Janas L.

Rzeszów University of Technology
Faculty of Civil and Environmental Engineering
Poland, 35-959 Rzeszów, W. Pola St. No. 2
E-mail: ljanas@prz.edu.com

IDENTIFICATION OF THE NOISE SOURCES IN A STEEL RAILWAY BRIDGE

This paper presents the results of a noise study in the areas surrounding a railway line and a bridge, in a large municipal agglomeration. Sound characteristics were determined in the one-third octave bands and narrow frequency bands, and bridge vibration studies were carried out. The relationships between the vibrations of some elements of the structure and the acoustic pressure in its environment were revealed by applying a coherence function. The sources of excessive noise emissions to the surrounding environment were identified, and solutions for modernizing the railway infrastructure of the region were proposed.

Introduction. Moving railway transport vehicles are sources of noise, and determine the acoustic climate around railway lines. Bridge structures can also act as sources of noise when railway vehicles travel over them [1, 2]. In addition to the aerodynamic noise of travelling vehicles, and the sounds emitted directly by wheels and rails when they pass over steel bridges, the transverse vibrations of structural sheets can emit aerial sounds that are an environmental nuisance [3]. ‘Material’ sounds of various types (e.g. longitudinal, transverse or bending waves) can be produced by numerous mechanisms, such as periodic or periodically changeable influences that alter the position or force constants (the rolling process). Steel provides low internal attenuation, and structures made of steel can easily be subject to poorly damped free vibrations and/or resonance of high amplitudes. In particular, in structures with large-surfaced elements, the induced transverse vibrations can lead to large emissions of aerial sound that are received by the human ear as noise. This noise, which is dominated by low-range frequencies due to its long wavelengths, spreads across large distances as it is only slightly attenuated by obstacles, and easily penetrates into residences. The unpleasant buzzing characteristics of this noise make it particularly vexing to the human ear, both outside and inside residential dwellings.

Characteristics of railway lines and bridges. This study investigated a railway line and bridge located within an intensively developed industrial area. There were multi-family residential houses (Figs. 1, 2) located within its immediate neighbourhood (i.e. 28 m from the railway track). The railway track was jointless, and ran along an embankment in the form of a horizontal bend with a radius (R) of 250 m. The technical condition of the track was unsatisfactory (i.e. its horizontal curvature deviated from the correct theoretical shape and was, in fact, a broken line consisting of several arc sections).

Fig. 1. Top view of the railway bridge and multi-family residential house

The acoustic climate was aggravated considerably by the steel bridge. This structure was built in 1973, and consisted of four spans in the form of a continuous beam (Figs. 2, 3). It had plate-type main girders and a platform in the form of an orthotropic plate. The rails were fixed directly to the bridge structure (i.e. they had neither ballast nor sleepers/cross-ties).

