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VIBROACOUSTIC TRACK ANALYSIS AND NOISE MEASUREMENTS ON THE R201 ZAPREŠIĆ - ZABOK RAILWAY LINE

Ivo Haladin, Krešimir Burnać, Mate Ivančev, Janko Koščak
University of Zagreb, Faculty of Civil Engineering, Croatia

Abstract

In the process of renewal and electrification of 24 km of the R201 Zaprešić – Zabok section, noise measurements had to be carried out to re-evaluate model-based noise protection measures (noise walls). Task requires noise measurements during standard operating conditions of new EMU trains at 120 km/h. Such conditions cannot be met until the operating permit is issued; hence an alternative method of measurement has been proposed. It involves vibroacoustic characterization of the Zaprešić – Zabok section and reference section, where such EMUs can operate at 120 km/h, to establish if comparable noise emission characteristics of the railway tracks are achieved (rail roughness and track decay rates). Further, pass-by noise measurements on alternative track are performed at various speeds and distances from the track axis. Using a reference section with comparable vibro-acoustic properties, environmental noise measurements made on the Zaprešić-Zabok section could be amended with EMU at 120 km/h pass-by data to get a very precise estimate of future track conditions and to re-evaluate the noise protection measures along the renewed railway line.

Keywords: vibroacoustic, noise, railway, noise protection, pass-by noise

1 Introduction

The problems of noise and vibration from rail traffic in urban areas are highlighted due to the proximity of railway infrastructure and surrounding buildings in which people live and work. It is necessary to determine the main sources and mechanisms of noise and vibration propagation and ways of their elimination or reduction to acceptable limits. Sources of noise and vibration during the operation of rail vehicles can be determined by numerical simulations of the interaction of wheels and rails, by conducting experimental tests, or by a combination of these two methods [1]. When the vehicle moves on the track, the wheel interacts with the rail, which leads to the appearance of horizontal and vertical vibrations.
In the European Union, the regulation of the European Commission no. 1304/2014 [2] which prescribes the maximum noise levels that railway vehicles may emit. The regulation prescribes the standard HRN EN ISO 3095: 2013 [3] according to which it is necessary to determine the maximum noise level of train passage. The track condition on which the vehicle noise is tested must meet the standard HRN EN15610:2019 [4] which refers to the roughness of the running surface of the rail and HRN EN 15461:2011 [5] which refers to the degree of vibration damping of the track structure.
When acoustic roughness and track decay rate of the track structure is defined, it is possible to determine the share of the track contribution to total noise levels during the passage of the train. Vehicle engines, aerodynamic noise at high speeds, and vehicle wheel and rail contact are the main sources of noise and vibration. The main parameter that affects the

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dominant noise sources is traffic speed, so the noise from the vehicle engine is prevalent at speeds up to 20 km/h, rolling wheels on rails from 20 km/h to 250 km/h, while at higher speeds the dominant source is aerodynamic noise [6].
In this work measuring track is railway line R201 Zaprešić-Zabok, while the referent track is M101(State border – Savski Marof – Zagreb Main station). In the design phase of the measuring railway track, a noise protection study was made. Noise levels have been estimated based on noise prediction model on a newly designed railway track. Actual noise levels in realistic conditions (design speed, number of trains, traction type – new, quieter EMUs) could only be measured after completing the modernization and electrification.
Research task was to check the noise protection study and predict future noise levels in order to validate if indeed extensive noise protection from rail traffic is needed. Accurate prediction of noise levels on a newly built line had to be made and since the line was still in construction there was no use permit that would allow new EMUs to operate at speed up to 120 km/h.
By determining the vibro-acoustic parameters of the track on the measuring and reference railway track, it is possible to apply the measured noise levels on the reference track section at a speed of up to 120 km/h (where realistic operating conditions are already met) as relevant on the measuring track. A necessary condition is that both tracks meet the vibro-acoustic parameters prescribed by the standard [3]. Determination of these track parameters enables the definition of the track share in the total noise levels generated during the passage of trains. On the track sections meeting the mentioned standards, whether the track is sufficiently "quiet" to enable determination of the noise generated by the vehicle itself during typical vehicle noise testing, without the noise caused by an acoustically poor track structure. In this case, the referent and measuring track can be declared comparable in acoustic terms. In addition, it is necessary to define the functional relationships of noise levels at different speeds of pass-by and distance from the track to apply the measured pass-by noise levels from the referent track to various speed/distance conditions at the measuring track. This paper aimed to:

- Measure pass-by noise at referent track
- Determine vibroacoustic similarity between referent and measuring track
- Create functional relationships between noise measurements for referent and measuring track
- Validate the relationships after EMU is put in service at the measuring track.

