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METHODOLOGY OF PROGNOSTIC VIBRO-ACOUSTIC ANALYSIS OF BUILDINGS FROM POTENTIAL DYNAMIC LOADS GENERATED BY RAIL VEHICLES

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Abstract: The dynamic load generated by traffic has a negative impact not only on human health and a well-being, but also on the lifetime of building structures. The article deals with the proposal of the prognostic vibro-acoustic analysis methodology of the building of the Slovak National Theatre, which, based on real vibro-acoustic measurements on a similar elevated building structure and potential sources of excitation, was applied to the premises of the cultural stand. The article also analyses the impact of vibration transmission from a potential source, which is a rail vehicle, on the generation of low-frequency noise in acoustically protected spaces.

KEYWORDS: rail vehicle, vibration, transmission, low-frequency sound, protected spaces.

1 Introduction

Noise sources mainly originate from the mechanical vibration of parts of a rigid flexible environment and also from the generation of an electromagnetic field. The noise caused by mechanical vibration is generally distributed in the lower and middle frequency band, and the noise of electromagnetic origin is in most cases derived from the power supply frequency. The more significant values are also in the area of low and middle frequencies, which is typical for the drives of rail vehicles, such as trams. Trams are among the noisiest vehicles in the traffic flow, whose noise generation also depends on the mounting of the railway track. Rail vehicles generate excessive amplitudes of low-frequency vibration propagating over a relatively long distance, depending on the subgrade. The intensity of such vibrations threatens the health and comfort of people and the lifetime of building structures [1, 2, 6, 10].

The stated methodology of prognostic vibro-acoustic analysis can be generalized and applied in the design of the construction site of building structures sensitive to vibro-acoustic energy with known sources of dynamic load or, conversely, to investigate the influence of a potential source of dynamic load on vibro-acoustic protected building objects.

Based on previous experience in the specified area, a methodology for prognostic vibro-acoustic analysis of the building was developed in connection with the planned construction of a railway track near the building of the cultural stand [6]. In order to apply a correct assessment of the effects of tram crossings on the vibro-acoustic load of the places of the building, it was necessary to find a railway track similar to the proposed track, i.e. a scaffold bridge connected to the classic earth embankment subgrade, and during the passage of rail vehicles, in particular, to measure the acceleration of vibrations. The goal was to evaluate the difference in the generation of vibro-acoustic energy of a railway track placed on an elevated building structure (the scaffold bridge) and on an earth embankment subgrade, which is the case of the planned railway track above the underground garages in front of the SND (Slovak National Theatre)

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building (Fig. 1). However, it should be emphasized that the commonly used vibro-acoustic sources of impact excitation cannot replace a real source, which is a tram generating much greater dynamic force [5, 7, 12]. Thus, if we talk about the dangerous frequency distribution of excitation forces with respect to buildings, then the upper limit of the load is significantly higher than stated in already realized measurements using heavy impact sources [16], while natural and technical seismicity is taken into account up to 35 Hz [8].

Typical increases in vibration and therefore the noise of railway vehicles operated on elevated structures (the scaffold bridge) depend on the type of structure and can reach up to 10 dB higher values compared to the normalized (standard) conditions of mounting the track on the earth (embankment) subgrade. That is, the rate/degree of attenuation of the railway track on elevated structures is therefore lower than on a normal track mounting on the ground [6]. Hence, in order to analyse the effects of dynamic excitation from tram crossings on the operation of the cultural stand and its lifetime, it is desirable to look for a similar placement of the tram track as planned in front of the SND building (Fig. 1).



Fig. 1 Assumed solution of the track in front of the SND building and the track placed on the earth embankment and the scaffold bridge

In general, the maximum values of the dynamic load of acoustically protected spaces are achieved when the Eigen frequencies of the Eigen modes of building structures correspond to the excitation frequencies. Thus, building components of acoustically protected spaces are characterized by natural frequencies which, when they coincide with the excitation frequency, cause resonance of the component, and thus also the possibility of standing or partially standing waves in the vibro-acoustically analysed spaces. In such a case, a low-frequency rumbling noise is generated, which can adversely affect the acoustics of the given space [12]. The analysis of the results of measurements of vibration acceleration on the scaffold bridge will show the possibility of coincidence of the excitation frequency with the natural frequencies of building structures, as well as the possible generation of low-frequency, the so-called rumbling noise in underground garages and in adjacent acoustically protected spaces. However, it should be emphasized that in prognostic measurements it is an open space, and in the case of a closed space, which is the planned case of running a railway track a closed underground space, the noise level will increase several times (see Fig. 1 left).

