EFFECTS OF HIGH-SPEED RAIL SUBSTRUCTURE ON GROUND-BORNE VIBRATIONS

Mohammad Fesharaki Amirmasoud Hamedi

ABSTRACT: Excessive vibration due to high-speed traffic, has always been a great concern for railroad engineers and people who live in track neighborhood. This problem usually arises in urban and suburban areas and may affect construction and operation of High-Speed Rail (HSR). To address this problem, this paper investigates the effect of track substructure and train parameters on vibration level. For this purpose, a Finite Element model developed to numerically investigate track substructure role on track and far-field vibrations. A series of loading, simulated based on high-speed trains configurations, applied on wheel-rail contact area. Different materials as soil layers were used and the results compared to show the influence of track stiffness on vibration. The results also presented for different distances from 2 to 40 meters away from point of loading. The effect of vehicle parameters on vibration level has also been taken into account. Vibration level monitored for different loads and speeds at different distances from track. The results indicated that selecting proper material can resulted in more than 30% decrease in track vibration.
Effects of High-Speed Rail substructure on ground-borne vibrations

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ABSTRACT: Excessive vibration due to high-speed traffic, has always been a great concern for railroad engineers and people who live in track neighborhood. This problem usually arises in urban and suburban areas and may affect construction and operation of High-Speed Rail (HSR). To address this problem, this paper investigates the effect of track substructure and train parameters on vibration level. For this purpose, a Finite Element model developed to numerically investigate track substructure role on track and far-field vibrations. A series of loading, simulated based on high-speed trains configurations, applied on wheel-rail contact area. Different materials as soil layers were used and the results compared to show the influence of track stiffness on vibration. The results also presented for different distances from 2 to 40 meters away from point of loading. The effect of vehicle parameters on vibration level has also been taken into account. Vibration level monitored for different loads and speeds at different distances from track. The results indicated that selecting proper material can resulted in more than 30% decrease in track vibration.

INTRODUCTION
High-Speed Rail is a safe, reliable, comfortable and environmentally friendly mode of transportation and is rapidly developing around the world. International Union of Railways reported that there are more than 18600 miles of HSRs in operation and 1.6 billion passengers per year are carried by them in the world (International Union of Railways 2015). However, except California High-Speed Rail, the United States still hesitant to develop its own HSR network. One the most important barriers to developments of HSR is environmental issues such as noise and vibration from trains. Recent reports on track vibration shows that vibration is a widespread railroad engineering challenge and mitigation measures were required on approximately 50% of projects. A database of ground-borne noise and vibration reports from different countries shows that 50% of them originated in the USA (Connolly et al. 2015). Such reports emphasize the importance of more research on track vibration. This issue arises especially in case of high-speed rail and tracks on soft soils. For example, the measurement of ground-borne vibration by Kouroussis et al shows that underlying soil stiffness plays a dominant role in vibration generation and propagation (Kouroussis et al. 2016). In Swedish high-speed railway, excessive vibration and track displacements were observed, affecting track stability and safety. In some points, track deformations up to 10 mm have been reported at a site in
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Ledsgård along the West Coast Line in Sweden. (Lombaert et al. 2006)

A review of the literature shows that although many researchers have investigated this problem by studying train parameters (Suhairy 2000), (Kouroussis et al. 2014), track materials properties (Esmaeili et al. 2014), (Esmaeili & Rezaei 2016) and finding new methods to analysis and design of railroad track (Sadeghi & Fesharaki 2013), there are still many issues need to be addressed. For example, Federal Railroad Administration (FRA) reported that one of the major problems in developing suitable criteria for ground-borne vibration is that there has been relatively little research into human response to vibration, in particular, human annoyance with building vibration (Carl E. Hanson; David A. Towers; and Lance D. Meister 2006). Railroad engineering still awaits more research to fill this gap.

The purpose of this paper is to investigate the following issues:

- The effect of train parameters on track and far-field vibration,
- The effect of varying materials as track substructure on vibration level,
- The effect of distance from train loading on vibration

To get the best results, the modeling of track is based on AREMA standard track and train loading is modeled considering high-speed Thalys train used in Europe. The developed finite element method performs dynamic analyses in time domain and the results will be presented to demonstrate the importance of train and track factors on vibration.

### TRAIN MODELING

Train is modeled as a series of loads applied on wheel-rail contact area. Considering wheel and rail as two moving cylinders, the contact area will be a circle with radius “a”

$$a = \left( \frac{3PR}{4E} \right)^{1/3}$$

$$\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

Where $v_1$, $v_2$ and $E_1$, $E_2$ are Poisson’s ratio and modulus of elasticity of wheel and rail respectively. $R_1$ and $R_2$ are radius of wheel and rail and $P$ denotes pressure from wheel on rail.