In Chapter 2. are presented in situ testing of the track decay rate and acoustic rail roughness, with aim of proof of the acoustical compliance of the measuring and referent track. Chapter 3 shows the measurement of the pass-by noise after a train passes on observed locations. All vibroacoustic measurements and measurements of the noise levels are conducted within the report [7]. In Chapter 4. An analysis of the obtained results is presented.

2 Vibro-acoustic similarity of the measurement locations

To provide the acoustic resemblance of the measuring track R201 Zaprešić - Zabok railway line and the referent railway section of the track M101 following activities were conducted:

- Visual inspection of the track superstructure
- Determination of the track decay rate according to HRN 15461:2011 [5]
- Measurements of the railhead according to HRN EN 15610:2009 [4].

Railway line R201 Zaprešić-Zabok has one rail track, and it is a ballast superstructure built from rails (60 E1), steel-concrete sleepers (B70, 60 E1), elastic fastening (SKL-14), and ballast bed. The Railway section of the M101 railway line (State border – Savski Marof – Zagreb Main station) close to the Brdovec station was chosen as the reference railway section with same superstructure characteristics with only difference being that it is constructed as a double track. The allowed noise measurements of new EMU-s (designated for Zaprešić-Zabok section) at speeds of up to 120 km/h (design speed for Zaprešić- Zabok section). This railway section was chosen based on geometric properties (prescribed by the standards) and a detailed inspection of the rail track condition.

Figure 1 Analysed track section R 201 – left; and referent track section M101 – right

2.1 Track decay rate

The track decay rate is a vibroacoustic property that describes the amount of vibrations the track can absorb, i.e., how far vibrations travel through the rail from the excitation source before they are fully attenuated. The longer the rail section that vibrates, the greater noise emitted during the passage of the train [8]. The purpose of this measurement is to determine the quality of the referent and measure the rail track in the aspect of reduction of unwanted noise and vibrations. Standard [5] requires the railway superstructure to be uniform considering the parameters that might influence the track decay rate. Those parameters are rail cross-section, rail pad stiffness, rail inclination, and distance between two sleepers. The test sections must be welded into a long rail track and must not have a rail joint in the area covered by testing. When selecting a position where the vibration measurement sensors are to be set, the following must be taken care of: the minimum distance of the accelerometer to a weld must not be less than 5 m and the minimum distance of the accelerometer from the rail joint must not be less than 40 m.

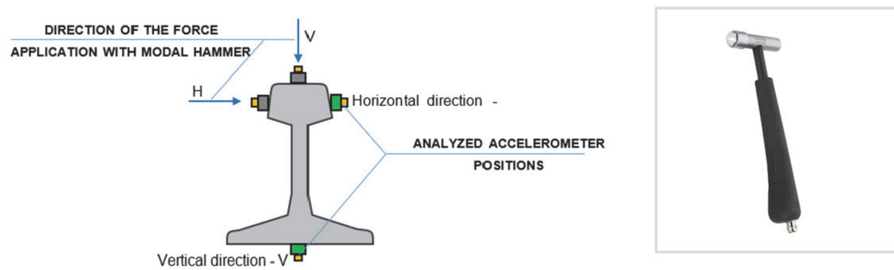

Figure 2 Accelerometer positions and modal hammer type 8206

The force pulse is applied with a modal hammer of appropriate stiffness containing an accelerometer to keep the excitation in control. A modal hammer “Brüel & Kjær” type 8206 with an aluminum tip was used for testing on the observed section to apply the force. For each test position on the rail, the average FRF value determined from a minimum of 4 frequency response functions (4 modal hammer hits at each point) must be determined. All vibrations observed in the frequency domain are then analyzed and presented in the third octave band of central frequencies between f_c = 100 Hz and f_c = 5000 Hz. Figure 3 shows a comparison between limit track decay rate values on the referent track with the measuring track in the horizontal and vertical directions.