2 Objectives, methodology of vibro-acoustic measurements and measurement technique and measurement points

2.1 Objectives

The aim of the vibration acceleration measurements at the selected measuring location was to analyse the potential vibro-acoustic straining of the building structures and spaces of the SND building, i.e. to measure the vibration acceleration on a structurally similar section of the tram track (laid on the ground and on the scaffold bridge), as planned in front of the cultural stand (see Fig. 1), since laying the track on the scaffold bridge generates significantly higher

vibro-acoustic energy than laying the track on an earth embankment subgrade [6]. The goal of the experimental modal analysis was to determine the Eigen frequencies of the Eigen modes of the selected building structures in order to assess the possible correspondence of the natural frequencies with the excitation frequencies generated by the passage of trams. Modal analysis was performed on selected vertical walls, mainly perpendicular to the direction of propagation of longitudinal and transverse seismic waves from the potential source of excitation, which should be a tram passage near the building. The modal analysis was also performed on the floors in the individual halls and in the underground parking lot on the floor, wall and also on the ceiling panel.

2.2 Methodology of prognostic vibro-acoustic analysis

The assessment of the effects of vibration on buildings is mainly focused on the response of the building structure. The influence of the intensity of excitation of building structures from the passage of rail vehicle will depend primarily on the mass and speed of the tram and the quality of the driving profile of the wheel and rail [14, 15]. However, it should be emphasized that the excitation of the Eigen frequencies of the Eigen modes of building structures is not dependent on the speed of the rail vehicle.

As a rule, the vibration acceleration parameter is transformed into the vibration velocity in mm/s, which represents the severity vibration, according to which the dynamic load of building structures is evaluated [13]. The measurement was carried out at different speeds of several trams and at approximately the same running path of the railway track. The object of measurement was the selected measuring points of the scaffold bridge and the subgrade near the rail and support columns [6, 9, 11].

Building structures are predominantly made of reinforced concrete components, which are a very good conductor of vibro-acoustic energy from the primary source, which is the contact of the wheel with the rail, to large-scale acoustically protected spaces of cultural production. In the analysed case, all the foundation and load-bearing building structures were made of reinforced concrete lying on a sandy subsoil with a high level of groundwater, which are favourable conditions for the propagation of low-frequency waves.

The reduction of vibration energy generated by the rolling of the wheel on the rail, transmitted to the supporting building structures (pillars) of the scaffold bridge, depends on the transmission attenuation from the source through the vibro-isolation to the reinforced concrete block of the scaffold bridge. Thus, the transmission of vibration energy through the structural blocks of the scaffold bridge depends on their construction, the material used and the method of application (modification of contact surfaces, mounting and attachment) [3, 4, 8, 9, 12]. By comparing the amplitudes of the frequency characteristics of the acceleration at the output with the input, in decibels, for individual structural blocks, significant differences in the values of the vibration acceleration representing the transmission loss of the vibration energy depending on the frequency were recorded. Thus, the dynamic load of building structures is influenced by the unevenness of the rail and the running profile of the wheel, the placement of the rail, especially its vibration isolation, as well as the roughness of the rail, and with increasing roughness, their dynamic load also increases [14, 15].

By means of the measured vibration acceleration, the transmission loss from the auto-spectra at the entrance (reference measurement point) and exit through the support structures of the scaffold bridge was also analysed, namely at the level of the foundation of the support columns of the scaffold bridge. It should be emphasized that the transmission loss decreases with decreasing frequencies and therefore, if technical seismicity is to be analysed, the transmission loss will be negligible.

In order to assess the dynamic load in accordance with the valid standards and based on the professional experience of the authors, the acceleration of the mechanical vibration was transformed into the vibration velocity and the effective velocity representing the vibration severity was also determined [3, 8, 9, 13]. The maximum dynamic force generated by the passage of the tram $F_{\max} = ma_{\max}$, where m is the mass of the tram including the mass of the corresponding part of the scaffold bridge and $a_{\max}$ is the measured maximum acceleration of vibration, is transmitted through the support columns to the subgrade and the generated wave propagates through the subgrade, where it has a negative effect on the lifetime of the surrounding constructions.

Since this paper presents a proposal for a railway track above underground garages, it was desirable to find an equivalent real measurement environment and measurement conditions corresponding to the planned railway track (Fig. 2). After a detailed analysis of the possible location of the planned tram track [6], a similar measurement point corresponding to the actual location of the placed track was found. It should be emphasized that the actual excitation source was also very important, which, in this case, could not be replaced by standard impact excitation machines [16].



