MIDDLE POMERANIAN SCIENTIFIC SOCIETY OF THE ENVIRONMENT PROTECTION

Rocznik Ochrona Środowiska

Volume 21. Year 2019 ISSN 1506-218X 600-610

Identification and Analysis of Noise Sources in a Plate Girder Railway Bridge with Orthotropic Deck

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1. Introduction

Moving railway transport vehicles are sources of noise and determine the acoustic climate around railway lines. When they pass over steel bridges, the transverse vibrations of structural sheets can emit aerial sounds that are an environmental nuisance (Costley et al. 2015, Li et al. 2016, Li & Wu 2014, Zvolenský et al. 2017, Janas 2018). This problem is mainly observed in the vicinity of steel structures but also nearby steel-concrete bridges (Oostdijk et al. 2015, Saito et al. 2015), concrete bridges (Li & Wu 2012, Song & Li 2018) and on high–speed railway bridges (Kozuma & Nagakura 2012, Liu et al. 2014). A comparison of noise surrounded by different types of bridges was presented in (Thomspon 2009). Steel provides low internal attenuation and structures made of steel can easily be subject to poorly damped free vibrations and/or a 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. The unpleasant buzzing characteristics of this noise make it particularly vexing to the human ear, both outside and inside residential dwellings. The problem of bridge noise is mentioned in the Eurocode [EN 1993-2, 2010], some rules for designing quiet bridges are presented in International Union of Railways recommendations (UIC Code 717R, 2010).

This article presents the results of noise and vibration testing on a plate girder railway bridge. The main purpose of the research was to determine the causes of noise increase in the surroundings of such a bridge.

2. Characteristics of the tested object

The tested bridge was a free supported, plate girder structure with a steel platform and a track located on the ballast (Figure 1). It was a kind of structure that is nowadays often designed and built. The span length of the tested bridge was 31.68 m, the height of girders amounted 2.47 m. The ballast was laid on the deck made of an orthotropic metal plate. The thickness of the ballast layer under the concrete sleepers was at least 0.35 m. There was no vibroisolation under the ballast. The object was in a very good technical condition, was opened to operation just a few months before the test.

a) b)

Fig. 1. The tested bridge: a) side view, b) bottom view

3. Study of acoustic phenomena

In order to determine the bridge impact on noise, synchronized measurements were carried out at three measuring points (m.p.):

- M1 – the microphone beside the track, 50 m beyond the bridge, at the distance of 7.5 m from the track axis and 1.5 m above the rail level (reference point),
- M2 – the microphone next to the bridge, at the distance of 7.5 m from the track axis and 1.5 m above the rail level,
- M3 – the microphone under the bridge, 1.5 m above the ground level.

Arrangement of measurement points is shown in Figure 2.

The multi-field B&K 4961 microphones were used, with frequency range of 5 Hz – 20 kHz and dynamic range 20-130 dB. The measurements were taken at air temperature +20°C, with relative humidity of 50-70% and weak wind strength (<3 m/s). The microphones were covered by B&K UA-0237 windscreens and set up on a tripod and special masts. Signals were recorded by means of 6-channel B&K LAN-XI 3050-A-060 measuring modules (cassette). The analysis was performed using the B&K PULSE Reflex program. Before testing, the measuring system was checked with the B&K 4231 sound calibrator.

