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LOW FREQUENCY SOUND GENERATED BY INDUSTRIAL EQUIPMENT AND ITS NEGATIVE IMPACT ON HUMAN HEALTH

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Abstract: Low-frequency sound, including infrasound, generated by machines, industrial plants, vibrating structures, is characterised by its strong energy propagating over relatively large distances and affecting human health, comfort and activity. It has been found that if a person is exposed to low-frequency sound, he or she may have difficulty in carrying out mental work and may also experience some discomfort. The article discusses the negative effects of acoustic energy on human health, comfort and activity, which have also been confirmed by measuring the sources of low-frequency waves in the places where the residents complain. These are mainly low-frequency noise generated by powerful combustion processes, cogeneration units, diesel engines, vibrating piping systems of heating systems and wind turbines. It analyses the conditions of standing waves in residential areas as well as legislation assessing the limits of low frequency sound affecting human health and comfort. It also proposes measures to reduce low-frequency sound.

KEYWORDS: Low-frequency sound, health effects, sources, standing waves, legislation, reduction.

1 Introduction

Low-frequency acoustic waves (infrasound, sound), which propagate over distances of several kilometres, in the frequency band from approximately 0.1 Hz to 80 Hz, transmit relatively very strong acoustic energy compared to the energy of acoustic waves of medium and high frequencies. The range of low-frequency sound (LFS) depends on the frequency, i.e. the lower the frequency the longer the range from the sound source, and also depends on weather conditions such as wind strength and direction. A good example is the wind turbines that are planned to be built in Slovakia. It should be borne in mind that the higher the source, the greater the impact, which will also be influenced by the wind direction [11, 14]. For planned wind turbine heights of 250 m to 270 m, the range of infrasonic and low-frequency sound waves is several kilometres. For more than one turbine, the interference of infrasonic and sound waves occurs, increasing their energy more or less, depending on their spatial distribution in the wind farm. Low-frequency noise is also typical for large diesel engines of ships and locomotives, gas and steam turbines, power plants, cogeneration units, industrial air-conditioning, powerful combustion processes in industry, and with relatively lower acoustic energy, for example, diesel engines of automobiles, HVAC (Heat Ventilation Air-Condition) equipment of buildings, heating systems (boiler rooms) and vibrating piping systems, heat pumps and other machinery used in human work activities, such as low frequency noise generated by laser cutting of composite materials, especially in pulsed cutting mode, and associated machinery such as compressors. Low frequency noise generation is also influenced by the cutting speed and the start-up and end effector deceleration, where unwanted vibrations and hence noise are generated [18].

From the analyses of low-frequency acoustic waves performed to date, it has been confirmed that they are significantly more harmful and annoying than expected from A-weighted sound

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pressure levels [2, 7, 8, 11-16]. The difference between the A level (the A filter monitors the sensitivity of the human ear organ) and the Z level (real sound without filtering) of the sound pressure indicates whether the sound contains low-frequency components that increase the annoyance to humans and have a negative effect on their health. Infrasound contains a spectrum with significant frequency components below 16 Hz. We perceive these waves not as sound, but rather as alternating pressure on the eardrum [11, 12]. The assessment of low-frequency acoustic waves at the limit of audibility is under investigation and is currently only partially covered by international and European standards, in contrast to low-frequency mechanical vibrations, which are monitored and assessed in the range from as low as tenths of a Hertz up to 80 Hz. The predominant source of acoustic vibration is the mechanical vibration of machine systems and structures, and to a significant extent it is also the aerodynamic generation of low-frequency noise, especially by combustion processes in high-performance combustion furnaces, gas turbines, heating boiler systems and wind turbines [13, 18, 19].

2 Effects of low-frequency sound (noise) on human health

The area of low-frequency waves also includes infrasound (below 16 Hz), generated by natural and artificial sources, which we cannot hear, but it's relatively strong energy affects our health, well-being and activity. Very low frequencies of infrasound can be perceived if they are of sufficient intensity. It has been found that if a person is exposed to infrasound, they may have difficulty doing mental work and experience some discomfort. If the sound pressure level of infrasound exceeds 100 dB, a person suffers from dizziness, mental fatigue, irritability, straining to vomit, headaches and loss of balance. However, there is a small sensitive segment of the population that can experience the annoyance of infrasound from as low as 65 dB if the appropriate combination of frequency and duration of exposure is involved. Effects are described as general malaise, nausea, disorientation, increased fatigue, sleep disturbance or drowsiness and other combinations of unspecified symptoms. The cerebral cortex is particularly sensitive to infrasound with a frequency of 7 Hz, which coincides with the frequency of the alpha waves of the cerebral cortex. Exposure to these types of infrasound can prevent clear thinking or concentration on the task at hand. Studies show that infrasound is not a more serious problem than low-frequency acoustic waves from 16 Hz to 80 Hz [2, 11, 12, 15]. The effects can also be caused by the action of infrasound and low-frequency sound on the human body by directly building up the oscillation of organs, tissues, or body parts, where their resonance occurs when the excitation and natural frequencies match, for example, in a person who is near a speaker at a disco, concert, etc. Very low frequencies of infrasound can activate the intestinal system if the excitation frequency coincides with the frequency of the peristatic movement of the intestinal system.

