

Emission of Structural Noise of Tank Wagons Due to Induced Vibrations during Wagon Operation

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Abstract: Railway transport is considered relatively environmentally friendly in terms of energy consumption and air pollution, but it is relatively unfriendly in terms of noise pollution. Noise and vibrations propagating to railroad surrounding areas are disturbing populations. In order to minimize this noise, legislation and regulations such as TSI NOI have been adopted and research of noise and vibrations generated by railway transport has been carried out. Such research has been carried out also by our team focused on experimental investigation of noise generated by railway wagons, in this particular case on tank wagons. We simulated the structural eigenfrequencies of both bogies and tanks using FEM models to find vibrations and corresponding noise levels generated by these vibrations. Theoretical results have been compared with results of measurements of noise generated by impact hammer and visualization of noise fields using a digital acoustic camera Soundcam. Based on the simulation and measurements, principal frequency noise domains of fundamental noise sources were determined—rolling (40–63 Hz), tank (200–1000 Hz), bogie (400–1600 Hz), and wheel (800–10,000 Hz). Measurements on the railway line under real operational conditions at two train speeds have been carried out, too, to see the actual external noise levels.

Keywords: tank wagon; noise and vibrations; noise simulation; noise measurements

1. Introduction

A typical phenomenon occurring during movement of machines is excitation of vibrations that can be perceived as sound (or noise) within the human ear perception frequency range approximately from 20 Hz up to 20 kHz. Rail vehicles are not an exception. There have been numerous research works and investigations carried out for many years globally with the aim of noise source analysis and proposing vibrations and noise mitigation. The efforts in the area of noise reductions are necessitated by more and stricter legislation, especially in the European Union with the introduction of NOI TSI regulations under technical specification for interoperability relating to the 'rolling stock—noise' subsystem of the rail system in the Union [1]. The extent of noise pollution in European Union member states can be found, e.g., in the EAA study [2], by which about 10 million people inside urban areas and about 5 million outside urban areas are affected by noise higher than 55 dB produced by railways. This situation is continually worsening due to the simple fact that the residential areas are gradually spreading closer to railroads.

Examples of research on noise annoyance and its undesirable effects on human health caused by railway transport have can be found in [3–6]. Although much has been improved by construction of noise barriers along the tracks (e.g., [7,8]), the most effective measure is the reduction of vibrations and noise at their sources. This is stressed also in the Directive 2002/49/EC of the European Parliament and of the Council [9]. It says: "EU noise-at-source legislation remains the most cost-effective means to address noise"—simple in principle but effective solutions are very difficult and any improvement in terms of a lower decibel count is difficult. The poor quality of tracks may also cause the excitation of noise, but also



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). the severe vibration of vehicle bodies, which is harmful to the rail infrastructure [10] and passenger comfortability [11].

The most effective measures to reduce the noise of trains seem to be a set of measures aimed at both reducing the noise at the source and on the propagation path, i.e., noise barriers and their combination with measures to improve rolling stock and acoustic properties of the track [12]. It should be added that the quality condition of both the track and vehicle is a key success factor for low noise and vibrations levels.

In this study, we follow up on our previous research on vibrations and noise generated by railway passenger wagons [13], but in particular on research on freight wagons [14], in which we focused on the bogies type of Y25Ls(s)e-K that are widely used in Europe, as they are in Slovakia. The noise analysis was based on preliminary numerical simulations of bogie-frame vibrations and localization of the vibration modes. Consequently, silencing pads made from porous fiber material were proposed to attenuate the noise radiating from the surface. The efficiency of the silencers was evaluated by measurement on a test track in a maintenance workshop on a moving bogie. The results showed a promising drop in noise levels so more research and experiments have been carried out.

The actual research extended the focus on tank wagons as a whole, not only bogies as it was in our preceding research works, as this time we also considered the superstructure of the wagon—tank (vessel).

2. Noise and Vibration Simulations and Measurements Methods

A comprehensive overview of methods for noise and vibrations modeling and control is given in [15]. The book combines the theory of railway noise and vibration with practical applications of noise-control technology at the source to solve noise and vibration problems from railways. However, mostly only results of noise measurements are being published (e.g., [16]). Although they are valuable in terms of providing a real picture of the existing status of the particular type, in this case a tank wagon, which was also the focus of our research, there are no more details on noise sources or propagation paths.

In our research, we tried to go deeper and we used FEM models for simulation of eigenfrequencies of bogies and tanks, we carried measurements of noise generated by rolling on track as well as noise excited by vibrations imposed by impact hammer. Noise propagation was recorded and visualized by SoundCam acoustic camera. So, a much more detailed picture of vibrations and sound was obtained.

