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EXPOSURE OF HUMANS TO LOW-FREQUENCY NOISE GENERATED BY PIPING SYSTEMS

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Abstract: Pipe systems supported by brackets are excited to their natural frequency by the flow of fluid through them. This article deals with identifying the causes of low-frequency vibrations in heating pipe systems, their transmission, and their analysis as structural noise in an acoustically protected environment. It analyzes the possibility of resonance occurring in an acoustically protected space, which has a negative impact on human health and comfort. It proposes effective vibration isolation for the piping system with the aim of reducing unwanted noise in living spaces.

Keywords: Heating pipes, vibration, structure-borne noise, human, annoyance

1 Introduction

Low-frequency sound and infrasound in the frequency range from tenths of a hertz to approximately 80 Hz generate significantly more acoustic energy than the acoustic waves of middle and high frequencies; in other words, the lower the frequency, the more powerful the sound energy. Heating systems (boiler rooms, heating plants), which are essential for human life, also generate this type of sound and infrasound. These systems generate high-energy low-frequency sound through the combustion process as well as through the mechanical vibration of components such as piping systems and pumps. However, the Z-weighted level, representing acoustically unfiltered low-frequency sound waves, is significantly more annoying than the A-weighted sound pressure level, which reflects the sensitivity of the human auditory system to sound energy. The spectrum of low-frequency acoustic waves typically contains energetically significant frequency components that have a negative impact on human health and comfort. At higher Z-weighted levels, exceeding 100 dB, or 65 dB for more sensitive population, this leads to symptoms such as increased fatigue, dizziness, irritability, nausea, headaches, sleep disturbances, loss of balance, and change in neurohormonal and neurovegetative regulation. The cerebral cortex is particularly sensitive to infrasound at a frequency of 7 Hz, which corresponds to the frequency of the cerebral cortex's alpha waves. Exposure to these low-frequency sounds can interfere with clear thinking or concentration on performing a given task [6, 7, 8, 11, 13]. The evaluation of low-frequency acoustic waves at the threshold of audibility is still under investigation and is currently not objectively covered by international legislation and standards, unlike low-frequency mechanical vibrations, which are monitored and evaluated in the range from 0.1 Hz to 80 Hz. It should be emphasized, however, that infrasound generated by vibrations can also be evaluated by measuring vibration acceleration [13]. Given the high energy of low-frequency waves, it can be concluded that sound energy in the frequency range from tenths of a Hertz to approximately 80 Hz can be dangerous to life if the sound pressure level (Z-weighted) exceeds 170 dB to 180 dB; exceeding 150 dB can cause more serious functional changes, and depending on the duration of exposure, exceeding 100 dB, or 65 dB for more sensitive people, can cause discomfort and harm health [2, 16]. The long-term effects of

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low-frequency sound on the human body, work performance, and sense of well-being remain an open issue and require ongoing attention in both epidemiological and laboratory studies, a fact further confirmed by the potential construction of wind farms in relative proximity to human residences [1, 2]. Wind turbines are generally a continuous source of low-frequency vibrations over distances of up to several kilometers, depending primarily on the power output of the wind turbines, their location, and environmental conditions [8].

Unlike wind turbines, however, it is possible with most technical equipment to reduce sources of low-frequency waves and thus protect people from unwanted low-frequency noise [13]. Vibration diagnostics is used to meet the requirement of reducing the transmission of unwanted dynamic load energy from a vibration source to the surrounding area, specifically to detect vibration sources; where it is not possible to eliminate a significant source of vibration, vibration isolation and noise isolation of the vibration and noise source are used. Vibration isolation is a measure used to reduce any transmission of dynamic loads (structure-borne noise), including from piping systems to surrounding building structures (source isolation, protection against vibration emissions), or to protect building structures and people from vibrations received from their surroundings (receiver isolation, protection against immissions). In both cases, passive dynamic load isolators (vibration isolators) consist of a system comprising a mass and a flexible element (an energy absorber), whose dynamic response is critically influenced by the properties of the dynamic load source. Optimizing the system to meet protection criteria requires comprehensive and detailed knowledge of all factors that influence the design and effective application of vibration isolation for the piping system, its mounting, or its application at contact surfaces with vertical building structures, such as partitions through which the piping passes [3, 5, 9].

It should be noted that even the flow of fluid through a pipe can excite the pipe's natural frequency of vibration, which is then transformed into unwanted noise in an acoustically protected environment via structure-borne noise [10, 12]. For this reason, during measurements, attention should also be focused on the vibration-isolating mounting of potential sources of dynamic loads on building structures. Properly designed passive dynamic load isolators, intended to protect mechanical systems, building structures, the surrounding environment, and people are used to reduce the transmission of vibroacoustic waves in the audible frequency range (structure-borne noise from 16 Hz to 16 kHz) in a structure that may, for example, radiate sound into the surroundings (air transmission, water transmission, transmission through the building structure) and to reduce the transmission of low-frequency vibrations (typically from 0.1 Hz to 80 Hz), which can have a negative effect on humans and generate structure-borne noise or cause damage to building structures and safety equipment if the vibration severity or acceleration is high [13, 15].

2 Objective, Methodology of Vibroacoustic Measurements and Measurement Points

2.1 Objective

The objective is to identify, based on measurements of vibration and noise parameters, the causes (source(s)) of vibration (noise) and the transmission of vibration and noise from the source; to analyse the impact of dynamic loads from the heating system on the acoustically protected environment and building structures; analyse the creation of standing or partially standing waves in the acoustically protected environment, and propose effective, economical measures to reduce the energy from dynamic loads generated by the heating and piping systems as they are transmitted through rigid environments – building structures. The analysis is performed based on measurements of the dynamic load parameters of piping systems, installed

boilers, their pumps, and valves, as well as data on the piping system's installation configuration, and on measurements of sound pressure levels.