Fig. 2 Equivalent real measurement environment of mounting the rail track on the ground embankment and on the scaffold bridge

To approximate the results of the real situation in the best possible way, the selected environment where the measurement was supposed to be carried out was taken into account before and after the dilatation joint, which separated the railway track laid on the earth embankment subgrade and on the scaffold bridge (Fig. 2 bottom left). Vibro-acoustic measurements were performed as close as possible to the track (Fig. 2, top right).

The measurement environment under the scaffold bridge is shown in Figure 2 (bottom right). Vibro-acoustic measurements were performed at a reference point near the railway track and at the location of the surface of the support structures in three mutually perpendicular directions [13].

The measurement of vibro-acoustic parameters (vibration acceleration and sound pressure) was carried out while the trams were moving on an equivalent real measuring section with a different operating speed from 33.8 km/h to 46.8 km/h. In total, the passage of thirteen trams was measured, which exceeded a significant statistical sample, and a sufficient number of vibration parameters were obtained for a correct assessment of the dynamic load of the elevated building structure (the scaffold bridge) and its surroundings for possible further dynamic analysis. At the same time, the acoustic pressure was also recorded when the tram passed

(Fig. 2, top left). The only source of dynamic straining on the scaffold bridge were new trams passing in both directions (see Fig. 1).

2.3 Measuring technique and measuring points

A modern measuring technique from the Bruel & Kjaer (B&K) company was used to measure mechanical and acoustic vibrations, namely the 12-channel B&K PULSE measurement card; accelerometers with usable frequency ranges of 0.2 Hz – 12 800 Hz; accelerometer B&K 8340 with a usable frequency range from 0.1 Hz to 150 Hz sensitivity to 10 000 mV/g (seismic sensor) and weighing 775 g; an integrating vibrometer for measuring acceleration with the output of vibration severity, which is a quantitative and qualitative indicator of dynamic straining of building structures, as well as impact load in accordance with the ISO 4866 standard [13]; a sound analyser with a usable frequency range up to 25 600 Hz for control recording of measured signals, including residual noise; a B&K impact hammer with a maximum impact force of 35 584 N to excite the building structure's natural vibration modes during the verification of the measuring chain and other additional technology supporting the measurement [11].

3 Analysis of the time history of the passage of trams

The time records shows the course of the kinematic excitation generated by the unevenness of the running profile of the wheels of the rail vehicle and the unevenness of the rails. In addition to the mass and speed of the vehicle, the amplitudes of impact excitation are also significantly dependent on the perfection of the contact surface of the wheel with the rail [14, 15]. Figure 3 shows the measurement locations in the horizontal direction perpendicular to the track and in the vertical direction and the time history of the measured vibration accelerations from the dynamic load generated by the passing of the tram over the measured section of the track laid on the embankment and on the scaffold bridge for the defined measuring points in the vertical direction, in which the highest values were measured. Figure 4 shows the time history of the transmission of vibro-acoustic energy from the reference measurement point on the scaffold bridge to the anchor point of the support columns. The time records show the transmission of vibrations from the reference point R to the base of the support columns anchor in the x, y and z axes.

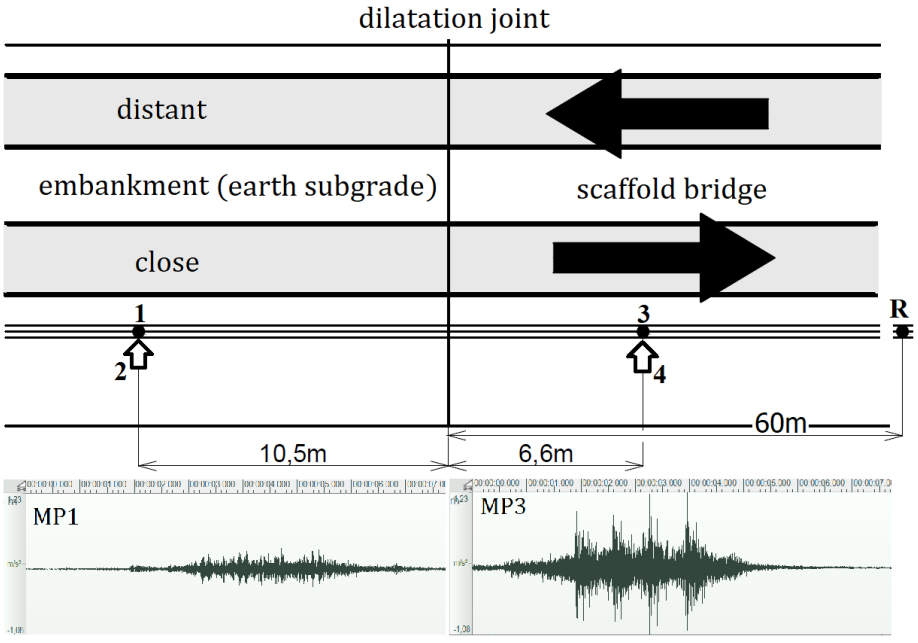


Fig. 3 Measuring points near the rail track lay and time history of tram passage at measurement points 1 (track on the ground surface – left) and 3 (track on the scaffold bridge – right) in the vertical direction

