PAN
ARCHIVES OF ACOUSTICS
Vol. **38**, No. 2, pp. 243–252 (2013)

DOI: 10.2478/aoa-2013-0029

Assessment of Ultrasonic Noise Hazard in Workplaces Environment

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(*received April 9, 2013; accepted April 29, 2013*)

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

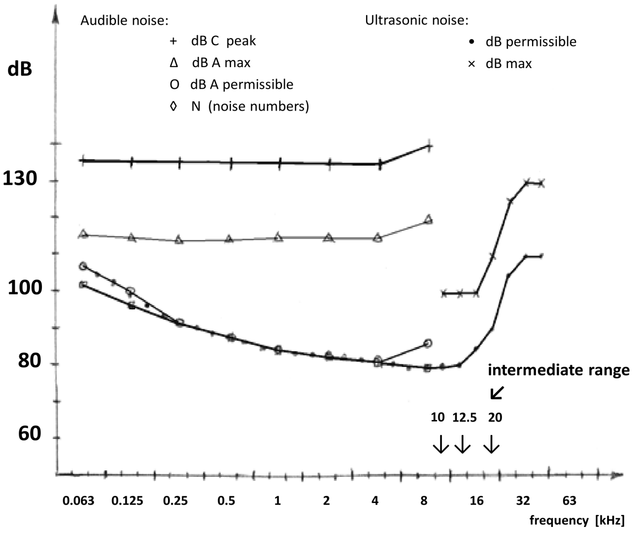

Fig. 1. A comparison of the curves for evaluation of permissible values for audible noise and for ultrasonic noise at work places L_{eq} and $L_{\max}$, respectively.

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 $\mathrm{L}(_\mathrm{NP})$,

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

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.

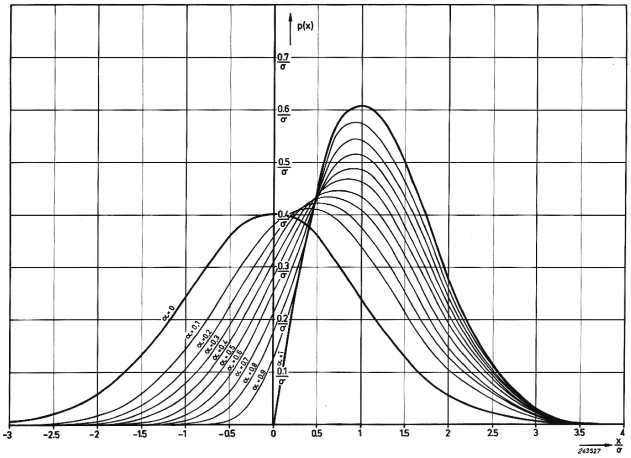

Fig. 2. Set of curves of probability density function of peak values of signal $p(x)$ against random variable x/σ; (σ – standard deviation) for the Rice distribution as variation of the α parameter from 0 to 1 (Broch, 1963).

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.

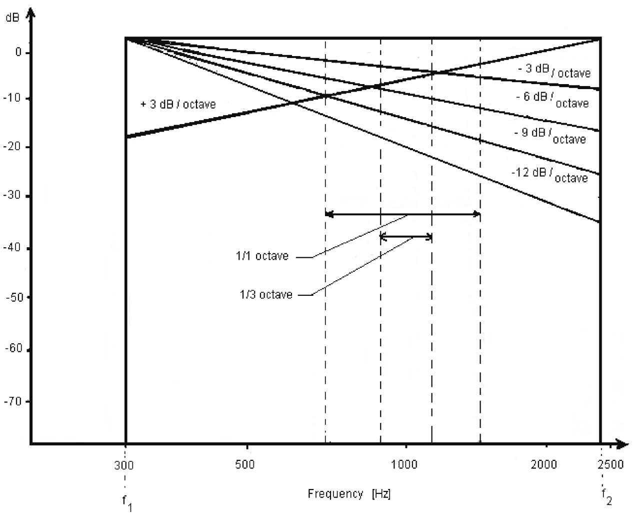

Fig. 3. Plots of power spectral density for various "theoretical" noise spectra, (Broch, 1963).

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):

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

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.

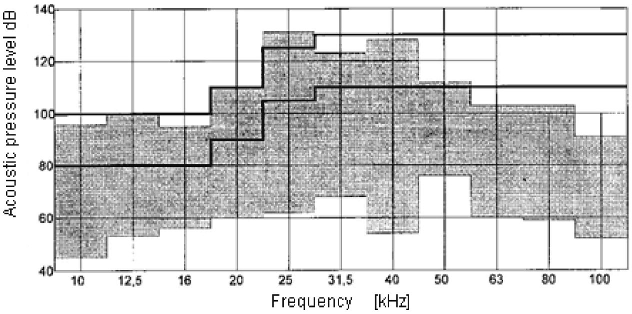

Fig. 4. The 1/3 octave spectrum of an ultrasonic noise level of a typical ultrasonic washing device, (Koton, 1999); the solid lines represent the permissible values for L_{eq} and $L_{\max}$ (upper line), respectively.

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.

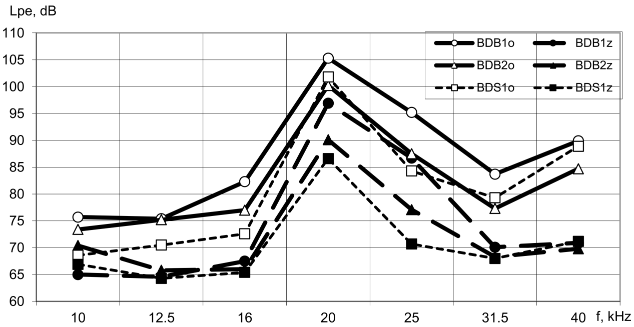

Fig. 5. Acoustic pressure emission levels in 1/3 octave bands of ultrasonic drilling devices (types BDB and BDS) noise, (Smagowska, Mikulski, 2008).

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 75 dB; 75 dB	5.0 82 dB; 75 dB	1000 105 dB; 75 dB	100 95 dB; 75 dB	7.8 84 dB; 75 dB	0.3 90 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 88; 94.3 dB	0.200 87.3; 94.3 dB	27.6 108.7; 94.3 dB	0.288 88.9; 94.3 dB	0.302 89.1; 94.3 dB	0.725 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.

Acknowledgment

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

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