 1 kHz. The results indicate that sufficiently dense vegetation belts along the roadsides may prove as effective noise barriers and significant attenuation may be achieved over the critical middle frequencies (1–4 kHz).

Keywords: noise, attenuation, traffic, frequency, vegetation belt, Tarai.

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Assessment of Ultrasonic Noise Hazard in Workplaces Environment

Śliwiński Antoni, fizas@univ.gda.pl

University of Gdańsk, Institute of Experimental Physics
Wita Stwosza 57, 80-952 Gdańsk, Poland

The hazard assessment of ultrasonic noise impact on human body at workplaces presents an open problem; it is not satisfactorily solved comparing the fund of knowledge and standard regulations established for the case of audible noise. Some research carried on in the Central Institute of Labour Protection – National Research Institute, Poland, are essential for elaboration reliable procedures for the assessment of ultrasonic noise hazard and they have to bring to modernization and creation the corresponding standards in this field. In the presentation, some problems related to measurement procedures applied as well as to the interpretation of results essential for hazard assessment of ultrasonic noise impact on human body will be considered; in particular such cases where some procedures elaborated for audible noise assessment are being transferred to apply in the ultrasonic range without taking fully into account some specific aspects of the high frequency components of the noise.

Keywords: ultrasonic noise hazard assessment, maximal acoustic level values distribution, technological ultrasonic devices.

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Experimental Acoustic Flow Analysis Inside a Section of an Acoustic Waveguide

Weyna Stefan, weyna@ps.pl
Mickiewicz Witold, Pyła Michał, Jabłoński Michał

Szczecin University of Technology
Applied Vibroacoustics Department
al. Piastów 41, 71-065 Szczecin, Poland

Noise propagation within ducts is of practical concern in many areas of industrial processes where a fluid has to be transported in piping systems. The paper presents experimental data and visualization of flow in the vicinity of an abrupt change in cross-section of a circular duct and on obstacles inside where the acoustic wave generates nonlinear separated flow and vortex fields.

For noise produced by flow wave of low Mach number, laminar and turbulent flows are studied using experimental sound intensity (SI) and laser particle image velocimetry (PIV) technique adopted to acoustics (A-PIV). The emphasis is put on the development and application of these methods for better understanding of noise generation inside the acoustic ducts with different cross-sections. The intensity distribution inside duct is produced by the action of the sum of modal pressures on the sum of modal particle velocities. However, acoustic field is extremely complicated because pressures in non-propagating (cut-off) modes cooperate with particle velocities in propagating modes, and *vice versa*. The discrete frequency sound is strongly influenced by the transmission of higher order modes in the duct. By understanding the mechanism of energy in the sound channels and pipes we can find the best solution to noise abatement technology.

In the paper, numerous methods of visualization illustrate the vortex flow as an acoustic velocity or sound intensity stream which can be presented graphically. Diffraction and scattering phenomena occurring inside and around the open-end of the acoustic duct are shown.

Keywords: sound intensity, laser anemometry, acoustics flow, sound visualization.

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The Soundscape Design. Factors Impacting the Spatial Orientation of Blind and Visually Impaired People

Wiciak Jerzy, jerzy.wiciak@agh.edu.pl

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

The term soundscape was proposed by R. Murray Schafer in 1977 as an auditory equivalence to landscape. It is defined as an environment of sounds – actual or abstract. In opposite to noise control soundscape approach treats sound as a resource rather than a waste. Its main applications focuses on managing urban public spaces in order to improve quality of life. Psychoacoustic experiments on the soundscapes shows that recognition of particular environments is based on identification of the physical sources and average recognition time for humans is about 20 s. According to (Dubois D., Guastavino C., Raimbault M., *A Cognitive Approach to Urban Soundscapes*, Acta Acustica united with Acustica, **92**, 6, 865–874, 2006, semantic data must be obtained as well as numerical estimators for the development of the categorization and quality labels.

Sound acting on human body stimulates certain parts of the brain. It's usually different for different types of said stimuli (visual, acoustic, tactile, etc.). But basically thanks to EEG, PET or/and MRI it can be said that we know which part of a person's brain will "lit up". There are several studies that incorporate EEG, PET or/and MRI to compare brain functions in sighted and blind persons during different types of auditory (or tactile for that matter) tasks.

Soundscape could be connected with visual impaired people in many ways. Sounds are key in blind people's spatial orientation. Without sounds blind person feel like normally sighted person in darkness. The role of sound could be compared with turning on the light.

Schafer in The Tuning of the World formalized the soundscape terminology. Background sounds were defined as "keynotes", foreground sounds which intended to attract attention as "sound signals" and sounds that were particularly regarded by a community and its visitors are called "soundmarks".

The paper presented attempt of classification of the acoustic signals that can be useful for spatial orientation. This classification was made based on Shafer's division. Data from a survey carried out in group of blind and partially people were used for analysis. In survey respondents were asked about sounds that can assist or disturb the spatial orientation and for negative impact of weather conditions on the perception of sounds in an urban environment.

