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Research Paper

Field Experiment as a Tool to Verify The Effectiveness of Prototype Track Structure Components Aimed at Reducing Railway Noise Nuisance

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The almost unlimited possibilities of modern computational tools create the temptation to study phenomena related to the operation of engineering objects exclusively using complex numerical simulations. However, the fascination with multi-parametric complex computational models, whose solutions are obtained using iterative techniques, may result in qualitative discrepancies between reality and virtual simulations. The need to verify on real objects the conclusions obtained from numerical calculations is therefore indisputable. The enormous cost and uniqueness of large-scale test stands significantly limit the possibility of conducting tests under real conditions. The solution may be an experiment focused on testing features relevant to the given task, while minimising the dimensions of the objects under consideration. Such conditions led to the concept of conducting a series of field experiments to verify the effectiveness of prototype track components, which were developed using numerical simulations to reduce the noise caused by passing trains. The main aim of this study is to examine the acoustic efficiency of prototype porous concrete sound absorbing panels, in relation to the ballasted and ballastless track structures. Presented results of the proposed unconventional experiments carried out on an improvised test stand using the recorded acoustic signals confirm the effectiveness of the developed vibroacoustic isolators.

Keywords: vibroacoustic isolator; ballasted track structure; ballastless track structure; noise reduction; field test.

1. Introduction

Current regulations impose high requirements with regard to the protection of people and the environment against noise emissions (World Health Organization, 2018). At the same time, efforts are made to increase the capacity of railway lines, e.g., by increasing train speeds, which leads to higher levels of noise emitted to the environment. According to the report of the European Environment Agency (2020), railways are the second most dominant noise source in Europe. There are several solutions that can be applied to reduce such negative effects (Scossa-Romano, Oertli, 2012; de Vos, 2016; Thompson, 2008), for example: traditional acoustic screens, low-height noise barriers or various vibro-acoustic isolators integrated with the track.

Acoustic screens (Thompson, 2008) are placed along communication routes and their aim is to reduce the level of noise which is transmitted from the source of their emission (i.e., a railway route) to the surrounding environment. However, these traditional methods of protection against noise are not always possible to use for technical (location, necessary dimensions), economic or aesthetic reasons, or they do not give satisfactory results. In many cases, there is a need to reduce the noise level also at its source, i.e., in the emission zone. Considering that the modernised railway lines usually connect largest cities, and some of the railway line sections are located within the cities, and often in their very centres, it is necessary to use other, alternative solutions.

A good alternative are vibro-acoustic isolators, which are an integrated part of the track structure. Various solutions have been investigated and described in the literature. Glickman *et al.* (2011) conducted research on porous concrete sound absorptive panels used on the concrete slab trackbed to reduce the level of noise emitted to the surroundings. A similar solution was investigated by Zhao *et al.* (2014), where the authors examined the effect of porous sound-absorbing concrete slabs on the reduction of railway noise. They measured absorption coefficients of various materials in the laboratory and then, they tested selected slabs in a test section. They proved that porous sound-absorbing concrete slabs can significantly reduce railway noise at different train speeds.

Hong *et al.* (2005) studied the sound absorbing characteristics and performance of parallel perforated plate systems. They used an equivalent electroacoustic circuit approach, which was validated by comparing the calculated absorption characteristics with the ones measured by the two-microphone impedance tube method. Li and Guo (2017) proposed a numerical optimization method for acoustic performance of a micro-perforated plate aimed at the application in high-speed trains. Yori (2020) proposed a mathematical method for calculating the sound absorption coefficient of various sound absorbing materials depending on the incidence angle.

A group of scientists from the Seoul National University of Science and Technology conducted research on acoustic characteristics of the track structure in the urban train tunnel. They proposed an optimal mix design of a porous sound absorbing block applied on a concrete ballast (Lee *et al.*, 2016). They also developed a monitoring system measuring the noise reduction characteristics and structural behaviour of sound absorbing panels applied on the concrete trackbed (Oh *et al.*, 2017).

Shimokura and Soeta (2011) determined acoustic characteristics of the train noise for different types of railway stations: above-ground and underground, with side and island platforms. Matej and Orliński (2023) investigated possible ways of reducing wheel and rail wear in the operation of underground wagons on a curved track with small curve radii. Groll *et al.* (2023) studied transitional phenomena in railway systems with a focus on rail joints.

Vogiatzis and Vanhonacker (2015) investigated three different solutions for the reduction of railway rolling noise in light rail transit: sound absorbing precast elements, noise barriers, and rail dampers. They tested the proposed elements using a detailed rolling noise calculation procedure, and then, implemented selected solutions on site. Lázaro *et al.* (2022) studied the performance of low-height railway noise barriers with the addition of porous granular material on the inner face of the barrier.

According to the experience of foreign railway infrastructure managers (e.g., Germany and China), vibroacoustic isolators in the form of rail dampers or sound absorbing precast elements (usually made of porous concrete) are commonly used in the ballastless track structures and are able to effectively reduce the level of noise emitted to the environment. However, currently, Poland lacks a proper test site with a ballastless track system that would make it possible to conduct large-scale acoustic tests, as the ballastless track structures are used in the railways of PKP PLK S.A. marginally. The authors of this study have investigated ballastless track systems equipped with vibration isolators both experimentally and analytically (Zbiciak *et al.*, 2021), however, the laboratory research has focused on testing the particular vibration isolators, not the whole large-scale track section.