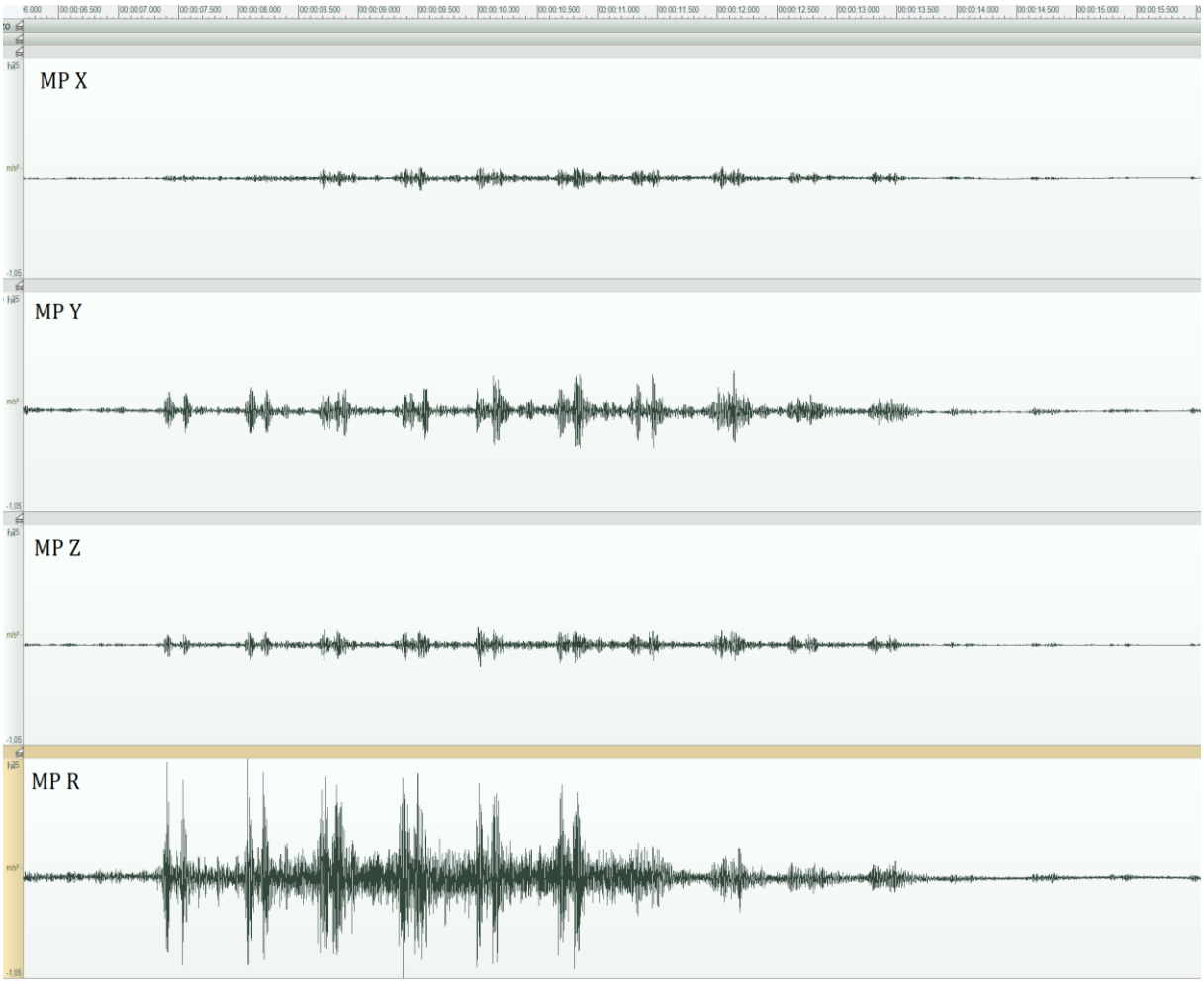


Fig. 4 Time history of the tram passage at the measurement points in the mounting of the support columns of the scaffold bridge in the x, y, z directions and at the reference point R.