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Controllability-Oriented Placement of Actuators for Active Noise-Vibration Control of Flexible Structures Using Memetic Algorithms

Wrona Stanisław, stanislaw.wrona@polsl.pl
Pawełczyk Marek, Marek.Pawelczyk@polsl.pl

Silesian University of Technology
Institute of Automatic Control
Akademicka 16, 44-100 Gliwice, Poland

For successful active control with a vibrating plate it is essential to appropriately place actuators. One of the most important criterion is to make the system controllable, so any control objectives can be achieved. In this paper the controllability-oriented placement of actuators is undertaken. First, a theoretical model of a fully clamped plate is obtained. Influence of actuator placement on the structure is considered. Optimization criterion based on maximization of controllability of the system is developed. Residual modes are taken into account to reduce a spillover effect. The memetic algorithm is used to find the optimal solution. Obtained results are compared with those obtained by the genetic algorithm. The configuration is also validated experimentally.

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Uncertainty of Acoustic Measurements Performed with Audio Analyzers

Wszołek Grażyna, grazyna.wszolek@agh.edu.pl

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
al. Mickiewicza 30, 30-059 Kraków, Poland

For some time the users of various types of sound measurement devices and speech transmission indicators (STI and STIPA) express an increased demand for metrological testing of their devices. In a number of cases the devices are rather cheap products that are supposed to substitute for dedicated devices that are inaccessible for the "economy-class" users, because of their price range. The calibration of such devices, conformant to the rules imposed on professional devices, is rather difficult if not impossible. In order to perform the testing properly it is necessary to elaborate individual testing methods for each device. The author of the present paper managed to elaborate a set of such methods. In the process she has used her knowledge concerning the essence of normative testing and the knowledge related to logic of functioning of these devices. She gained the experience in testing measuring devices during her long-time work in accredited calibration laboratory (AP 022).

The paper presents the basic technical, metrological and legal information, concerning the requirements imposed on sound level meters and the methods of their calibration. The paper also describes specific problems encountered during application of normalized methods to testing of audio devices. Exemplary results are also presented for calibration and testing of the following devices: ECM800 microphone by Behringer, AZ8921 meter by AZ Instrument and the NTI Audio XL2 and NTI Acoustilyzer AL1, audio and acoustic parameter analyzers by NTI Audio AG.

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Parameterization and Assessment of Curve and Brake Squeal from Train Approaching to the Station

Wszołek Tadeusz, tadeusz.wszolek@agh.edu.pl
Koter Marcin, mkoter24@gmail.com

AGH University of Science and Technology
Faculty of Mechanical Engineering and Robotics
al. Mickiewicza 30, 30-059 Kraków, Poland

The most important source of noise from railways at most speeds is rolling noise caused by wheel and rail vibrations induced at the wheel/rail contact. Rolling noise is fairly broadband in nature, the relative importance of higher frequency components increasing as the train speed increases. But the curve squeal is one the loudest and most disturbing noise sources from railways metros and tramways. It is also caused by interaction between wheel and rail but has a quite different character. It is strongly tonal noise occurring in sharp curves, being associated with vibration of the wheel in one of its resonances. It is also necessary to distinguish between squeal caused by lateral creepage, top of rail squeal as well as flange squeal. A similar phenomenon is brake squeal which is emitted during braking.

When the train commute to the station the two phenomena may be a source of great inconvenience to passengers and station staff. The experimental investigations of aforementioned noise squeals were performed when the train approaching into the platform. The results show increased noise ratios up to over ten dB, in addition to a high content of the tonal components with frequencies above 5 kHz. It was shown that the spectral moments of the noise can be an useful tool in automatic identification squealing noise in continuous monitoring systems.

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Simultaneous Exposure to Hand-Arm and Whole-Body Vibration at One-Track Vehicles Drivers Workstations

Zając Jacek, jazaj@ciop.pl, Kowalski Piotr, pikow@ciop.pl

Central Institute for Labour Protection
– National Research Institute
Czerniakowska 16, 00-701 Warszawa, Poland

The increasing traffic contributes to a greater interests in one-track vehicles. They require much less space both on the road and parking and allow for reach places inaccessible to other vehicles. The growing number of one-track vehicles in work environment (e.g. the police, emergency medicine, courier companies) also affects the increase in the number of workers exposed to vibration hazards associated with their use. The methods of measurement and evaluation of vibration on workers described in the European standards EN 14253 and EN ISO 5349 establish separate treatment of hand-arm vibration (HAV) and whole-body vibration (WBV). However, at one-track vehicles the risk of HAV and WBV coincides. The dose of vibroacoustic energy absorbed by the worker is greater larger when the impact of both kinds of vibration occurs simultaneously than when the worker is exposed to only one kind of vibration. The paper presents evaluation of simultaneous exposure to hand-arm and whole-body vibration for selected one-track vehicles drivers. The results show that the vibration hazards at these workstations may be significant.

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Assessment of Exposure to Excessive Sounds and Hearing Status in Students Enrolled in Academic Music Education

Zamojska Małgorzata, zamojska@imp.lodz.pl
Pawlaczyk-Łuszczyńska Małgorzata,
Dudarewicz Adam, Zaborowski Kamil

Nofer Institute of Occupational Medicine
Department of Physical Hazards
Św. Teresy 8, 91-348 Łódź, Poland

The overall aim of this study was to evaluate the hearing status, exposure to excessive sounds and the risk of noise-induced hearing loss (NIHL) in college music students.

