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Low Frequency Noise and Its Assessment and Evaluation

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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.

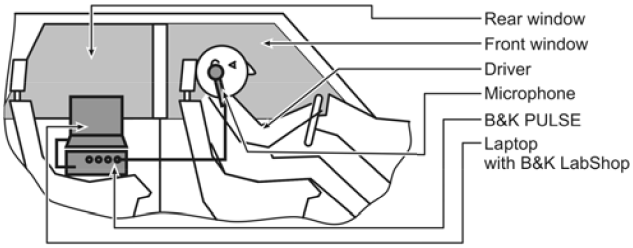

Fig. 1. Schematic of the measurement setup inside of a passenger car while driving.

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.

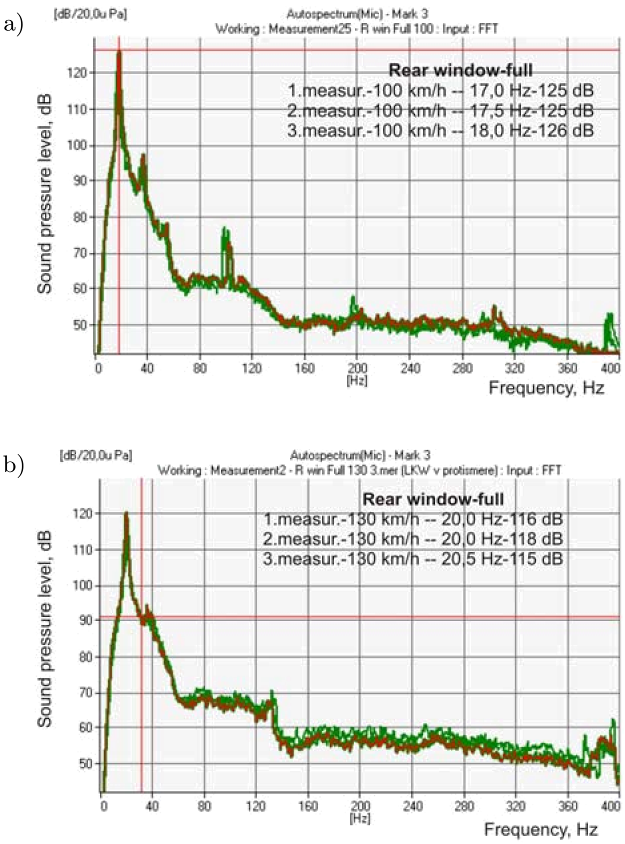

Fig. 2. FFT analysis of the generated noise in the car interior – three measurements with two different car speeds: a) 100 km/h; b) 130 km/h.

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

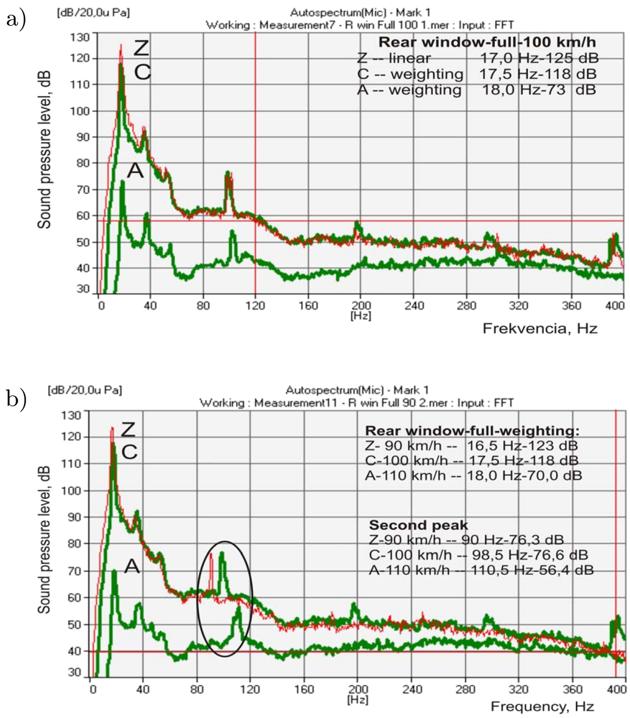

Fig. 3. Comparison of energies using Z-, C- and A-weighting of the same acoustic signal at different car speeds: a) 100 km/h; b) different speeds.

