PROPAGATION OF VIBRATION INDUCED ON TRACK: IMPLEMENTATION OF PREVISIONAL MODELS FOR LOW AND HIGH SPEED TRAINS AND COMPARISON WITH EXPERIMENTAL MEASUREMENTS

Salvatore Curcuruto, Delio Atzori, Rinaldo Betti, Giuseppe Marsico and Enrico Mazzocchi

ISPRA - Italian Institute for Environmental Protection and Research, via Vitaliano Brancati 48 - 00144 Rome, Italy
e-mail: enrico.mazzocchi@isprambiente.it

Ernesto Monaco, Francesco Amoroso and Vincenzo Limone
Sonora S.r.l., via dei Bersaglieri 9 - 81100 Caserta, Italy

Giuseppe Loprencipe and Fabio De Felice
DICEA – Dept. of Civil, Building and Environmental Engineering, Sapienza University of Rome, via Eudossiana 18 - 00184 Rome, Italy

In recent years, the topic of vibrations in homes and workplaces has grown in importance. In order to reduce the vibrations due to road and rail traffic, several actions can be implemented, some of which are economically very expensive. As a consequence, before implementing any mitigation measures, the availability of appropriate simulation tools able to characterize the effectiveness of the chosen solutions becomes more and more relevant. As part of this work, the development of a predictive software has been addressed, combined with experimental measurements, in order to assess with acceptable accuracy the vibration levels caused by rail transport – trams, low-speed and high-speed trains. Predictions are obtained by characterizing waves propagation through the ground by the mean of separate approaches for low and high velocity trains. In this paper the results achieved has been presented, as well as the future potential of the activity.

1. Introduction

Recently, the problem of vibrations induced into homes and workplaces has achieved a relevant importance, related to the various types of buildings – varying greatly by moving from city centers to new residential neighborhoods of the cities – and also because of the increase of vibratory sources that has provided more sensitivity to this environmental component. As a consequence, more frequently than in the past, the assessment of the impact due to vibrations is carried out.

In order to reduce the vibrations induced by road and rail traffic and mitigations costs, it is very important to make a previsional study for vibration levels assessment at the receivers. Nevertheless, to correctly determine the vibration levels, it is necessary to study the dynamic characteris-
tics of sources – spectral content, levels of excitation, energy etc., as well as the waves propagation. That is a considerably complex matter, since characteristics and geological structure of a soil can be difficult to determine.

The implementation of calculation methods has been addressed, in order to predict the vibration levels induced by rail transport systems – tramways, low and high speed trains. The aim of this work is to develop a software tool based on predictive models from the scientific literature of recent years that – combined with accurate measurement techniques and characterization of the vibrational waves in the soil under consideration – can allow end-users and infrastructure designers to assess the vibration impact in a with a sufficient accuracy. In this paper we present also the results achieved and the future potential of this activity.

2. Experimental measurements: low-speed trains

Two cases have been taken into account: the first focused on the prediction of vibrational waves generated by tramways and the second one on the vibrational levels by a high-speed train running at low speed (50 km/h).

2.1 The attenuation model

The transit of trains generates both body waves (compression and shear) and surface waves (Rayleigh and Love), to a different extensions in relation to the type of infrastructure. In particular, the equation used to calculate the attenuation of vibrations, expressed in dB, along their propagation path is:

\[
L = 20 \log \left[ 10^{\frac{L_c}{20}} + 10^{\frac{L_t}{20}} + 10^{\frac{L_s}{20}} \right]
\]

where \(L_c, L_t, L_s\) – respectively the levels in dB transmitted through compression, shear and surface waves – are given by the following relations:

\[
L_c = L_0 + 20 \log \left( \frac{R}{R_0} \right) - \alpha_c (R - R_0) \frac{f}{V_c}
\]

(1.a)

\[
L_t = L_0 + 20 \log \left( \frac{R}{R_0} \right) - \alpha_t (R - R_0) \frac{f}{V_t}
\]

(1.b)

\[
L_s = L_0 + 20 \log \left( \frac{R}{R_0} \right) - \alpha_s (R - R_0) \frac{f}{V_s}
\]