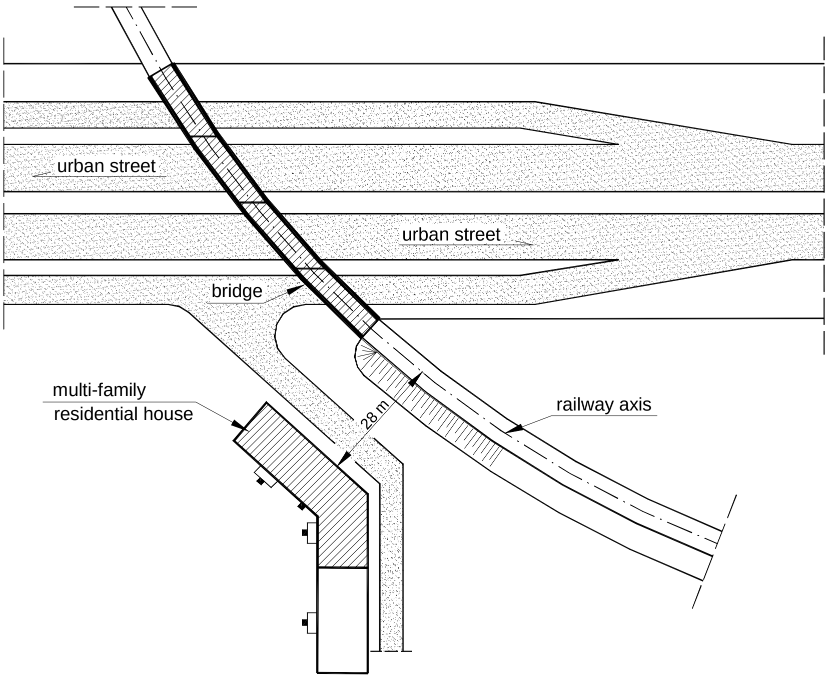

Fig. 2. Layout of the railway line, bridge and residential houses

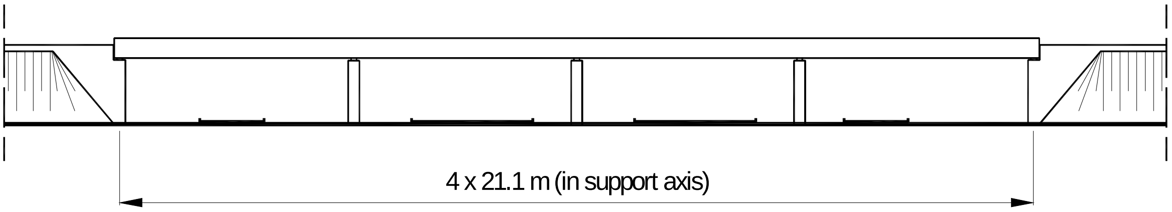

Fig. 3. Bridge span numbers and length, side view

The bridge span structures were supported on two massive abutments and three ferro-concrete pillars. The main girders had a curvilinear shape in top view. The track on the bridge were no expansion joints in the rails on the studied bridge or in its vicinity.

Study of acoustic phenomena. In order to determine the magnitude of the noise hazard/exposure, measurements were taken at the following points (Fig. 4): in a residential house (measuring point [m.p.] #1), in front of the residential house (m.p. #2), near the bridge (m.p. #3) and near the track beyond the bridge (m.p. #4).

The measurements were taken at air temperatures ranging from +10 °C to +20 °C, with average humidity (no precipitation) and weak wind strength (<3 m/s). The tests were carried out at night (from 22.00 h to 06.00 h), because the volume of traffic on the street under the bridge during that period was low enough not to affect the results of the measurements of noise generated by passing trains. The microphone was installed at a distance of 7.5 m from the extreme *(nearest)* rail on the bridge, and 7.5 m from the extreme *(nearest)* rail beyond the bridge (m.p. #4). In the residential house, the noise was measured with the windows closed.

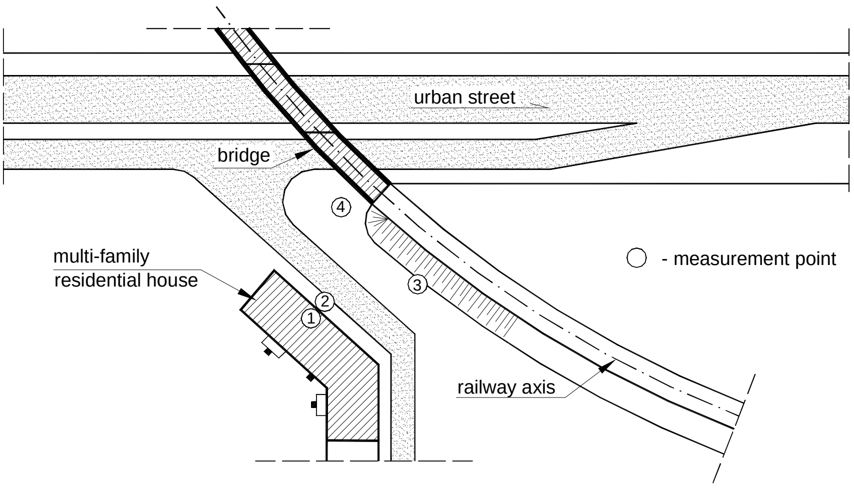

Fig. 4. Distribution of noise measurement points

The recorded signals were analysed in one-third octave bands and narrow frequency bands. The tertiary analysis included a comparison of the levels of acoustic pressure and determination of the summary levels, whereas the narrow frequency band analysis included a detailed identification of the frequency composition of the generated sounds. Selected results from these measurements are presented in Fig. 5. The L_p values represent the total (general broad-band) level of acoustic pressure, while the L_{pA} values represent the sound (noise) level with the characteristic (A) taken into account.