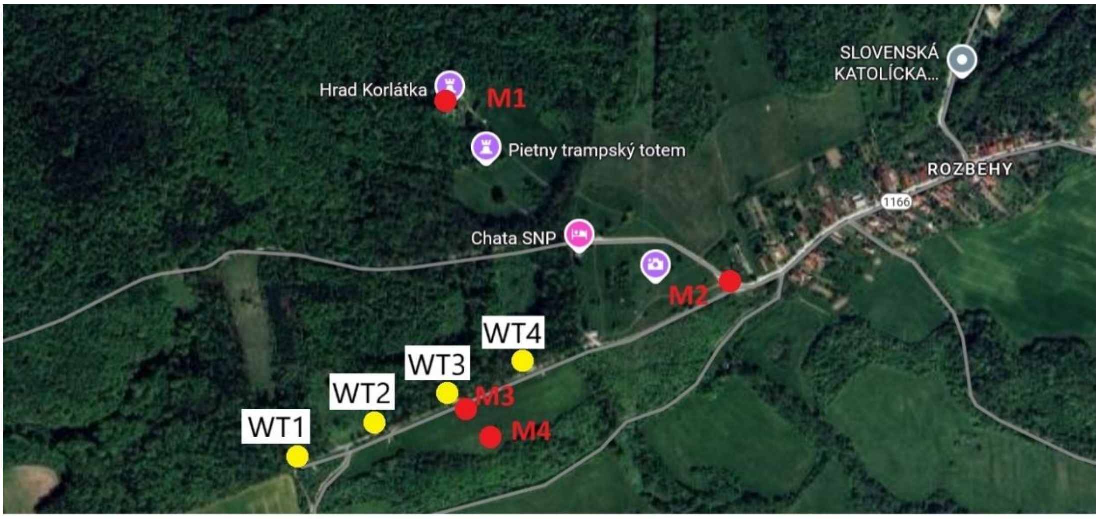
The energy of low-frequency acoustic waves has a negative effect on the neuropsychic and cardiovascular apparatus and on sensory-motor functions. The non-auditory systemic effects of noise can be characterized as changes in heart rate reflecting not only the physical effects but also the psychological stress of a person. Functional changes of the nervous, pulmonary and cardiovascular systems have been registered. Subjective increased irritability, headaches, dizziness, tinnitus, impaired hearing acuity, increased sweating, sleep disturbances, pain in the heart region, difficulty in breathing, nausea, i.e. a feeling of sickness and discomfort in the stomach and head with an urge to vomit, have been noted in persons exposed to low-frequency acoustic waves. With exposure to high levels and low frequencies, nystagmus, muscle tremors, increased discomfort and prolonged reaction time occurred. The energy of low-frequency acoustic waves acting on cell membranes causes disturbances in oxidative processes and is also transformed into energy for biochemical and bioelectrical processes. It can cause direct toxic effects on the central nervous system, cause disturbances in higher nervous activity and affect the course and regulation of processes in the body.

3 Examples of low-frequency sound generation

3.1 Wind turbine

Wind turbine power generation is becoming increasingly important worldwide, with the result that more and more people are being exposed to wind turbine noise. There is evidence that wind turbine noise has a high potential for disturbance, which may be due to specific sound characteristics such as amplitude modulation. For this reason, there is also a desire by the responsible authorities to install wind turbines away from residences. If this is not the case, people are mobilising to stop the continued construction of wind farms.

The distant impact of low-frequency wind turbine noise is also confirmed by acoustic measurements carried out at the Rozbehy wind park. At the time of the measurements, three wind turbines (WT) were in operation, namely WT1, WT3 and WT4, ranging from 200 kW to 660 kW, with a horizontal axis height of 76 m and rotor blade diameter of 47 m, which represent low-power wind turbines (Fig. 1). The measurement duration was 5 min for each measurement point, which is in agreement with the standard [20]. The estimated power at the time of measurement was not maximum and was approximately 2/3. During the measurement, the maximum wind speed at the measurement site was 4.7 m/s at gust. At steady state it did not exceed 2 m/s and the temperature was 19.6 ºC.



M1 - measuring point behind WT, 480 m from WT4, 700m from WT1
M2 - measuring point from the side, 390 m from WT4, 840m from WT1
M3 - measuring point in front of WT3, 19 m
M4 - measuring point in front of WT3, 60 m

Fig. 1 Distribution of wind turbines and measuring points in the vicinity of the village Rozbehy

Measurement point M2 was selected on the border of the village Rozbehy situated perpendicular to the horizontal axis of rotation of the wind turbines (WT) at a distance of (390-840) m and measurement point M1 situated on the ruins of the castle Korlátka at a distance of (480-700) m (Fig. 2).

