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Propagation of vibrations induced on track: implementation of previsional models for low and high speed trains and comparison with experimental measurements

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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 costly. 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 a higher 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, different actions can be implemented, such as the improvement of pavement (railway) structures and the realization of screens and barriers into the soil. For these mitigations can be economically very costly, it is very important to make a previsual study that, assessing the exact vibratory levels at receivers, allows to determine the right implementations and the most effective technical solutions. Nevertheless, to correctly determine vibration levels, it is necessary to study the dynamic characteristics 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 soils could be difficult to determine.

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

2 Experimental measurements of vibrations induced by tramways

Experimental measurements have been carried out aimed at characterizing the vibration sources and at validating the propagation model. 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 instrumentation used for the acquisition of data is composed of:

- signal acquisition system, 16-ch 24-bit resolution
- pc for data recording
- PCB triaxial accelerometer, 0.1 V/g, mod. 356A16

- PCB triaxial accelerometer, 1.0 V/g, mod. 356B18.

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 centers of cities where the sensitivity to vibrations – for both inhabitants and buildings – can be very relevant, for historical heritage should be preserved and monitored. The second ones, though confined in areas often characterized by a low density of potential receivers, can generate vibrational fields, entirely different from the others, producing phenomena related to the genesis of vibrations that, for a fast enough speed (>300 km/h), can reach very high levels.

Below an analysis is reported about the vibration levels measured in the city of Rome on a tramway line advised as critical by the Municipality. The data analysis has been 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 three measurement axes
3. Calculating the acceleration levels for each frequency band and axis
4. Calculating the amplitude of the acceleration vector for each band.

The event identification 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 acceleration levels of the identified events (Figure 1) are a function of frequency in a range of a few dB, and only some events vary from the average value of about ± 5 dB. This trend is the same for all the events and at the receiver such values are very close to the average value.

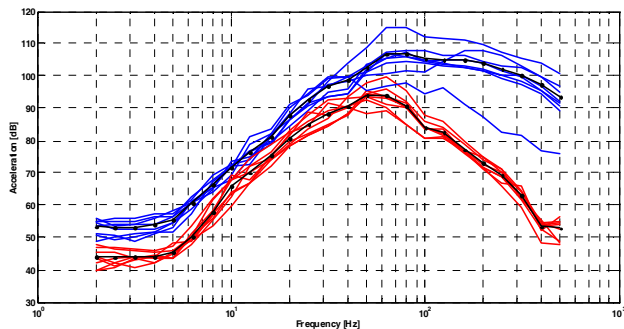


Figure 1: Acceleration amplitude at the source (blue) and at the receiver (red) for all events – in black the average value of the acceleration amplitude.

From the average spectrum at the source and at the receiver, it is possible to determine the law of attenuation in the frequency domain. Figure 2 shows the 1/3-octave attenuation in dB of the measured accelerations levels, calculated from the measuring point at the source and from that nearby the receiver.

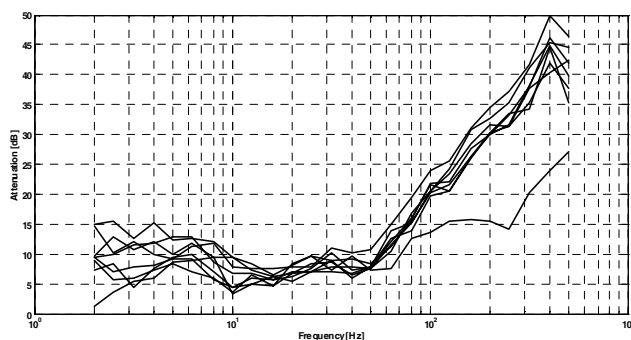


Figure 2: Attenuation of the acceleration levels in 1/3-octave between source and receiver.

There are semi-empirical models in the literature [1] [2] [3] [4] used in the determination of the 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 waves propagation and attenuation (amplification) along the transmission path: vibration source, railway infrastructure, type of soil to cross, building's structural type, physiological sensitivity of the people etc.

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

$$L = 20 \log \left[10^{\frac{L_c}{20}} + 10^{\frac{L_t}{20}} + 10^{\frac{L_s}{20}} \right] \quad (1)$$

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:

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

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

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

in which:

- L_0 , L : 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,
- α : attenuation factor;
- β : 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:

$$L = a(R - R_0)F_c + b \log \left(\frac{R}{R_0} \right) \quad (2)$$

where F_c is the central frequency band.

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 (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 soil for the simplified model. In this case, Eq. (2) gives this formula:

$$L = 0.125F_c + 5.09 \quad (3)$$

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

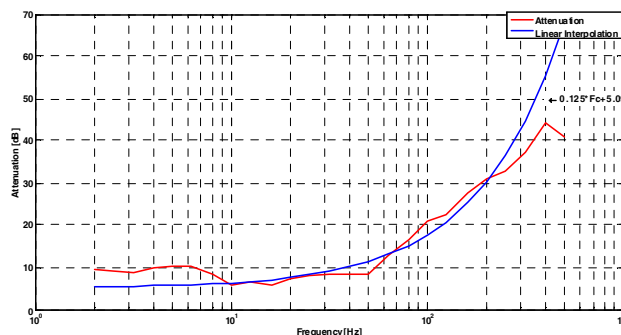


Figure 3: Assessing the attenuation parameters using best-fitting interpolation.