(1.c)

in which:
- \(L_0\): vibration levels in dB at \(V\) (transit speed) and \(V_0\) (reference speed);
- \(R\): distance of receiver from the line axis;
- \(R_0\): distance of source from the line axis (reference point);
- \(V_c\): speed of compression waves;
- \(V_t\): speed of shear waves;
- \(V_s\): speed of surface waves,
- \(\alpha\): attenuation factor;
- \(\beta\): factors taking into account of the relative importance among the different kinds of wave propagations into the soil;
- \(k\): geometric attenuation coefficient;
- \(c, t, s\): indexes referred respectively to compression, shear and surface waves.
It can be noted that the simplified model, described by Eq. (1), implements this kind of attenuation law:

\[ L = a(R - R_0)F_c + b \log \left( \frac{R}{R_0} \right) \]  

(2)

where \( F_c \) is the central frequency band.

2.2 Vibrations induced by tramways: linear attenuation law

Experimental measurements have been carried out aimed at the characterization of the vibration source and at the validation and verification of the propagation model in the soil. Actually, the measurement positions have been chosen either in the vicinity of the source and in a point located at a given distance; the simultaneously acquisition of accelerations at the two points allows to assess the reduction trend of vibrations as a function of frequency and distance.

The attention has been focused on vibrations induced by urban railway lines (tramways) – considered as low-speed trains – and high-speed trains. The first ones represent an important source of vibrations, crossing the historic centres of cities where the sensitivity to vibrations – for both inhabitants and buildings – can be very relevant, because the architectural heritage should be preserved and monitored.

Below an analysis is reported about the vibration levels measured in the city of Rome on a tramway line advised as critical by Municipality. The data analysis is divided into the following points:

1) Event detecting from the time-history
2) Application of a 1/3-octave band filter to the signal acquired along the three measurement axes
3) Calculating the acceleration level for each frequency band and axis
4) Calculating the amplitude of the acceleration vector for each band.

The identification of the events has been performed along the vertical direction to the line linking the measurement point to the source. The beginning and the end of an event have been established by evaluating the difference from the maximum peak; points 2, 3 and 4 have been performed for both the measuring positions. The final result of the analysis consists of determining the spectrum of the amplitude for the acceleration vector, at the source and the receiver, for each event.

The measuring point at the source was placed at about 0.7 m from the outer rail of the line (i.e. 1.4 m from the line axis), while the point at the receiver was fixed at 7.15 m from the point source, at 8.55 m from line axis.

The different events identified (Fig. 1) have acceleration levels as a function of frequency in a range of a few dB, and only some events have a deviation from the average value of about ± 5 dB. This trend is the same for all the events and at the receiver they are very close to the average value.
Figure 1. Acceleration amplitude at the source (blue) and at the receiver (red) for all events – in black the average value of the acceleration amplitude.

From to the average spectrum at the source and at the receiver, it is possible to determine the law of attenuation in the frequency domain.

There are semi-empirical models in the literature\textsuperscript{1,2,3,4} used in the determination of vibration levels caused by rail transport.

According to this approach, the vibrational annoyance at the receivers, evaluated in the frequency domain, depends on the different kind of wave propagation and attenuation (or amplification) along the transmission path: source of the disturbance, railway infrastructure, type of soil to cross, building’s structural type, physiological sensitivity of the people etc.

It is possible to calculate the curve best-fitting the attenuation law in frequency, measured at a given distance. Since the simplified model implements a linear frequency dependence as shown in Eq. (2), a linear interpolation has been used, where \((R-R_0)\) and \((R/R_0)\) are known parameters. This provides an experimental procedure useful to determine the input attenuation parameters of the soil for the simplified model. In this case, Eq. (2) gives this formula:

\[
L = 0.125F_c + 5.09
\]  

Figure 2 shows the average attenuation calculated by using the measured data and the best-fitting linear frequency interpolation given by Eq. (3).