2.1. Simulation Methods of Tank Structural Noise

New technical possibilities and procedures in noise reduction are gradually transferred to more complicated machinery such as rolling stock, using simulations together with acoustic experiments. The main goal is to use simulations to predict how a vehicle will behave acoustically in the event of a technical intervention, and thus it is possible to speed up and improve the technical innovations of the vehicle. In the case of experimental measurements and verification of engineering theories during the operation of rolling stock, high demands are placed, e.g., on the track, the layout of the wagons, the speed, etc., so the simulation also reduces the development costs quite significantly. In the simulation, we also have to simulate the conditions and with the purpose of shortening the calculations, the simplest model is to use a single-mass model of the vehicle with one degree of freedom, which can be used to simulate a simple response of vibrations.

The natural (eigen) frequency of an undamped system is the frequency at which the systems tend to vibrate when excited and no damping element is present. Each eigenshape is characterized by one of its own frequencies, depending on the number of degrees of freedom of the system. The eigenshape is a motion in which all parts of this system move sinusoidally with a constant phase and frequency. The frequency at which the system vibrates at its natural frequency is called the resonant frequency. Physical objects have a set of their eigenshapes, the resonant frequencies of which depend on their structure, material, and boundary conditions.

The COMSOL Multiphysics program was used for FEM modelling and calculation of eigenfrequencies of the tank (Figure 1) as well as for calculation of eigenfrequencies of the bogie (used in the first stage of research [14]).



Figure 1. A mesh model of the tank prepared in the COMSOL Multiphysics program.

The calculation of eigenshapes is used to compare the measured values of the noise levels with the noise generated by the impact hammer. As part of the reduction of noise, we want to identify the dominant frequency spectrum that is generated during the operation of the wagon so that we can focus on these frequency areas (locations of origin and propagation paths) and subsequently propose suitable anti-noise measures.

Figure 2 shows a simulation of one of the first 23 own shapes. The experiment served to confirm the simulation of the tank's own shapes, on the basis of which it is possible to establish engineering theories with the aim of reducing the impact of the tank's reverberation effect, which will have a positive impact on the overall noise level of the car.





Figure 2. The calculation of sound-pressure levels at eigenfrequency 499.034 Hz for tank structure.

Length of wagon	16,400 mm
Wagon tare	22,600 kg
Length of the tank	14,660 mm
Tank diameter	3000 mm
Loading volume	98 m ³
Tank wall thickness	6.5 mm

The basic parameters used in the tank structure model are:

2.2. Methodology of Measurement of External Noise Emitted by Tank Wagons

The subject of the test was a tank wagon. Technical acoustical measurements took place on the main railway corridor line Žilina—Bratislava, while they were carried out with three repetitions at two operating speeds (80 km/h and 120 km/h). Based on the standard EN ISO 3095:2013 [17], the measurement of external noise emitted by vehicles was carried out in practice. For the test at a constant speed around the measuring point, two places were chosen at a distance of 7.5 m from the track axis at a height of 1.2 m above the top of the rail. The measured positions in this case were chosen on three sections 9 m apart (Figure 3).



Figure 3. On-track sound measurement layout.

The instrumentation used in the technical measurements consisted of a B&K Pulse 3560B portable transducer with three microphones and a SoundCam acoustic camera. The lengths of the records were tied to the length of the train passage. The measurement site contained 3 measurement points at an even distance from each other to minimize the measurement error.

Consequently, it was necessary to recalculate the values for specific wagons from the total equivalent sound level of the train passage. The equivalent continuous A-weighted sound pressure level $L_{pAeq,T}$ was used as the main descriptor for the stationary test and steady speed running in accordance with the standard. This level, in decibels, is given by Equation (1):

$$L_{pAeq,T} = 10 \log \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right]$$
(1)

where

 $t_2 - t_1$ is time *T*, for which the calculation is done (time of train passage),

p is A-weighted acoustic pressure in Pa,

 p_0 is reference acoustic pressure 20 pPa according to ISO 1683.

In the case of measuring the noise of the wagon during operation, it is possible to identify discrete values in the spectrum and locate the emission points using an acoustic

camera. In our experiments, a digital acoustic camera Soundcam [18] was used. An "online beamforming" algorithm was used in the selected frequency range from 1000–16,000 Hz.

2.3. Exciting the Tank Wagon with an Impact Hammer

We subjected the components of the bogie, wheels, and the tank itself to experiments that were carried out by using an impact hammer (in fact, an impactor actuated by a spring) perpendicular to the rail axis, thanks to which we were able to hit the individual metal parts with a uniform same force, so that we could guarantee a sufficient number of measurements with the same conditions. In this way, it was possible to measure the frequency characteristics of the excited eigenshapes of the individual parts of the wagon (Figure 4).



Figure 4. Measurements and analysis of the response to vibrations generated by impact hammer.

3. Results

The main objective of the simulations and measurements was to identify noise produced by tank wagons generated from running on a track as well as to identify the noise generated by the impact hammer.