2.2 Methodology of Vibroacoustic Analysis and Measuring Technique

Vibration and noise measurements are always preceded by an analysis of the transmission path of vibroacoustic energy in order to identify the possible causes of this energy, which may contribute to undesirable noise levels in an acoustically protected space. It is also advisable to perform a control acoustic measurement in the acoustically protected environment and at the location of the heating system. To ensure an effective reduction in the flow of vibroacoustic energy from the heating system into the surrounding soundproofed space, originating from unidentified sources of vibration, a detailed technical and functional analysis of the mechanical and piping systems and their mounting will be performed, along with a modal analysis, technical measurements of vibration and noise and their transmission, including spectral analysis, even within the acoustically protected space, for each potential source of dynamic load. An analysis of these vibration (noise) sources will be performed with regard to the assignment of added values (corrections), such as the generation of tonal noise, high-energy impulse noise, low-frequency noise, etc., as well as an analysis of the surrounding environment in terms of acoustics and vibration isolation with regard to the specified sources of vibration (noise), measurement of the sound insulation of building structures, analysis of possible technical solutions or measures for the required reduction of vibroacoustic energy, vibroacoustic design of specific technical measures to reduce the vibroacoustic energy of identified sources and recommendations for suitable vibration-isolation materials [13, 15].

Modern measuring equipment from Bruel & Kjaer was used for the vibroacoustic measurements, namely the PULSE analyser: 12-channel B&K PULSE 3053-B-120 measurement card with a usable frequency range up to 25 600 Hz for recording measured signals; acceleration sensors: B&K 4534-B-001 and B&K 4533-B-001 accelerometers with usable frequency ranges from 0.2 Hz to 12 800 Hz, B&K 8340 accelerometer with a usable frequency range from 0.1 Hz to 1 500 Hz (seismic sensor); impact hammer: B&K 8206 with a sensitivity of 22.7 mV/N and an effective mass of 100 g, with a maximum impact force of 4 448 N; PULSE software package: for processing and analysing measured data; measuring microphones: B&K 4189 microphone with a frequency range from 6.3 Hz to 20 kHz and B&K 4964 with a frequency range from 0.038 Hz to 20 kHz; type 2250 portable sound analyser with an acoustic calibrator: accuracy class 1 and special equipment related to the measurement of low-frequency dynamic loading: a computer and a steel cylinder with three spikes. In addition to the frequency range, it was also very important to choose a suitable averaging method for the signal type and the number of averaging per time unit, as well as a suitable time window [14]. For this reason, the Hanning window with linear averaging and 66.67 % overlap that provides completely uniform weighting was chosen, as it is was deemed useful for analysing generated signals. The results of the FFT analysis were presented through the square root of the one-sided amplitude spectrum. An exponential window was used for the experimental modal analysis.

2.3 Measurement Points

The selection of measurement points was determined based on an analysis of excitation sources at the points where vibration sources come into contact with building structures in defined directions and on the floors of acoustically protected areas. Microphones were placed in the centre of the protected area, at the residents' reference relaxation point, and in the room containing a potential source of vibroacoustic energy. The sensors were attached using a magnet or affixed using mounting pads supplied by the manufacturer, into which the sensors were

inserted. The seismic sensor, used on horizontal building structures, was magnetically attached to a metal cylinder (Fig. 1) [4, 14, 19, 20].

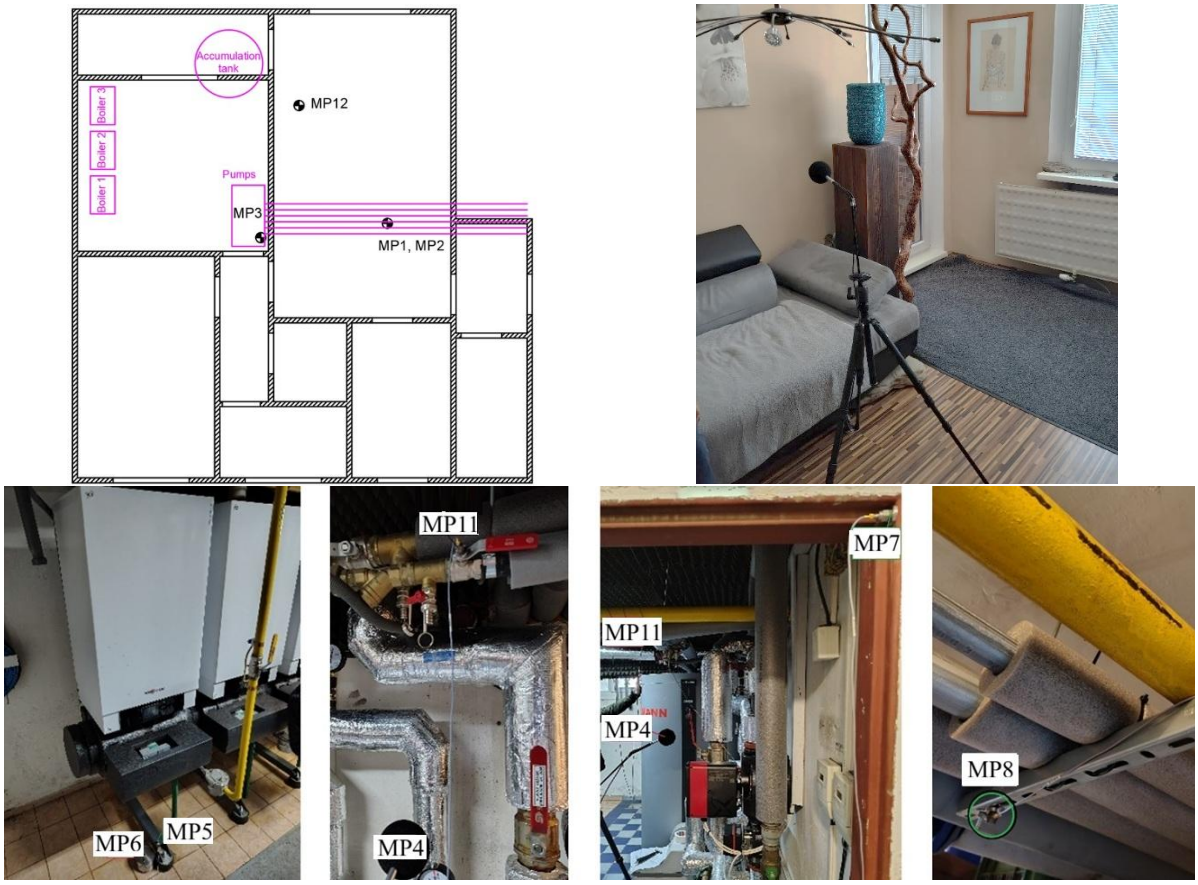


Fig. 1 Sound measurement points for acoustically protected areas (MP1, MP12) and vibration measurement points (MP2, MP3), and measurement points for vibration and noise in the boiler room