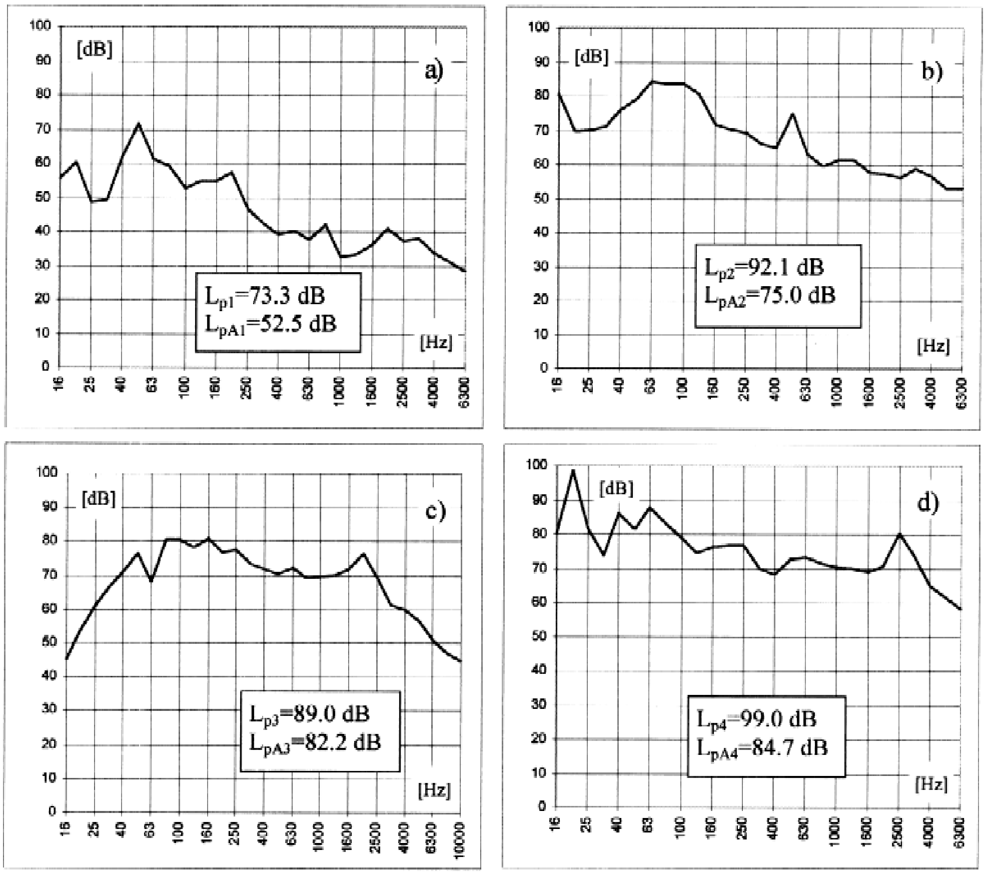

Fig. 5. Level of acoustic pressure versus tertiary frequency bands at the measuring points:
a) No. 1: passing of a train consisting of tank wagons; b) No. 2: passing of a train consisting of platform wagons; c) No. 3: passing of a train consisting of tank wagons; d) No. 4: passing of a train consisting of covered goods wagons

During the measurements, particular attention was paid to the following facts: trains passing on the embankment directly in front of the flat building generated noise mainly as a result of wheel–rail interactions (with a high share of rolling-surface irregularities), locomotive engine operation and train stopping and starting (i.e. operation of brakes and wagon couplings). Railway stock that was in poor condition contributed by producing additional sounds, such as the squeaking of axles and wheels, the knocking of empty goods wagons and so on. These sounds were produced despite a low travelling speed that did not exceed 20–30 km/h. The sound generation was highly influenced by the track position on a horizontal curve with a small radius (R=250 m), its incorrect profile and the inadequate condition of the rail stock.