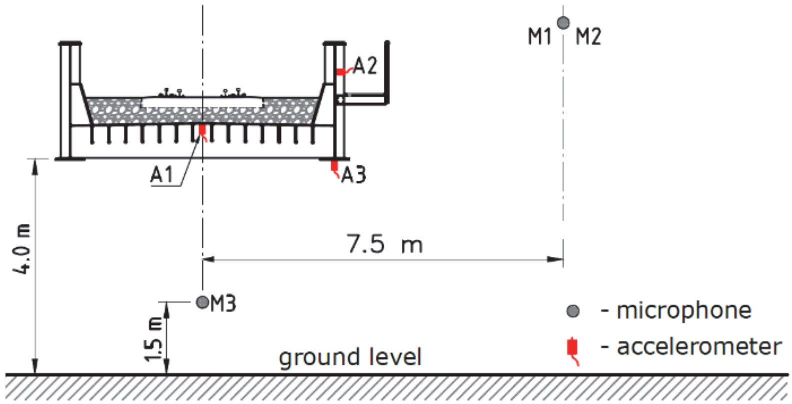

Fig. 2. Cross-section of the tested bridge and measuring points

The acoustic effects were registered during the passage of passenger trains, including long-distance trains, railbuses, regional trains and cargo trains - results of the research are presented in the article (Janas 2019). The total noise under the bridge (m.p. M3) was higher from 4.0 to 7.8 dB than the noise beside the track, beyond the bridge (m.p. M1). The noise beside the bridge (m.p. M2) does not differ significantly from the noise beside the track beyond the bridge (m.p. M1).

In order to precisely determine the reasons for the increase in noise, in this article the acoustic phenomena surrounding the bridge were analyzed in detail. The signals recorded during the train passage were divided into parts, for which harmonics were calculated using the FFT method. Amplitudes are spectrogram values, whereas frequency and time are arguments.

Figure 3a shows the background spectrogram. The spectrograms obtained during the passage of a cargo train at the speed of 40 km/h are shown in Figure 3b, c, d.

The sound pressure level next to the track, beyond the bridge in comparison to the background level increases in the entire analyzed range of the frequencies (Figure 3b). The sound pressure level next to the bridge (Figure 3c) is larger in the low frequency range (up to approx. 250 Hz) than the level next to the track, beyond the bridge. The sound pressure level under the bridge (Figure 3d) is much larger in the low frequency range (up to approx. 400 Hz) than the level next to the track, beyond the bridge.

For a detailed analysis of the sound, the amplitude-frequency characteristics averaged during the passage, in the third octave bands, are shown in Figure 4. The total level of noise is also shown in this figure.

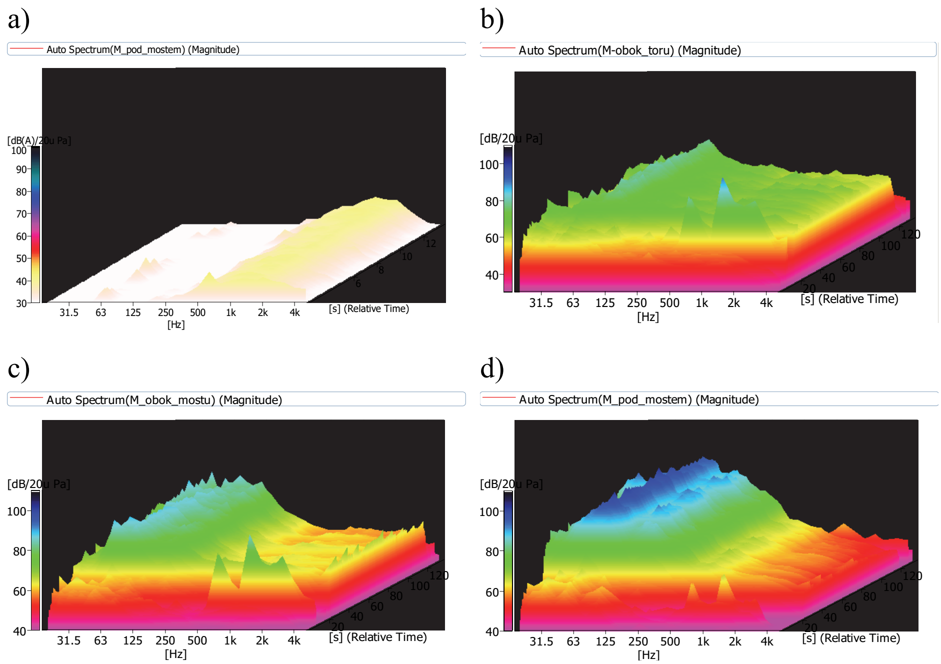

Fig. 3. Spectrogram of a background sound pressure (a) and spectrograms recorded during the passage of a cargo train: b) beside the track beyond the bridge (m.p. M1), c) next to the bridge (m.p. M2), d) under the bridge (m.p. M3)

In the standards, the permissible noise level in the vicinity of a bridge when traveling on individual trains is not defined. But, it can be noticed that during the analyzed passage (cargo train, 40 km/h) the total noise under the bridge was 7.2 dB higher than the noise next to the track, beyond the bridge. Such an increase in noise is perceived by people as about a twofold increase in nuisance. The highest sound level values are in the range of 50-125 Hz. The total noise beside the bridge was only 0.6 dB higher than the noise next to the track, beyond the bridge.