The research presented in this paper is a part of the BRIK InRaNoS project, co-financed by the European Union and PKP PLK S.A., which is aimed at developing an efficient vibroacoustic isolator to be applied in Polish railways for the reduction of railway noise emitted to the environment. Several works containing results of this research have been published so far. Kraśkiewicz *et al.* (2021a) proposed an experimental methodology for the identification of dynamic characteristics of a track structure, based on the determination of the track decay rate (TDR). They conducted field tests on the railway line section in Warsaw, where they measured TDR with the use of impulse tests. In another work, Kraśkiewicz *et al.* (2021b) investigated possible applications of rubber granulate SBR (styrene-butadiene rubber) produced from recycled waste tires as an elastic cover for prototype rail dampers. The authors performed laboratory tests on seven different SBR materials, with a focus on their operational durability.

The present paper aims at examining the acoustic efficiency of prototype sound absorbing panels based on porous concrete, in relation to the ballasted and ballastless track structures. So far, most of the studies on vibroacoustic isolators have concerned only the ballastless systems, assuming in advance that the ballast as a granular layer (crushed aggregate – usually crushed stone with the granulation of 31.5/50 or 31.5/63) provides a sufficient level of noise reduction, by absorbing and dissipating the acoustic wave. However, as stated by Zhang *et al.* (2019), the ballasted track does not always suppress noise better than the slab track. In their research, at lower frequencies (below 200 Hz) the noise level from the ballasted track was greater than that from the slab track, while at higher frequencies (250 to 1000 Hz) the slab track was noisier due to its lower track decay rates. What is important, the authors emphasised that although the results confirmed that the ballastless track is typically noisier than the one with ballast, the differences in the radiated noise depend on the physical properties of the compared tracks and should not be seen as universal.

Taking into account the results discussed above and the researchers' own experience, the authors of this paper have decided to investigate the noise reduction effectiveness of prototype porous concrete panels applied both in the ballasted and ballastless track structures. An innovative approach used in this study consists in implementing the same set of tests for the same prototype elements installed in two different types of track structures: ballasted and ballastless systems, in order to examine the acoustic efficiency of the developed sound absorbing panels.

2. Test methodology

The tests were aimed at determining the acoustic characteristics of prototype sound absorbing porous concrete panels installed on a full-scale test section of the track structure. The field experiment was an original idea of the authors, resulting from the lack of the real railway test section and a necessity of replacing it with a newly designed and constructed test stand, where sounds recorded during the passage of trains were used instead of actual excitations. A comparative approach was applied, which consisted in measuring the sound pressure levels in 1/3 octave bands in the reference and isolated systems:

- reference system – track structure without any vibroacoustic isolators;
- isolated system – track structure equipped with the tested sound absorbing panels.

In both systems, identical (as to the level and spectrum of the acoustic signal) excitations were emitted, that is: pink noise and real train passages, in the form of audio files. Measurement microphones were used to record the response of the tested systems at points located in their vicinity. Then, differences in the sound pressure levels in 1/3 octave bands were determined. It should be emphasised that the emitted sound levels were fully repeatable – the repeatability of the sound levels for various configurations of the track structure was ensured by using a microphone located in the immediate vicinity of the sound source (measurement point P0 – see Subsec. 3.2).

The effectiveness D_B of the solution (vibroacoustic isolator) is calculated as a difference of the sound pressure levels determined for a given observation point before and after the installation of the vibroacoustic isolator, provided that the noise source, terrain profiles, potential interference and reflective surfaces, as well as ground properties and meteorological conditions have not changed. It is a value expressed in decibels, which is determined for individual distances from the noise source using the formula:

$$D_B = L_{\mathrm{ref},d} - L_{\mathrm{iso},d} \quad [\mathrm{dB}], \tag{1}$$

where $L_{\mathrm{ref},d}$ is the sound pressure level in the reference system, measured at a distance d from the track axis, and $L_{\mathrm{iso},d}$ is the sound pressure level in the isolated system, measured at a distance d from the track axis.

In the conducted tests, a procedure of continuous recording of the acoustic signal was used, from which, at the analysis stage, acoustic events related to individual excitations were selected (emission of pink noise, passage of particular types of trains) and for those events, sound pressure levels in 1/3 octave bands and the values of the A-weighted equivalent sound level were determined.

The testing procedure was prepared by the authors based on two ISO standards: 3095 (2013) and 10847 (1997). However, the guidelines of ISO 3095 with regard to the location of measurement points could not be followed due to the technical limitations of the test stand. The measurement points were located closer to the railway noise source than specified in the standard, which resulted from the limited dimensions of the track structure sections prepared for experimental tests and the emitted levels of acoustic signals.

The applied procedure, however, is consistent with the main purpose of the research and does not affect the obtained measurement results. In the classic-speed railway lines, rolling noise is the dominant source of noise, and in the context of the realised research project, which focuses on the development and testing of vibroacoustic isolators, only this type of noise is the subject of further consideration. Such noise is generated due to the geometrical irregularities in the rolling surface of the wheel and the rail head, which generates dynamic forces acting on their contact surface. This, on the other hand, leads to relative vibrations of the wheel and the rail, with the vibration amplitude of each element depending on its dynamic properties. The resulting vibrations are the main source of noise.

During the measurements, the tested prototype sound absorbing panels had a total area of about 4.5 m^2, and the noise was not caused by the actual passing trains, but by emitted acoustic signals. Therefore, in order to observe and record the effect of absorption and dispersion of sound waves, smaller distances of measurement points from the track structure sections were applied.

3. Samples and test stand

3.1. Tested samples

The tested sound absorbing panels were made of porous concrete, whose recipe was marked with the symbol 220/10 – number 220 refers to the volume of cement grout (220 dm^3), number 10 indicates the percentage of sand in the crumb pile. The concrete recipe was elaborated within laboratory tests, and the surface grooving was designed using numerical simulations. All tested elements were produced in the laboratory of the Faculty of Civil Engineering at the Warsaw University of Technology.