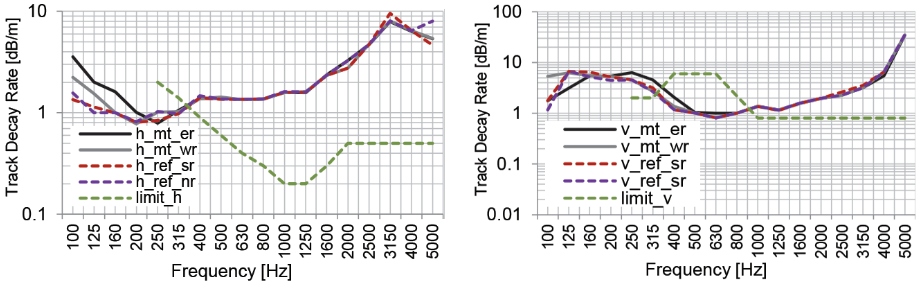

Figure 3 Horizontal TDR comparison-left, and vertical TDR comparison-right (er-east rail, wr-west rail, sr-south rail, nr-north rail; mt-measuring track, ref-referent track)

2.2 Acoustic railhead roughness

The method of measuring the direct acoustic roughness of the running surface of the rails aims to determine the roughness of the rails that affects the generation of noise when railway vehicles pass - by. On the contact surface of the vehicle wheels and the rail, due to the imperfection of the running surfaces, vibrations occur, which are emitted as noise into the environment at higher frequencies. Measurement of the roughness of the running surface of the rail for standard noise measurements is determined by the standard [4]. The measurements of the acoustic rail roughness were carried out at the selected location on the referent track M101 and the 3 locations of the measuring track R201. Roughness was measured with the device RAILPROF 1000, which conducts non-contact measurements based on inductive sensors. The effective measurement length is 1 m, while the accuracy of data collection 0.002 mm to -0.009 mm in the vertical direction, respectively 0.003 mm to -0.005 mm in the horizontal direction. Before measuring the roughness of the running surface, the rail surface is thoroughly cleaned of grease and dirt.

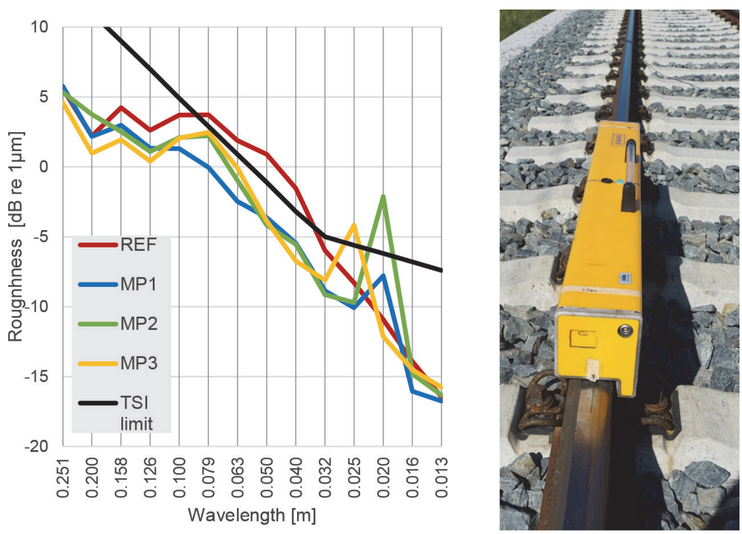

Figure 4 Comparison of the direct acoustic roughness for the reference track section M101 and three measured positions on measuring track section R201

From the results of measuring the acoustic roughness of the track surface (Figure 4), it can be concluded that for most of the observed wavelengths (from 0.158 m to 0.032 m) the level of track surface roughness is higher by 2 dB to 5 dB on the reference section. At wavelengths of 0.020 - 0.025 m, an increase in roughness values of 2 dB to 5 dB was on the measuring section Zaprešić - Zabok, which is most likely the result of the rail grinding carried out immediately before measuring the rail head roughness.
According to obtained results of track decay rates and acoustic rail roughness, the measuring track on the railway section R201 is acoustically comparable to the referent track M101 and it is possible to apply noise measurement on the referent track to assess noise levels on the measuring track. It is expected to achieve marginally higher resulting noise levels on test track due to higher rail roughness on test track which can lead to overestimation of noise level on measuring track on the safe side for determining environmental noise levels indicative for constructing noise barriers.