A pilot study, including questionnaire inquiry and sound pressure level (SPL) measurements, was carried out in 35 students. From these data, the risk of noise-induced hearing loss (NIHL) was assessed according to ISO 1999:1990.

It was found that college music students were exposed to excessive sounds at the A-weighted equivalent-continuous SPL of 81–99 dB for 2.5–44.0 hours per week (mean: 21.3 ± 13.8 hours per week). The highest SPLs were observed among percussion, trumpet, trombone, saxophone, horn and flute players.

Such exposures for 5 years of academic education are associated with the risk of hearing impairment (expressed as mean hearing threshold level for 2, 3 and 4 kHz equal to or greater than 25 dB) in the range of 0–46%. The highest risk is related to playing percussion section (up to 46%), saxophone (up to 16%), trumpet (up to 15%), trombone (up to 14%) and bassoon (up to 7%).

About 37% of students noticed hearing impairment, including difficulty in speech intelligibility in noisy environment (51%). Nearly every tenth of respondent complained of tinnitus, while 29% of them reported hyperacusis. Only a few students declared usage of hearing protectors, while 31% of them – listening to music via mp3. Thus, the results confirm the need of further studies and development of hearing conservation program for college student musicians.

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Low Frequency Noise and Its Assessment and Evaluation

Žiaran Stanislav, stanislav.ziaran@stuba.sk

Slovak University of Technology in Bratislava
Faculty of Mechanical Engineering
Nam. slobody 17, 812 31 Bratislava, Slovak Republic

The main aim of this paper is to present recent knowledge about the assessment and evaluation of low frequency noise and infrasound close to the threshold of hearing and the potential effects on human health. Low frequency noise generated by air flowing over a moving car with the open window is chosen as a source of noise. The noise within the interior of the car and its effects on a driver's comfort at different velocities is analyzed. An open window at high velocity behaves as a source of specifically strong tonal low frequency noise which is annoying. The interior noise of a passenger car was measured under different conditions; while driving on normal highway and roadways. First, an octave-band analysis was used to assess the noise level and its impact on the driver's comfort. Second, a *Fast Fourier Transform* (FFT) analysis was used for the detection of tonal low frequency noise. Finally, the paper suggests possibilities for scientifically assessing and evaluating low frequency noise but not only for the presented source of the sound.

Keywords: low frequency sound, human being, health, evaluation.

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Chronicle

15th International Symposium on Sound Engineering and Tonmeistering ISSET 2013

Cracow, Poland, June 27–29, 2013

The 15th International Symposium on Sound Engineering and Tonmeistering will be held on June 27–29 in Cracow. The Symposium is organised by the Department of Mechanics and Vibroacoustics, AGH University of Science and Technology, under the auspices of the Polish Section of the Audio Engineering Society. The Symposium is held biannually. The organisers invite representatives of the academic community, sound engineers, music producers and representatives of the audio industry.

The scope of the Symposium covers a broad range of topics related to sound engineering, from audio production through perception. Twenty five submissions have been accepted.

The programme of the Symposium includes lecture sessions and workshops, two student competitions, two meetings with founders of Polish companies which gained international success, and a unique theatre play.

Abstracts

Microphone Crosstalk Cancellation – the Comparison of Two Original Methods

Barański Robert, robertb@agh.edu.pl
Kleczkowski Piotr, kleczkow@agh.edu.pl

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
Adama Mickiewicza 30, 30-059 Kraków, Poland

Two original algorithms for cancellation of microphone crosstalk are presented and compared. Both algorithms are based on time-frequency signal decomposition. The first method makes use of selective mixing of sounds. An utmost version of this technique is used, consisting in removal of any spectro-temporal overlap between sound sources. The other consists in filtering with the application of the wavelet transform. The latter method has been developed specifically for cancellation of crosstalk in the recording of percussive instruments. With this method, patterns of individual percussive instruments are generated and then the recorded signal is compared with the patterns. Both methods were applied to the same excerpt of drums recording. Subjective evaluation according to several criteria was carried out.

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Using Everyday Objects as Sound Sources in Live Electronics

Błażejczyk Wojciech, wojciech@blazejczyk.eu

The Fryderyk Chopin University of Music
Okólnik 2, 00-368 Warszawa, Poland

This paper presents the possibilities of using everyday objects as sound sources processed live in MAX/MSP environment. In electroacoustic music live electronics is usually regarded as processing of acoustic instruments sound or controlling synthesizers and samplers. It is proposed to replace them with properly selected objects, stimulated to vibrate traditionally (tapping, rubbing) or in a special way (rubbing with bow or super ball), amplified with contact microphones. Sound processing consist of granulation, spectral modeling, transposition and time stretching. The result is the creation of a new musical instrument, consisting of the physical part (object) and virtual part (DSP), with vast expression possibilities.