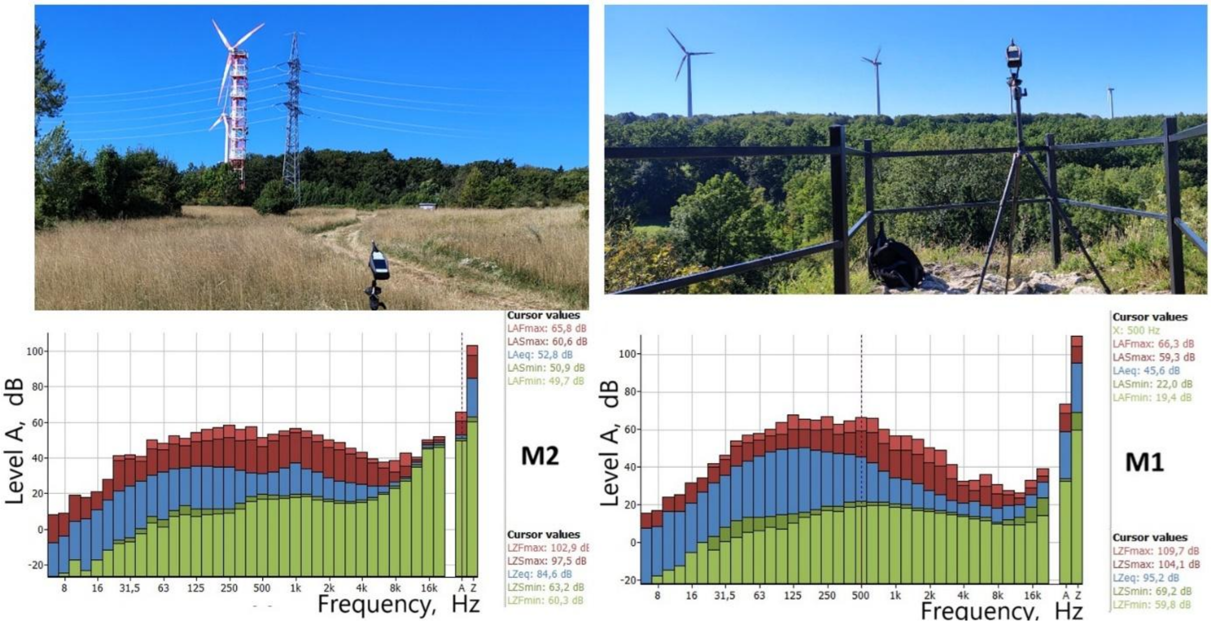


Fig. 2 Measurement point M2 on the border of the village Rozbehy and M1 on the ruins of the castle Korlátka

A third-octave analysis of infrasound and low-frequency sound shows a substantial increase in the equivalent Z-weighting level (approximately 95 dB) compared to the A-weighting level (approximately 52 dB), but the maximum Z-weighting level is above 100 dB, which already has a negative effect on a person's health, and for more sensitive persons the threshold is much lower, at 65 dB, and a person does not need to perceive the origin of the disease for a pathological effect to occur in the body. In this case, visual contact that is not direct to the wind turbines also plays a role.

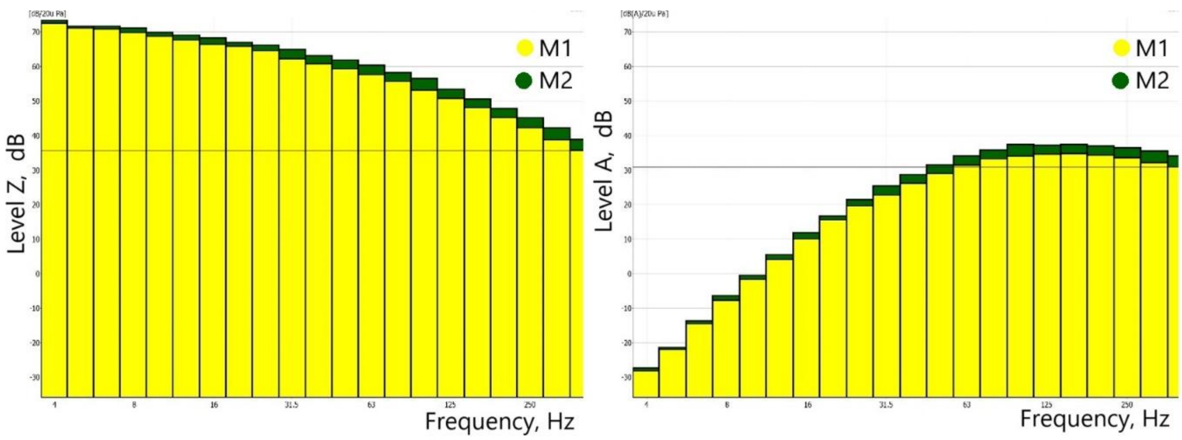


Fig. 3 One-third-octave analysis of sound in the low and middle frequency range at measurement point M2 on the border of the village Rozbehy and M1 on the ruins of the castle Korlátka without filter (Z-weighting level on the left) and with filter A (on the right)

The third-octave analysis of infrasound, low- and mid-frequency sound for measurement sites M1 and M2 shows a significant energy difference between the Z-weighing and A-weighing levels in its individual bands (Fig. 3). The bands with Z-weighing levels represent the overall effect of acoustic energy on humans, and the bands with A-weighing levels represent human audibility in the low and medium frequency range. Figure 3 shows the energetic load on humans from the low frequency sound from the three wind turbines as opposed to the audibility of this sound representing the much lower energy of the low frequency waves. Due to the principle and design of the wind turbines, it is not possible to reduce the low frequency noise to the extent required. The solution is to build wind farms well away from human living and working areas.

3.2 Industrial gas combustion in the furnace

In human life, we often encounter complaints about low-frequency noise generated by the combustion process in industrial plants, furnaces and boiler rooms. Figure 4 shows the FFT analysis of the noise in industrial furnace gas combustion process. The combustion process generates aerodynamic low-frequency noise that also propagates to nearby residences, and people complain of annoying booming noise that bothers them and negatively affects their health [18]. However, it should be borne in mind that the energy of this low-frequency noise also negatively affects the employees of the plant itself. The frequency generated by the combustion process has a value of 39 Hz and its Z-weighing level reaches an effective value of 107,7 dB at a distance of approximately 2 m from the outlet of the energy air fan of the combustion furnace in the plant. When filter A is used, the effective level is reduced by this filter representing the insensitivity of the hearing organ to low frequencies, which reaches a value of 72,7 dB. The generation of aerodynamic noise by combustion is generally of a pulsating nature ranging from 3 dB to 7 dB, as confirmed by the time history in Fig. 5.

