INFLUENCE OF TRACK-WORK ON BUILDING RESPONSE TO RAILWAY VIBRATION

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Abstract
A simplified multi layered railway track model is first used to estimate and compare the frequency dependant insertion loss of three different types of track-work: under bearing plate pads, under sleeper pads and ballast mat. A 2D BEM / FEM ground structure vibration interaction model, experimentally validated, is then used to estimate the influence of track-work on the building response: the estimated transfer function between free field ground vibration and building vibration is applied to measured railway free field ground signals, modified by the track-work insertion loss, in order to get the resulting building floor vibration signals. Results are finally expressed in terms of currently used vibration exposure indicators.

Keywords: ground borne vibration from railways, track-work, building vibrational response, vibration exposure indicator.

1 Introduction

Nowadays, new train tracks are installed close to existing buildings in cities. Track-work has to be designed to dampen the transmission of the vibration caused by the running of the trains on metal rails, the rails joints, and the rails defects, from the track to the neighboring buildings. This vibration as well as the corresponding re-radiated noise are perceptible and therefore may cause great annoyance to residents. Ground vibration propagation from railways has been investigated previously using two- and three-dimensional models [1-3]. A simplified multi layered railway track model is first used to estimate and compare the frequency dependant insertion gains of three different types of track-work: under bearing
plate pads, under sleeper pads and ballast mats. A measurement site was selected: it included a building structure located at about 6 m from the train tracks. Measurements were carried out for different types of rolling stocks (mostly freight and domestic passenger stocks); they included the recording of free field ground vibration velocity level, as well as velocity level in front of and inside the building at different locations in the structure. A 2D BEM / FEM ground structure vibration interaction model was experimentally validated for this measurement site. This model is then used to estimate the influence of track-work on the building response: the estimated transfer function between free field ground vibration and building vibration is applied to measured railway free field ground signals, modified by the track-work insertion gains, in order to get the resulting building floor vibration signals. Results are finally expressed in terms of currently used vibration exposure indicators. In this paper, the effect of the track-work on ground vibration is evaluated for both freight stocks and domestic passenger stocks; then the effect of the track-work on the building vibration pollution is investigated using vibration exposure indicators.

2 Track-work prediction model

In this first section, the simplified multi-layered railway track model is introduced. This prediction tool based on a two-dimensional model is developed for a track-work composed of the track (two rails with rail pads), under bearing plate pads, sleepers, under sleeper pads, ballast and ballast mat. The track and the ballast are considered as infinite beams with bending stiffness, loss factor and mass per meter. The track-work is represented by its impedance per meter length of track and the ground by its line input impedance calculated using a 2D elastic half space ground model based on the wave approach. The unsprung mass of the vehicle is considered as a concentrated mass at the excitation point on the rail head. The effect of the resilient element dynamic stiffness on the vibration isolation is studied in detail; the vibration isolation provided by the track-work being quantified by an insertion loss in dB per 1/3 octave band. This prediction model is an extension of the one presented in [4].