3 Frequency Analysis of Vibration and Noise Sources

3.1 Analysis of the Natural Frequencies of a Heating System

Modal analysis is used to determine the natural frequencies of the natural vibration modes of duct systems suspended from the ceiling (Fig. 1, MP8), on a linear scale in the frequency range up to 12 kHz and on a logarithmic scale in the frequency range up to 100 Hz, which is most suitable for analysing vibration sources in this case (Fig. 2). One natural frequency is near 30 Hz, which can cause sound resonance in an acoustically protected environment [10, 13]. In this case, resonance means a significant increase in the amplitude of the pipe's vibration and, consequently, an increase in vibroacoustic energy. In such a case, a tonal noise amplitude is generated; if the wavelength of this tonal amplitude corresponds to the dimensions of the protected space, it will excite standing waves or partially standing waves, depending on the absorptivity of the walls. Other natural frequencies up to 100 Hz are also analysed, which may excite acoustic resonance in the protected space, for example 57 Hz, depending on the characteristic dimensions of the acoustically protected spaces.

From the frequency characteristics up to 100 Hz, it is possible to identify the natural or more significant tone frequencies of the piping system, specifically the heating supply pipes at 30 Hz and 45 Hz, the heating return pipes at 18 Hz, 30 Hz, 42 Hz, 50 Hz, 61 Hz, and 92 Hz; cold water pipes at 14 Hz, 29 Hz, 45 Hz, and 68 Hz; hot water supply pipes at 45 Hz, 50 Hz, 61 Hz, 88 Hz,

and 92 Hz; hot water return pipes at 45 Hz, 53 Hz, 58 Hz, 88 Hz, 92 Hz, and 102 Hz; and gas pipes at 14 Hz, 46 Hz, 56 Hz, 60 Hz, and 96 Hz, which may negatively affect the acoustically protected environment, particularly near 30 Hz, 45 Hz, 58 Hz, and 88 Hz.

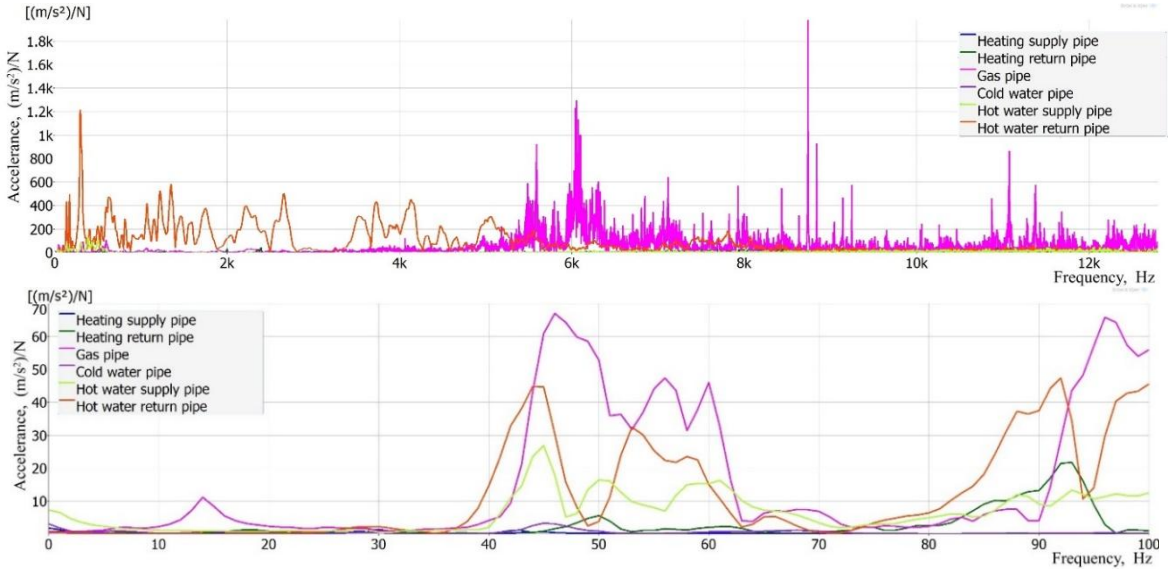


Fig. 2 Natural frequencies of piping systems obtained by modal analysis on a linear scale (top) and a logarithmic scale (bottom) for the low-frequency range up to 100 Hz

3.2 Vibration Transmission in Boiler Mountings

In this case, the boilers are interconnected; therefore, vibration measurements were taken at measurement points on the stand of one of the boilers and on the floor, which is connected to the vertical crossbeams supporting the floor of the acoustically protected areas, as shown in Fig. 1 and at measurement points MP5 and MP6.

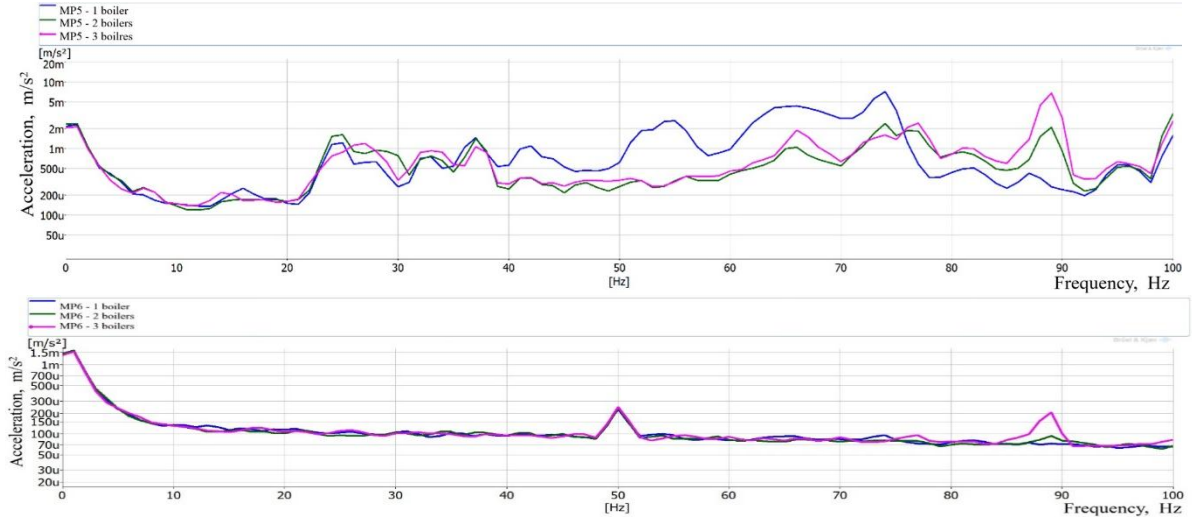


Fig. 3 FFT frequency analysis of boiler vibrations (top) and their transmission to the floor (bottom)