Two types of panels were considered:

- panel 1 – porous concrete panels of 500 × 500 × 100 mm, with trapezoidal grooves;
- panel 2 – porous concrete panels of 500 × 500 × 100 mm, with half-round grooves.

In the conducted tests, nine panels of type 1 and nine panels of type 2 were applied together, with the aim of keeping the symmetry of the system. In this way, a hybrid system with 18 sound absorbing panels made of the same material, but with two different grooving patterns, was obtained.

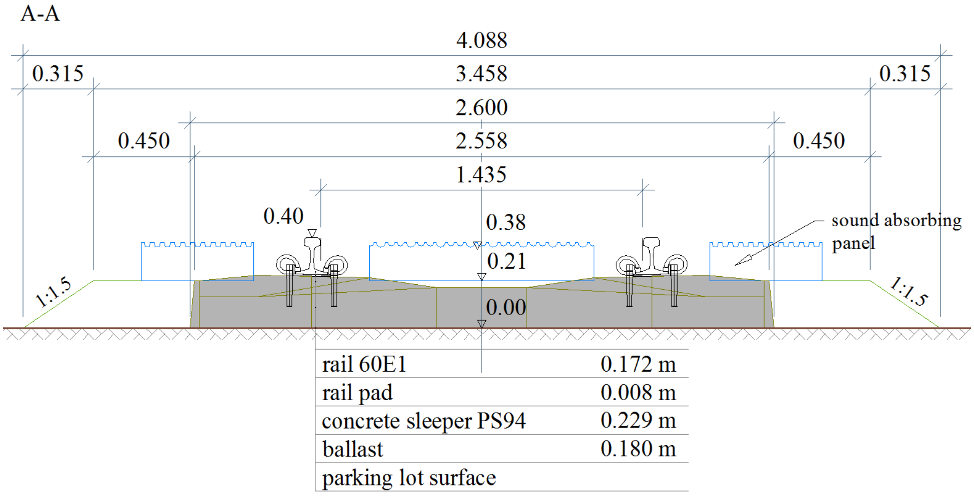
The created vibroacoustic isolation system was tested on two different types of track structures: ballasted and ballastless. In the ballasted section, the panels were laid on the upper surface of the sleepers, between and outside the rails. The cross-section of the test stand is presented in Fig. 1, and the photographs of the tested section – in Fig. 2.

In the ballastless track system, the vibroacoustic isolators were installed on the slabs simulating the concrete track slabs, between and outside the rails. The cross-section of the test stand is presented in Fig. 3, and the photographs of the tested section – in Fig. 4.

The arrangement of the sound absorbing panels on the ballasted and ballastless track section was identical, as shown in Fig. 5.

3.2. Test stand

An original test stand was designed by the authors and constructed on the premises of the Warsaw University of Technology, in front of the building of the Faculty of Civil Engineering. The scheme of the test stand with marked locations of tested samples and measurement points is presented in Fig. 6.



rail 60E1	0.172 m
rail pad	0.008 m
concrete sleeper PS94	0.229 m
ballast	0.180 m
parking lot surface	

Fig. 1. Cross-section of the ballasted track structure with sound absorbing panels.

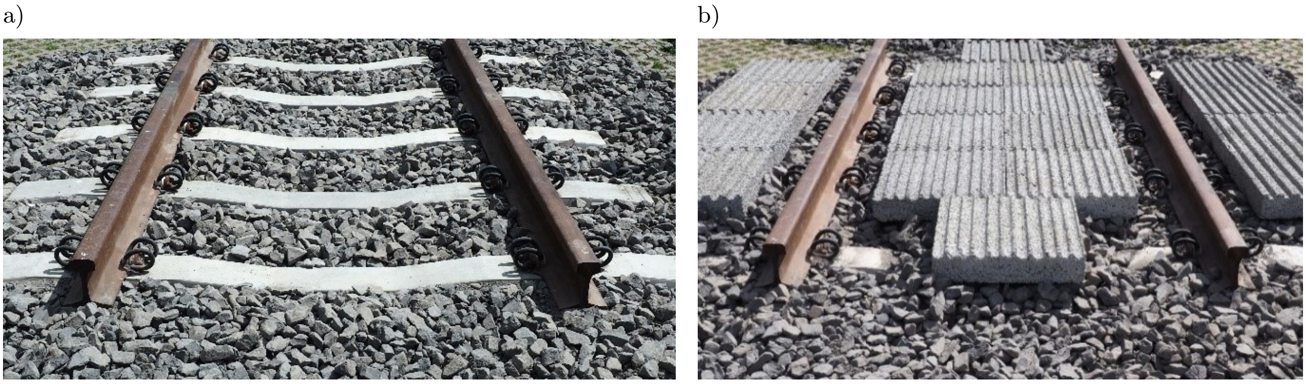
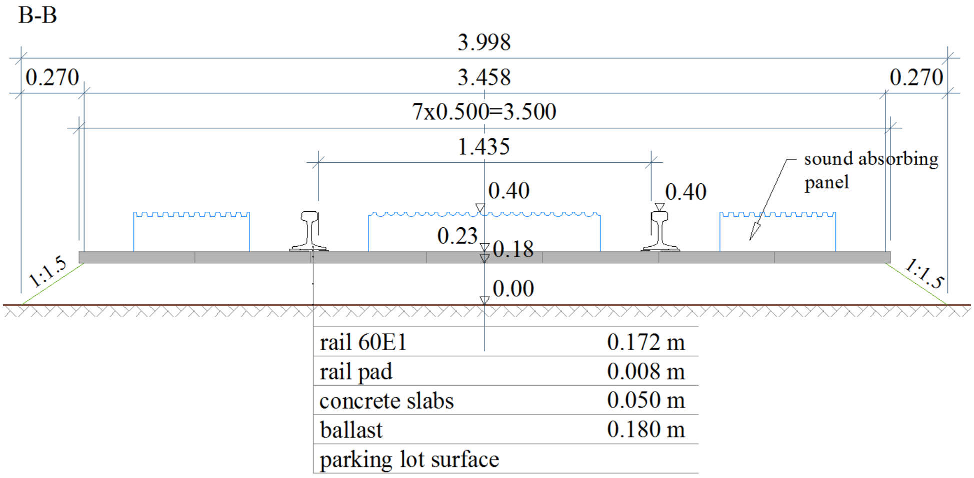