2.1 Model description

The model developed is two dimensional and its diagrammatic representation is presented in Figure 1. The rail track (two rails) and the ballast base are considered as infinite beams and are characterized by their mass per meter length (\(m_{\text{rail}}\) and \(m_{\text{ballast}}\) respectively) and their complex bending stiffness taking into account the damping (\(B_{\text{rail}}\) and \(B_{\text{ballast}}\) respectively). It should be noted that damping is modeled for every track component as hysteretic damping (as opposed to viscous damping) and is therefore taken into account by using a complex stiffness. In the track-work proposed, resilient elements are introduced in order to diminish the vibration level induced in the ground: under bearing plate pads, under sleeper pads, and ballast mat. The rail, under bearing plate and sleeper pads are defined by their dynamic stiffness (N/m) denoted \(K_{\text{rail-pad}}\), \(K_{\text{bpl-pad}}\) and \(K_{\text{slp-pad}}\) respectively; this leads to a stiffness per meter length (N/m²) depending on the distance between sleepers. The ballast mat is defined by its dynamic stiffness per meter area (N/m³), \(K_{\text{bst-mat}}\). The considered sleepers are monoblock sleepers and are represented by their mass per unit length \(m_{\text{spl}}\). The rail bearing plates are represented by their mass per unit length \(m_{\text{bpl}}\). The mass per unit length of the sleepers and bearing plates depends on the distance between sleepers considered. The ground is modelled as semi-infinite 2-dimensional system defined by its line input impedance \(Z_{\text{ground}}\) calculated using a 2D elastic half space ground model based on the wave approach [5]. The unsprung mass of the vehicle denoted \(M_u\) is considered as a concentrated mass at the
excitation point on the rails head. Both the unsprung mass and the excitation force are applied on the rails at the position x=0. In order to investigate the effect of a single resilient element, the stiffness of the other resilient element is set to a very large value (i.e. very stiff), furthermore the mass of the rail bearing plates is set to zero when this element is not considered in the track-work. The loss factor for the resilient elements are taken equal to 30%, except for the rail pads which loss factor is chosen to be 20%. Following the approach taken [4], the displacement of the ground $w_{\text{ground}}$ can be evaluated after evaluating an inverse Fourier transform (note that the displacement of the different components is also obtained, i.e. $w_{\text{rail}}$, $w_{\text{orpil-pad}}$, $w_{\text{slp}}$ and $w_{\text{bst}}$ respectively). For sake of brevity, the theoretical development is not included in this paper.

![Figure 1 – Diagrammatic representation of the model.](image)

The vibration isolation provided by the track-work is quantified by an insertion loss in dB per 1/3 octave band, defined as the difference between the vertical vibration velocity level on the ground, predicted for the proposed track-work (i.e. with one resilient element) and a reference track-work that does not include extra resilient element but only the rail pads. Therefore, a negative insertion loss corresponds to vibration amplification, while a positive one yields a vibration decrease.

### 2.2 Model results

Some vibration isolation results provided by different resilient elements are given in this section in the case of freight stock corresponding to an unsprung mass of 3750 kg/axle and a domestic passenger stock corresponding to an unsprung mass of 1300 kg/axle. The characteristic of the reference track-work is given in Table 1. It should be mentioned that the stiffness values for the rail, under bearing plate and sleeper pads given in this paper refers to half of the the track-work (i.e. one single rail). The ground is constituted of a standard soil (neither hard or soft) whose characteristics are shown in Table 2. It should be mentioned that this standard soil characteristic have shown to allow good comparison of measured and calculated free field ground acceleration spectra at different distances from the tracks (3, 6,
9, 12, 17 and 20 m) over third octave bands from 12 to 200 Hz [6]. The track-work is then mounted with either under bearing plate pads, or sleepers pads or ballast mat. When the track-work includes the under bearing plate pads as resilient elements, the weight of the bearing plate is assumed to be 20 kg (per rail). The under bearing plate pads and the sleepers pads are assumed to have a dynamic stiffness of either 50 or 100 MN/m (per rail). These dynamic stiffness values allows to have a static deflection below 2.5 mm. The dynamic stiffness of the ballast mat is assumed to correspond to 30 MN/m³. The results are presented for the third octave bands between 10 and 250 Hz.

Table 1 – Reference track-work characteristics.

<table>
<thead>
<tr>
<th>Element</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>UIC60 Rail</td>
<td>60 kg/m</td>
</tr>
<tr>
<td>Rail pad</td>
<td>220 MN/m</td>
</tr>
<tr>
<td>Sleeper</td>
<td>300 kg</td>
</tr>
<tr>
<td>Distance between sleepers</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Ballast thickness</td>
<td>20 cm</td>
</tr>
</tbody>
</table>

