THE SOUND RADIATION OF A TRAM RAIL

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Trams are generally viewed as an environmentally-friendly and popular means of public transportation. However, one of their disadvantages is the noise exposure of neighbouring populations. The most important source of noise from rail transport is rolling noise, which is caused by wheel and rail vibrations induced at the wheel/rail contact. The component of the noise radiated by the rail is often the largest, particularly for light rail systems where the speed is low. It is therefore necessary to understand the acoustic properties of tram rails before implementing strategies of noise control in the system. In practice, for street running sections, the tram rails are commonly installed by embedding them in the road surface. Tram tracks are also installed in more conventional ballasted track or on concrete slab tracks. In these latter situations they are in close proximity to an absorptive ground or a rigid ground. This paper investigates theoretically the sound radiation of a tram rail in these different conditions. The specific case of the sound radiation from a 60R2 groove rail embedded in the ground is predicted by using an approach based on a combination of waveguide finite element and wave-number boundary elements. Comparison is then made with the results for a 49E1 Vignole rail in close proximity to a rigid or absorptive ground based on a combination of two-dimensional boundary element models and the differences of their noise radiation are summarized.

Keywords: sound radiation, tram rail, finite element method, boundary element method

1. Introduction

Trams are generally considered as a popular means of urban public transportation in daily life. However, one of the challenging issues for their development is the noise impact on local residents. The most important source of environmental noise from rail transport is rolling noise. It is produced by vibration of the track and wheel, which is induced by their combined surface roughness at the wheel/rail contact. The relative importance of the wheel and track radiation depends on details of their design, the roughness spectra and the vehicle speed [1, 2]. Nonetheless, the component of the noise radiated by the rail is often the largest, particularly for light rail systems where the speed is lower. It is hence important to understand the characteristics of the sound radiation from tram rails before implementing noise mitigation measures in the system.

Previous studies have focused mainly on the effect of the noise from tramways on human health [3-5]; little literature has been found on the investigation of the sound generation from the tram rail itself. The sound power from an embedded tram rail was studied by Nilsson et al. using a waveguide finite element and boundary element method and compared with the corresponding results from a free rail [6, 7]. However, the authors have shown recently that the case of a free rail is unrealistic; the sound radiation
of a rail is significantly affected by the ground conditions close to it. This has been studied for railway tracks by using the two dimensional boundary element method (BEM) [8].

The aim of the current work is to explore the acoustic properties of a tram rail in practical installations. The sound radiation of an embedded rail is calculated using a 2.5D finite element / boundary element model, similar to that used by Nilsson et al. [6, 7]; the noise from a Vignole rail in close proximity to the ground, representing either ballasted track or slab track, is predicted by using the same method used in [8, 9]. Finally, the differences between the acoustic characteristics of these three types of tram track are assessed using the TWINS (‘Track-Wheel Interaction Noise Software’) model for rolling noise [10].

2. Modelling the sound radiation from an embedded rail

The sound radiation from an embedded rail is first investigated here. It is modelled in the 2.5D finite element / boundary element software WANDS [7]; the modelling approach is similar to that described in [6]. This rail has a standard 60R2 profile (mass per unit length 60 kg/m) used for tram tracks. It is installed in a channel in the track slab and elastomeric embedding material is used to fill the region around the rail, as shown in Figure 1; this also illustrates the finite element mesh. Eight-noded quadrilateral elements are used throughout the finite element domain. The rail is installed on a softer ‘pad’ material and a stiffer ‘fill’ material is installed around the rail. Similar configurations are used in the construction of the tramways in practice.

The properties of the rail are listed in Table 1 and those of the embedding material are given in Table 2; these have been obtained from the literature [6]. In addition to the regular parameters for the embedding material, a case with reduced mass (0.1% of the normal one) is considered to check the influence of the dynamic behaviour of the embedding material on the response of the rail. The maximum distance between adjacent nodes in the model is about 10 mm. As the shear wave speed in the ‘fill’ material is 70.3 m/s, the requirement for the element size to be at least of one quarter of the shear wavelength is only met in the frequency range up to 1750 Hz. Nevertheless results are presented over the whole range up to 5 kHz.