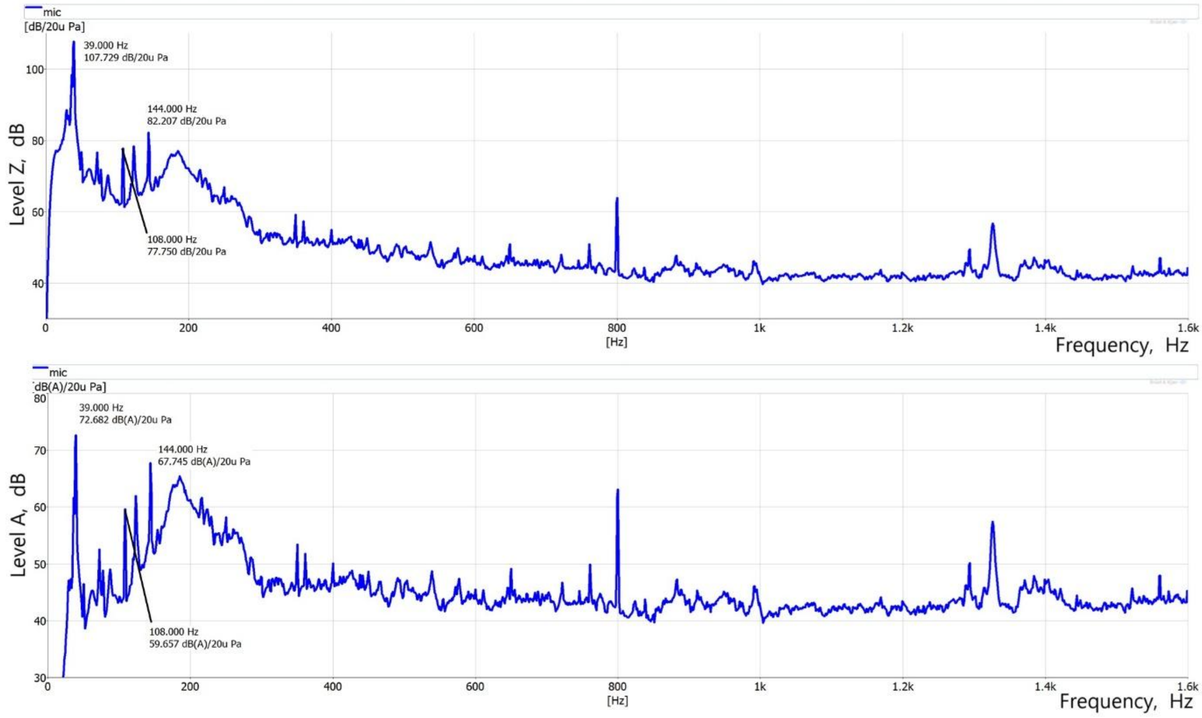


Fig. 4 FFT analysis of noise in the vicinity of an industrial combustion furnace using a Z filter (above) and an A filter (bottom)

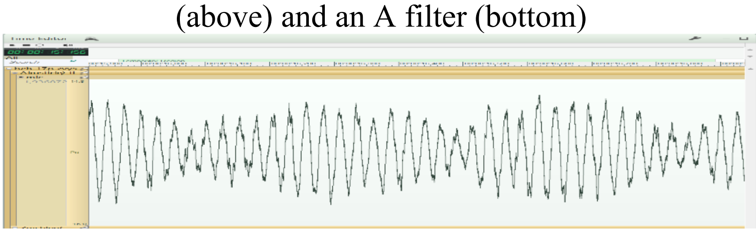


Fig. 5 Low-frequency pulsations of an industrial furnace combustion wave

The energy difference in the measured values at the generated firing rate between Z and A weighing is approximately 95 000 times. Although acoustic energy is negligible compared to other types of energy, the above differences in weights cannot be ignored when assessing the effects on the human body, since all energy has the ability to do work, whether negative or positive, from the point of view of human health. However, there is a boundary between positive and negative effects on the human organism and therefore it is necessary to determine this boundary correctly or to approach the most accurate determination of this boundary [9, 10, 17]. Unfortunately, the current Regulation of the Ministry of Health of the Slovak Republic 549/2007 Zb. does not allow this.

From the FFT analysis, it can be concluded that there are significant outliers in the low frequency region of the amplitudes, which mainly represent the aerodynamic noise of the combustion process. The region of emission of significant acoustic energy is from 25 Hz to 40 Hz, i.e. for the middle frequency of 31.5 Hz, where the sensitivity of the auditory organ is very low (approximately from 60 dB). In this case, it is possible to effectively reduce the low frequency noise by the application of suitable silencers.

3.3 LFN in office room from Diesel engine

Theoretical analysis of the closed space: The generation of the standing waves in closed space due to low-frequency noise is a problem which can be commonly faced up in everyday life. People are complaining about insomnia, migraine, unconcentration, or other even more serious health problems. To investigate the standing waves, the theoretical model needs to be found [7, 8]. The Eigen frequency of the approximately rectangular closed space can be found as

$$f_{\mathrm{n}_x n_y \mathrm{n}_z} = \frac{c_0}{2}\left[\left(\frac{\mathrm{n}_x}{L_x}\right)^2 + \left(\frac{\mathrm{n}_y}{L_y}\right)^2 + \left(\frac{\mathrm{n}_z}{L_z}\right)^2\right]^{\frac{1}{2}} \tag{1}$$

For first axial mode in x-direction the factors (n_x, n_y, n_z) are in the form (1,0,0), i.e. then the equation simplifies to

$$f_{n_x} = \frac{c_0}{2}\frac{n_x}{L_x} \tag{2}$$

Assuming that the closed space is approximately rectangular (taking the furniture as a rigid wall) and the walls are of infinite stiffness (which is an approximation), then for speed of sound c_0 and characteristic dimension of the closed space can be calculated first or higher Eigen frequencies of this closed space.