Fig. 2. View of the ballasted track structure: a) reference system; b) isolated system.



rail 60E1	0.172 m
rail pad	0.008 m
concrete slabs	0.050 m
ballast	0.180 m
parking lot surface	

Fig. 3. Cross-section of the ballastless track structure with sound absorbing panels.

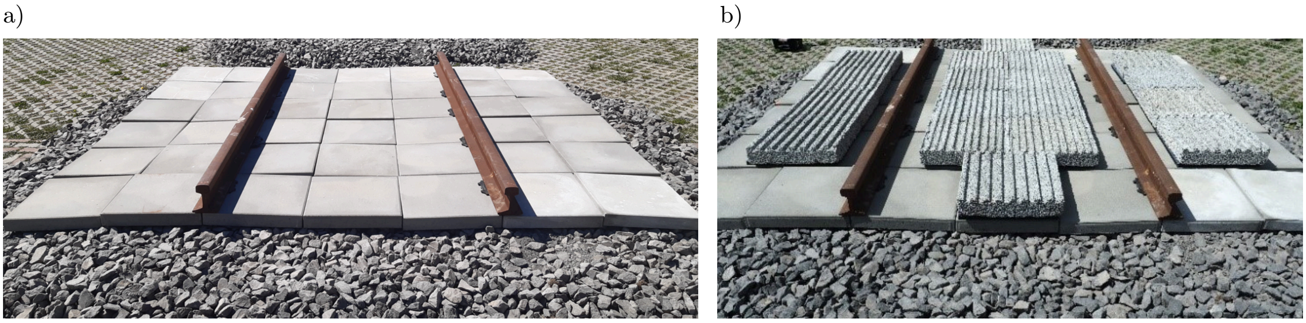


Fig. 4. View of the ballastless track structure: a) reference system; b) isolated system.

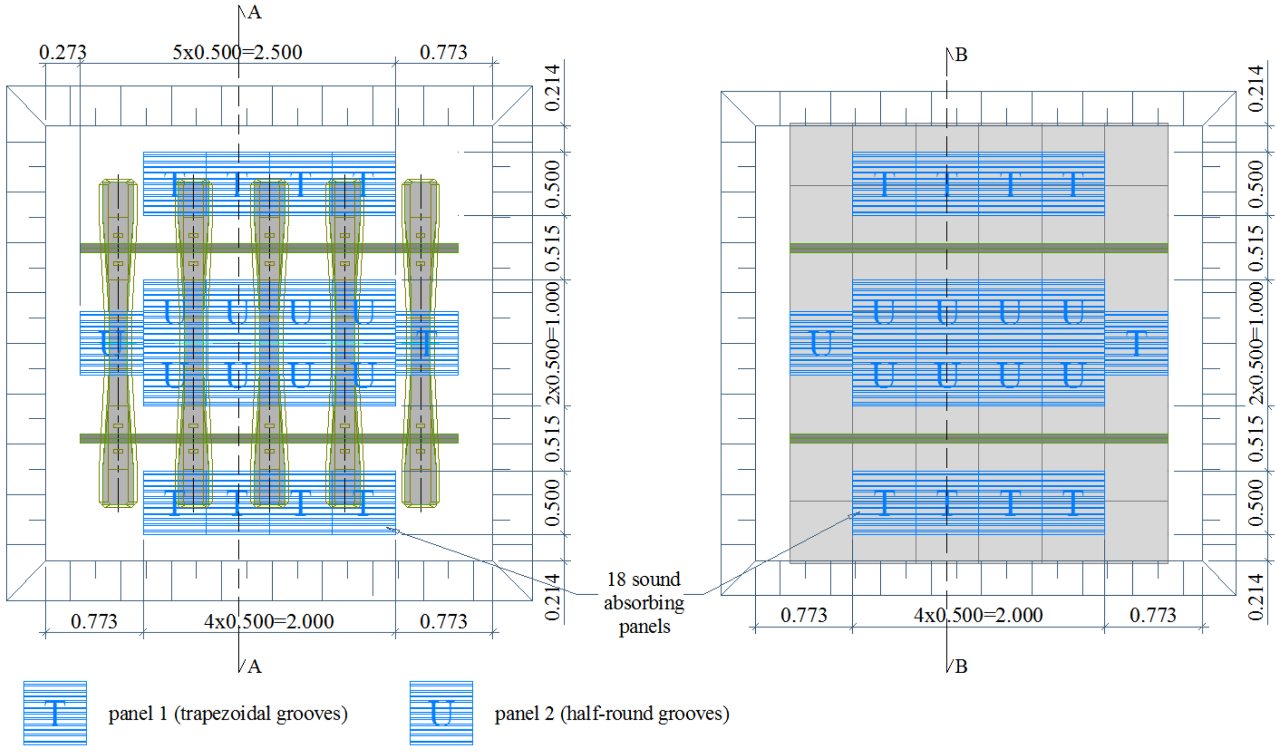


Fig. 5. Top view of the ballasted and ballasted track structure with the arrangement of sound absorbing panels.