Even from the time history obtained on the embankment and the scaffold bridge, a significant difference can be seen between the passage of the tram on the embankment and on the scaffold bridge. The time history represents the acceleration of the generated vibration, which when multiplied by the mass of the elevated building structure, including the mass of the tram, gives the impact excitation force acting on its mounting and supporting structures. And this maximum impact excitation force can be estimated to reach hundreds of kN.

4 Frequency analysis of vibrations during passing trams

4.1 Frequency analysis near the railway track

The frequency response analysis near the track laid on the ground and the scaffold bridge was carried out in the vertical direction and in the horizontal direction perpendicular to the rails at the measurement points according to Figure 3. The aim of these measurements was to show the difference in the dynamic excitation of the surrounding environment when a rail vehicle passes over a classic earth subgrade of the track and when the track is placed on a scaffold bridge.

It can be seen from the frequency analysis that the frequency spectra contain significant amplitudes in the area of low frequencies (technical seismicity), from 1 Hz to 35 Hz (Fig. 5). Most damage to buildings by sources caused by human activities occurs in the frequency range from 1 Hz to 150 Hz [13]. This frequency range, in the range up to 100 Hz, is compared in the next section of the article with the amplitudes of the frequency spectra obtained by experimental

modal analysis, i.e. the natural frequencies of the load-bearing structures bounding the acoustically protected spaces of cultural events.



Fig. 5 FFT analysis of the vibration near the track laid on the ground embankment (blue) and on the scaffold bridge (green) in the vertical direction (top) and in the horizontal direction (bottom) with respect to the background.

4.2 Frequency analysis of the transmission of vibrations from the rail track to the mounting of supporting structures

The frequency response analysis near the mounting of the scaffold bridge support columns was performed in the vertical direction and in the horizontal plane in two mutually perpendicular directions at the measurement points respecting the ISO 4866 standard (see Fig. 2 bottom right [13]. The aim of the measurements was to confirm the transmission of vibro-acoustic energy during the passage of the railway vehicle into the surrounding constructions and during the laying of the railway track on the scaffold bridge.

The frequency transmission of vibro-acoustic energy from the reference measuring point, i.e. the point near the railway track through the supporting columns to their mounting point, is shown in Figure 6, and the time history is shown in Figure 4. The FFT analysis confirms the frequency conformity with the measurement near the track (see 4.1). The difference is only in the size of the amplitude. This frequency range, in the range up to 100 Hz, is compared in the next part of the article with frequency spectra obtained by experimental modal analysis.

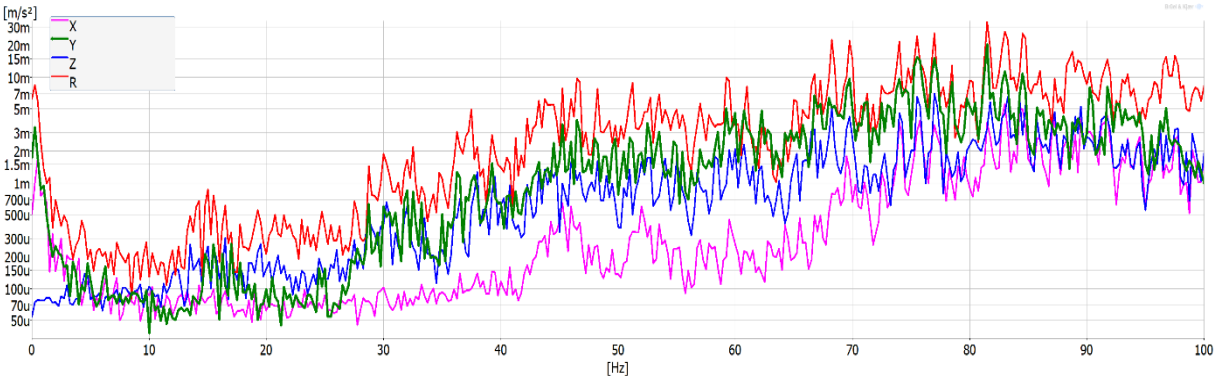


Fig. 6 FFT analysis of the vibration of the scaffold bridge and its supporting structure

5 Experimental modal analysis of the support structures of the hall

The experimental modal analysis is used to determine the Eigen frequencies of the Eigen modes of components of building as well as technological structures with the aim of comparing them with excitation frequencies in order to identify resonance areas of building or technological structures. Structural vibration problems generated by external sources represent significant risks and limitations in the design of a wide range of building and technological structures. They can be the cause of damage to the integrity of these structures. Vibration also causes noise generation and has a negative impact on the surrounding environment, especially in restricted spaces. The modal properties of the structure itself also contribute to the increased dynamic load. These properties were determined and then evaluated by experimental modal analysis, the results of which made it possible to predict the behaviour of a building or technological structure during its operation under unwanted external excitation by real sources.