Table 2 – Soil characteristics.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>1600</td>
</tr>
<tr>
<td>Elasticity modulus (MN/m²)</td>
<td>200</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.25</td>
</tr>
<tr>
<td>Loss factor (%)</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 2 presents the insertion loss for the two different types of rolling stocks when sleeper pads are introduced as resilient elements in the track-work. As expected, the insertion loss presents a minimum (negative value), corresponding to a vibration increase of the ground vibration level, at the resonance frequency of the track-work system. This resonance frequency is modified by the sleeper pad stiffness as well as by the unsprung mass corresponding to the type of rolling stocks considered. This resonance frequency decreases with a reduction of the sleeper pad dynamic stiffness: for the domestic passenger stock, the resonance frequency reduces from 80 to 63 and to 40 Hz when the sleeper pad dynamic stiffness is changed from 100 MN/m to 50 MN/m, and to 20 MN/m. An increase of the unsprung mass (corresponding to the type of rolling stock) yields a decrease of the resonance frequency. In the case of sleeper pad with 100 MN/m in dynamic stiffness, the resonance frequency decreases from 80 Hz for the domestic passenger stock (corresponding the lightest unsprung mass considered) to 50-63 Hz for the freight stock (the heaviest unsprung mass considered). A maximum of insertion loss (positive value of more than 10 dB in Figure 2), i.e. a ground vibration level decrease, is obtained above this resonance frequency. The maximum value in vibration level decrease depends on the sleeper pad dynamic stiffness: the lowest sleeper pad dynamic stiffness is associated to the highest vibration decrease. Furthermore, a decrease in insertion loss also appears around the third octave bands of 200 and 250 Hz.
Figure 2 – Effect of rolling stock type on vibration isolation associated to under sleeper pads.

Figure 3 presents for the freight stock the insertion loss of the different improved track-work considered, i.e. including either under bearing plate pads, or sleeper pads, or under ballast mat. It can be seen that the track-work system including the ballast mat is the most efficient in terms of reducing the ground vibration level: indeed, the insertion loss is positive above the third octave band of 25 Hz. The other two modified track-works including either under bearing plate pads or under sleeper pads perform similarly; however, the track-work with under bearing plate pads is associated to a larger ground vibration level increase at the system resonance frequency and a larger ground vibration level decrease (maximum of insertion loss at 125 Hz third octave band) compared to track-work with under sleeper pads. Furthermore, the insertion loss obtained for the track-work including under bearing plate pads does not present a decrease around 200-250 Hz third octave band as it is the case for the track-work including under sleeper pads. For these two modified track-works, it is however not possible with the pads stiffness considered (even for the 20 MN/m pads) to achieve a positive insertion loss (i.e. a decrease in ground vibration level) for the third octave bands of 40 and 50 Hz.

Results for the domestic passenger stock are not presented in this paper but show similar trends.
3 Vibration exposure indicators

In [6], a prediction software denoted MEFISSTO based on a 2D BEM / FEM ground structure vibration interaction model [7], was used to estimate the influence of building types on the building response to railway vibration. The results were expressed in terms of transfer function between free field ground vibration and building floor vibration. The ground / structure model was first experimentally validated from field measurements of ground and building vibration performed near railway and then used in a parametric study to evaluate the influence of floor thickness and span, as well as the thickness of buried walls and façades. This MEFISSTO prediction software is used in this paper to estimate the influence of track-work on the building response: the estimated transfer function between free field ground vibration and building vibration is applied to measured railway free field ground signals, modified by the track-work insertion loss, in order to get the resulting building floor vibration signals. Results are then expressed in terms of vibration exposure indicators. These vibration exposure indicators are obtained from real signals measured for freight stocks as well as for domestic passenger stocks.
3.1 Building description

The MEFISSTO prediction tool based on BEM / FEM ground structure vibration interaction model, has been used here in a 2D configuration composed of a half space ground and the building structure as shown in Figure 4. The modeled building structure is simplified compared to the real building but building elements in terms of length and thickness are the same. Building elements are made of 20 cm thick reinforced concrete, except the façade (partly above ground and partly embedded in ground), which was particularly thick (i.e. 40 cm) in the in-situ evaluated structure (due to the structure building period). The building structure is located at 6 m from the track-work (which position is shown by the excitation force F in Figure 4).