It should be noted, however, that even when the boiler system was switched off, small vibration amplitudes were recorded at frequencies of 50 Hz and 88 Hz. The 50 Hz frequency was generated by the residential building's electrical system, which remained active during the measurements. The 88 Hz frequency was generated by the hot water supply and return pipes, which could not be controlled during the measurement. However, these frequencies do not

affect the acoustically protected environment, as confirmed by the A-weighted sound pressure level frequency spectrum (see Fig. 9).

3.2 Transmission of Vibrations through the Mountings of Heating Components

The components of the boiler system, such as pumps and ball valves, are interconnected within the piping system and suspended from the ceiling slab, that is, from the floor of the acoustically protected areas (see Fig. 1 and measurement points MP4, MP7, and MP11). Vibration measurements were taken at a measurement point on a valve in the piping system near the suspension point (MP11), on a vertical crossbeam near the pipe suspension (MP7), and on the floor of the acoustically protected room (MP3). Figure 4 shows the frequency analysis of vibrations in the suspension of heating piping system components (pumps, valves) as a potential source of structure-borne noise transmitted through the floor of the acoustically protected space. From the perspective of structural noise, however, the transmission of vibrations into the ceiling slab, and thus into the floor of acoustically protected spaces and partitions, via the suspended mounting of the piping system components is significant. Figure 4 shows that suspending the piping system components attenuates vibration transmission down to a value of approximately 644 μm/s² in the frequency range from 5 Hz to 100 Hz, which is a lower value for the vibration acceleration transmitted to the floor of the acoustically protected space than to the floor of the boiler room. This is also confirmed by the measured acceleration at the crossbeam (MP7) of the building structure. However, it should be noted once again that even with the boilers, and thus the entire boiler system, switched off, small vibration amplitudes were recorded at frequencies of 50 Hz and 88 Hz.

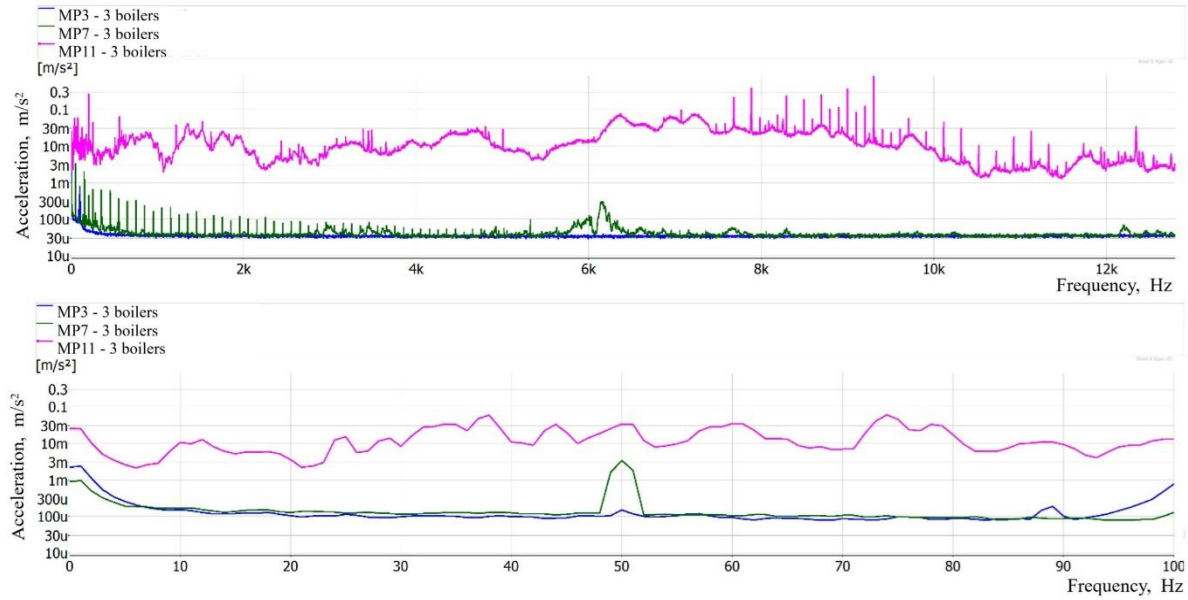


Fig. 4 FFT frequency analysis of vibration transmission through the hangers of the heating components and the partition wall during maximum operation

3.3 Transmission of Vibrations through Pipe System Hangers

Piping systems are typically suspended from the ceiling slabs of boiler rooms and storage rooms, which also serve as the floors of acoustically protected rooms (see Fig. 1, measurement point MP8). Vibration measurements were taken at the measurement point on the support section of the piping system's suspension (MP8) and on the floor of the acoustically protected space (MP2) while the heating system was operating at maximum capacity. From the perspective of structure-borne noise, however, the transmission of vibrations into the ceiling slab, and thus into the floor of the acoustically protected space, via the suspended mounting of

the piping systems is significant. Figure 5 shows that the suspended piping systems dampen vibration transmission up to a value of 1.176 mm/s², which is approximately 1.4 times higher than the vibration acceleration value transmitted to the floor of the acoustically protected space compared to that transmitted to the boiler room floor. During maximum power, an amplitude of 88 Hz was recorded, generated by the hot water supply and outlet pipes, which could not be controlled during the measurement.