Traffic induced standing waves in office: In this section, just a specific outdoor source – transportation noise, caused by vehicles with Diesel engines in idle running, while standing at traffic lights, is analysed. The emitted noise from the engine contains a tonal frequency, which coincides with the first resonance mode of the office analysed and thus the standing wave in the office is generated. The problem with standing wave generation in the office was observed especially when public transport busses and some Lorries or passenger cars (with Diesel engines) stopped at the buildings.

Considering a closed room having approximately rectangular shape, the standing wave is generated, if at least one of the room's dimensions coincides with multiple of the half of the wavelength ($\lambda/2$) of the source's tonal frequency. Then the location of the nodes may be found from

$$x = (2n+1)\frac{\lambda}{4} \tag{3}$$

Similarly, having the dimensions of the closed space, the natural frequency of the office (for axial closed spaced modes) can be calculated from Eq. (1).

The office room in the building of the Faculty of Mechanical Engineering located close to the cross-road, was analysed (Fig. 6). During a normal office work, with a window located to the road having open or closed, generation of standing wave and thus annoying noise was observed when some vehicles stopped at traffic lights.

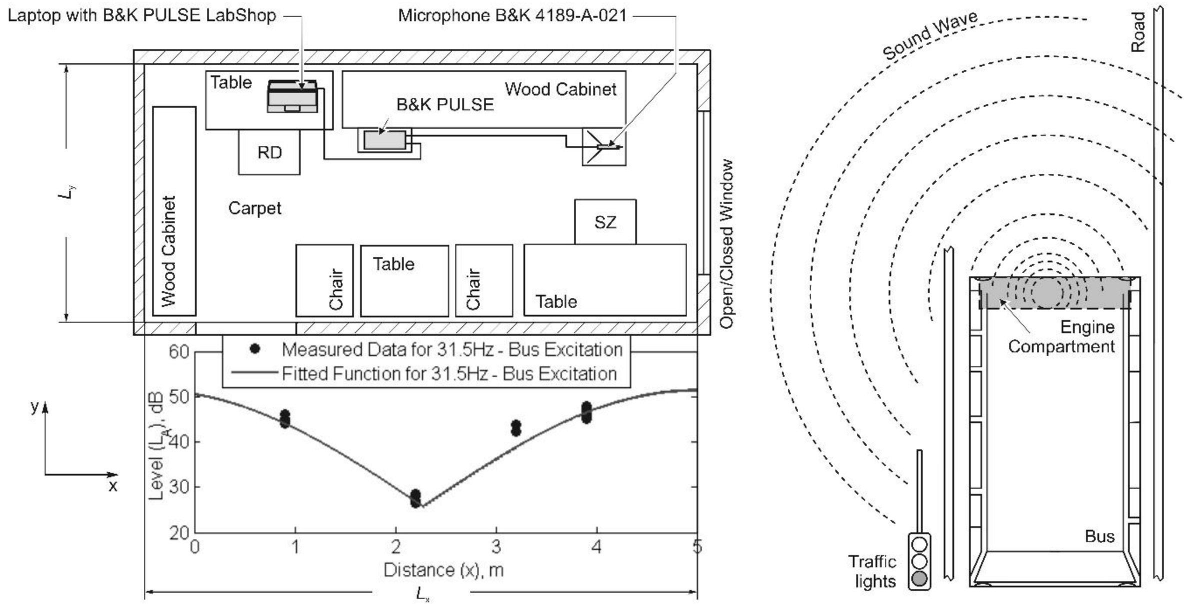
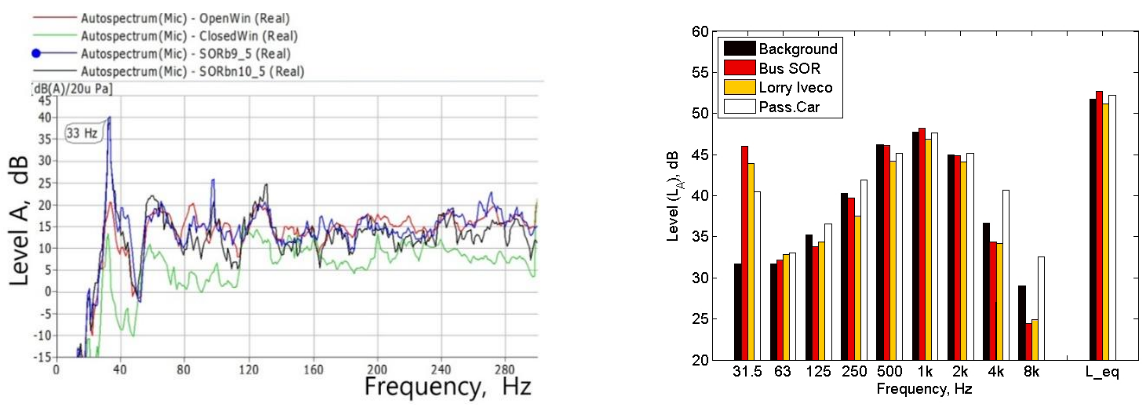


Fig. 6 – Measurement set-up with results plotted for bus excitation (SOR B 9.5)

In the office room, additional measurements on source identification were done. Fig. 7a presents FFT analysis of the noise measured in the room while a bus was standing on the cross-road close to the window and compared with the 'ideal' case without the bus (and also window closed). Fig. 7b compares the three diesel engine vehicles and their contribution to low-frequency noise generation. It can be clearly recognizable (Fig. 7b) that the tonal noise around frequency 31.5 Hz is generated. This frequency coincides with the first lateral mode of the office room. FFT analysis (see Fig. 6) with higher resolution in low frequencies proves this observation.