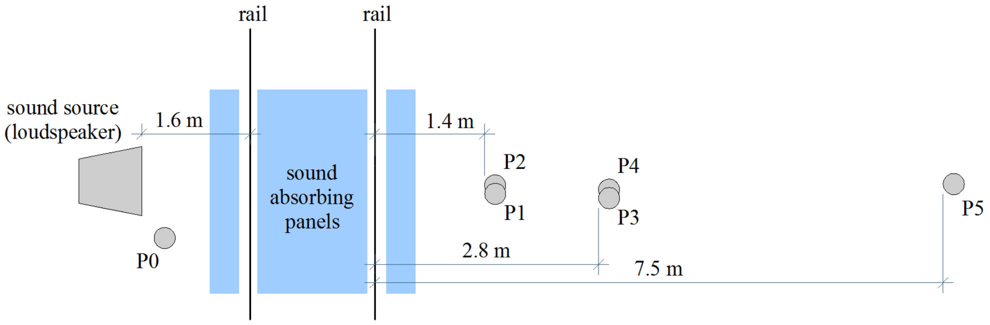


Fig. 6. Scheme of the test stand with marked location of measurement points.

Four configurations of the test stand were prepared:

- configuration I – ballasted track structure, isolated system;
- configuration II – ballasted track structure, reference system;
- configuration III – ballastless track structure, isolated system;
- configuration IV – ballastless track structure, reference system.

The ballasted track system consisted of: rail profiles 60E1, rail fastening system of SB type with the elastic rail pads PKV, and five sleepers PS-94 with 600 mm spacings. Such a track grid was placed directly on the parking lot slabs, and then covered with ballast to the level of the sleeper top in the zones between the sleepers and outside, at both sides of the track structure. Inclination of the ballast prism walls was 1:1.5. In this way, a total system width and length of around 4000 mm was obtained.

The ballastless track system was constructed on the newly laid paving slabs with the dimensions of 500 × 500 mm. The slabs were placed on the compacted ballast, in order to achieve a uniform level of the rails in both the ballasted and ballastless track system. PKV rail pads were laid on the slabs every 600 mm, and rail profiles 60E1 were placed on the pads with an axial spacing of 1500 mm (which corresponds to the track width of 1435 mm).

In each configuration, the measurements were made at four fixed measurement points (marked from P1 to P4 in Fig. 6) located at the constant distance from the tested samples and the constant height above the rail head/ground level, at the opposite side of the tested system in relation to the sound source (directional loudspeaker):

- P1 – 1.4 m from the closest rail head, at a height of 0.9 m;
- P2 – 1.4 m from the closest rail head, at a height of 1.8 m;
- P3 – 2.8 m from the closest rail head, at a height of 1.5 m;
- P4 – 2.8 m from the closest rail head, at a height of 3.5 m.

Moreover, in order to monitor the operation of the sound source and confirm the repeatability of the emitted acoustic signals, an additional point marked as P0 was used, located at a short distance of 0.4 m from the upper corner of the loudspeaker. Meteorological conditions during the measurements were monitored at the point marked as P5 – located 7.5 m from the rail head, at a height of 4.0 m

The signal source (loudspeaker) was located 1.8 m from the closest rail head, on a platform 0.85 m high. The loudspeaker diaphragm was directed at the tested sample of vibroacoustic isolators, at an angle of 25° to the ground plane. The chosen location of the sound source (loudspeaker) and microphones on the test stand resulted from the objective of the study, that is comparison of the acoustic signals reflected from the test samples. In the authors' opinion this location best reflected the adopted concept of outdoor testing, as the signals of passing trains used in the tests were recorded next to the track.

Fig. 7. View of the test stand with visible loudspeaker and microphones.

3.3. Measuring equipment

The measuring instruments were used in the conducted tests:

- SV 279 PRO Noise Monitoring Station (in points P1 to P5);
- SV 36 Acoustic Calibrator;
- Vaisala Weather Transmitter WXT530.

For the generation and emission of acoustic signals, the following measuring equipment was used:

- AMG mini amplifier/pink noise generator;
- laptop as a sound player;
- omnidirectional loudspeaker.

Six different types of acoustic signals (with a known spectrum measured in P0) were generated:

- no. 1 – pink noise;
- no. 2 – passage of the passenger train Pendolino ED250 (speed 152 km/h);
- no. 3 – passage of the freight train ET22 (speed 74 km/h);
- no. 4 – passage of the old-type (locomotive and carriages) passenger train EP09 – composition 1 (speed 106 km/h);
- no. 5 – passage of the old-type (locomotive and carriages) passenger train EP09 – composition 2 (speed 111 km/h);
- no. 6 – passage of the passenger train ED160 (electric multiple unit) (speed 105 km/h).

The train passages were recorded during acoustic tests carried out at the test section located in Nowy Dwór Mazowiecki, during real scheduled train passages on railway line no. 9 (LK-9), on the Legionowo–Nasielsk section. The audio signal (in WAVE format) was recorded using SVAN 979 sound analyser with GRAS 40AE microphone, with a sampling frequency of 48 kHz. For the purpose of the research objective, the microphone was located at a distance of 7.5 m from the track axis, at a height of approximately 2 m above the rails. The passing speeds of the individual trains whose acoustic signals were recorded are given in the brackets above.

Figures 8–13 present spectra of the emitted acoustic signals – sound pressure levels in 1/3 octave bands measured for individual signals within the frequency range of 20 Hz to 16000 Hz. The individual spectra were measured at a point marked as P0, located near the loudspeaker. All spectra are averaged for the measurement time covering: in the case of signal no. 1 (pink noise), the time is 60 s, and in the case of signals no. 2 to 6 – the duration of recorded train passages (from 33 to 107 s).