These factors caused momentary or temporary noises exceeding 100 dB. Passing trains on the bridge generated sounds with causes similar to those passing on the embankment — namely, wheel-and-rail interactions, locomotive engine operation, train stopping and starting (operation of brakes and wagon couplings), poor condition railway stock (squeaking of axles and wheels, and knocking of empty wagons) and the small radius of horizontal curvature of the track. It should be noted that these sounds were poorly attenuated by the bridge plate girders, which also created a peculiar type of screen for sounds generated at the points of wheel–rail contact. In addition, trains passing across the bridge generated noise that resulted from vibrations induced in the structural elements. The relative contribution of this source to the total noise level was high. The acoustic pressure levels measured directly under the bridge reached 95 dB. Limiting the noise by removing just one of the abovementioned main sources only slightly reduced the total noise.

Study of acoustic vibration phenomena. Acoustic vibration tests were carried out in order to determine the effect of bridge elements on sound emissions to the environment. The following elements were subjected to tests: the platform plate, the main girder, the transverse beam, the longitudinal beam and the bridge sidewalk plate. In addition, the rail was also tested. Along with vibration measurements of structure elements, the level of acoustic pressure near the bridge was measured. During this study of acoustic vibration, the microphone was located at a distance of 7.5 m from the extreme *(nearest)* rail on the bridge, and 1.2 m above ground level (m.p. # 4), whereas the vibrations were measured on individual elements of the bridge structure. The tests involved the following: the extreme plate of the bridge between the girder and rail ($P1_v$); the middle plate of the bridge between the rails ($P2_v$); the web of the main girder (D_H); the lower strip of the main girder (D_V); the web of the transverse beam (PO_H); a strip of the transverse beam (PO_V); the web of the longitudinal beam (PD_H); a strip of the longitudinal beam (PD_V); the sidewalk plate (PC_V); and the rail foot (S_V) (Fig. 6).

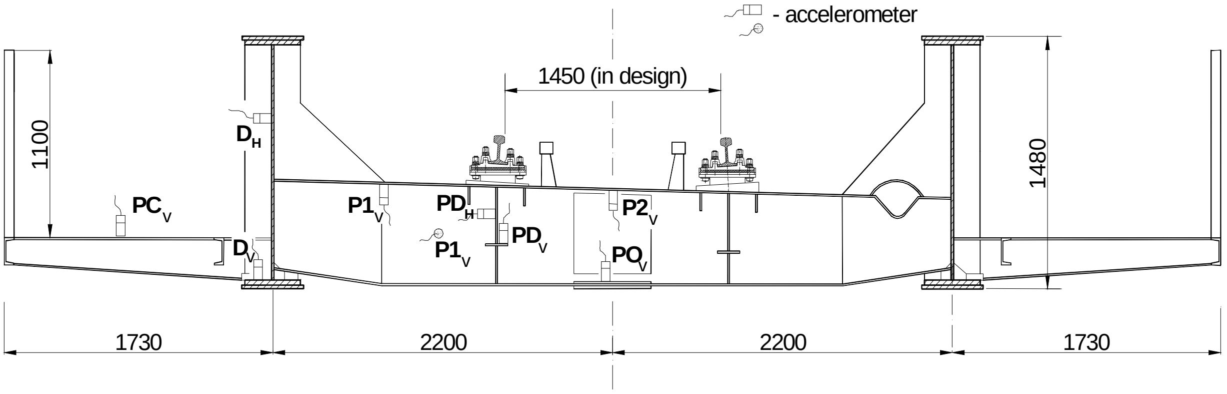

Fig. 6. Cross-section of the bridge and layout of vibration measurement points

A diagram of the measurement system is presented in Fig. 7.

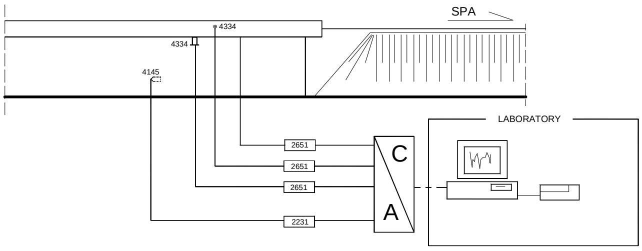

Fig. 7. Measurement system diagram

Examples of variations in acoustic pressure and accelerations in structural elements versus time are shown in Fig. 8.