It is assumed that train dynamic loads uniformly distributed on the contact area. As a result, Train loading is considered as a series of distributed loads on rail. Figure 1 shows the side view of Thalys high-speed train and the loading pattern used in this paper. Thalys train consists of two locomotives and eight carriages and the total length of train is about 200 m. each locomotive has two bogies and each bogie has two axles.

The carriages next to the locomotives share one bogie with the neighboring carriage, while the six other carriages share both bogies with neighboring carriages. Table 1 shows the carriage length $L_c$, the distance $L_b$ between bogies and the axle...
distance $L_a$. (DEGRANDE & SCHILLEMANS 2001)

![Figure 1. Thalys train and loading pattern](image)

**Table 1. Characteristics of Thalys Train** (DEGRANDE & SCHILLEMANS 2001)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Locomotives (2)</th>
<th>Outer Carriages (2)</th>
<th>Central carriages (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axles/vehicle</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>$L_t$ (m)</td>
<td>22.15</td>
<td>21.84</td>
<td>18.70</td>
</tr>
<tr>
<td>$L_b$ (m)</td>
<td>14.00</td>
<td>18.70</td>
<td>18.70</td>
</tr>
<tr>
<td>$L_a$ (m)</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

**TRACK MODELING**

As figure 2 shows, track cross section is modeled based on standard track suggested by American Railway Engineering Maintenance of way Association (AREMA) specifications. The distance between rails is 56.50 inches (1.435 m) and the depth of ballast (BDD) and sub-ballast (SBD) layers is set to 12 (0.305 m) and 6 inches (0.152 m) respectively. The length and thickness of cross tie is considered to be 94.5 (2.4 m) and 10 inches (0.254 m). Since the purpose of this study is to evaluate the propagated wave to the surrounding media, the model was extended to 132 feet (40 m) (American Railway Engineering and Maintenance-of-Way Association 2010).

Table 1 presents the material properties of track and underlying soil. In order to consider the effect of subsoil properties on track and far-field vibration, four types of soil have been taken into account and the results of analyses are presented for different conditions. Four types of subsoil were selected: dense sand, loose sand, stiff clay and soft clay. The constitutive equations for cross tie is linear elastic with viscous damping ratios of 1%. For granular material, the constitutive relationship used is linear elastic with Mohr-Coulomb plasticity. Considering the relatively small strain level in the soil, this is a reasonable approach and the soil damping ratio is 2% (Zeng 2005) and (Choudhury et al. 2008). Table 2 shows the properties of cross-tie...
and granular layers.

![Figure 2. Typical AREMA track substructure](American Railway Engineering and Maintenance-of-Way Association 2010)

**Table 2. Material properties subsoils**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>E (MPa)</th>
<th>Poisson’s ratio</th>
<th>Friction Angle (degrees)</th>
<th>Cohesion (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross tie</td>
<td>2500</td>
<td>38450</td>
<td>0.3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Ballast</td>
<td>2100</td>
<td>250</td>
<td>0.3</td>
<td>35</td>
<td>0</td>
</tr>
<tr>
<td>Sub-Ballast</td>
<td>2100</td>
<td>100</td>
<td>0.3</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>Dense Sand</td>
<td>2050</td>
<td>51</td>
<td>0.3</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>Loose Sand</td>
<td>2000</td>
<td>18</td>
<td>0.3</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Stiff Clay</td>
<td>2000</td>
<td>10</td>
<td>0.3</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Soft Clay</td>
<td>1800</td>
<td>3</td>
<td>0.3</td>
<td>15</td>
<td>18</td>
</tr>
</tbody>
</table>

**NUMERICAL ANALYSIS**

To perform dynamic analyses of track and surrounding media, a Finite Element model developed. 4-node bilinear plain strain elements, CPE4R, are used for meshing of track and soil layers. Infinite elements also modeled in conjunction with finite elements. Infinite elements are used in boundary value problems defined in unbounded domains or problems in which the region of interest is small in size compared to the surrounding medium. Infinite elements can only have linear behavior and provide “quiet” boundaries to the finite element model in dynamic analyses. During dynamic steps the infinite elements introduce additional normal and shear tractions on the finite element boundary that are proportional to the normal and shear components of the velocity of the boundary. These boundary damping constants are chosen to minimize the reflection of dilatational and shear wave energy back into the
finite element mesh. (Dassault Systèmes Simulia Corp 2012) In this paper, 4-node infinite element CINPE4 is used. Figure 3 shows the location of infinite elements in the right and left side of the model.