3 Pass – by noise measurements

Pass–by measurements were performed to determine the noise levels from the passing railway vehicles operating at different speeds and different distances from the rail track axis.
Measurements were carried out at 2 locations on the measuring section (R201 Zaprešić – Zabok) and at 2 locations on the reference section (M101 railway line near the station Brdovec).
For the reference railway section, noise levels from the train were measured according to the pass-by method in two locations – one with train operating at 120 km/h and other where speed is reduced because of nearby station to 80 km/h.
To evaluate and confirm the method, repeated measurements were carried out at 3 locations on the R201 Zaprešić – Zabok railway line (EMUs started to operate on the line at the speed of 120 km/h).
The measurement devices used were Brüel & Kjær - Hand-held Analyzers Type 2260, 2250, 2245, and 2270. Measurement microphones were installed at each measuring site at distance 7.5 m away from the track axis (height 1.5 and 3.5 m above top of rail) as well as 15 m and 25 m away from track axis (height 4 m above ground).

3.1 Results analysis

Based on the recorded pass-by noise levels of the EMU HŽPP 6112 on the reference section at different operating speeds and different distances, with results analysis, pass-by noise levels could be estimated for any combination of distance away from track, and train speed. These results are to be used for implementation in environmental noise measurements.
After the measurements, taken from time records, equivalent noise levels were given for every individual pass–by of the train, at different distances from the rail track axis.
The equivalent noise level for every pass–by is calculated with the formula:

$$L_{PAeq,\ Tp} = 10\ \log\left(\frac{1}{T_2 - T_1}\int_{T_1}^{T_2}\frac{p_A^2(t)}{p_0^2}dt\right)\ [dB]$$

where:

$L_{pAeq,Tp}$ - equivalent A - valued continuous sound pressure level in time Tp expressed in dB
T_p - pass–by time of the railway vehicle (the time it takes to reduce the sound pressure level by 10 dB before and after pass–by of the vehicle)
p_A (t) - measured A - valued sound pressure value in Pa
p_0 - reference sound pressure value (20 μPa)

To calculate the equivalent noise levels for the pass–by of railway vehicles at arbitrary speed and distance from track, on the measuring section Zaprešić – Zabok, three regression curves have to be defined: for distance, speed and pass-by time.
For calculating the equivalent noise levels depending on the different speed of the vehicle, a general equation for noise vs speed dependence was used (with different coefficient for acceleration and deceleration):

$$L_{p,\,V} = L_{p,\,V0} + \text{k}\,\log\left(\frac{V}{V_o}\right)\left[dB\right]$$

where:
$L_{p,V}$ - noise level from train pass–by at speed V
V - arbitrary speed for which noise level is determined
$L_{p,\,V0}$ - noise level from train pass–by at reference speed (100 km/h)
V_0 - reference train pass – by speed (100 km/h)
k - coefficient (25 for acceleration, 20 for decceleration)

Based on the equivalent noise levels normalized to a reference speed of 100 km/h ($L_{p,\,V0}$), regression curves were created for the variation of the distances from the rail track axis. Based on these curves, two regression formulas were extracted (for acceleration and deceleration):

$L_{p,V0,D} = -5.97 \cdot \ln(D) + 93.14$ ($R^2 = 0.86$) (acceleration)

$L_{p,V0,D} = -7.68 \cdot \ln(D) + 97.39$ ($R^2 = 0.95$) (deceleration)

where:
$L_{p,\,V0,D}$ - noise level from train pass–by (in dB) at the reference speed V_0 and distance D
D - chosen distance from the rail track axis [m]

To determine the variation of the pass–by time T_p related to the speed of the train pass–by, two formulas were used:

$T_{p,V} = -0.12 \cdot V + 18.90$ ($R^2 = 0.94$) (acceleration)

$T_{p,V} = -0.09 \cdot V + 15.19$ ($R^2 = 0.89$) (deceleration)

where:
$T_{p,\,V}$ - time of train pass – by in [s] at the speed V
V - speed of the train in [km/h] on a chosen measuring point

4 Results analysis

Using a model that is made with the help of the listed six formulas, it is possible to calculate equivalent noise levels on the measuring section, at various distances from the track axis and for different vehicle speeds. Based on noise level values that were measured on the reference equivalent noise level values ($L_{pAeq,\,Tp}$) in the measured section were calculated.
An example of the results that were calculated according to the explained model is shown in Table 1. Those calculated values were compared to the ones from repeated measurements on Zaprešić – Zabok railway section (once EMUs started operating at V_{max} = 120 km/h.