3.1. Measurement of Sound from Excited by Vibrations from Impact Hammer

After the impact, the structure of the tank behaved like a reverberation chamber with a reverberation of approximately 4.5 s.

In Figure 5a, the visualized acoustic field from the left side of the tank after excitation by impact hammer can be seen. On the spectrogram in Figure 5b, three repeated impacts can be observed and the corresponding frequency spectrum from one impact is on the right side of the figure (turned vertically).

Additionally, in the case of excitation of the structure by impact hammer in the middle of the empty tank perpendicular to the rail axis, part of the acoustic energy is transmitted by the structure of the wagon and radiates into the space from the lower part of the structure of the wagon (Figure 6).

The situation at a short instance of time after the excitation is presented in Figure 7, where the visualized acoustic field can be identified on the left end of the wagon (a) and the right end of the wagon (b). The acoustic camera enabled clear identification of sound propagation through the tank structure from the impact point to its ends. This can be seen best on the series of pictures (frames) from the acoustic camera (100 fps). Similarly, visualization of acoustic field radiated from wheel by excitation by impact hammer can be seen in Figure 8.



Figure 5. Measurements and analysis of the response to vibrations generated by impact hammer; (a) Visualization of the acoustic field by Soundcam, and (b) Sound pressure levels after 3 successive impacts and frequency spectrum of the induced sound (turned vertically).



Figure 6. Recording from the acoustic camera—visualization of acoustic field radiated from tank by excitation by impact hammer. Distance from the wagon 7 m, frequency range 1000–16,000 Hz.



Figure 7. (**a**,**b**) Recording from the acoustic camera—visualization of acoustic field radiated from tank by excitation by impact hammer—propagation of the acoustic field to the ends of the wagon.



Figure 8. Recording from the acoustic camera—visualization of acoustic field radiated from wheel by excitation by impact hammer. Distance from the bogie 3.5 m, frequency range 1000–16,000 Hz.

3.2. Results of Measurement of External Noise Emitted by Tank Wagons

During the vehicle run, the structure of the empty tank is a source of excessive noise. Results of measurements of external noise generated by tank wagons running at a speed of 80 km/h and 120 km/h together with visualized acoustic field from SoundCam are presented of Figures 9 and 10, respectively.



Figure 9. External noise generated by tank wagons running at a speed of 80 km/h.



Figure 10. External noise generated by tank wagons running at a speed of 120 km/h.

The results of the noise measurements of four types of freight wagons running at a speed of 120/h can be seen in Table 1. For comparison, the table also contains information on whether the given wagon would pass the TSI test, whose limit for external noise of the wagon is 79 dB. In the past, when modernizing a wagon, it was sufficient to declare that there was no increase in external noise compared to the condition when the given wagon was new. This was relatively easy to achieve, because the acoustic properties could only be improved by modernizing the given wagon. Currently, achieving the new TSI limit can be very difficult even with modernized wagons; therefore, in many cases, modification of in the structural design might be necessary. As can be seen in Table 1, if the modernization of measured wagons would have not been done, most of them could not be allowed into service.

When measuring the wagons, we also made a comparison between freight wagons of the same type, where it is possible to see the difference in the weighted sound pressure level $L_{pAeq,T}$ at 120 km/h from 0.3 dB to 8.8 dB. Here, the question arises of the appropriately chosen maintenance periodicity of the vehicles to determine whether they still meet the prescribed parameters and whether their acoustic parameters do not significantly deteriorate over time. In this way, it would be possible to prevent degraded conditions of the wagons in the future and also to reduce the noise level of the wagons.

Wagon Type	M1	M2	M3	Average Value	
Tank wagon	83.5	83.3	83.6	83.4	
Tank wagon	83	83.2	82.9	83	
Tank wagon	86.5	85.8	85.5	85.9	
Tank wagon	82.3	82.9	81.6	82.3	
Tank wagon	83.8	83	83.3	83.4	
Tank wagon	78.9	78.5	78.6	78.6	
Open wagon type 1	85.5	85.2	84.3	85	
Open wagon type 1	79.8	79.8	79.5	79.7	
Open wagon type 1	81.3	81.4	80.9	81.2	
Open wagon type 1	78.2	77.8	77.7	77.9	
Open wagon type 2	87.3	86.4	86.3	86.6	
Open wagon type 2	78	77.7	77.8	77.8	
Flat wagon	79.8	79.8	79.2	79.6	
Flat wagon	79.3	79.4	79.2	79.3	

Table 1. Sound pressure levels $L_{pAeq,T}$ at 120 km/h for four types of wagons, three measurements for each.

Legend: Green: satisfies TSI requirements (<79 dB); Yellow: >79, <81 dB; Orange: >81 <85 dB; Red: >85 dB.