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The Objectives and Sound Engineering Measures at the Creation of the Acoustic Speech Balance of Acting in the Sonic Image of the Radio Play Script. Selected Issues

Brzoska Andrzej, andrzej.brzoska@polskieradio.pl

Polskie Radio SA
Al. Niepodległości 77/85, 00-977 Warszawa, Poland

One of the most important measures of expression in the radio play is the human voice. The voice sounds can also carry some further information necessary to materializing imagination about special relationships in the sonic image for the listeners.

Creation acoustic speech balance of acting during recording session with the actors is a very important means of sound engineering referring to specified images and associations in the imagination of the radio play listeners.

A different strategy of recording the actors voices determines picture in the audiovisual media work e.g. film. The real message from picture clearly organizes the spatial relationships between characters in the scene.

The paper is discussed a range of issues including the creation of the acoustic speech balance in the radio play with the use of sound engineering and acting techniques.

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Young People Hearing Losses Affected by Listening to the Music on Headphones

Dobrucki Andrzej, andrzej.dobrucki@pwr.wroc.pl
Kin Maurycy J., maurycy.kin@pwr.wroc.pl
Kruk Bartłomiej, bartlomiej.kruk@pwr.wroc.pl

Wrocław University of Technology
Faculty of Electronics, Chair of Acoustics
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The main aim of the work was to find an influence of type of headphones (closed, semi-open, open and in-ear) used by young people for hearing of music on the threshold of hearing. The results of hearing loss measurement provided for over that 80 young people (from 16 to 25 yers old). The greatest hearing losses were observed for the people who work as sound reinforcement engineers and, moreover, no influence of headphones type was found for them. It turned out that the use of in-ear headphones causes the greatest hearing losses for other people (thresholds shifted up to about 20 dB at 4 kHz). The daily time of a listening also affected hearing thresholds and it was found that for users of in-ear and close headphones, an average time of musical exposure was of three hours and it causes the hearing loss of 10–15 dB at higher frequencies. The use of open as well as semi-open headphones has no influence on hearing damage and it would be stated that these kinds are safety in use. Almost 15% of investigated young people have their thresholds shifted up at higher frequencies.

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Pitch Perception for Mixtures of Harmonic Complex Tones Before and After the Operation of Selective Summing

Dziedzic Tomasz, dziedzic@student.agh.edu.pl
Kleczkowski Piotr, kleczkow@agh.edu.pl

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
Adama Mickiewicza 30, 30-059 Kraków, Poland

Micheyl *et al.* (2010) measured pitch perception of spectrally overlapping harmonic complex tones (HCTs). One of the issues investigated in that study was the impact of a masker HCT on the pitch perception of another, target HCT. In this paper the experiment of Micheyl *et al.* was replicated in some of their conditions, but both of the HCTs were mixed using the operation of selective summing, consisting in the removal of any spectrotemporal overlap between sounds. During the tests the procedures by Micheyl et al. were repeated twice - with and without the operation of selective summing.

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An Approach for Automatic Audio Event Recognition Using SVM in Terms of Threat Detection

Glowacz Andrzej
Altman Grzegorz, grzesiek-altman@o2.pl

AGH University of Science and Technology
Department of Telecommunications
Adama Mickiewicza 30, 30-059 Kraków, Poland

Audio events analysis, processing and classification is an important part of modern surveillance and monitoring systems. The subject of this research is detection and classification of threatening sounds representing dangerous events that can occur in real-world, urban environment. These issues differ from speech-recognition systems mainly because of the signal frequency characteristic, duration, variety and noise content. In this paper we propose an algorithm based on the Support Vector Machine and Mel-Frequency Cepstral Coefficients with the decision-making system and show that it performs well in comparison to more computationally complex systems.

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Temporary Threshold Shift Phenomenon vs. Recording Activity

Kamińska Magdalena, magdalena.kaminska@aes.pwr.wroc.pl
Kruk Bartłomiej, bartlomiej.kruk@pwr.wroc.pl
Kin Maurycy J., maurycy.kin@pwr.wroc.pl

Wrocław University of Technology
Institute of Telecommunications and Acoustics
Janiszewskiego 7/9, 50-372 Wrocław, Poland

For the efficient work in recording studios it is to necessary to avoid continuous exposure to loud sounds and thus take regular breaks. This is the key to keep fresh ears and a fresh perspective in created music. The main aim of this paper is to provide information and explanation of Temporary Threshold Shift phenomena to understand basic principles and to help understand how to work more effectively and efficiently in the recording studio. The paper presents results of TTS measurement provided over than 30 recording engineers.

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Britten Culshaw

Kubera Maciej, mackub@interia.pl

The Fryderyk Chopin University of Music
Okólnik 2, 00-368 Warszawa, Poland

The paper concerns a very important issue of music recording history and aesthetics – cooperation of a famous composer with an ambitious recording producer at the beginning of the stereophonic era. Benjamin Britten and John Culshaw worked together on the recordings of War Requiem, The Burning Fiery Furnace and other Britten compositions. The recordings are brilliant examples of how the sound engineer can build a “theater” between the loudspeakers or even achieve some effects, which were impossible in a traditional opera house and how he finds the way from the techniques to the aesthetics.