Table 1 Calculated and measured noise levels for different speeds and distances from the axis on the measuring section Zaprešić-Zabok

		7.5 m			15.0 m			25.0 m		
Train	Speed [km/h]	LAeq [dB]		Δ LAeq [dB]	LAeq [dB]		Δ LAeq [dB]	LAeq [dB]		Δ LAeq [dB]
		Meas	Calc		Meas	Calc		Meas	Calc	
1	102	81.6	82.03	0.43	76.3	76.72	0.42	72	72.8	0.8
2	101	80.7	79.11	-1.59	76.4	75.36	-1.04	72.5	72.59	0.09
3	41	74.5	74.2	-0.3	68.4	68.89	0.49	65.2	64.97	-0.23
4	41	73.7	74.2	0.5	68.3	68.89	0.59	64.8	64.97	0.17
5	65	76.9	73.56	-3.34	71.7	69.81	-1.89	68.1	67.04	-1.06
6	52	75	76.26	1.26	71.1	70.95	-0.15	67.8	67.03	-0.77
AVERAGE DIFFERENCE [dB]				**-0.50**			**-0.26**			**-0.14**

The difference between values from the repeated measurements and those that were calculated, was less than 1 dB. Such a small difference between measured and calculated (projected) noise levels was a confirmation that the model was made accurately.
Results could finally be used as an input for modifying the 24-hour environmental noise levels that were recorded on the R201 Zaprešić – Zabok railway line. Namely, 24-hour noise levels were recorded with diesel–motor units (DMU - HŽPP 7121), operating at the lower speeds (Vmax = 80 km/h) which would not fit the future situation after the modernisation and electrification. Noise records of those DMU were replaced with the equivalent noise emission level records coming from the electric-motor unit (EMU HŽPP 6112) recorded on the reference railway section, where trains are operating at 120 km/h, which is the planned future situation on the Zaprešić – Zabok railway section (Figure 5).

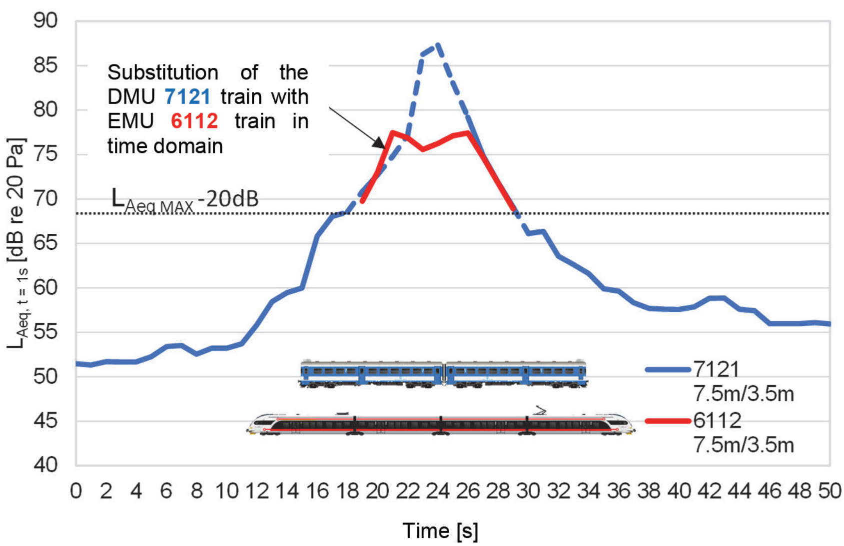

Figure 5 Example of the pass-by noise substitution of the DMU (HŽPP 7121) with noise generated by EMU (HŽPP 6112) in a section of 24h long environmental noise record

5 Conclusion

Various numerical simulations of the wheel-rail interaction can be used to determine the source of noise and vibration during the operation of rail vehicles. Source separation based on vehicle and track parameters can also provide valuable parameters for determining noise levels of a vehicle on any track where it currently doesn't operate. In this paper, two vibroacoustic parameters are measured and analysed, to evaluate if the two observed railway sections (measuring and reference section) have similar vibroacoustic properties. The aim of the work was to create a functional relationship between noise measurements for reference and measuring track and to validate the relationship after EMU is put in service at the measuring track. This kind of alternative measurement/modelling was made because there was no possibility to measure noise levels on the measuring railway section (at operating speed of 120 km/h).
After the measurements of the vibroacoustic parameters were made and it was concluded that two sections are similar, pass – by noise measurements were made on reference track with EMU running at speed of up to 120 km/h. Based on the noise level values of the pass-by measurements at the reference section, a model was made to calculate the noise levels for measuring track that will be used to alter the 24-hour environmental noise level values that were recorded on the measuring section.
Finally, repeated pass-by noise measurements were made on the measuring section to evaluate and confirm the used model. Results from those measurements were compared to the noise levels that were calculated. Average difference between measured and calculated results was less than 1dB and it was concluded that the model was accurate.

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