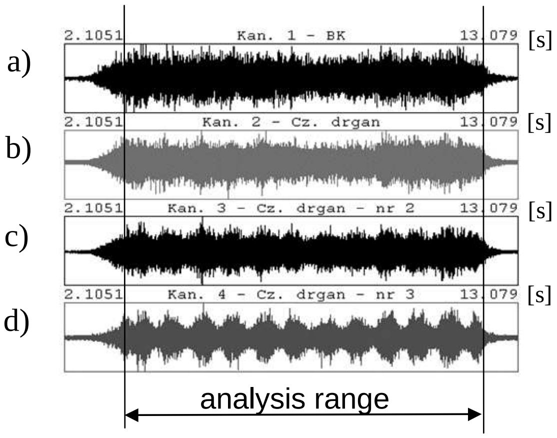

Fig. 8. Variations in (a) acoustic pressure and (b, c, d) accelerations in structural elements versus time

The signals obtained from the measurements had an analogue form. The initial stage of the analysis involved the conversion of analogue signals to a digital form, which produced a sequence of discrete values determined at consecutive time intervals. The next stage of the analysis involved transforming the signal from the time domain to the frequency domain using a Fast Fourier Transformation. Selected characteristic results of these analyses are presented in Figs. 9–14.

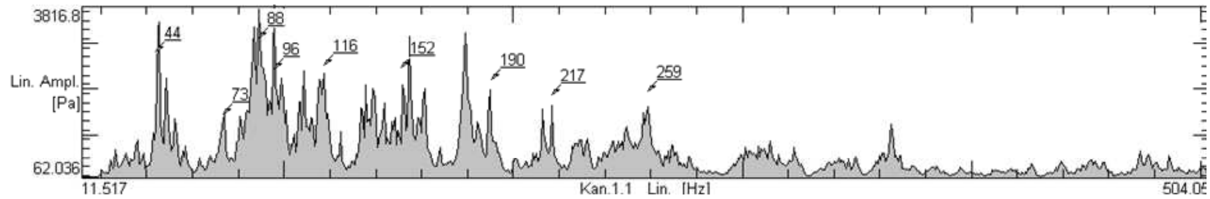

Fig. 9. Amplitude–frequency characteristics of acoustic pressure near the bridge (m.p. #3)

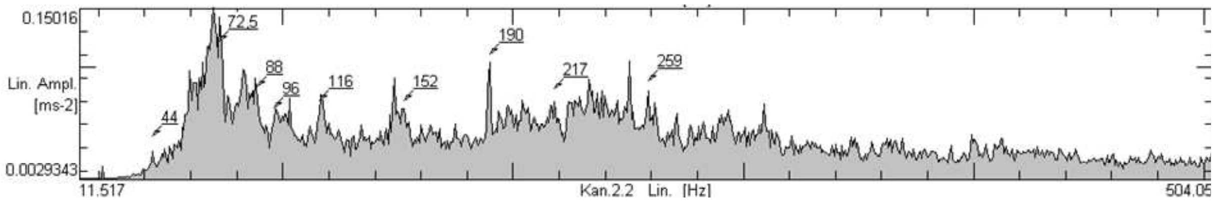

Fig. 10. Amplitude–frequency characteristics of platform plate accelerations (m.p. $P1_v$)

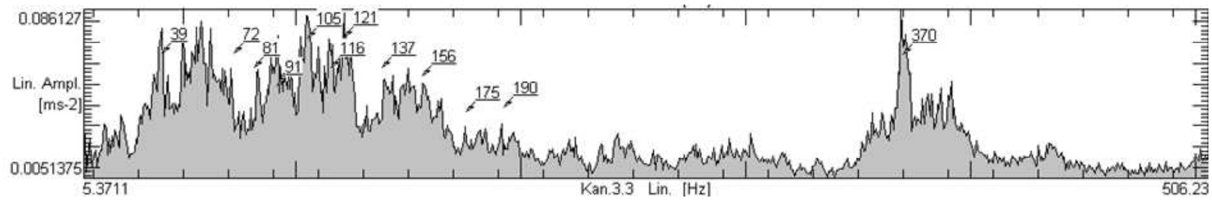

Fig. 11. Amplitude–frequency characteristics of main-girder web accelerations (m.p. D_H)