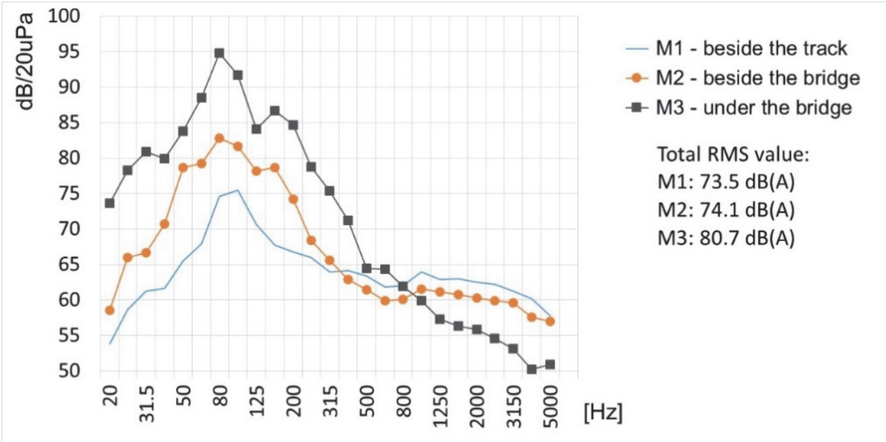

Fig. 4. Levels of the acoustic pressure versus frequency bands during the passage of a cargo train at the speed of 40 km/h

In order to extract the frequency bands for which the largest changes in sound pressure levels occur, the differences between measuring points in individual frequency bands were calculated – the results are shown in Figure 5.

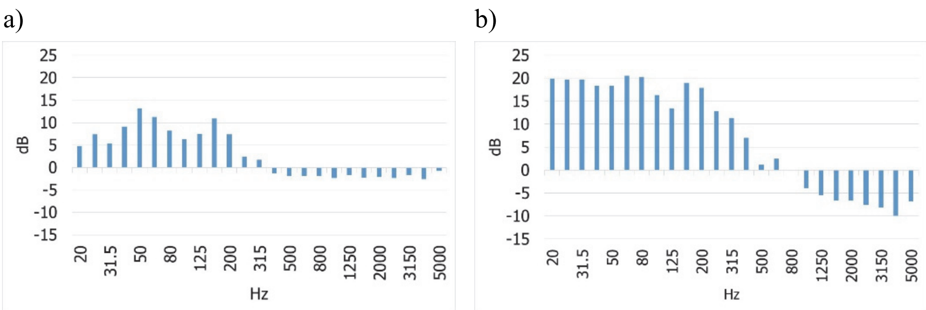

Fig. 5. Differences in the sound pressure levels: a) between point M1 and point M2, b) between point M1 and point M3

The sound pressure level next to the bridge (m.p. M2) is slightly larger in the range of 20-200 Hz than the level at the reference point (m.p. M1). For higher frequencies, the pressure level is almost equal or slightly lower – the differences do not exceed 2.5 dB.

The sound pressure level under the bridge (m.p. M3) is in the range of 20-400 Hz and much larger than the noise at the reference point – the differences reach 20 dB. For higher frequencies, above 1000 Hz, the sound level is lower even by 5 to 10 dB.

4. Study of acoustic and 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 (Figure 2): the deck in vertical direction (m.p. A1), the girder web in horizontal direction (m.p. A2) and the girder in vertical direction (m.p. A3). For vibration measurements B&K 4507B-006 accelerometers were used with sensitivity of 50 mV/ms^{-2}, frequency range of 0.2 Hz – 6.0 kHz and measuring range of 140 m/s^2 (±peak). The accelerometers were mounted with special magnet holders. The measuring system was checked by the B&K 4294 calibration exciter.