3 Experimental and theoretical comparisons

Figure 4 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 values of literature 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

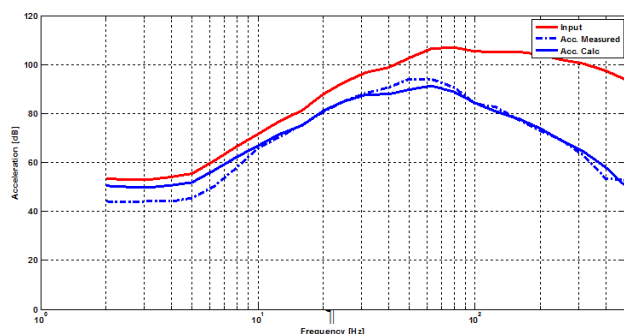


Figure 4: Excitation spectrum and comparison of numerical and experimental acceleration level at the receiver - Simplified Model.

The software tool also implements the possibility to insert a different law of attenuation – constant, linear, quadratic and cubic in the frequency domain. A linear 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 5 shows a comparison between the data acquired as in the previous paragraph and a calculation performed with the software tool, implementing the linear attenuation law as above mentioned.

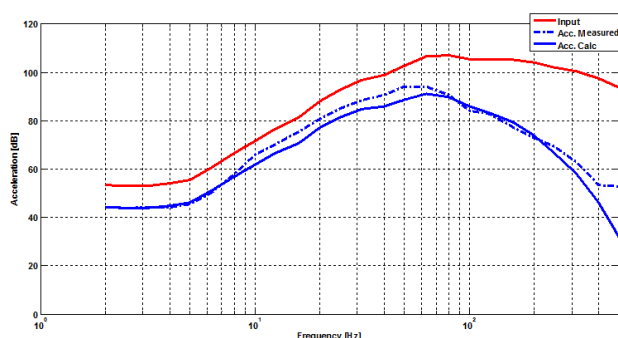


Figure 5: Excitation spectrum and comparison of numerical and experimental acceleration level at the receiver – Attenuation law.

4 Model for predicting vibrations induced by high-speed trains

The measurements performed on high-speed railways aimed at characterizing the source and verifying the waves propagation of vibrations into the soil. The measurements have been performed both nearby the source and in two points, 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.

The instrumentation used for the data acquisition is composed of:

- Signal acquisition system, 16-ch 24-bit resolution
- pc for data recording
- n. 1 PCB triaxial accelerometer, 0,001 V/g
- n. 1 PCB triaxial accelerometer, 0.1 V/g, mod. 356A16
- n. 1 PCB triaxial accelerometer, 1 V/g, mod. 356B18
- n. 2 photocells, located at 12 m distance, with trigger function, measuring the transit speed and therefore also the length of the train.

The 0.001 V/g accelerometer was rigidly fixed under the track.

The accelerometers mod. 356A16 and mod. 356B18 was fixed respectively on two struts implanted into the soil to a depth of about 40 cm.

Below an analysis is reported about the vibration levels measured on the Rome-Naples high-speed railway.

The data analysis has been divided into the following points:

1. Event detecting 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 the correlation with the kinematic and geometric parameters of trains
4. Calculating the transfer function at the two measurement points on the ground.

In Figure 6 the steps of bogies in the measuring section of the track are shown, at a speed of about 220 km/h, similarly to what reported in [5].

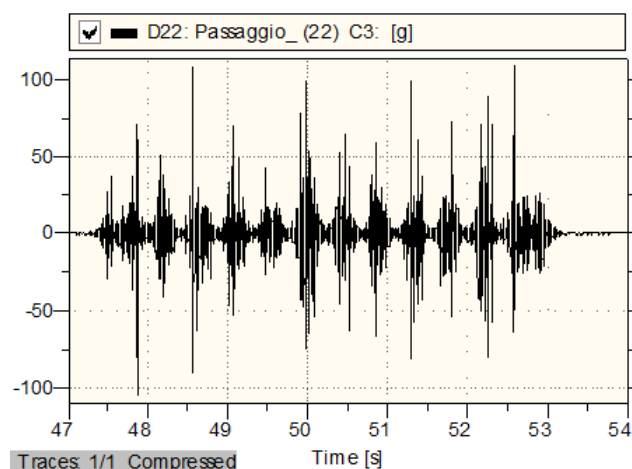


Figure 6: Steps of the bogies for a high-speed train.

The need to use different models than those used in the previous paragraph is due to the characteristics completely different in amplitude and frequency between the two types of rail infrastructure.

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.

5 Conclusions

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.

This study will be integrated by implementing specific models for the assessment of the vibrations induced by subway railways, that should be take into account of the complex structure of the soils of the historical European cities, such as Rome. Another feature to be implemented is the assessment of the vibrations from road traffic.

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