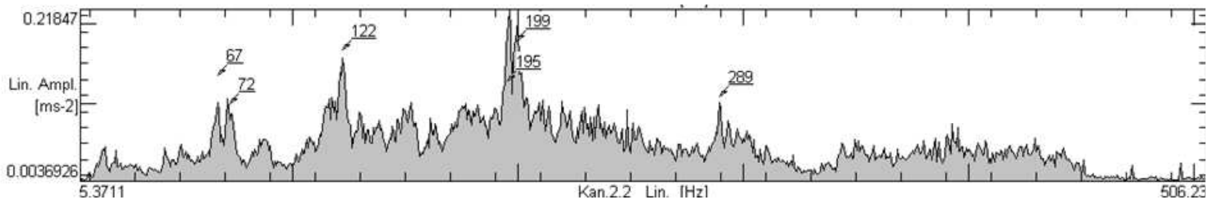

Fig. 12. Amplitude–frequency characteristics of main-girder strip accelerations (m.p. D_V)

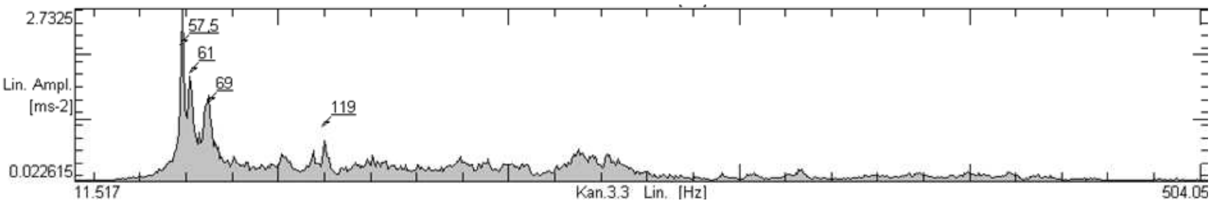

Fig. 13. Amplitude–frequency characteristics of sidewalk plate accelerations (m.p. PC_v)

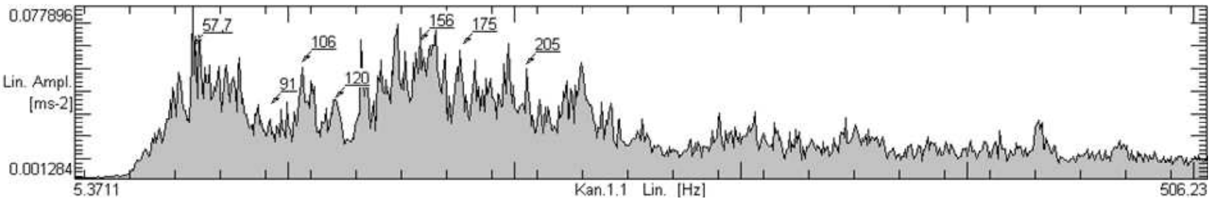

Fig. 14. Amplitude–frequency characteristics of transverse beam accelerations (m.p. PO_H)

A coherence function was applied to identify the main sources of noise in the bridge structure, based on the two-channel measurement of vibration and acoustic signals. The analysis of these signals made it possible to determine which frequency bands were present, where the resonances occurred and from which elements they originated. A comparison of the coherence function values for various elements of the bridge allowed the main sources of acoustic energy radiation to be determined [4, 5]. It should be stressed that the square of the standardised function of mutual correlation between the vibration-speed and acoustic-pressure signals was a measure of the share of each specific vibrating element in the radiated acoustic pressure. Subjecting the measured signals to a Fourier transformation allowed an analysis of the signals in the frequency domain, where the square of the standardized function of mutual correlation corresponded to the value of the standardised coherence function. This method (i.e. the determination of coherence functions of the ‘material’ vibration–acoustic vibration type) can be utilized for studying the effect of individual vibration sources on the acoustic pressure at a specific point of an acoustic field.