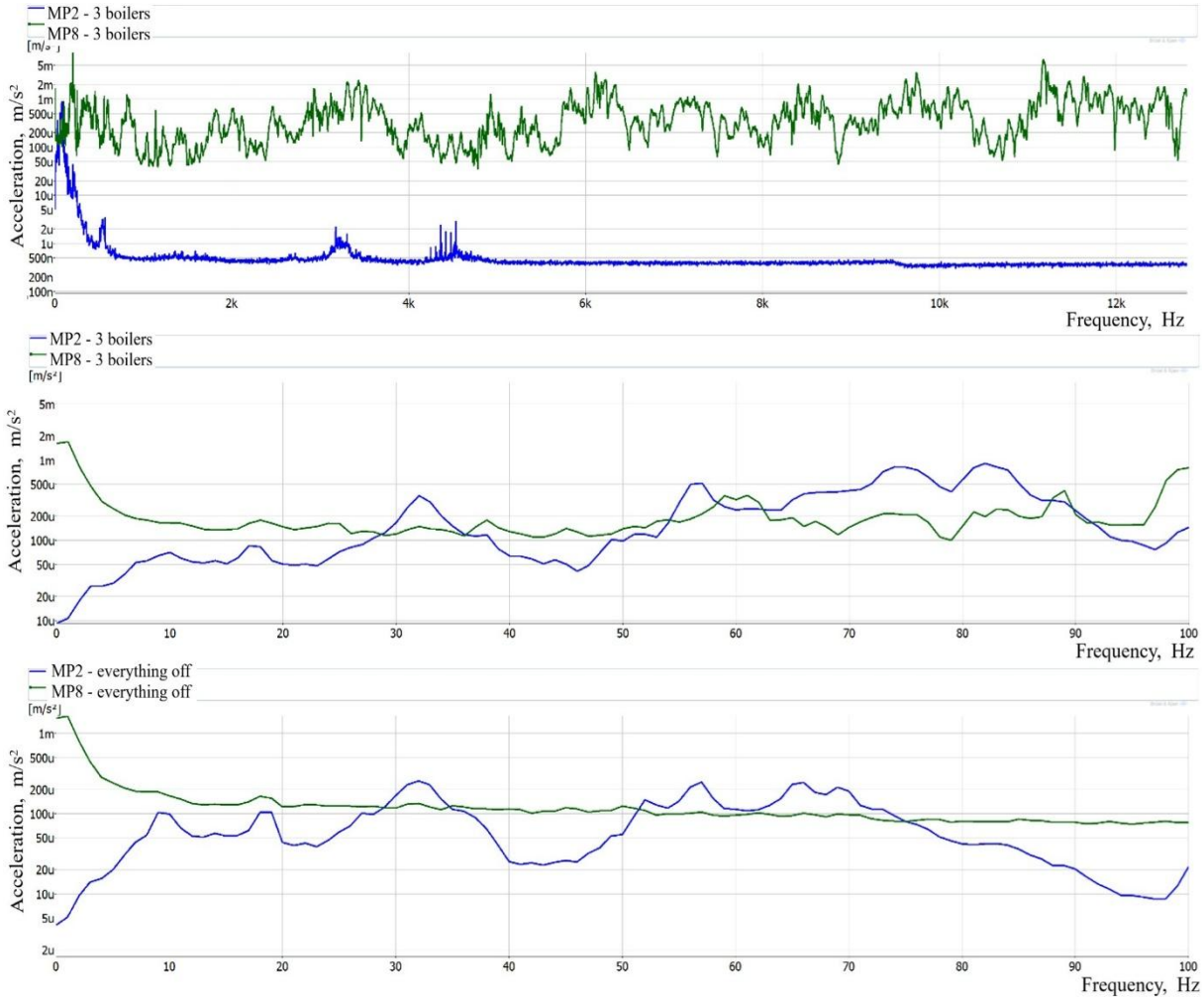


Fig. 5 FFT frequency analysis of vibration transmission through pipe system hangers during maximum operation and when the system is shut down

The measured vibration values at the above-mentioned measurement points indicate that the mounting of the boilers and the suspension of the heating components and piping system are not a source of significant structure-borne noise transmission into the acoustically insulated space that would negatively affect the acoustic comfort of the residents. The vibroacoustic analysis shows that the source of vibration, and consequently the source of structure-borne noise and noise generation in the acoustically protected spaces, is the piping systems, which are laid on the building structure's partitions without vibration isolation (see Fig. 7) [10, 12, 13].

The principle and intensity of low-frequency noise generation are primarily related to the flow of the medium through the piping [6-8]. Low-frequency vibrations and noise (structural-borne noise) propagate very well to more distant areas, while higher-frequency noise attenuates more rapidly with distance, which explains the possible rumbling of noise in acoustically protected areas. If the dimensions of the protected space correspond to the wavelengths of low-frequency noise and their multiples, standing waves or, more commonly, partial standing waves may form [11, 13], thereby amplifying the rumbling quality of the noise in these spaces. This

is most pronounced near the room boundaries and at the point of maximum amplitude. A condition for the excitation of standing waves is that one dimension of the enclosed space be at least half the wavelength of the acoustic wave present in the acoustically protected space. Therefore, the dimensions of the space, as well as the acoustic stiffness of the walls and their parallelism, are very important parameters that influence the acoustic conditions at the noise source and in the living space.

Modal and frequency analyses were used to determine the natural frequencies of pipeline systems up to 90 Hz. The natural frequencies of the pipe's mode shapes, when excited by water flow, can cause the pipe to enter a resonant vibration state. In this case, resonance means a significant increase in the amplitude of the pipe's vibration, and consequently an increase in the vibroacoustic energy transmitted through the building structure into acoustically protected spaces. In such a case, a tonal noise amplitude is generated which, when the wavelength (or half of that value) of this tonal amplitude corresponds to the characteristic dimensions of the acoustically protected space, will excite resonance, which noticeably increases the noise level in the enclosed environment and thus produces rumbling and annoying noise [5-8, 11, 13]. The frequency of 57 Hz, characteristic of household appliances, cannot be excluded from this range (see Fig. 9).

The dynamic analysis (vibration and noise) carried out shows that the analysed piping systems exert undesirable dynamic loads (vibration) on the surrounding building structures and, consequently, on nearby acoustically protected spaces. This problem can be solved by designing effective vibroacoustic measures using anti-vibration materials [3, 9, 15].

4 Damping of Mechanical Vibration Propagation – Implementation of Vibroacoustic Modifications

Structures made of typical building materials and reinforced concrete structures are good conductors of vibroacoustic energy; therefore, special attention must be paid to reducing the transmission of this energy from the source. Under certain conditions and compositions, the vibration-isolation structure itself creates conditions for the propagation of vibro-acoustic waves when it resonance. Any reduction in vibration in these structures has a positive effect on reducing the intensity of dynamic load transmission to building structures and, consequently, on reducing the emission of acoustic waves into acoustically protected spaces.