With the help of the obtained natural frequencies, it is possible to determine dangerous operating conditions that a well-designed building or technological structure must avoid. If the natural frequencies coincide with the frequencies of the excitation forces, the resonance of the structure or its part will occur, which increases the risk of their damage and, at the same time, the creation of an undesirable acoustic field with possible standing waves, and in large-scale spaces of cultural facilities, this can be generated as a rumbling noise.

The aim of these measurements was to obtain the values of vibration acceleration at the point of excitation by the impact hammer and at selected measurement points on vertical walls and floors in acoustically protected spaces. The measurement results were used in the determination of the natural frequencies of the building structures bordering the operating halls. From the point of view of the dynamic load of the analysed building structures, it is necessary to have information about the natural frequencies when excited by an external source, i.e. by passing a tram. Load-bearing bare concrete walls were selected for the experimental modal analysis. The measurement points for the modal analysis with a detailed attachment to the rear and side walls and the floor are shown in Figure 7.

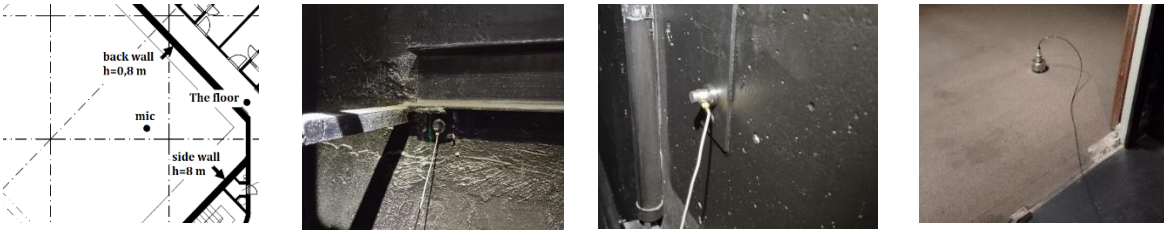


Fig. 7 Siting the measuring points in the opera and ballet hall with accelerometers attached to vertical load-bearing walls and to the floor

From the experimental modal analysis, it can be seen that the frequency spectra contain significant amplitudes in the area of low frequencies (technical seismicity), from 1 Hz to 35 Hz (Fig. 8), which also coincide with the frequency spectrum of the wall-generated sound excited by the impact (Fig. 8-below). Most damage to the building by sources caused by human activities occurs in the frequency range from 1 Hz to 150 Hz [13]. This frequency range, in the range up to 100 Hz, is compared in the next chapter of the article with the amplitudes of the frequency spectra generated on a similar mounting of the railway track as planned in front of the cultural stand, that is, with the frequency spectra obtained from the measurements on the scaffold bridge. The danger of damage to building structures increases with the decreasing frequency, as lower frequencies are energetically stronger and largely coincide with the natural frequencies of building structures.