The model results were validated with the data recorded on the corresponding measurement site [6]. This model is used to estimate the influence of some building modification on the resulting building floor vibration signals [6]. The building modification considered in this paper is first a decrease in the façade thickness (from 40 cm to 20 cm which is more representative of current building), and then an increase in floor span (from 3.4m to 6.8m the floor becoming more supple). These two modifications are associated to a degradation of the building vibration conditions.

![Figure 4 – Simplified 2D geometry of the measurement site used by the 2D BEM / FEM ground structure vibration interaction model.](image)

3.2 Vibration exposure indicators

In France, vibration from railways and its effects on people is not regulated yet. Therefore, the Norwegian standard NS 8176.E [8], in accordance with ISO 2631-1 and very well documented, was used to express the results in terms of vibration exposure indicators and corresponding annoyance.

The procedure for calculating the Norwegian vibration exposure indicators can be applied on either acceleration or velocity time signal and uses several steps. First, the time signal is filtered in third octave band in order to get N filtered time signals $s_i$ corresponding to the N third octave bands considered. Then, the time dependant rms value (with time window $\tau$ equal to 1s) of each signal $s_i$ is calculated according to
\[ s_{i,\text{rms}}(t) = \left[ \frac{1}{\tau} \int_{t-\tau}^{t} s_i^2(t') \, dt' \right]^{1/2} \]  

Then, at each instant \( t \), the \( N \) third octave band signals \( s_{i,\text{rms}}(t) \) are weighted using the weighting coefficients defined in the standard ISO 2631-2 (weighting coefficients \( w_i \) given for each third octave band). This weighted signal \( s_{w,\text{rms}}(t) \) is calculated according to

\[ s_{w,\text{rms}}(t) = \left[ \sum_i s_{i,\text{rms}}^2(t) \cdot w_i \right]^{1/2} \]  

For each rolling stock passage, the above procedure was first applied to the floor velocity signal measured in the real building to obtain the weighted signal \( v_{w,\text{rms}}(t) \). Then, the effect of either the building structure variations in the third octave band floor vibration spectra calculated using MEFFISTO, or the third octave band insertion loss associated to different track-works were added to the third octave band \( w_i \) weighting coefficients (see Equation (2)) in order to obtain a new weighted signal \( v_{w,\text{rms,modified}}(t) \) associated the system modification considered. Finally and according to standard NS 8176, the maximum value \( v_{w,\text{max}} \) during the rolling stock passage was calculated.

In a second step, the same procedure was applied to the floor signals measured for all the freight stocks and the domestic passenger stocks (a dozen in each case); the mean value \( \mu_{v_{w,95}} \) as well as the standard deviation \( \sigma \) calculated in order to get the 95\% confidence value was evaluated for the two different types of rolling stocks considered circulating on track-work. Finally, the vibration exposure indicator was obtained following the Norwegian standard [8]

\[ \mu_{v_{w,95}} = \mu_{v_{w,\text{max}}} + 1.6 \sigma \]  

The informative annex B of the Norwegian standard NS 8176.E [8] defines 4 guidance vibration classes with respect to the vibration exposure indicator:

- Class A with \( v_{w,95} \leq 0.1 \) mm/s corresponds to very good conditions
- Class B with \( 0.1 < v_{w,95} \leq 0.15 \) mm/s corresponds to relatively vibration conditions
- Class C with \( 0.15 < v_{w,95} \leq 0.3 \) mm/s is the recommended limit value for vibration in new residential buildings and in connection with the planning and building of new transport infrastructures
- Class D with \( 0.3 < v_{w,95} \leq 0.6 \) mm/s corresponds to vibration conditions that ought to be achieved in existing residential buildings