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

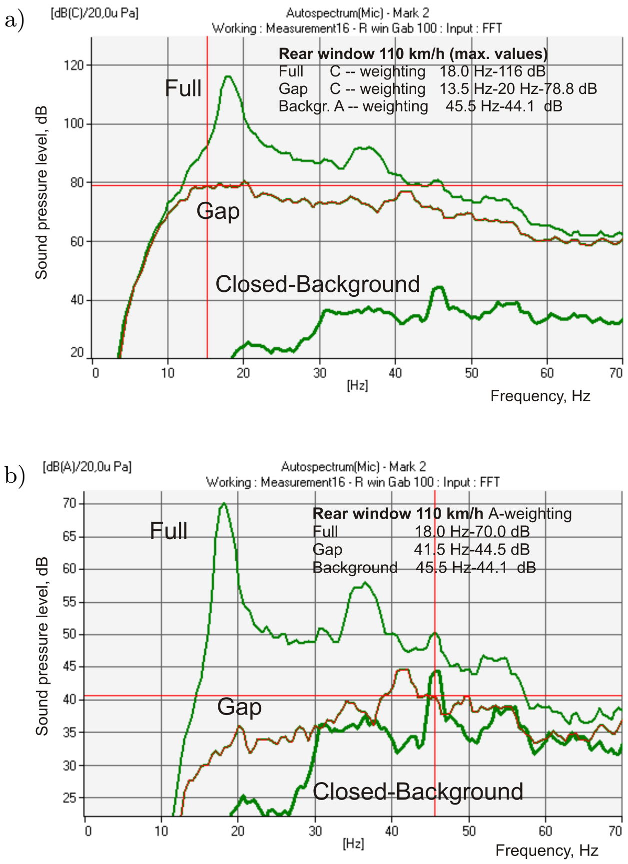

Fig. 4. Comparison of energies using A- and C-weighting of the same acoustic signal with constant car speed (110 km/h).

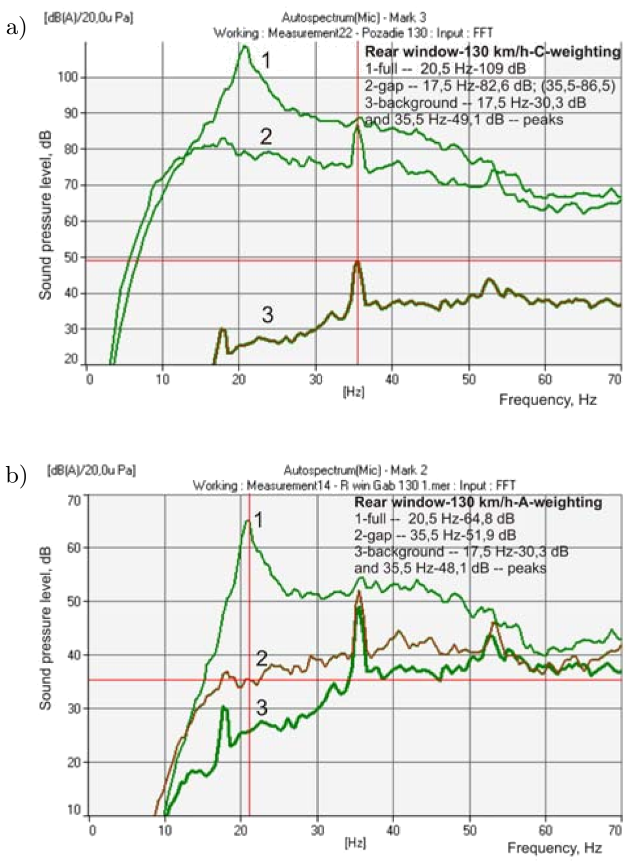

Fig. 5. Comparison of energies using A- and C-weighting of the same acoustic signal at constant car speed (130 km/h).

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

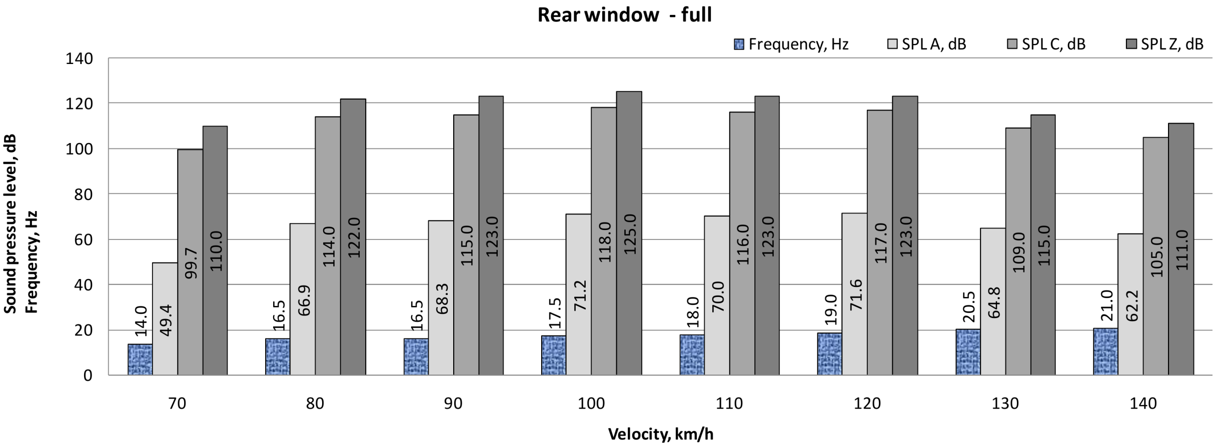

Fig. 6. The levels of A-, C- and Z-weighted sound pressure and variation of the frequency as a function of the car speed.

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.

Acknowledgments

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