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Time-Domain Analysis of Sigma-Delta Audio DAC

Lewandowski Marcin, Marcin.Lewandowski@ire.pw.edu.pl

Warsaw University of Technology
Institute of Radioelectronics
Nowowiejska 15/19, 00-665 Warszawa, Poland

Nowadays, sigma-delta ($\Sigma\Delta$) audio analog-to-digital and digital-to-analog converters (ADC and DAC) are commonly used in both consumer and professional audio equipment. The ADC and DAC conversion parameters depend mainly on features of digital $\Sigma\Delta$ modulators. While frequency-domain and statistical-domain analyses of $\Sigma\Delta$ modulators' parameters exist in literature there is a lack of rigorous analysis in time domain especially when input to the modulator is a real world audio signal. The paper introduces a new approach to time-domain analysis of non-stationary audio signals at the output of sigma-delta ($\Sigma\Delta$) audio DAC.

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Efficiency of Automatic Online Music Recognition on the Internet

Mahboob Mieszko[(1)], mieszko@mahboob.pl
Żera Jan[(2)], j.zera@ire.pw.edu.pl

[(1)] The Fryderyk Chopin University of Music
Okólnik 2, 00-368 Warszawa, Poland

[(2)] Warsaw University of Technology
Institute of Radioelectronics
Nowowiejska 15/19, 00-665 Warszawa, Poland

Performance of the SoundHound application, designed to identify songs by singing/humming melody (Query by Humming, QbH), has been examined in the experiments. Assessment

was conducted by recognition of 256 music samples representing 64 tracks of popular music. Tests measured the effects of selecting of male or female voice, detuning from the original key, interfering presence of background noise, and the duration of audio sample on the percent correct recognition. Results indicated that tested QbH application demonstrated the overall 80% correct music sample recognition, with little influence of voice type and detuning, which is sufficient for practical use by Internet users.

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Multi-Channel Auralization

Małecki Paweł, pawel.malecki@agh.edu.pl
Wierzbicki Jacek

AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
Adama Mickiewicza 30, 30-059 Kraków, Poland

One of the main problems in both the interior acoustics and environmental acoustics is determination of the directions of approach of acoustic waves. That information might be used to locate the source of sound and to indicate the areas where the acoustic adaptation should be used. With the development of devices that allow recording of the spatial sound, it is also possible to reproduce it with use of multi-speaker systems and auditive analysis of the acoustic field performed in other time and place than the record. The article presents the comparison of currently used auralisation methods such as the binaural techniques, ambisonic and wave field synthesis. The methods were applied to define the accuracy of location of the sound source. The main aim of the performed research is development of the complete system for recording, processing and reproduction of the spatial sound.

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Perception of Irregularity in the Musical Rhythm

Plaskota Przemysław, przemyslaw.plaskota@pwr.wroc.pl

Wrocław University of Technology
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The perception of musical rhythm is an issue that is relevant to the sound recordings. Because the rhythm is one of the main elements of a musical work, for the sound engineer important information is how much can be irregularity in the musical rhythm, that they are not perceived by the listener. This is particularly important for setting the parameters of automatic smoothing algorithms rhythm.

The paper presents a study of perception threshold of irregular changes in the musical rhythm. The analysis was performed using a soundtrack containing sounds with different spectrum. It was also examined the dependence of the threshold on the localization of change relative to the rhythmic structure.

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Linearization of Ear Transmission Characteristics with the Usage of Low Level Ultrasonic Noise Applied to Patients Suffering from Tinnitus

Poremski Tomasz, tomasz.poremski@geers.pl

Gdansk University of Technology
Faculty of Electronics, Telecommunications and Informatics
Multimedia Systems Department
Narutowicza 11/12, 80-233 Gdańsk, Poland

GEERS Hearing Acoustics
Training and Development Department
Narutowicza 130, 90-146 Łódź, Poland

In this work tinnitus, an otological problem, along with hypotheses of its causes as well as the methods used in its therapy are briefly reviewed.

Additionally, one of the theory referring to generation of tinnitus, based on mechanisms of signal quantization is recalled. A research study conducted with patients who suffer from tinnitus is shortly described. The linearization mechanism employing low levels ultrasonic noise is used while conducting the patients' examination. As a result of the study performed, it is concluded that utilizing ultrasonic noise can be beneficial for some patients to weaken the tinnitus felt. Also a detailed discussion on obtained results and conclusions are included.