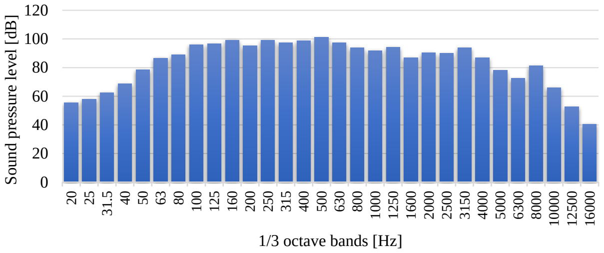


Fig. 8. Spectrum of the acoustic signal emitted by the sound source, no. 1 – pink noise.

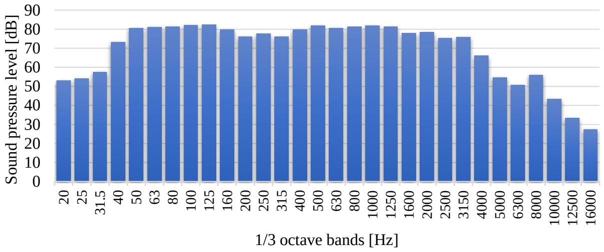


Fig. 9. Spectrum of the acoustic signal emitted by the sound source, no. 2 – Pendolino ED250.

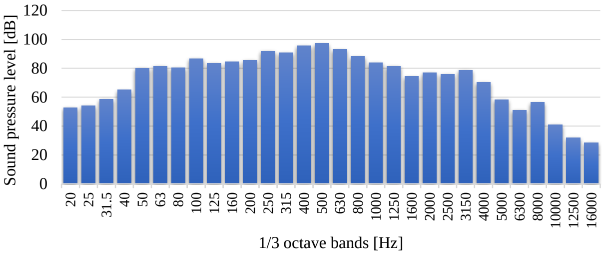


Fig. 10. Spectrum of the acoustic signal emitted by the sound source, no. 3 – ET22.

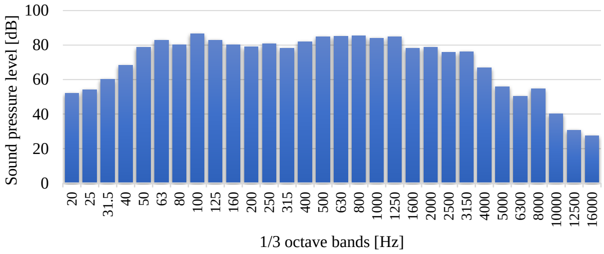


Fig. 11. Spectrum of the acoustic signal emitted by the sound source, no. 4 – EP09 composition 1.

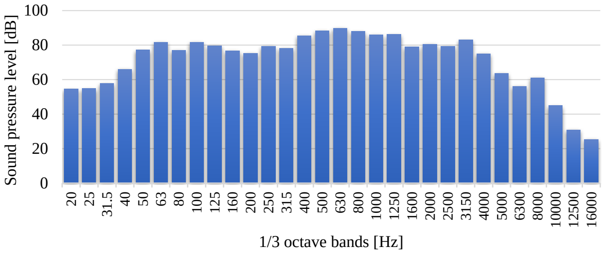


Fig. 12. Spectrum of the acoustic signal emitted by the sound source, no. 5 – EP09 composition 2.

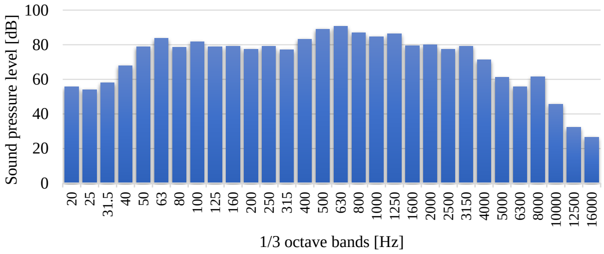


Fig. 13. Spectrum of the acoustic signal emitted by the sound source, no. 6 – ED160.

Environmental conditions during the measurements were monitored, controlled and recorded from

10 a.m. to 2:30 p.m. to prove that they had no negative impact on the reliability of the test results. Thanks to the SVAN PC++ software, the temperature, air humidity and wind speed were correlated with the measurement results obtained in the individual time intervals. The average wind speed was 1.65 m/s, the air temperature ranged from 15.6°C to 17.4°C, the atmospheric pressure was 1006 hPa, and the relative humidity ranged from 35% to 41%.

4. Results

4.1. Preliminary remarks

The tests were carried out on an open-air test stand, which does not provide a full reproduction of the conditions for real train passages. The technical limitations of the performed experiments meant that a number of simplifying assumptions had to be adopted which were relevant to the conclusions drawn from the study.

First of all, different propagation paths of the sound waves cause the phenomena of diffraction and interference of the sound waves generated by the loudspeaker, which, in practice, precludes the possibility of carrying out tests under free acoustic field conditions. Moreover, the sound signal generated by a sound source located at a fixed point (loudspeaker) does not make it possible to analyse the interaction between the moving vehicle and the environment: it is not possible to take into account the influence of phenomena caused by the air flow at the locomotive and carriages, or the dynamics of vibrating rails forced by the interaction of the wheel-rail pair (variable load on the rail, wheel passes over the joints, etc.).

Nevertheless, in the authors' opinion, the results of the research presented in this paper are of cognitive significance, and are important from the point of view of future application of the developed sound absorbing panels on various railway track systems.