Along with the vibration measurements of structure elements, the level of acoustic pressure next to the bridge (m.p. M2) and under the bridge (m.p. M3) was measured.

A coherence function was applied to identify the main sources of noise in the bridge structure. Subjecting the measured signals to the Fourier transform 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. A comparison of the coherence function values for various elements of the bridge and directions allowed the main sources of acoustic energy radiation to be determined. The value of the coherence function can be reduced (lowered) as a consequence of the interfering noise. In the current study, the coherence function was determined using the formula (1):

$$\gamma_{xy}^2(f) = \frac{|\bar{G}_{xy}(f)|^2}{\bar{G}_{xx}(f)\cdot\bar{G}_{yy}(f)} \tag{1}$$

where:
$G_{xy}(f)$ – the cross-spectral density between signals x and y,
$G_{xx}(f)$, $G_{yy}(f)$ – the auto spectral density of x and y, respectively.

This method (i.e. determining the coherence functions of the ‘material’ vibration and 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. Selected results of this analysis are presented in Figure 6 and Figure 7.

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 an interfering noise, the coherence function is equal to 1. If a linear relationship does not occur, the function is equal to 0.

The above-mentioned functions revealed that relationships existed between the vibration phenomena of structural elements and the acoustic phenomena. The coherence function has the highest values between the deck vertical vibrations and noise (Fig. 7a). Therefore, it can be assumed that the main source of the noise under the bridge (m.p. M3) is the platform plate (m.p. A1). The coherence between the horizontal vibrations of the girder web is definitely smaller (Fig. 7b). There was no coherence between the vertical girder vibrations and noise under the bridge (Fig. 7c).

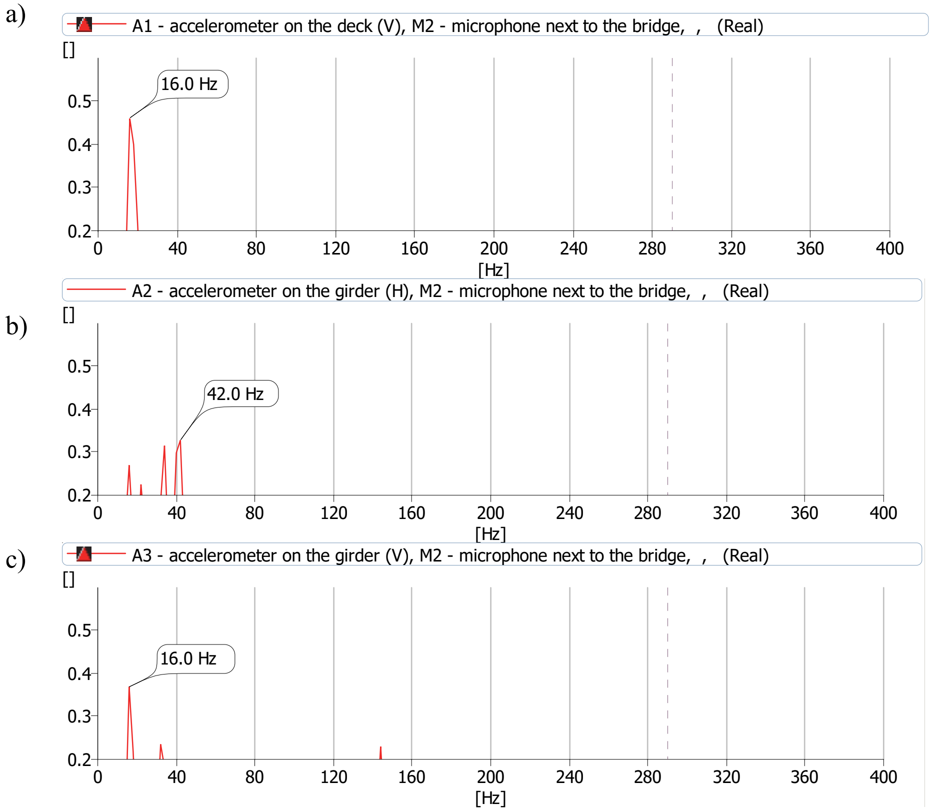

Fig. 6. Coherence function between acoustic pressure at point M2 and: a) vibrations at point A1, b) vibrations at point A2, c) vibrations at point A3