### 3.3 Track-work effects on vibration exposure indicators

In this section, the vibration exposure indicator for different track-works considered in Section 2 and for the different building situations is given for the freight stocks in Table 3. First it should be noted that the original building is Class B for freight stocks; for this class people can to some extent be expected to be disturbed by vibration. The track-work modification with 20 MN/m under bearing plate pads or under sleeper pads, or with under ballast mat (60 MN/m²) allows reaching Class A in terms of vibration exposure indicator. The other considered modifications of the track-work actually slightly increase the vibration exposure indicator. When the thickness façade is decreased from 40 to 20 cm (more representative of current buildings), the vibration exposure indicator is largely increased: the building cannot be classified with regards to Annex B of the Norwegian standard NS 8176.E [8]. The use of an under ballast mat with dynamic stiffness of 30 MN/m³ allows making Class D, for which still 25\% of people can be expected to be disturbed by vibration. The use of
20 MN/m under sleeper pads almost allows reaching Class D (indicator of 0.61 instead of 0.6). The building with an increase of the floor span is also evaluated in Class D. Only the use of an under ballast mat with dynamic stiffness of 30 MN/m³ allows obtaining Class C for which 15% of people can be expected to be disturbed by vibration. The use of 20 MN/m under sleeper pads almost allows reaching Class C (indicator of 0.33 instead of 0.3). For freight stocks, an interesting improvement of the vibration exposure indicator is only obtained when using 20 MN/m under sleeper pads or under ballast mat for the track-work. Indeed, since some of the proposed track-work modifications are associated with negative insertion losses (i.e. an increase in ground vibration level) for third octave bands between 32 and 63 Hz, they can induce an increase of the vibration exposure indicator, even though the maximum value $v_{w,\text{max}}$ during the rolling stock passage could for some rolling stocks be decreased.

For domestic passenger stocks, the results are not detailed in this paper. However, it was obtained that the original building is also Class B. For the different building modifications, the vibration exposure indicator can only be decreased when using under ballast mat; the other track-work solutions with under bearing plate pads and under sleeper pads are associated to an increase of this vibration exposure indicator.

<table>
<thead>
<tr>
<th>Building</th>
<th>Track-work</th>
<th>Façade thickness modification</th>
<th>Floor span modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>Façade thickness</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original</td>
<td>0.11</td>
<td>0.90</td>
<td>0.56</td>
</tr>
<tr>
<td>Bearing plate pads 20 MN/m</td>
<td>0.09</td>
<td>0.77</td>
<td>0.41</td>
</tr>
<tr>
<td>Bearing plate pads 50 MN/m</td>
<td>0.13</td>
<td>1.10</td>
<td>0.59</td>
</tr>
<tr>
<td>Bearing plate pads 100 MN/m</td>
<td>0.13</td>
<td>1.02</td>
<td>0.55</td>
</tr>
<tr>
<td>Sleeper pads 20 MN/m</td>
<td>0.07</td>
<td>0.61</td>
<td>0.33</td>
</tr>
<tr>
<td>Sleeper pads 50 MN/m</td>
<td>0.12</td>
<td>0.97</td>
<td>0.51</td>
</tr>
<tr>
<td>Sleeper pads 100 MN/m</td>
<td>0.12</td>
<td>0.97</td>
<td>0.52</td>
</tr>
<tr>
<td>Ballast mat 30 MN/m³</td>
<td>0.06</td>
<td>0.50</td>
<td>0.27</td>
</tr>
<tr>
<td>Ballast mat 60 MN/m³</td>
<td>0.08</td>
<td>0.69</td>
<td>0.37</td>
</tr>
</tbody>
</table>

4 Conclusions

In this paper, a simplified multi layered railway track model was used to estimate and compare the frequency dependant insertion loss of three different types of track-work: under bearing plate pads, under sleeper pads and ballast mat. Two different types of rolling stocks were taken into account; freight and domestic passenger stocks. A 2D BEM / FEM ground structure vibration interaction model, experimentally validated, was then used to estimate the influence of track-work and building modification on the building floor response. Results were expressed in terms of currently used vibration exposure indicators. For freight stocks, an improvement of the vibration exposure indicator is only obtained when using 20 MN/m under sleeper pads or under ballast mat for the track-work. For domestic passenger stocks, the vibration exposure indicator can only be decreased when using under ballast mat for the different building modifications.
These preliminary results have to be validated. The insertion loss obtained with this simplified track-work model should be compared with some obtained from more complex models. The simplified track-work model presented in this paper could also be modified to 3D geometry to take into account for example non symmetric excitation on rails, rolling stock passage, etc…

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References