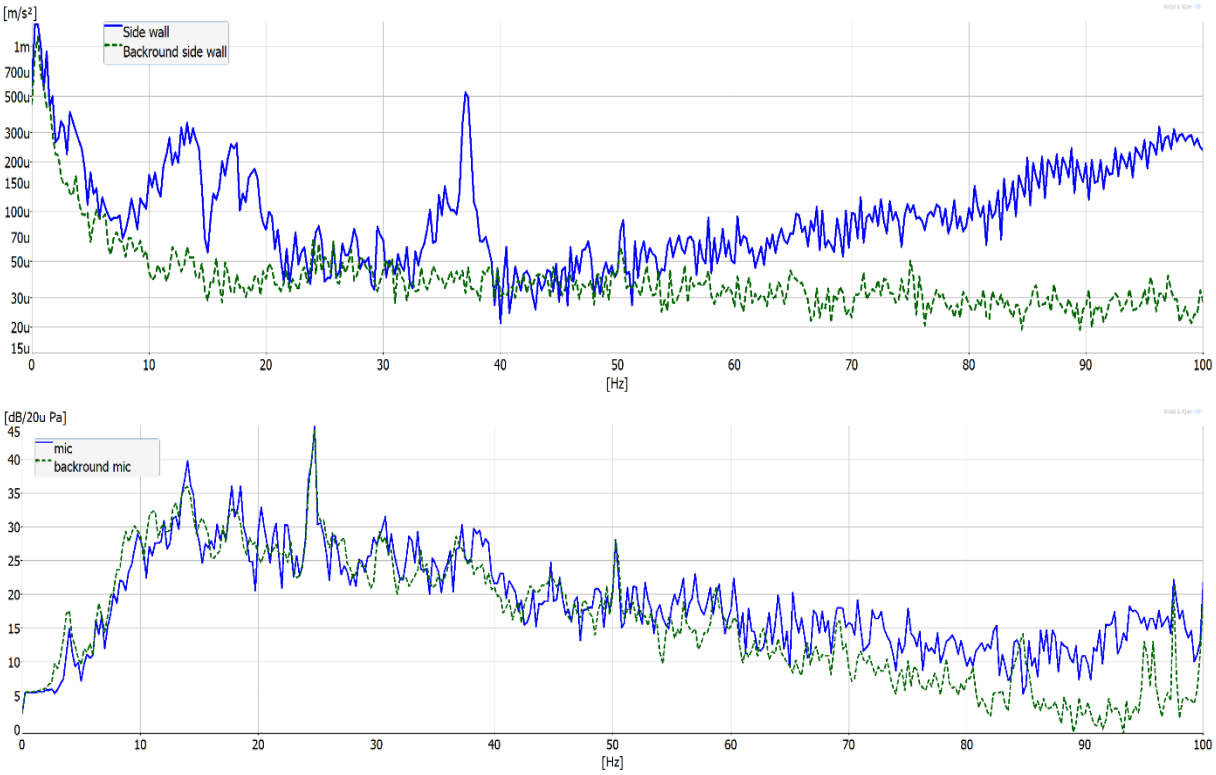


Fig. 8 Experimental modal analysis of load-bearing wall and frequency analysis of sound during modal analysis in an opera and ballet hall

5 Comparison of vibration frequency spectra with modal analysis

The frequency analysis on the scaffold bridge showed the generation of more significant amplitudes of low-frequency vibration up to 80 Hz (see Fig. 5 and 6). These are primarily low-frequency tone frequencies from approximately 5 Hz to 80 Hz. When these frequencies are transmitted to the SND building, they can excite the natural frequencies (resonance) of the measured building structures in this space and, through standing waves, or partially standing waves, generate rumbling and annoying noise [12]. The maximum values of the sound pressure levels are achieved primarily at the boundary of the room.

As already noted, the attenuation of seismic waves (up to 35 Hz) propagating from the source through the environment is negligible. From Fig. 9 shows the excitation of seismic wave frequencies by the potential passage of a tram, where a conformity is found with the natural frequencies of building structures obtained by experimental modal analysis. It is therefore likely that the passage of train vehicle will cause vibrations in the building structures bordering the

operational halls of cultural events and thus low-frequency acoustic waves in these large-scale rooms.