![Figure 1 Mesh of the embedded rail in the 2.5D FE/BE software](image-url)
Table 1 Material properties used for the rail

<table>
<thead>
<tr>
<th>Young’s modulus, GPa</th>
<th>Density, kg/m³</th>
<th>Poisson’s ratio</th>
<th>Damping loss factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>7850</td>
<td>0.3</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 2 Properties used for the embedding materials in the model

<table>
<thead>
<tr>
<th>Pad</th>
<th>Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus, MPa</td>
<td>4.0</td>
</tr>
<tr>
<td>Density (for normal mass embedding), kg/m³</td>
<td>1000</td>
</tr>
<tr>
<td>Density (for reduced mass embedding), kg/m³</td>
<td>1.0</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.45</td>
</tr>
<tr>
<td>Damping loss factor</td>
<td>0.25</td>
</tr>
</tbody>
</table>

A unit vertical force is applied to the rail head, as indicated in Figure 1. The vertical point mobility obtained is shown in Figure 2(a), which includes a comparison with the result for the reduced mass embedding. They have nearly same mobility level at low frequency, where they are in the stiffness-controlled region. The first peak corresponds to the bounce of the combined mass of the rail and the embedding material on the pad stiffness. This peak moves to a higher frequency for the case with the reduced mass embedding material. The fluctuations seen are due to the internal resonances of the normal embedding material; they are suppressed for the reduced mass embedding material. The second peak at around 2.5 kHz for the reduced mass embedding corresponds to a higher order rail mode with large deformation of the rail foot; it is attenuated by the presence of the normal embedding material. Results are also shown for the Vignole rail considered below which will be discussed later.

The predictions of the track decay rates for these two embedding materials are presented in Figure 2(b). As can be seen, the mass of the embedding material affects the decay rate of the track, especially above 500 Hz. This will then have an influence on the sound radiation.

To calculate the sound radiation a 2.5D boundary element model is coupled to the above 2.5D FE model. The corresponding boundary element model for this embedded rail is shown in Figure 3. The blue dots represent the boundary elements. A half-space formulation is used so that an infinite ground plane is included beyond the mesh. The dimensions of the ground box are 15 m × 3 m at low frequency and 3 m × 0.1 m at high frequency.

The sound power radiated by the rail (and embedding material) is normalised by the squared velocity of the rail at the excitation point. The result is shown in Figure 4. The noise from the two models are the same at low frequency, where it is in the stiffness-controlled region, but the rail with reduced mass embedding has a larger sound radiation than the case of the normal embedding material at high frequency. This can be related directly to the differences in track decay rate seen in Figure 2(b).
Figure 2 Comparison of the vertical dynamic properties between TWINS and WANDS

Figure 3 Mesh of the boundary element model for the embedded rail

Figure 4 Sound power from the embedded rail with normal and reduced mass embedding materials normalised by the squared velocity of the rail at the excitation point.
3. Sound radiation from a bare tram rail in close proximity to the ground

In ballasted tracks or slab tracks, part of the tram rail is located at a certain distance above the ground (ballast or concrete slab), whereas the remainder is attached periodically to the concrete sleepers, via a rail pad, such that the bottom of the rail foot cannot radiate sound. These two situations are shown in Figure 5. As well as the case in which the rail is attached to the rigid ground, shown in Figure 5(a), two models are considered in which the rail is located above the ground (Figure 5(b)): one with the rail foot located 85 mm above a rigid ground (slab) and the other with the rail foot 50 mm above an absorptive surface (representing the ballast). The absorptive ballast is represented by its impedance according to the Delany and Bazley model [11] of an infinite layer with a flow resistivity of 50 kPa.s/m², as in [9]. A standard tram rail profile 49E1 is considered in each case. Using a 2D BEM model, the sound power per unit length is predicted separately for the cases in which the rail is either above or attached to the ground [8]. In each case the rail is assigned a unit velocity in either vertical or lateral directions. Figure 6 shows the results, from which it can be seen that the rail exhibits typical acoustic properties in the different conditions. For lateral motion, the radiation follows the characteristics of a line dipole (30 dB/decade slope at low frequencies). The inclusion of ballast absorption gives a reduction in the sound radiation over much of the frequency range but does not change this basic characteristic. For vertical motion, however, the rail in proximity to the ground has a line quadrupole characteristic (50 dB/decade), whereas it shows the properties of a line monopole (10 dB/decade) when it is attached to the rigid ground [8]. When the ballast absorption is included, the radiation at low frequency is increased slightly compared with that for a rigid ground.