(a) (b)

Fig. 7 (a) FFT analysis of noise produced by a bus SOR and perceived in office room; (b) octave analysis of noise from three vehicles perceived in the office room

3.4 LFN in room from the vibrating pipe

Where frequency analysis of sound generated by mechanical vibration is required, acoustic measurements may be made in standardised octave and/or fractional octave bands, depending on the application and the resolution required. In cases where the sound spectrum contains tonal components of low-frequency sound (noise), it is necessary to analyse the sound using a frequency spectrum in order to separate the important frequency components of the sound (Fig. 8). Thus, to accurately identify the low-frequency components of sound (noise), it is convenient to use fast Fourier transform (FFT analysis). FFT analysis defines the levels of the measured at low and medium frequencies for each frequency as well as the harmonic multiples. This uniquely assigns the obtained amplitudes of the acoustic vibrations to specific frequencies, which allows to detect the cause of the increased emission of acoustic waves (noise), such as the vibration of the piping system in Fig. 8 generating the structural noise radiating into the acoustically protected space of the resident. The spectrum of vibro-acoustic waves determined in this way also allows more accurate prediction of the hazard impact of vibro-acoustic energy on the living and working environment and effective design of measures for its reduction and transmission to this environment. In this case, the cause of the generation of structural low-frequency noise was the built-up Eigen frequency of vibration of the piping system, which was not sufficiently vibro-isolated from the building structures. The residents of the flat concerned had complained for 5 years about low-frequency noise in the bedroom, but the hygiene measurements carried out concluded that the noise in the flat complied with the requirements of Regulation 549/2007 Zb. The resident's psyche was severely disturbed and he was able to make this noise outside the flat in a quiet environment.

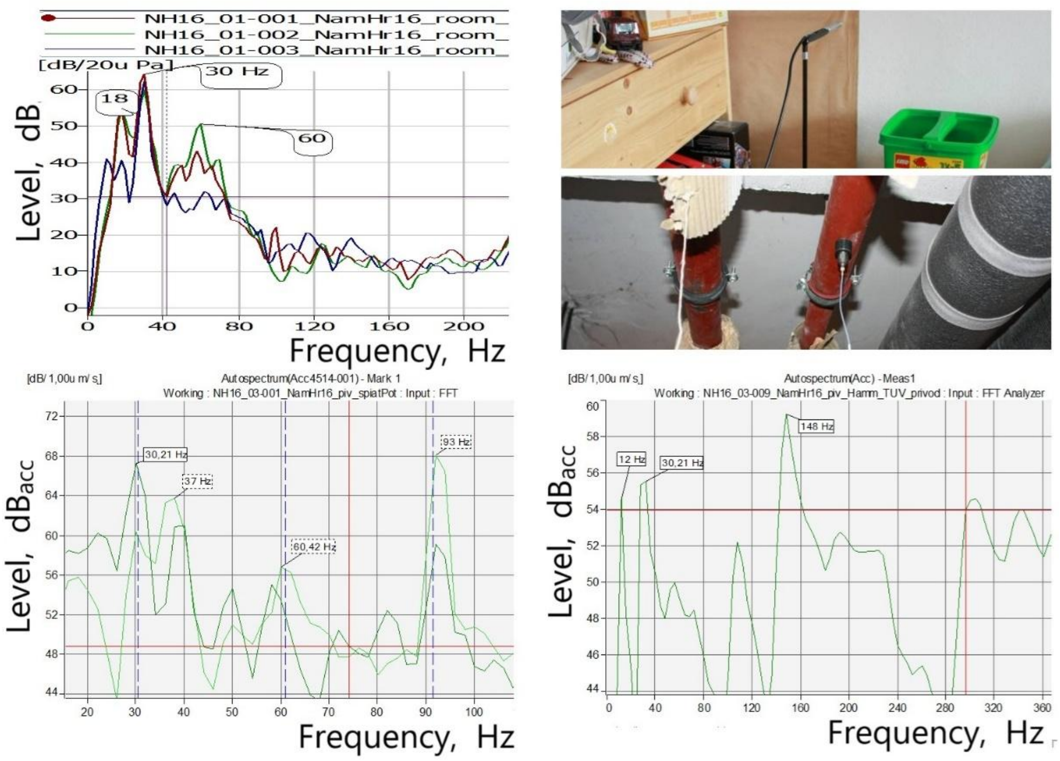


Fig. 8 FFT analysis of the noise in the protected area and measurement points in the apartment and on the piping system under the resident's apartment (above), frequency spectrum and modal analysis of the piping system under the resident's apartment (bottom)

3.5 Cogeneration units

The dominant source of vibro-acoustic waves is the combustion engine of the cogeneration unit (CGU). Its rotational frequency at the time of measurement was 1 500 r/min, corresponding to a frequency of 25 Hz. From the frequency spectra in Fig. 9, it can be seen that the dominant noise in the boiler room is the CGU noise. As the engine rotation frequency increases, the noise of aerodynamic origin starts to dominate, i.e. the higher frequency components (in particular the intake and exhaust noise) become more prominent. The sound (noise) of the middle and higher frequencies is attenuated more quickly by the environment and has less effect on more distant acoustically protected areas than low-frequency sound, which is energetically much more powerful and propagates over relatively long distances, where it can excite the already mentioned undesirable standing waves in the acoustically protected space, thereby significantly increasing the noise level in this space. This attenuation by structures and the environment is evident from Fig. 9, where the attenuation at a rotational frequency of 25 Hz is 10 dB at a distance of approximately 100 m, at a frequency of 100 Hz (4th harmonic of the rotational frequency) the attenuation is already 40 dB and at the boundary of the monitored band up to 55 dB.