3.3. Determination of Principal Frequency Noise Domains of Different Noise Sources

Based on calculation of eigenfrequencies and analysis of noise measurement results (both from excitation by impact hammer and in operation on tracks), we determined the principal frequency noise domains for different noise sources (rolling, bogie, wheel, and tank).

In Table 2, the first 23 calculated eigenfrequencies of a tank (vessel) are presented.

Table 2. Calculated structural eigenfrequencies of a tank; fist 23 eigenfrequencies.

Frequency Number	1	2	3	4	5	6	7	8	9	10	11	12
Eigenfrequency (Hz)	99.28	167.30	223.00	250.19	270.97	359.64	377.61	387.95	395.49	403.26	437.20	463.95
Frequency Number	13	14	15	16	17	18	19	20	21	22	23	
Eigenfrequency (Hz)	490.57	499.03	526.25	546.23	560.61	572.95	575.07	580.5	580.73	580.86	585.44	

As the speed changes, so does the overall noise level and the spectrum of the freight wagon emissions during operation. As the speed increases, the noise increases in the frequency band from 16–100 Hz and in the bands 630–16,000 Hz. For a speed of around 80 km/h, the highest values are in the 315 Hz band and for a speed of 120 km/h in the 2000 Hz band. From the excitation of the own shapes and the simulation, we can assume that the proportion of rolling noise in the total noise of the car during its operation increases with increasing speed (Figure 11).



Figure 11. Noise domains for different noise sources (rolling, bogie, wheel, and tank) of a tank wagon at a speed of 80 km/h and 120 km/h.

4. Discussion

As part of the approval processes of railway vehicles, their acoustic parameters are also included, both for new vehicles and vehicles after reconstruction. As part of the objectification of these measurements for external and internal noise (only for passenger wagons), the technical condition of the railway line is also important.

For the assessment of external noise within the TSI requirements, one of the primary requirements is a reference track, where measurements are carried out on a specific reference track where the acoustic parameters are known. These parameters are very difficult to achieve on a normally operated track, especially the requirement for the rail roughness. For the experimental measurements, we chose a straight section of the new corridor track with measured surface roughness and all comparisons were at identical positions. The results for individual roughness amplitude wavelengths are shown in Figure 12 for the outer and inner rail, as well as the averages of values of the outer and inner rail—all values comply with TSI requirements, they are closest to the limit for the roughness wavelength of 0.0315 and 0.0125 m. According to previous studies [19,20], it is known that if we did not observe this parameter, sound level L_{pAeqrT} might have a difference greater than 5 dB.



Figure 12. Measured values and TSI limit for rail surface roughness.

This has a clear implication that the quality of a track, besides acoustic properties and the condition of a vehicle, is a decisive factor in overall noise level generated by freight wagons in railway operation.

For the freight railway transport, the introduction of currently valid TSI limits for tank wagons at the level of 75 dB within the approved technical solutions would mean an immediate cessation of their use. From the measurements of the manufacturer [21], it can be seen (Figure 13) that this problem affects almost all types of freight wagons. Comparing the noise data of the tank wagons measured by us, the values are in the range from 79 to 86 dB, which corresponds well to the values presented by the manufacturer.





As concerns the production of new wagons of the same type, it would be interesting to verify how their acoustic values change in the future. Today, as part of the declaration, only one piece within the type is checked and this value is transferred to all other manufactured wagons of the same type. In terms of innovative acoustic design modifications and interventions, this process is very long-term and financially demanding for manufacturers of rolling stock. That is why it is almost impossible to cope with it without the possibility of using various EU grants. Many times, within the scope of various technical modifications, the benefit is only up to a certain speed, or only minimal. The testing process is frequently repeated and it is a lengthy process that must be carried out under very precise conditions (e.g., the same cover car, the same speed, suitable weather conditions, high precision measuring equipment, a specifically treated track, etc.).

Another issue of reducing the noise levels of railway wagons in the future is that it is necessary to focus on the noise changing due to changes in the technical condition and to adapt the maintenance intervals for the replacement of specific components.

5. Conclusions

The aim of this research work was to find and identify the dominant sources of noise and their propagation paths for tank wagons during their passing-by as well as by vibration excitation using an impact hammer, in order to propose the most suitable places for the necessary interventions in the structure.

We also wanted to point out the complexity of the requirements laid on manufacturers of rolling stock. If the solution to the noise problem in rail transport is left at the expense of manufacturers alone, it will lead to only a slight improvement in the medium term of around 10 years, but a drop in noise levels below 75 dB is highly unlikely. Approaching this value could be possible if high demands are asked on the quality of the infrastructure.

Many well-known anti-noise design solutions (types of bogies, wheels, types of brakes, etc.) can have a positive benefit on one type of wagon, but on another type they can have a very small or even the opposite effect. Therefore, testing the wagons and various anti-noise measures seems to be a very lengthy process.

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