In the current study, the coherence function was determined using the formula [5]:

$$\gamma_{xy}^{2}(f) = \frac{\left|\overline{G}_{xy}(f)\right|^{2}}{\overline{G}_{xx}(f)\cdot G_{yy}(f)}, \tag{1}$$

where G_{xy}, G_{xx} and G_{yy} are the mutual and proper spectrum densities of the signals.

The coherence function has real values, and describes the relationships between signals in the frequency domain. If there is a linear relationship between (vibration and acoustic) signals, and if the signals are not distorted by interfering noise, the coherence function is equal to 1. If a linear relationship does not occur, the function is equal to 0. The value of the coherence function can be reduced *(lowered)* as a consequence of interfering noise.

Assuming that the vibrating structure radiates acoustic energy through its individual elements, it can be presented as *n* sources emitting this energy to the environment. Estimating the effect of accelerations or the speed of vibrations from individual sources on the value of acoustic pressure can be carried out on the basis of the coherence functions between the accelerations or speeds of vibrations and acoustic pressure at a selected point of the acoustic field. The value of the coherence function binding the acoustic pressure and accelerations of vibrations in the bridge elements was used to identify similarities between the studied signals and, thus, to identify the main noise sources.

Selected results of these analyses are presented in Figs. 15–18.

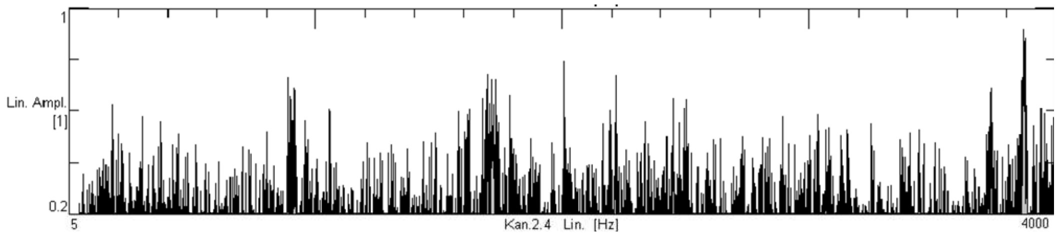

Fig. 15. Coherence function between platform plate vibration accelerations (P1$_v$) and acoustic pressure

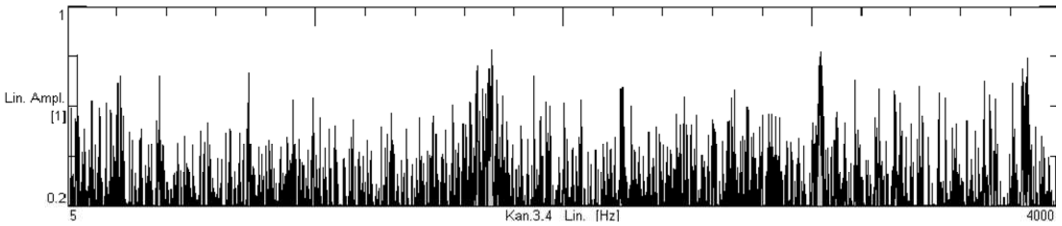

Fig. 16. Coherence function between accelerations of vibrations in the main girder web (D$_H$) and acoustic pressure

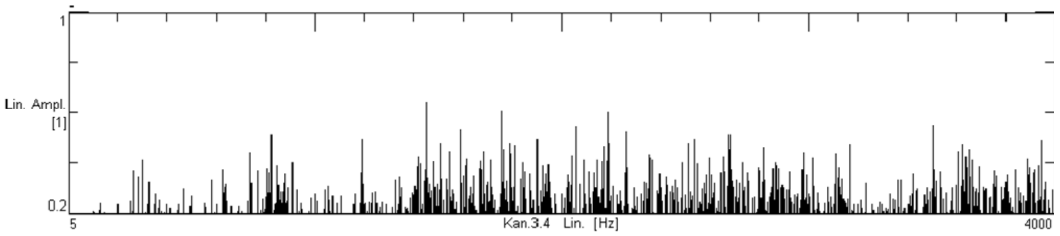

Fig. 17. Coherence functions between accelerations of vibrations in the transverse beam (PO$_H$) and acoustic pressure