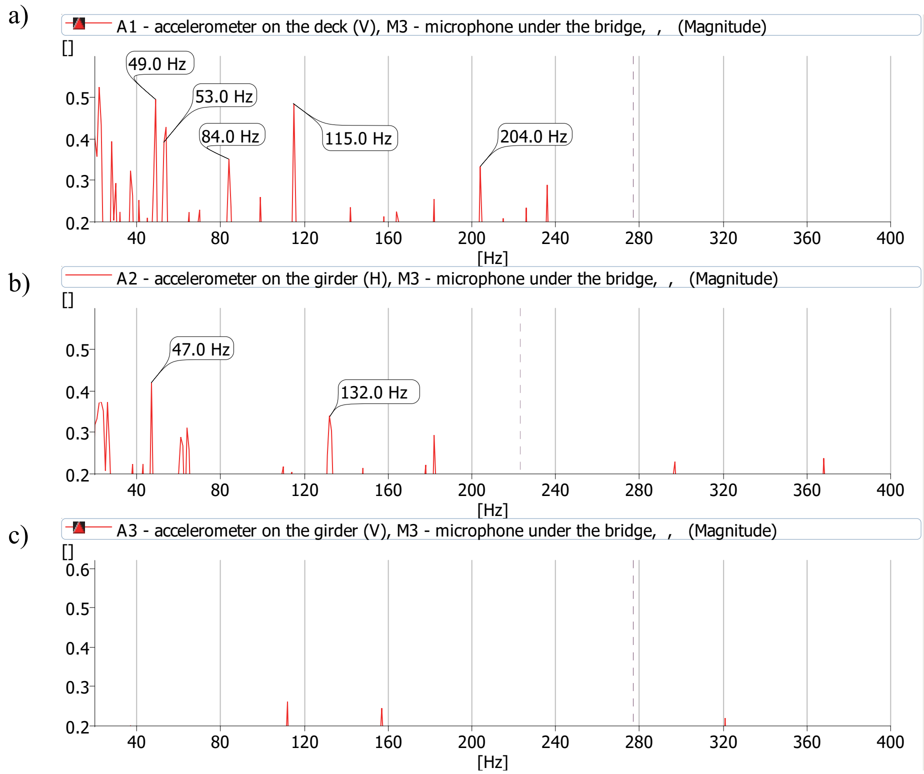

Fig. 7. Coherence function between acoustic pressure at point M3 and: a) vibrations at point A1, b) vibrations at point A2, c) vibrations at point A3

The measurements and analyses were performed several times at the same measuring points, but with different railway cargo vehicles passing. The coherence functions were invariably similar to each other. Therefore, it can be concluded that acoustic phenomena determined during a normal operation of the bridge result primarily from the type of structure (geometric properties, materials, equipment elements) and, to a small extent, from the type of load. This was confirmed by the constancy of the characteristic lines related to the resonance frequencies of the structural elements.

5. Conclusions

Steel plate girder bridges with an orthotropic deck and tracks laid on the ballast may pose a threat to environment. In the analysed case, the sound pressure level under the bridge was more than 7 dB higher than the noise next to the railway line, beyond the bridge. Such a large increase in noise was also observed in the vicinity of other bridges of similar construction, e.g. (Thomspon 2019). The increase is observed in the range of low and medium frequencies, up to 400 Hz.

This phenomenon was caused by vibrations of bridge structural elements. The passage of a train excited vibrations in large-surface elements - in this case orthotropic deck. The analysis in narrow frequency bands allowed to confirm the high compatibility of platform vibrations (deck) and sounds under the bridge. A small agreement or no agreement exists between vibrations of the girder and acoustic pressure under the bridge.

The noise next to the tested structure did not differ significantly from the noise next to the track, beyond the bridge. The sounds emitted by trains were partially damped by the bridge girders - they were a kind of acoustic screen.

Because the analysed object was located low over the ground, sounds were damped by the ground and did not disseminate. However, it must be noted that this type of structure used on populated areas on high supports may be inconvenient for the environment.