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The Application of Sound Synthesis in Determining the Characteristics of Subjective Tinnitus

Poremski Tomasz(1), (2), tomasz.poremski@geers.pl
Kotus Józef(1), joseph@sound.eti.pg.gda.pl
Odya Piotr(1), piotr.odya@eti.pg.gda.pl
Suchomski Piotr(1), pietka@sound.eti.pg.gda.pl
Kostek Bożena(1), bokostek@audioakustyka.org
Czyżewski Andrzej(1)

(1) Gdansk University of Technology
Narutowicza 11/12, 80-233 Gdańsk, Poland

(1) GEERS Hearing Acoustics
Training and Development Department
Narutowicza 130, 90-146 Łódź, Poland

In this paper the sound synthesizer dedicated to measurement of psychoacoustic parameters of tinnitus is described. First, definition of tinnitus, a set of procedures and tests, which are used to estimate it as well as the criteria of evaluating the tinnitus are described. Then, a synthesizer developed at the Multimedia Systems Department, Gdansk University of Technology is shortly presented along with an illustration of the user interface. In a study performed with patients suffering from tinnitus the effectiveness of the synthesizer is evaluated. A comparison between results related to duration of the conducted test and subjective evaluation of resemblance of patient's tinnitus sound pattern obtained utilizing the synthesizer and the clinical audiometer is given. Resulted from tests it is a conclusion that employing the synthesizer shortens the duration of tinnitus examination. Moreover the subjective evaluation of tinnitus sound type with the synthesizer is reported by patients as more similar to the tinnitus felt.

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Technical and Artistic Aspects of Bass Guitar Recordings

Przygodziński Łukasz
Bobiński Piotr

Warsaw University of Technology
Institute of Radioelectronics, Electroacoustic Division
Nowowiejska 15/19, 00-665 Warszawa, Poland

An overview of past and present recording methods and ways of balancing bass tracks are discussed in context of a role of bass guitar in various music styles and basic techniques of playing. Experiments included listening tests of bass tracks recorded with the use of condenser and dynamic microphones of different directional patterns and listening tests of complete multitrack alignments obtained with the use of different mixing techniques, frequency equalization, and dynamic range compression. Outcomes of this work may be used in recording processes intended to achieve special artistic effects, and can be helpful in classes for students of sound engineering.

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Recognition of Harmonic Intervals

Rogala Tomira, tomira@chopin.edu.pl

The Fryderyk Chopin University of Music
Okólnik 2, 00-368 Warszawa, Poland

The experiment was carried out to determine the influence of pitch register and sound duration on the recognition of musical intervals composed of two simultaneous pure tones. Sixteen musicians were asked to recognize 13 within-octave intervals in 18 conditions (3 registers × 6 tone durations). Results showed that recognition was much worse in the lowest than in the other pitch registers and decreased when the sounds were shortened in all registers. The differences in the accuracy of interval recognition correspond to the changes in the pitch strength.

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Audibility of Lossy Compression in Musical Recordings

Rogowska Agata, a.rogowska@ire.pw.edu.pl
Żera Jan, j.zera@ire.pw.edu.pl

Warsaw University of Technology
Institute of Radioelectronics
Nowowiejska 15/19, 00-665 Warszawa, Poland

Audibility of lossy compression produced by four codecs, Ogg, WMA, Mp3 (Fraunhofer) and Mp3 (Lame), in samples of classical and popular music was studied on naive and experienced subjects in quiet and in the presence of noise. At bit rates of 32 and 48 kbps compressed signal was easily discriminable with significant intersubject differences. Compression became inaudible at bit rates of 80–96 kbps. Experienced subjects demonstrated higher ability to discriminate compressed music than naive subjects, by about 16 kbps. The presence of noise had limited influence on discrimination at signal-to-noise ratios within the range of +4 to +16 dB.

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Vowel-Like Quality of Formant Noise

Rościszewska Teresa, tyska@chopin.edu.pl

The Fryderyk Chopin University of Music
Okólnik 2, 00-368 Warszawa, Poland

The purpose of the study was to determine the frequency ranges within which a single formant imposed over the spectrum of pink noise produces a quality of sound resembling Polish vowels. Fifteen subjects were required to assign a vowel category to noise bursts with a formant introduced in a band centered at one of 65 frequencies within a range of 198–8000 Hz. Results show that the vowel-like quality of sound produced by a single formant is most pronounced in the case of vowels /u/, /ɔ/, /a/ and /i/, whereas associations with vowels /ɛ/ and /ɨ/ are less distinct.

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Evaluation of Virtual Bass Performance in Mobile Device

Sanner Tomasz, sanner@sound.eti.pg.gda.pl
Łopatka Kuba
Czyżewski Andrzej

Gdańsk University of Technology
Gabriela Narutowicza 11/13, 80-233 Gdańsk, Poland

An experiment conducted to validate possibility of use virtual bass synthesis (VBS) algorithm in a portable computer is presented. The listening tests based on the procedure of pairwise comparison between VBS and standard bass boost technique are employed. The evaluation was carried out in two types of conditions: in a professional listening room and employing an ultrabook to play back the sounds. As is indicated by the results, the proposed technique proved the possibility of rendering bass-related components in audio signals in a better way than the standard bass boost technique.