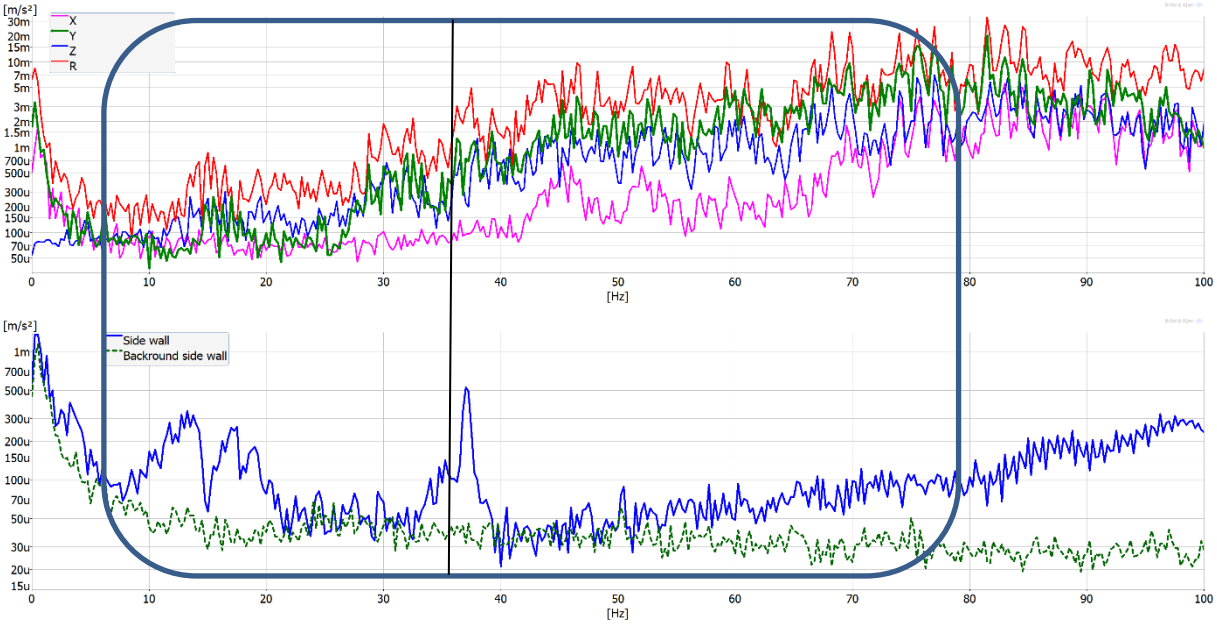


Fig. 9 Comparison of the frequency analysis of vibration on the elevated building structure (upper spectra) with the experimental modal analysis of the building structures of the SND building (lower spectra)

By means of the experimental modal analysis, the Eigen frequencies of the Eigen modes of vibration for the selected bounding building structures of large-scale halls were determined. The natural frequencies of building structures when excited by the passage of a railway vehicle can cause a resonant state of vibration of this structure. Resonance in this case means a significant increase in the structure's vibration amplitude and thus, also an increase in vibro-acoustic energy, which is transmitted by the building structure to acoustically protected spaces. In such a case, it involves the generation of a tonal noise amplitude which, when the dimensions of the wavelength (or its half value) of this tonal amplitude coincidence with the characteristic dimension of the acoustically protected space, will generate standing or partial standing waves heard as rumbling noise.

DISCUSSION AND CONCLUSION

Experimental tests of the vibration parameters were carried out when the trams passed over a track laid on a classic earth subgrade and subsequently on an elevated building structure (the scaffold bridge). An experimental modal analysis was performed on selected load-bearing structures in the large-area halls of the SND and in the underground garage, above which the railway track is planned to be mounting, with the aim of finding a coincidence between the potential excitation frequencies generated by the passage of a rail vehicle near the cultural stand with the natural frequencies of the load-bearing building structures of this building. The performed experiments confirmed a possible coincidence between the excitation frequencies generated by the potential passage of a rail vehicle in front of the analysed cultural stand and the natural frequencies of the load-bearing building structures of this cultural stand, which would lead to faster fatigue damage of the load-bearing building structures. The excitation of resonance of building structures results in the generation of low-frequency noise and the potential excitation of standing or partially standing waves (rumbling noise) in large-scale halls, which was confirmed in the experimental modal analysis.

The expressed ratio of the values of the measured effective vibration speeds in the field of technical seismicity on the scaffold bridge and on the classic earth embankment subgrade during tram crossings is more than 10 times higher on the scaffold bridge than on the ground subsoil. It should be emphasized that the square of the vibration velocity represents the kinetic energy that performs undesirable fatigue-destructive work on buildings located near train vehicle crossings. It should be borne in mind that the assumed vibration-insulating placement of the railway track above the underground garages will have negligible attenuation at seismic frequencies [3, 8, 9, 10, 12].

The results of the conducted experiments and similar projects solved so far speak against the construction of a railway track on an elevated building structure (ceiling slab of a garage) (see Fig. 1) [6]. This is also confirmed by a very significant ratio of effective vibration velocity, which, as mentioned above, is more than 10 times higher on an elevated building structure (the scaffold bridge) than on the ground.

From the performed dynamic analysis, it follows that the analysed elevated structure (the scaffold bridge) during the passage of rail vehicle exhibits an undesirable dynamic load on the surrounding building structures and thus also on nearby acoustically protected spaces from the point of view of generating low-frequency noise (rumbling noise) and also causes permanent fatigue damage to them.

The excitation of seismic wave frequencies by the passage of the tram is evident from Fig. 9 and there is certainly a coincidence with the natural frequencies of building structures obtained by experimental modal analysis. Based on the coincidence of the Eigen frequencies of the Eigen modes of the load-bearing building structures delimiting the environment of the theatre halls and the opera hall with the frequencies excited by passing trams (see chapter 6), acoustic low-frequency waves are generated that can affect the acoustic environment in these halls [6].

Solving the problems related to this practical task also required a theoretical research of the expert knowledge presented in the publications found below. Most of them are publicly available. In the implementation of this project, the theoretical and experimental knowledge was obtained as part of the project “Progressive hybrid high-speed spinning actuator”.

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