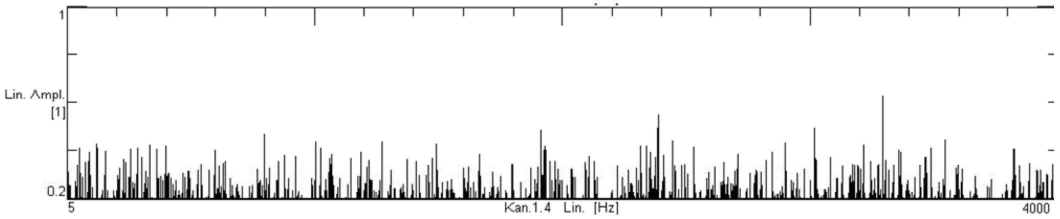

Fig. 18. Coherence functions between accelerations of vibrations in the sidewalk plate (D$_H$) and acoustic pressure

The abovementioned functions revealed that relationships existed between the vibration phenomena of structural elements and the acoustic phenomena. The main sources of the noise are: platform plate (P1$_v$) and main girder web (D$_H$).

Measurements and analyses were performed at least three times at the same measuring points, but with different passing railway vehicles. The coherence functions were invariably similar to each other. Therefore, the conclusion can be drawn that acoustic vibration processes determined during normal bridge functioning primarily reflect the geometric, mechanical and acoustic characteristics of the structure, rather than the characteristics of the loading applied. This was confirmed by the constancy of the characteristic lines related to the resonance frequencies of the structural elements.

In addition, on the basis of the determined coherence functions, acoustic phenomena occurring in the neighbourhood of the analysed bridge appeared to be connected to signals generated by a moving or travelling system over the entire analysed range of frequencies, with the platform plate and plate girder web accounting for the main share of the sound emission. For these elements, the coherence value was clearly higher than that of the other elements.

Summary and means of environmental protection against noise. The methods of acoustic and vibration-acoustic testing applied here enabled the identification of the main sources of noise emitted to the environment, which is a prerequisite for their effective reduction or elimination.

The results of these studies showed that the noise in residential houses was caused by three sources:

- first was noise generated by trains rolling over a railway track laid on the embankment,
- second was noise caused by trains passing over the track installed on the bridge; the causes of this noise were similar to those of the first source, but it should be noted that the sounds emitted by trains were partially dampened by the bridge girders, which constituted a type of acoustic screen,
- third was noise caused by vibrations of bridge structural elements; the passing of a train excited or induced vibrations in these elements, and those of large-surface elements (such as platform plates and plate girders) in particular caused the emission of undesirable sounds in the low-frequency and medium-frequency ranges.

Initially, an acoustic screen could be used in order to reduce the noise nuisance. A flat vertical screen can be applied here. Several different experimental screen locations were analysed. Detailed calculations were performed for two alternatives: option 1 was a 3-m high screen located at a distance of 3.8 m from the track axis, whereas option 2 was a screen that was also 3 m high but was situated at a distance 3.0 m from the track axis. A more favourable solution was to place a screen closer to the track — i.e. at a distance of 3.0 m from its axis.

In order to reduce the noise from the train on the bridge, it would be necessary to make an acoustic screen over the length of the minimum first span. The screen could be installed in the balustrade line, or in the line of the bridge girder on the sidewalk side. It is recommended that the screen should be fixed on the outside of the balustrade in such a way that its lower edge and the bottom of the bridge structure were at the same level. In order to reduce any unfavourable effects of the screen, it should be made of a translucent material (e.g. polycarbonate).

Moreover, in order to restrict the emission of sound as a result of the vibration of bridge elements, vibration insulation in the form of systems for the elastic fixing of rails should be applied. This would make it possible to avoid damping the vibrations in the platform plate or girder web. When analysing the vibration insulation systems, it is essential that the vibrations caused by rolling wheels should be dampened as much as possible. The vibration insulating material could be applied as a substrate pad, and should be shaped so that it cannot escape from under the ribbed-rail pad. The thickness of the damping material should be at least 30 mm.

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