4.2. Selection of the measurement point

When conducting acoustic tests under field conditions, the location of the microphone recording the signals used to interpret the studied parameters is crucial for the representativeness of the obtained results. As presented in Subsec. 3.2, the sound signals were registered synchronously with five microphones: the first one was located in the immediate vicinity of the source (in front of the test objects), the other four microphones were placed at different heights at two points: 1.4 m and 2.8 m behind the tested section of the track (Fig. 6).

As is known, the sound pressure in the free field is inversely proportional to the square of the distance from the sound source. This means that the decrease in the sound pressure between a point located in a distance of l_1 to a point located l_2 from the source is given by the formula:

$$\Delta L = 20\log\left(\frac{l_1}{l_2}\right), \tag{2}$$

where ΔL – decrease in the sound level [dB], l_1 – distance between the first microphone and the source, l_2 – distance between the second microphone and the source.

If we take into account the distances as shown in Fig. 6, then for the free field the sound levels at points P1 and P2 will be about 20.9 dB lower than at point P0, while at points P3 and P4 they will be about 23.3 dB lower than at point P0. Thus, the difference between the sound levels at points P1, P2 and P3, P4 is about 2.4 dB.

Differences in sound levels of the signals registered during the experimental tests (averaged in 1/3 octave bands for all test signals) deviate from those calculated according to Eq. (2). The actual differences between the average sound levels in the immediate vicinity of the source (point P0) and the levels at points P1, P2, P3, P4 are 14.3, 15.0, 16.5, and 17.8 dB, respectively. The discrepancies between the values from theoretical calculations and those obtained from measurements reflect the influence of the test stands on the sound propagation between the source and the receivers (measurement microphones). This results in the limited usefulness of the signals registered at points P1 and P2 for comparing the effectiveness of solutions developed to reduce noise nuisance due to sound propagation disturbances in the near sound field.

It should be noted that the averaged (in 1/3 octave bands and for all test signals) differences in the sound levels of the signals recorded during the experimental tests at points P1 and P2 versus P3 and P4 (2.2 and 2.7 dB, respectively) only slightly deviate from the value calculated according to Eq. (2). Therefore, both points P3 and P4 located 2.8 m from the track can be considered useful for analysing the effectiveness of the tested vibroacoustic isolators, with the indication of point P3 (microphone 1.5 m above the ground surface).

4.3. Test results

Measurements of the sound absorption and dissipation characteristics of prototype vibroacoustic isolators were carried out in four configurations of the test stand, described in detail in Subsec. 3.2. In each configuration, simultaneous measurements of the sound pressure level were carried out in 1/3 octave bands in the mid-frequency range of 20 to 16000 Hz, at the same measurement points, for the same six excitation signals described in Subsec. 3.3.

As a result of the analysis, signal no. 1 – the pink noise emitted from the generator, which is commonly used in building acoustics and in the research on sound absorption properties of various types of materials – was treated as the leading signal. The results obtained for other acoustic signals were treated as supplementary data, because, according to the authors, the use of the train passes (recorded and subsequently emitted during the conducted measurements) as forcing signals is limited. However, in the authors' opinion, the obtained results are sufficient to demonstrate the technology readiness level specified in the realised research project.

Figure 14 presents the effectiveness of the solution D_B for the excitation with signal no. 1 (pink noise) determined from the results of the sound pressure level in $^1/_3$ octave bands measured in the point P3, which was taken as the leading point.

Figure 15 shows the efficiency of the solution D_B for the average response of the vibroacoustic isolator system to excitation with signals no. 2 to 6 (acoustic signal emitted by passage of trains) determined from the results of the sound pressure level in $^1/_3$ octave bands measured at point P3.

Analysing the test results in $^1/_3$ octave bands for the mid-frequency range from 20 to 200 Hz, a reduction in sound pressure level values was found in each band after the application of the vibroacoustic isolators on both structures. In the ballastless system, for the frequencies from 20 to 40 Hz, very high values of the index determining the effectiveness of the solution from 4.8 to 7.7 dB were obtained. However, given the significant lengths of sound waves propagating in the air in the range of the analysed frequencies (from 8 to 17 m), it is unrealistic to obtain such values in real conditions due to the fundamental problem of limiting propagation of such long waves.

In the case of the mid-frequency range from 250 to 2500 Hz, a large variation was found in the obtained sound pressure level results, further varied by the structure under the isolators. For the ballasted system, the pressure level reductions were obtained for four bands with mid-frequencies of 250, 1000, 1250, and 2500 Hz. In contrast, for the ballastless system, the effectiveness of the panels was demonstrated for five bands with mid-frequencies of 250, 315, 400, 1250, and 1600 Hz. Only in two cases did the results coincide.

For the mid-frequency range from 3150 to 16 000 Hz, a reduction in the sound pressure level was found only for the panels located on the ballastless

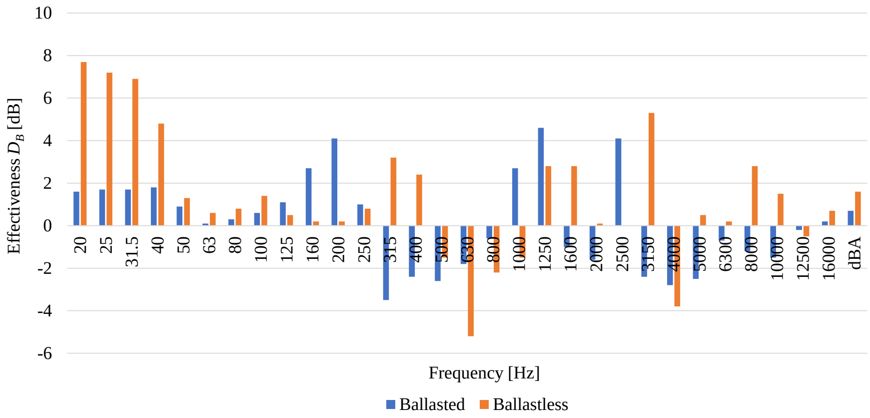


Fig. 14. Effectiveness D_B of the vibroacoustic isolators determined at point P3 for signal no. 1 (pink noise) in $^1/_3$ octave bands with mid-frequencies: 20–16 000 Hz.