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Abstract

The paper presents the results of a noise and vibration analysis of a steel railway plate girder bridge with an orthotropic deck and ballast. This kind of bridges may pose a threat to environment. In order to precisely determine the reasons for the increase in noise, in this article the acoustic phenomena surrounding the bridge were analyzed in detail.

Sound characteristics were determined in three points – next to the railway line outside the bridge, next to, and under the bridge. The sound characteristics are presented in one-third octave bands and narrow frequency bands. The analysis was based on comparing the levels of acoustic pressure and determining the summary levels. The narrow frequency bands analysis included an identification of the frequency composition of the generated sounds. A significant increase in noise under the bridge was found.

The sound pressure level next to the track, beyond the bridge in comparison to the background level increases in the entire analyzed range of the frequencies. The sound pressure level next to the bridge was only 0.6 dB higher than the noise next to the track, beyond the bridge The sound pressure level under the bridge is much larger in the low frequency range (up to approx. 400 Hz) than the level next to the track, beyond the bridge. It can be noticed that in analysed case the total noise under the bridge was 7.2 dB higher than the noise next to the track, beyond the bridge. The highest sound level values are in the range of 50-125 Hz.

This phenomenon was caused by vibrations of bridge structural elements. The passage of a train excited vibrations in large-surface elements - in this case orthotropic deck. The analysis in narrow frequency bands allowed to confirm the high compatibility of platform vibrations (deck) and sounds under the bridge. A small agreement or no agreement exists between vibrations of the girder and acoustic pressure under and next to the bridge. The analysed type of structure can be a nuisance to the environment if it is located on high supports in urbanized areas.

Keywords:
noise, vibrations, steel railway bridge, coherence

Identyfikacja i analiza źródeł hałasu w kolejowym moście blachownicowym z pomostem ortotropowym

Streszczenie

W artykule przedstawiono rezultaty analizy hałasu i drgań mostu stalowego blachownicowego, z pomostem ortotropowym i torem ułożonym na podsypce. Tego rodzaju obiekty mogą stanowić zagrożenie dla środowiska. W pierwszej kolejności szczegółowo przeanalizowano zjawiska akustyczne w otoczeniu mostu. Ciśnienie akustyczne mierzono w trzech punktach – obok linii kolejowej poza mostem, obok mostu i pod mostem. Charakterystyki dźwięku porównano w wąskich pasmach częstotliwości i w pasmach tercjowych. Określono również poziomy sumaryczne i stwierdzono znaczny wzrost hałasu pod obiektem.

Poziom ciśnienia akustycznego obok toru poza mostem, w porównaniu do poziomu tła, wzrasta w całym analizowanym zakresie częstotliwości. Poziom ciśnienia akustycznego obok mostu jest porównywalny do poziomu obok toru poza mostem – różnica wynosi jedynie 0.6 dB. Sumaryczny hałas pod mostem był o 7,2 dB wyższy niż hałas przy torze, poza mostem. Poziom ciśnienia akustycznego był wyższy w zakresie niskich częstotliwości – do ok. 400 Hz. Najwyższe wartości poziomu dźwięku mieściły się w zakresie 50-125 Hz.

Do identyfikacji źródeł dźwięku zastosowano metodę funkcji koherencji. Wykazano, że wzrost hałasu pod obiektem jest spowodowany wibracjami elementów konstrukcji. Przejazd pociągu wzbudzał drgania elementów wielkopowierzchniowych (w tym przypadku pomostu ortotropowego), które przyczyniły się do emisji hałasu. Analiza w wąskich pasmach częstotliwości pozwoliła na potwierdzenie koherencji drgań pomostu i dźwięków pod mostem. Nie stwierdzono występowania zgodności między charakterystyką drgań dźwigara blachownicowego i ciśnieniem akustycznym obok mostu.

Przeprowadzone analizy pozwalają stwierdzić, że analizowany typ konstrukcji może być uciążliwy dla środowiska, szczególnie wtedy, gdy będzie zlokalizowany na obszarze zurbanizowanym, np. na wysokich podporach.

Słowa kluczowe:
hałas, drgania, most stalowy kolejowy, koherencja