4.1 Determination of Transmission Attenuation in the Installation of Vibrating Heating Systems

The reflection of vibroacoustic waves occurs at those points in the structure where there is a certain discontinuity (e.g., a change in material or cross-section), resulting in a change in the mechanical impedance of the rigid structure, which is determined by the ratio of the tension in the structure to the vibration frequency of the elements of the radiating surface.

Under real conditions, in the case of longitudinal waves, a partial reflection of the incident wave energy occurs at the discontinuity. The remaining part of the energy passes through the interface, and the wave continues to propagate through the rigid structure. The physical phenomenon at the discontinuity can be expressed by the transmission factor, which is defined as the ratio of the vibrational energy that passes through the interface to the incident energy at that interface. If vibrational energy is defined in terms of vibrational intensity, then according to the above definition, the transmission factor is given by the relationship [15]

(1)

where

the intensity of the vibration that passed through the interface;

the intensity of the vibration acting on the interface.

If both parts of the surroundings are characterized by specific mechanical impedances , , then the transmission factor can be expressed in terms of these impedances. Let denote the velocity of the incident wave, the velocity of the reflected wave, and the velocity of the wave passing through the discontinuity. The stresses are denoted similarly. At the point of discontinuity, the following hold true:

a) equilibrium of stresses and (internal) forces;

b) continuity of mechanical vibration velocities.

This fact can be expressed using the quantities of vibration velocity and stress. Based on the law of momentum, the momentum of an element from a direct wave is equal to the sum of the momenta of the element from the reflected wave and the transmitted wave

$$= +$$

and of that, for velocity

$$= - \tag{2}$$

Furthermore, the equilibrium of forces, or stresses, at the point of discontinuity also holds: the sum of the forces on the left side equals the force on the right side at the point of discontinuity, or, expressed in terms of stresses,

(3)

and using the equation [15] equation (3) will be

(4)

Substituting from equation (2), equation (4) becomes, after rearrangement

(5)

By raising this relationship to a power and using the relationship [15] for the transmission factor, the following holds:

(6)

The transmission *d* factor is the base value used to calculate the transmission loss *D* (dB_{acc}) of the transmitted power

(7)

where the mechanical impedance *Z* can also be expressed by the equation for longitudinal or transverse waves

$$or \tag{8}$$

If , the reflection and thus the damping is zero. It follows from the above that the damping at the discontinuity is greater the larger the difference in impedance. The achieved transmission loss depends on the selected construction material. This finding is important when applying

flexible vibration-isolation elements to suspend piping systems and mount them on vertical building structures.

4.2 Realization of Vibro-acoustic Measures

Based on vibro-acoustic measurements, vibration analysis of the boiler and piping systems, and modal analysis of the piping systems, effective vibro-acoustic measures can be designed to achieve the required reduction in acoustic energy in acoustically protected spaces. These measures are aimed at interrupting the vibro-acoustic energy flow propagating from the vibration source through building and mechanical structures. In this case, it is desirable to implement certain measures aimed at interrupting vibro-acoustic bridges between piping systems and vertical building structures [3, 5, 9, 15].

Visual analysis and vibration measurements showed that when piping systems were mounted on building structures, vibroacoustic bridges were created, allowing energy from dynamic loads (vibrations) to flow into the building structures (Fig. 6). This causes the transmission of unwanted vibroacoustic energy from the vibration source to the structures surrounding the acoustically protected space, where it is transformed into acoustic energy. An increase in the area exposed to vibration results in increased acoustic energy radiation even in acoustically unprotected spaces.



Fig. 6 Mounting to the ceiling slab and installing the piping system on a crossbeam

When hot water is fed into a piping system and the water temperature changes, thermal expansion occurs within the system; when the piping is mounted directly on a vertical building structure, this causes, due to Coulomb friction, the generation of impulse noise, whose A-weighted sound pressure level at a distance of 1 m can exceed 50 dB. The generated impulse noise, as well as noise propagating through the piping, can be eliminated by creating a suitable discontinuity between the piping and the building structure. This means designing a transmission loss that ensures sufficient isolation of the vibroacoustic flow into the building structure. The transmission loss is calculated using Equation (7).

The transmission loss between the steel pipe and the reinforced concrete structure is only 3 dB_{acc}, which is insufficient. Inserting anti-vibration materials such as elastic polyurethane damping materials (Texizol, Sylomer®, Sylodyn), rubber, cork, reinforced fabrics, Novodur, and other similar materials will significantly increase the transmission loss. Therefore, the technology of compositions of glued layered materials should also be utilized [17]. The sound insulation between the damping material and the concrete can reach up to 30 dB_{acc} with a vibration-isolating material thickness of 30 mm [15]. Applying these materials, which are laid on a flat substrate, prevents the generation of structure-borne noise and thereby improves human acoustic comfort in acoustically protected spaces. Installation can be achieved using two

vibration-isolating materials with a combined thickness greater than 30 mm and different mechanical impedances, which effectively prevents the transmission of vibroacoustic energy into building structures. In this case, the piping is mounted on a vertical crossbar through which it passes, so that there is no direct contact between the pipe wall and the reinforced concrete building structure. An example of a piping system mounting is shown in Fig. 7. However, such installations are often complex in shape due to the need to fulfill multiple functions, such as ensuring vibration-isolation properties as well as sound insulation between rooms. For such cases, these shapes made of viscoelastic materials can be cut using production technologies such as laser cutting [18].