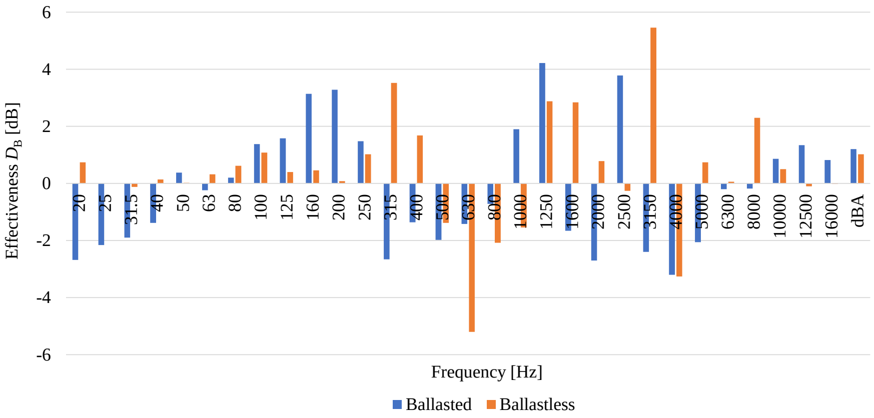


Fig. 15. Effectiveness D_B of the vibroacoustic isolators determined at point P3 for signals no. 2–6 (acoustic signal emitted by passage of trains) in $^1/_3$ octave bands with mid-frequencies: 20–16 000 Hz.

structure. Figure 15 shows additionally the resultant effectiveness of the vibroacoustic isolators for the A-weighted sound level [dBA] – in both systems the D_B index has a positive value (0.7 dB for the ballasted system and 1.6 dB for the ballastless system).

4.4. Discussion of results

Due to the fact that the measurement point P3 was chosen as representative for the analysis and interpretation of the obtained results, the discussion of results is limited to the ones registered at P3.

Based on the test results (differences in the sound levels registered at point P3 before and after the application of prototype sound absorbing panels), it was found:

- ballasted track system with vibroacoustic isolators: in the case of the pink noise, a reduction in the sound pressure level was observed in 1/3 octave bands in the mid-frequency ranges of 20–250 Hz, 1000–1250 Hz, and in the bands of 2500 and 16 000 Hz. In the remaining frequency bands, no positive changes were observed – differences in the results were negative. For the A-weighted sound level, a reduction of 0.7 dB was found. In the case of other emitted signals, except for the passage of a freight train, a decrease in the A-weighted sound level was observed in the range of 1.1 dB (for signal no. 5 – passage of the old-type passenger train EP09) to 1.9 dB (for signal no. 6 – passage of the passenger train ED160, electric multiple unit);
- ballastless track system with vibroacoustic isolators: in the case of the pink noise, a reduction in the sound pressure level was observed in 1/3 octave bands in the mid-frequency ranges of 20–400 Hz, 1250–2000 Hz, 5000–10 000 Hz, and in the bands of 3150 and 16 000 Hz. In the remaining frequency bands, no positive changes were observed. For the A-weighted sound level, a reduction of 1.6 dB was found. In the case of all other emitted signals, a decrease in the A-weighted sound level was observed in the range of 0.2 dB (for signal no. 3 – passage of the freight train ET22) to 1.8 dB (for signal no. 6 – passage of the passenger train ED160, electric multiple unit).

It should be emphasized that the results discussed above were obtained in experiments that did not reproduce the influence of a number of elements (indicated in Subsec. 4.1), which are significant for the analysed phenomena. However, the authors' experience in the research on acoustic properties of railway systems allows them to state that, although the applied original methodology with consciously adopted simplifications initiates various doubts, it does not undermine the validity of this type of research or the reliability of its performance.

5. Conclusions

In the present study an original field experiment was proposed as a tool to verify the effectiveness of the developed prototype vibroacoustic isolators aimed at reducing railway noise emitted to the environment. A set of porous concrete sound absorbing panels was tested on two types of track structures: ballasted and ballastless systems.

Results of the measurements confirm the required noise attenuation and dispersion capacity of the tested vibroacoustic isolators (a system consisting of two types of panels). The condition "X–0.5 dB" for the designed solutions has been fulfilled (where X is the initial value of the noise level measured for the reference track structure). The results confirm the higher effectiveness in reducing railway noise emitted to the environment after the installation of the prototype sound absorbing panels on the ballastless structure. The findings of this study coincide with the experience of foreign railway infrastructure managers (e.g., from Germany and China), where vibroacoustic isolators (usually made of porous concrete) are used and show the highest effectiveness in reducing noise levels mainly when using ballastless systems. Currently, Poland lacks a proper testing site with the ballastless track structure, as such systems are used on the PKP PLK S.A. network to a marginal extent. Consequently, there was no technical possibility to carry out reliable tests of the noise level in the real environment.

However, the results of unconventional experiments carried out on an improvised test stand using the recorded acoustic signals confirmed the effectiveness of the developed solutions of the track structure components aimed at limiting the noise nuisance caused by railway traffic. Taking into account the characteristics of the acoustic field when selecting the spatial location of the sound measuring point, makes it possible to solve tasks aimed at optimising the developed structural solutions. The examples presented in this study demonstrate the versatility of the proposed concept of comparative research and show good prospects for their further use.

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