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Live Electroacoustic Mix Based on "Combitaper" Application

Wilczyński Tomasz J.[(1)], twilczyn@agh.edu.pl
Bień Mateusz[(2)], Kosecka Martyna[(2)]
Żywiec Michał[(1)], Kleczkowski Piotr[(1)]

[(1)] AGH University of Science and Technology
Department of Mechanics and Vibroacoustics
Adama Mickiewicza 30, 30-059 Kraków, Poland

[(1)] Academy of Music
Institute of Composition, Conducting and Music Theory
Św. Tomasza 43, 31-027 Kraków, Poland

Combitaper is a software application inspired by classical tape delay. It was designed to allow simultaneous recording, mixing and reproduction of an acoustic signal. Software consists of two types of modules. First type – the buffer – is responsible for recording, optimization and storage of sound samples and short musical phrases (up to 4 seconds). The other one, called taper, deals with multiple repetitions of sounds and their processing. Such a system allows to perform live a musical composition consisting of sound samples which were prepared earlier or recorded during a performance. An advantage of Combitaper over other applications is the capability to work in the quadraphonic configuration. Four speakers placed on tops of the deltoid provide a highly realistic spatial sound, with the precision of localization in the horizontal plane of 7.5°. The Combitaper can be controlled from the PC keyboard or any MIDI controller.

Otwarte Seminarium z Akustyki 2013

Rzeszów - Polańczyk, 9-13.09.2013

60th Open Seminar on Acoustics

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AIMS AND SCOPE

Archives of Acoustics, the peer-reviewed quarterly journal publishes original research papers from all areas of acoustics like:

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2. The title of the paper should be as short as possible.
3. Full names and surnames should be given.
4. The full postal address of each affiliation, including the country name should be provided. Affiliations should contain the full postal address, as well as an e-mail address of one author designated as corresponding author.
5. The text should be preceded by a concise abstract (less than 200 words).
6. Keywords should be given. It is also desirable to include a list of notations.
7. The formulae to be numbered are those referred to in the paper, as well as the final formulae. The formula number should be written on the right-hand side of the formula in round brackets.
8. All notations should be written very distinctly.
9. Vectors should be denoted by semi-bold type. Trigonometric functions are denoted by sin, cos, tan and cot, inverse trigonometric functions – by arcsin, arccos, arctan and arccot; hyperbolic functions are denoted by sinh, cosh, tanh and coth.
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Instructions for citation and bibliographic references

References in the text (author(s) and year of publication) are to be cited between parentheses.

1. Direct quotations should be between quotation marks.

2. Indirect quotations (i.e. when the author's idea is explained but not directly quoted) do not use quotation marks or italics.

Examples:

a. The research of mufflers was started by Davis (1954).

b. To increase the muffler's acoustical performance, the assessment of a new acoustical element – a reverse-flow mechanism with double internal perforated tubes – was proposed and investigated by this author (Munjal, 1987),

3. When an author or group of authors has more than one publication in the same year a lower case letter is added to the date.

Example:

In two recent studies (Rakowski, 1993a; 1993b) it was suggested that…

4. Multiple author citation:

a. Two authors: both names should be listed in each citation.

Example: (Rakowski, Miyazaki, 2007)

b. Three or more authors: use the first author's name and "*et al.*"

Example: (Dobrucki *et al.*, 2005)

5. To cite a document produced by an organization, the first time write out the name of the organization in full and give the acronym or abbreviation in square brackets. For subsequent references you may use the acronym or abbreviation.

Example:

First time: Sanitary politics (United Nations High Commissioner for Refugees [UNHCR], 2006, p. 35)…

Then: Established politics (UNHCR, 2006, p. 45)…

In the reference list write the full name of the organization.

6. When a source has no identified author, cite the first two or three words of the title (in italics if it is a book, between quotation marks if it is an article) followed by the year and the page.

Examples:

In the recent book (Encyclopedia of Physics, 1993, p. 164)…

In the article ("The relation of pitch …", 1979, p. 67) it is held that…

The in-text reference should match the start of the reference in the bibliography/reference list.

7. Using quotations in the text may also be as it is shown in the following examples:

Examples:

a. "Field measurements of bistatic scattering strength (BSSS) are difficult and expensive to acquire at sea, in real conditions." (Blondel, Pace, 2009, p. 101)

b. Blondel and Pace (2009) held that "field measurements of bistatic scattering strength (BSSS) are difficult and expensive to acquire at sea, in real conditions" (pp. 101)

8. To cite a work that was discovered in another work, observe the following examples:

a. Brown (1967), cited by Smith (1970, p. 27), found…

b. It was found (Brown, 1967, cited by Smith, 1970, p. 27) that…

9. To cite e-mail messages:

If necessary, cite them within the body of the text as a personal communication.

Example:

a. …and this point was conceded (S. Weyna, personal communication, August 22, 2001), ...

Presenting bibliography/reference list

General matters

a. Reference list should be arranged alphabetically by author surname. Put all the entries in one long alphabetical list. Do not list books, journal articles, websites, etc. en in separate sections. Number them from 1 to n.

Example:

1.
2.
3.

b. When an author or group of authors has more than one publication in the same year a lower case letter is added to the date. This letters will be used when citing this source in the text.

Example:

Zou D., Crocker M.J (2009a), *Response of a plate to PZT actuators*, Archives of Acoustics, **34**, 1, 13–23.
Zou D., Crocker M.J (2009b), *Sound power radiated from rectangular plates*, Archives of Acoustics, **34**, 1, 25–39.

c. Book, encyclopedia and article titles should be italicized.

1. Books

Author, initials (year), *Title of the book* [language of publication – if other than English], Edition, if later than the first, Publisher, Place of publication.