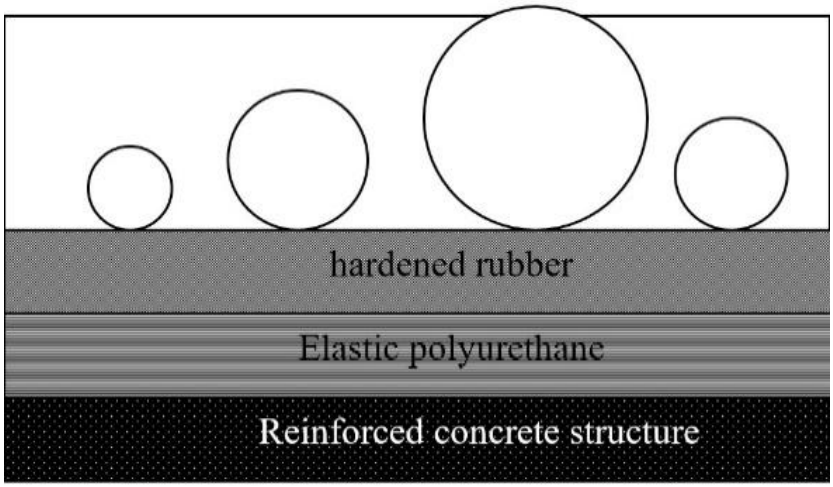


Fig. 7 Example of piping installation on building structures

DISCUSSION AND CONCLUSION

Measurements taken in acoustically protected areas, in the boiler room, and at the suspension points of the piping systems indicated increased dynamic loads from these piping systems on the surrounding environment. The flow of liquid in heating and cold and hot domestic water piping systems at operating velocities is practically silent. Fluid flow, when the direction of flow changes, excites the natural frequencies of the piping system, causing resonance in a system that is either freely suspended or supported by building structures. It should be noted that even a low excitation force is sufficient to induce a resonant state. The excited pipe systems under analysis generate natural vibration frequencies and, consequently, tonal noise in the low-frequency range. Thus, the dynamic analysis revealed that the analysed piping systems exert an increased dynamic load on the surrounding building structures, and consequently, on nearby acoustically protected spaces, which causes low-frequency noise that disturbs residents. This was also confirmed by sound insulation measurements at measurement points MP1 (acoustically protected space) and MP4 (boiler room). Figure 8 illustrates the sound insulation of the building structures between the acoustically protected space and the heating system, presented as A-weighted sound pressure levels in the third-octave band at maximum output. The low-frequency noise level is more pronounced in the acoustically protected space at low frequencies, depending on the frequency.

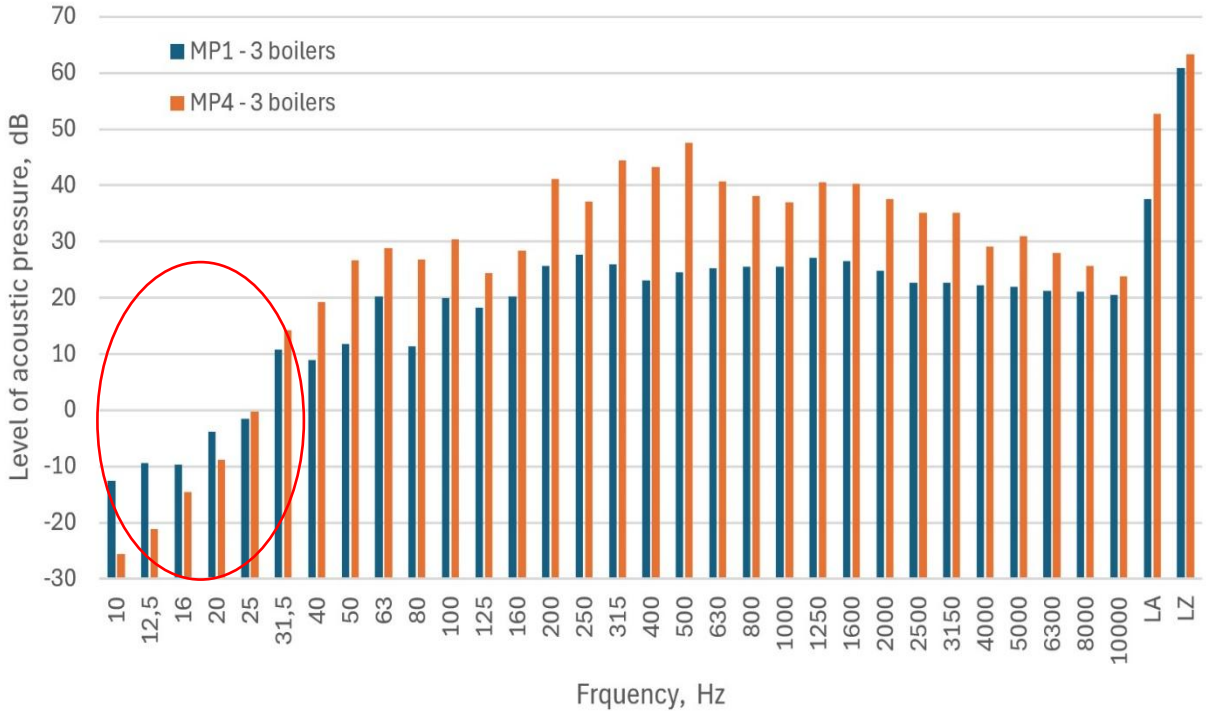


Fig. 8 Third-octave analysis of A-weighted sound pressure levels measured in the boiler room and in the acoustically protected space at maximum power

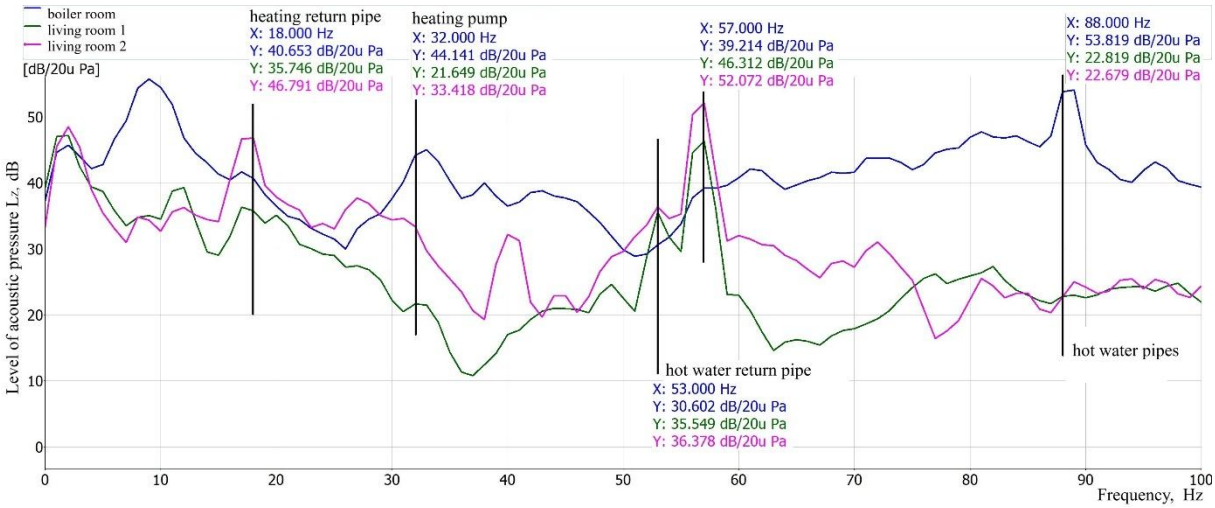


Fig. 9 FFT frequency analysis of noise in the acoustically protected room and in the boiler room

Vibroacoustic measurements showed that, as a result of disturbing the basic principles of piping system installation, vibroacoustic bridges were formed; their elimination is proposed in Chapter 4.