![Figure 3](image)

**Figure 3. Track modeled in finite element code and monitored points**

The damping of structure is viscous and frequency dependent. The proportional or Rayleigh damping is a widely used approach to estimate the damping of a structural system. Rayleigh Damping expresses damping as a linear combination of the mass and stiffness matrices or (Chopra 2011)

\[ [C] = \alpha [M] + \beta [K] \]

Where \( \alpha \) and \( \beta \) are coefficients that show the proportion of mass and stiffness on damping.

**RESULTS**

Ten points were monitored for their time histories of displacement, velocity, and acceleration during the simulations: four points directly underneath the loading at different depth; one at location of load application and the other three points at 0.2, 2.5 and 5 m below rail level. The six remaining points are located at 2m, 4m, 8m, 16m, 22m and 40 meter away from the loading to measure the vibration of track and surrounding soil at different distances.

Figure 4 shows the acceleration of ballast and subsoil at 0.2 and 2.5 meters beneath train loads. As the results suggest, with increasing distance from loading point, vibration decreases considerably. The maximum ballast acceleration is 25 m/s\(^2\) but the peak accelerations are 7 m/s\(^2\) and 1 m/s\(^2\) for subsoil at 2.5 and 5 m below loading points.

This trend can also be observed for the points away from track. Figure 5 depicts the velocity of different measured points located from 2 m to 40 m from track. The maximum velocity decreases considerably from 0.013 m/s to 2.5×10\(^{-4}\) m/s which show the importance of stiffness and damping of track materials such as rail pad and ballast on vibration reduction. Figure 6 demonstrates the reduction of velocity with increasing distance from track. For example, a point at 4 meters away from track exhibits about 60% decrease in velocity compared to the point located 2 meters closer to loading point.

In this study, three sets of simulations were carried out in order to determine the
effects of varying subsoil materials, varying load amplitudes and varying load speed. To describe vibration from HSR, decibel notation is used. Note that, in calculation of vibration in terms of decibels, instead of peak velocities, Root Mean Square (RMS) velocities will be used. Vibration velocity level in decibels is defined as:

\[ V_{dB} = 20 \log \frac{V_{RMS}}{V_{ref}} \]

\[ V_{RMS} = \sqrt{\frac{1}{T} \int_0^T V^2(t) dt} \]

Where “VdB” is the velocity level in decibels, “\(V_{RMS}\)” is the Root Mean Square (RMS) velocity, and “\(V_{ref}\)” is the reference velocity amplitude. A reference always must be specified whenever a quantity is expressed in terms of decibels. The accepted reference quantities for vibration velocity are 1×10^{-6} in/s in the United States and either 1×10^{-8} or 5×10^{-8} m/s in the rest of the world. All vibration levels in this paper are referenced to 1×10^{-6} in/s.

Figure 4. (Right) Ballast acceleration at 0.2 m from loading point (Left) subsoil acceleration 2.5 m from loading point
Figure 5. Velocity at different distances from track center line (a) 2m (b) 4m (c) 8m (d) 16m (e) 22m (f) 40m

Figure 6. Maximum velocity at different points from track

Figure 7 shows the effect of train axle load and train speed on vibration. It is evident that vibration directly under train load is much higher than the surrounding points. Vibration at the point under loading is about 30% higher than that of 2 meters away from loading. As expected, increasing axle load leads to increasing vibration and the average difference between vibration caused by 12 ton and 18 ton axle-load trains is
about 10 dB. Figure 7 also demonstrates the influence of train speed on vibration. The figure suggests that the effect of train speed is highly nonlinear and increased after speed passed 200 km/hr. It should be noted that for the presented results a 15-ton axle load train has been used and the monitored point located 22 meters from track. Figure 8 shows the importance of different materials as substructure on vibration level. Based on the results, using soft clay as subsoil, causes a great amount of vibration both near track and at far field. The vibration at 40 meters from track is still very high and near 80 dB. This figure suggests that utilizing dense clay would be the best material for track substructure from vibration point of view. The average drop in ground-born vibrations due to using proper materials is about 30%.

CONCLUSIONS

The development of high-speed trains in the US necessitates to address the current issues regarding construction and operation of HSRs. Vibration is one of the most
important environmental issues that needs to be addressed. This paper investigated the effect of train and track parameters on vibration using finite element method. Some important parameters including train speed and axle load and subsoil material took into account and the results presented for different distances from track structure. The results of this study showed that track vibration highly dependent on soil properties and choosing proper material would lead to more than 30% decrease in vibration. Train speed is another important factor on vibration problem. More than 11 decibel increase in vibration observed by increasing train speed from 100 to 300 km/hr. this amount of excessive vibration can be compensated by decreasing train axle load from 18 ton to 12 ton.

REFERENCES


Dassault Systèmes Simulia Corp, 2012. ABAQUS 6.12, user manual,