Figure 2. Assessing the attenuation parameters using best-fitting interpolation.
Figure 3 reports a comparison between the data acquired as in the previous paragraph and a calculation performed with the software tool developed to implement the simplified model given in Eq. (1). As input data for the tool, the following literature values have been assigned:
- Typology of source: linear
- Layout: superficial
- Distance from receiver point: 8.5 m
- $\alpha_c = 3.5$
- $\alpha_t = 3.5$
- $\alpha_s = 3.5$
- $V_c = 700$ m/s
- $V_t = 150$ m/s
- $V_s = 120$ m/s

![Figure 3](image3.png)

**Figure 3.** Excitation spectrum and comparison of numerical and experimental acceleration level at the receiver – Simplified Model.

The software tool also implements the possibility to insert a different law of attenuation – constant, linear, quadratic and cubic vs. frequency. A linear frequency attenuation law, such as that of the Eq. (2), has been chosen, calculating the best-fitting parameters: $R=8.5$, $R_0=1.4$, $a=0.0174$ and $b=6.44$. Figure 4 shows a comparison between the data acquired as in the previous paragraph and a calculation performed with the software tool, implementing the linear frequency attenuation law as above mentioned.

![Figure 4](image4.png)

**Figure 4.** Excitation spectrum and comparison of numerical and experimental acceleration level at the receiver – Attenuation law.
2.3 Vibrations induced by a high-speed train running at low speed: non-linear attenuation law

The second case considered is related to the study of vibration produced by high-speed trains running at low speed (about 50 km/h). Vibration measurements have been carried out at the source rail and at the receiver placed at 12 m from the source.

The comparison of the spectra obtained from the measurements has allowed to derive the non-linear transfer function representative of the attenuation law along the source-receiver path (Fig. 5).

In the literature a model for the estimation of the vibrations in the non-linearity case is still not available. Therefore, the shape of the transfer function obtained suggests to bring back the study to the linear case already discussed for tramways. Two frequency bands have been considered separately, (1 Hz - 25.4 Hz) and (32 Hz - 250 Hz), as shown in the Fig. 6:

For each frequency bands, a linear curve fit has been fund by calculating the $a$ and $b$ parameters of the Eq. (2).

Figure 7 shows the comparisons between the spectrum of the acceleration calculated through the linear propagation model and the measurements at the receiver.
3. Model for predicting vibrations induced by high-speed trains

The high-speed trains, though confined in areas often characterized by a low density of potential receivers, can generate vibrational fields entirely different from the others above mentioned cases and, for high speed (>300 km/h), can reach particularly high levels. It is due to the characteristics completely different in amplitude and frequency between the two types of rail infrastructure.

The measurements carried out on high-speed railways aimed to characterizing the source and verifying the waves propagation of vibrations into the ground. Three points have been chosen, one nearby the source and the others along the propagation path located at about 4.5 m and 9 m from the railway. The acquisition of acceleration levels in the three points has been performed simultaneously.

Below an analysis is reported about the vibration levels measured on Rome-Naples track whose data analysis has been divided into the following points:
1. Event detection from the time-history using signals of the photocell
2. FFT of the acceleration signals measured at different points
3. Identifying the fundamental harmonics and correlation with the kinematic and geometric parameters of trains
4. Calculation of the transfer function at the two measurement points in the ground.

In Figure 8 the steps of bogies in the measuring section of the track are visible, at a speed of about 220 km/h, similarly to what reported in 5.

![Figure 8. Steps of the bogies for a high-speed train.](image)

The models used to simulate the vibrations induced by high-speed trains are still the ones reported in 5, 6 whose procedure is:
- studying the vibrations of the load transferred only between wheel and rail
- neglecting the effects of the presence of joints and the roughness or track irregularities
- considering only Rayleigh waves.

4. Conclusions and future developments

From the measurements made and the numerical comparison-experimental it is possible to conclude that, regarding to the simplified model used for the prediction of the vibrational levels relative to low-speed sources, the attenuation law in frequency can be considered validated. Actually, the value of the coefficient to be calculated experimentally in the examined cases allows the calculation of the level at the receiver in a manner known fairly accurate and based on the average spectrum of the vibration levels to the source.

Regarding to high-speed trains, the phenomenology is completely different to the previous case, resulting very complex and the results of measurements agree with the measurements reported in the literature.

In order to develop a new model for the characterization of vibrational levels generated by underground lines, a collaboration has been planned with the management company of public transport of the Municipality of Rome.

REFERENCES