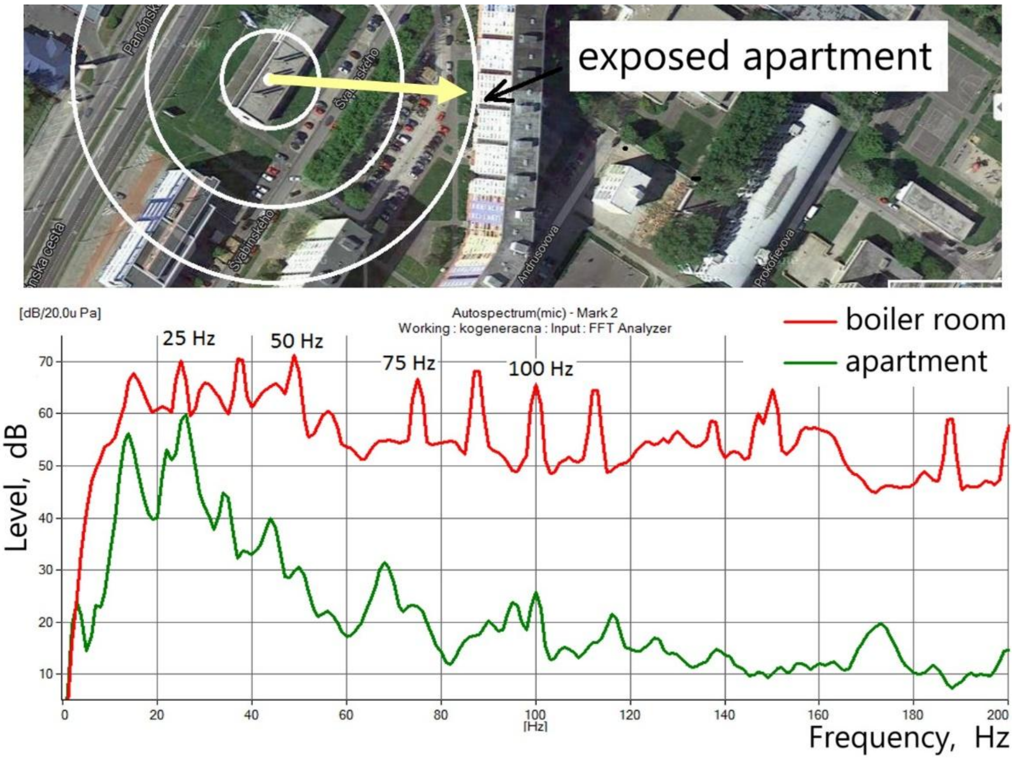


Fig. 9 Noise spectrum emitted by the heater in the boiler room and in the exposed apartment

In the analysed case, the cause of the generation of low-frequency noise was the improper vibration isolation of the cogeneration unit, which caused the transmission of vibrations from the source to the building structures and the subsequent radiation to the acoustically protected residential spaces.

The transmission of vibration energy through the CGU vibration isolation (silent-blocks) depends on its load and the method of application (attachment). The frequency transfer through the two selected silent-blocks and the transfer to the vibration-isolated building structure is shown in Fig. 10. Comparison of the frequency-amplitude characteristics for these silent-blocks shows significant differences in the attenuation of the vibration energy transfer. The correctly installed analysed silent block (Fig. 10 above) performs the function of damping in the transmission of vibration energy, where its attenuation in the monitored frequency band (5 Hz to 200 Hz) was 21.4 dB and at a rotational frequency of 25 Hz it was 20.4 dB, while the incorrectly installed silent block (Fig. 10 below) had the function of an amplifier of vibration energy transmission in this band, and therefore its attenuation had a negative value of -4.3 dB. However, at a rotational frequency of 25 Hz, the attenuation of the vibration amplitudes was 7.9 dB versus 20.4 dB with a correctly installed silent-block. However, the measuring point at the output of the silent-block may also interfere with vibration propagating from other locations of the mechanical system frame. In general, vibration isolators are only effective between structures of relatively large dynamic stiffness on either side of the isolator [4, 5, 19].