A source of noise in hot-water systems can be noise from pipe expansion, which, when the pipes are improperly installed, causes impulse noise. Both of these types of noise reduce the quality of the indoor acoustic environment and, consequently, human comfort. In general, it can be stated that this noise has not exceeded the permissible level set by legislation; nevertheless, this noise has a negative effect on human sleep and well-being, as it is low-frequency tonal noise that generates standing or partially standing waves, resulting in rumbling noise [5-7, 11-13, 16].

The FFT frequency analysis in the low-frequency range confirms a prominent 57 Hz frequency generated by internal sources located within the analyzed acoustically protected space, as this frequency has a significantly lower amplitude in the boiler room (Fig. 9). Similarly, a more significant amplitude was recorded at 18 Hz, which is noticeably lower in the boiler room, as well as at 40 Hz. These frequencies may negatively affect residents' relaxation. In the boiler room, more pronounced noise amplitudes were measured at frequencies near 9 Hz, 32 Hz, and 88 Hz, whereas these amplitudes were not as pronounced in the acoustically protected space.

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REFERENCES

[1] Alves-Pereira, M., Castelo Branco, N. "Clinical protocol for evaluating pathology induced by low frequency noise exposure", In: Euronoise, Maastricht, Netherlands, pp. 2653 – 2658, **2015.**

[2] Castelo Branco, N., Alves-Pereira, M. "Low frequency noise-induced pathology: contributions provided by the Portuguese wind turbine case", In: Euronoise, Maastricht, Netherlands, pp. 2659 – 2663, **2015**.

[3] Danko, J., Dobrovolný, J., Magdolen, Ľ., Milesich, T., Kevický, I., Bernáth, M., Nemec, T. "Parametric generation of datasets for the creation of reduced order models of rubber-metal elements", Strojnícky časopis – Journal of Mechanical Engineering 75 (1), pp. 1 – 8, **2025**. DOI: 10.2478/scjme-2025-0001

[4] Darula, R., Žiaran, S. "On experimental study of optimal measurement point location for gear wheel state-of-wear measurements by means of vibro-acoustic diagnostics", Strojnícky časopis – Journal of Mechanical Engineering 62 (2), pp. 61 – 79, **2011**.

[5] Chlebo, O., Žiaran, S., Hučko, B., Čekan, M. "Reduction of tonal noise in residential buildings", Akustika 31, pp. 36 – 44, **2019**.

[6] Žiaran, S., Šooš, Ľ., Čačková, I., Chlebo, O. "Low frequency sound generated by industrial equipment and its negative impact on human health", Strojnícky časopis – Journal of Mechanical Engineering 75 (2), pp. 131 – 142, 2025. DOI: 10.2478/scjme-2025-0030

[7] Žiaran, S., Chlebo, O. Čačková, I. "Low-frequency noise annoying residents in the vicinity of industrial plants and heating plants", In: Proceedings of scientific papers "Living conditions and health", Issued by Comenius University in Bratislava, pp. 51 – 59, **2025**.

[8] Žiaran, S., Čačková, I., Chlebo, O. "Wind turbines generate low-frequency noise that affects human health within their low-frequency range", In: Proceedings of scientific papers "Living conditions and health", Issued by Comenius University in Bratislava, pp. 32 – 38, **2026**.

[9] Žiaran, S., Chlebo, O. "Effects of isolating machine vibrations on the transmission of structure-borne and air-borne sound energy", In: Proceedings of the INTER-NOISE 2017, Hong Kong, China, pp. 6335 – 6344, **2017**.

[10] Žiaran, S., Chlebo, O. "Structure-borne noise generated by means of cogeneration units in boiler-plants". In: Proceedings of the INTER-NOISE 2016, Hamburg, Germany, pp. 7481 – 7490, **2016**. ISBN 978-3-939296-11-9

[11] Ziaran, S. "Potential health effects of standing waves generated by low frequency noise", Journal Noise and Health 15:65, pp. 237 – 245, **2013**. DOI: 10.4103/1463-1741.113518

[12] Žiaran, S. "Analysis of annoying low frequency noise boiler-rooms", In: INTER-NOISE 2009: The 38th International Congres & Exhibition on Noise Control Engineering, Ottawa, Canada, 23.-26.08. 2009. – b.m.: INCE/USA, **2009**.

[13] Žiaran, S. "Low-frequency noise and vibration", Scientific monograph, Issued by STU in Bratislava, ISBN 978-80-227-4536-9, pp. 316, **2016**.

[14] Žiaran, S. "Technical diagnostics", Scientific monograph, Issued by STU in Bratislava, ISBN 978-80-227-4051-7, pp. 332, **2013**.

[15] Žiaran, S. "Vibration and Acoustics. Noise and Vibration Reduction in Industry", Scientific monograph, Issued by STU Bratislava, ISBN 80-227-2366-5, pp. 330, **2006**.

[16] Žiaran, S. "Protection of Humans against Vibration and Noise", Issued by STU Bratislava, ISBN 978-80-227-2799-0, pp. 264, **2008**.

[17] APVV-23-0619 "Research of progressive technology of decomposition of glued layered materials".

[18] VEGA 1/0387/24 "HAZ index analysis of carbon fibre reinforced plastic (CFRP) composites using quasi-continuous wave (QCW) fibre laser".

[19] STN ISO 5348: Mechanical Vibration and Shocks. Mechanical Mounting of Accelerometers. Published in Switzerland, **2024**.

[20] STN ISO 4866 Mechanical vibration and shock. Vibration of fixed structures. Guidelines for the measurement of vibrations and evaluation of their effects on structures. Published in Switzerland, **2023**.