In order to combine the periodic influence of the rail attached to the rigid sleepers and the rail above the ground between the sleepers, an average rail radiation is needed. An approach is adopted here by taking a suitable weighted average of the sound power levels from the two 2D models to take account of the monopole and quadrupole source terms; this has been verified by a 3D BEM track model. The average sound radiation of the rail for both ballasted and slab track is presented in Figure 7. The dip at around 250 Hz is caused by the interaction between the different noise sources.

Figure 5 A tram rail in close proximity to the ground

![Attached to the ground](image1)
(a) Attached to the ground

![Above the ground](image2)
(b) Above the ground
4. Comparison of the sound radiation from the tram rail with different boundary conditions

In order to compare the sound radiation of the Vignole rail close to the ground with that of the embedded rail, the results obtained from the 2D BEM model (Figure 7) are converted to the same form as those shown in Figure 4. To obtain them in this form, they should include the effect of the track decay rate in the longitudinal direction and then be normalised by the squared velocity at the excitation point. The TWINS model [10] is used here to carry out this calculation. For simplicity, the rail is assumed to be mounted on a single layer foundation consisting of a rail pad with vertical stiffness equivalent to the embedded rail. The value of this stiffness is chosen by matching the point mobility and track decay rate predicted by the track model in TWINS with the corresponding results for the embedded rail from WANDS. The track parameters used for the open tracks are listed in Table 3. As shown in Figure 2(a), good agreement is achieved in terms of the point mobility. The track decay rate of the Vignole rail is...
lower than that of the embedded rail above 500 Hz, which is due to the influence of the embedding material.

Table 3 Track parameters used for the open tracks

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus</td>
<td>$2.1 \times 10^{11}$ N/m²</td>
</tr>
<tr>
<td>Density</td>
<td>7850 kg/m³</td>
</tr>
<tr>
<td>Rail mass per length</td>
<td>49 kg/m</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Vertical bending stiffness</td>
<td>$3.81 \times 10^6$ Nm²</td>
</tr>
<tr>
<td>Shear coefficient</td>
<td>0.4</td>
</tr>
<tr>
<td>Rail loss factor</td>
<td>0.02</td>
</tr>
<tr>
<td>Vertical rail pad</td>
<td>210 MN/m</td>
</tr>
<tr>
<td>Vertical pad loss factor</td>
<td>0.2</td>
</tr>
<tr>
<td>Fastener spacing</td>
<td>0.6 m</td>
</tr>
</tbody>
</table>

The sound power normalised by the squared velocity at the excitation point can be calculated by combining the response of the rail obtained from TWINS with the sound power per unit length shown in Figure 7. The results are shown in Figure 8 and compared with those for the embedded rail from WANDS. As can be seen, the embedded rail has lower sound levels than the open tram rail above 500 Hz. This is mainly caused by the difference in their track decay rates, see Figure 2(b). However, at low frequencies the embedded rail has about 15 dB lower sound levels than the open rail. This is caused by the fact that the whole rail acts as a line monopole, unlike the open rail, and that the embedding material increases the radiating area. Comparing the two tracks with the open rail, the track with the absorptive ground (ballasted track) radiates around 2 dB less noise than that one with the rigid ground (slab track) above 500 Hz.

Figure 8 Comparison of the normalised sound power in one third octave band
5. Conclusions

The sound radiation from three types of tram track are investigated theoretically and compared in this paper. The sound radiation from a 60R2 groove rail embedded in the ground is predicted by a combination of a 2.5D waveguide finite element and boundary element approach. It has been shown that including the mass of the embedding material will reduce the noise at high frequency, due to its effect on the track decay rate. For comparison, the two dimensional boundary element method is used to calculate the noise from a 49E1 Vignole rail in close proximity to a rigid ground (slab track) or ballast (absorptive ground). The rail in these tracks has been found to radiate more noise than the embedded rail above about 500 Hz. This is mainly due to the differences in their track decay rates. However, at lower frequencies the embedded rail radiates up to 15 dB more noise than the open rail. The absorptive ground is shown to be beneficial to reduce the noise from the open tram rail by up to 2 dB above about 500 Hz. The specific level differences between different track types depend on their parameters such as the stiffness and mass of the embedding and the rail pad stiffness and should therefore be estimated on a case-by-case basis.

6. Acknowledgements

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REFERENCES