Examples:

a. American Psychological Association (2001), *Publication manual of the American Psychological Association*, 5th Ed., Washington D.C. [Author].
b. *Encyclopedia of Physics* (1993), 2nd edition, McGraw-Hill, New York.
c. Varshneya A. (1944), *Fundamentals of inorganic glasses*, p. 111, Academic Press, New York.
d. Moore M.H., Estrich S., McGillis D., Spelman W. (1984), *Dangerous offenders: the elusive target of justice*, Harvard University Press, Cambridge.
e. Strunk W., White E.B. (1979), *The elements of style*, 3rd Ed., Macmillan, New York.
f. Engel Z., Piechowicz J., Stryczniewicz L. (2003), *The fundaments of industrial vibroacustics* [in Polish], WIMIR AGH, Kraków.
g. Nowicki A. (1995), *Basics of Doppler Ultrasonography*, [in Polish:] *Podstawy ultrasonografii dopplerowskiej*, PWN, Warszawa.

List up to six (6) authors. If there are seven (7) or more, list the surname and initials of the first one and then “et al.”

2. Edited book

Editor, initials (Ed.), (year), Title of the book, Edition if later than the first one, Volumes if there are more than one, Publisher, Place of publication.

Examples:

a. Crocker M.J. [Ed.], (2007), *Handbook of Noise and Vibration Control*, John Wiley & Sons, Inc., New York.
b. Klinke R., Hartman R. [Eds.], (1983), *Hearing – physiological bases and psychophysics*, Springer, Berlin, Heidelberg, New York, Tokyo.

3. Chapter in edited book

Author of chapter, initials (year), *Title of chapter*, [in:] *Title of the book*, Name of the Editor/s Initials [Ed.], pp. start and end of chapter page numbers, Publisher, Place of publication.

Example:

a. Rakowski A. (1991), *Context-dependent intonation variants*, [in:] *Music, language, speech and brain*, Sundberg J., Nord L., Carlson R. [Eds.], pp. 203–211, MacMillan Press, London.
b. Berlincourt D.A., Curran D.R., Jaffe H. (1964), *Piezoelectric and Piezomagnetic Materials and Their Function in Transducers*, [in:] Physical Acoustic, Mason W.P. [Ed.], vol. 1, part. A, pp. 169–270, Academic Press, New York.

4. Journal article

Author, initials (year), *Title of the article* [language of publication – if other than English], Title of the journal, Volume number(bold face), issue number, start and end page numbers of article.

Write directly page numbers (not preceded by p. or pp.),

Examples:

a. Houtsma A. (2007), *Experiments on pitch perception: Implications for music and other processes*, Archives of Acoustics, **32**, 475–490.
b. Sęk A., Moore B. C. J. (1995), *Frequency discrimination as a function of frequency, measured in several ways*, Journal of the Acoustical Society of America, **97**, 2479–2486.
c. Ranachowski P., Rejmund F., Pawełek A., Piątkowski A. (2005), *Studies of cordierite material under compressive load at different temperatures and after thermal shock* [in Polish], Ceramics, **89**, 101–115.

5. Conference paper in published proceedings

Example:

a. Rakowski A., Miśkiewicz A. (2002), *Pitch discrimination of low-frequency tones*, Proceedings of 7th International Conference on Music Perception and Cognition , pp. 538–540, Sydney.

6. Dissertations in congresses and meetings (unpublished)

Example:

a. Tucker S. (2003) , *An ecological approach to the classification of transient underwater acoustic events: perceptual experiments and auditory models*, Ph.D. Thesis, Department of Computer Science, University of Sheffield.
b. Salamon R. (2009), *Contemporary military sonar system*, Dissertation presented during the 56th Open Seminar on Acoustics, OSA 2009, Goniądz, Poland.

7. Electronic sources

Author, initials (year), *Title*, Retrieved month, day, year, from Internet adress.

If no date is shown on the document, authors should use n.d. (no date)

If the author is not given, authors should begin the reference with the title of the document.

If a document is part of a large site such as a university or a government department's website, give the name of the parent organization and the relevant department before the web address.

Examples:

a. Cox T. (n.d.), *Sound quality*, from www.acoustics.salford.ac.uk/res/cox/sound_quality/
b. Deciding your future (2000), Retrieved September 5th, 2001, from University of Portsmouth, Careers Service: www.port.ac.uk/departments/careers/plancareer/deciding-your-future.htm
c. Alexander J., Tate M.A. (2001), *Evaluating web resources*, Retrieved August 21st, 2001, from Widener University, Wolfgram Memorial Library: www2.widener.edu/Wolfgram-Memorial-Library/webevaluation/webeval.htm

Authors should not write the web address (URL) within the text of the paper, it should appear only in the reference list/bibliography. To cite this source within the text they should use the author's name (if the reference has one) or the first few words of the website title.

8. Audiovisual sources: music

Author, initials (Date of copyright), *Title of the song*. On Title of the album [medium of recording], Location: Label (Recording date if different from copyright date)

Example:

a. Puccini G. (1990), *Nessun dorma*, On Carreras Domingo Pavarotti in concert [CD], Decca, London.