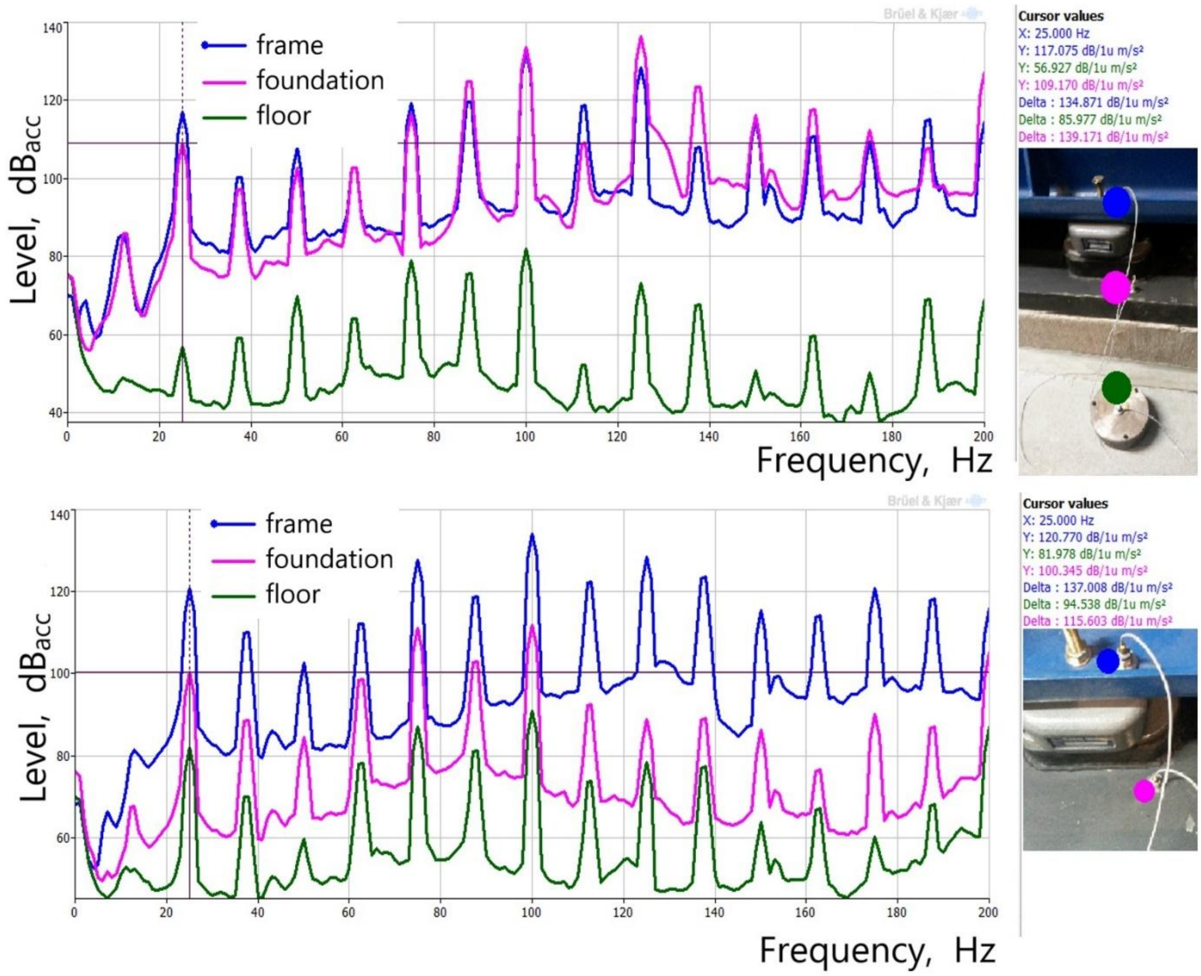


Figure 10 Vibration energy transfer through silent-blocks; (above) correctly installed, (bottom) incorrectly installed

The content of low-frequency noise components in the protected areas of the analysed apartment and their increased level due to standing waves, negatively affected the sleep of the residents, who complained of more frequent migraines, stomach problems, waking up and the resulting malaise, fatigue, irritability, stress, depression and more nervousness, which are typical manifestations of long-term exposure to the acoustic energy of low-frequency waves, especially at the time of relaxation [19]. Due to the negative health effects, the residents temporarily moved out of the exposed apartment.

It can be concluded that undesirable low-frequency waves in the boiler room and in the protected area are caused by a person who, by an unprofessional approach in the application and operation of mechanical systems, affects the health and comfort of another person and also affects the durability and reliability of machinery, technological and building structures.

DISCUSSION AND CONCLUSION

Industrial combustion furnaces and boiler units with the necessary piping system are a frequent source of complaints from residents. The cause is the unwanted generation and subsequent transmission of low-frequency noise to the surrounding acoustically protected areas of both residents and workers of the plant concerned, through the air, the heating medium, the building structures and the subsoil. In this case, it is necessary to analyse this transmission and take appropriate measures such as the inclusion of an absorption-reflective silencer in the combustion system, vibration isolation of the components of the industrial combustion furnace and the boiler unit and sometimes acoustic treatment of the immediate surroundings of the combustion process is also necessary. Such an approach will reduce the transmission of vibro-acoustic energy to the required level that will not endanger human health and comfort. Residential and work areas that are exposed to low-frequency noise from the above sources are generally of such dimensions that partial or standing waves (resonance) are generated in these areas, thereby significantly increasing the level of low-frequency noise detrimental to human health [8]. Thus, a more pronounced sound pressure difference in the area under consideration increases the annoyance and harms the health of people living and working near industrial incinerators and boiler houses. It should be emphasized that for significant discrete values of acoustic waves, which is typical for the combustion process (see Fig. 4), the inaccuracy of acoustic measurements also increases. When the sound level meter is placed in or near a node, distortion of the measurement results may occur, therefore FFT analysis should also be used for a correct assessment of the acoustic waves at the source location and in protected areas.

During long-term monitoring of the impact of low-frequency sound (noise) on human health, these impacts on people whose residential house was were located at a distance of (321-642) m from three wind turbines were confirmed, culminating in a court case. The Supreme Court ruled that the 3 wind turbines near the complainant's property must be removed [3]. Histologically, the pathology induced by the low frequency noise was also confirmed in the thoroughbred horses of this family. Thus, low-frequency sound also has a negative impact on animals and birds. A similar article by medical experts [1] states that the type of toxicological impact and the development and onset of disease caused by exposure to low-frequency waves (infrasound, sound) are partly analogous to the effects caused by radiation. As with radiation exposure, the onset of disease induced by low-frequency sound is largely dependent on the time of exposure, with different wavelengths of the physical agent affecting different organs and tissues. It should be emphasised that one does not need to perceive the disease agent for a pathological effect to occur in the body.

In a laboratory study [6], low-frequency wind turbine noise was found to be significantly more disturbing than road traffic noise, especially in situations with "booming" amplitude modulation, but also in other situations. The high potential for interference from infrasound and sound, also generated by wind turbines, should be taken into account in the environmental impact assessment in order to ensure adequate protection from the adverse effects of low-frequency sound (noise) from wind turbines on human health and well-being. For this reason, too, the responsible authorities are keen to install wind turbines away from residences.

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