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AN EXPERIMENTAL NUMERICAL COMBINED APPROACH TO FORECAST GROUNDBORNE VIBRATIONS AND NOISE DUE TO TRAINS IN UNDERGROUND LINES

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ABSTRACT

A numerical experimental combined approach to forecast groundborne vibrations and noise has been implemented to support the design of track bedding to be adopted in order to properly limit trains transit disturbance. The experimental phase consists in the application of train loads on the tunnel base to obtain a comprehensive knowledge of vibrations propagation from tunnel to buildings. The numerical phase, starting from the experimental measures, allows evaluating the effective disturbance level on surrounding buildings as the result of adding the loads simultaneously applied by different train boogies taking into account of train length. Attenuations provided by the use of advanced isolated track systems can be thus evaluated. Tests are usually carried out on typical sections characterized by different relevant parameters to enable reliable extrapolations to comparable conditions. The paper presents the base notions of the proposed approach and describes real study cases based on experimental tests and numerical analysis.

1 INTRODUCTION

Different design solutions can be adopted to properly attenuate groundborne vibration and noise due to trains transit especially for critical buildings and factories where precision works are carried out. Practical solutions are mainly addressed to the use of special types of track bedding. To contain construction costs isolated track systems are to be used only where it is strictly necessary and their design must be exactly sighted to limit disturbance under allowable values. To support design choices, a numerical experimental combined approach to forecast groundborne vibrations and noise has been implemented.

The experimental phase consists in the application of train loads on the tunnel base and measure of induced vibrations on tunnel walls and inside existing buildings nearby train line. Load application is performed by a hydraulic exciter that allows generating a force whose intensity and frequency content corresponds to real load spectra. To achieve the requested accuracy often a wide transducers network is installed (typically accelerometers, seismometers, sound level meters) both inside tunnel and surrounding buildings to cover different positions at foundation level and elevation floors. At the same way, the hydraulic exciter can be applied in several positions along tunnel line. To obtain a good quality simulation of train load spectra, forces up to several tons are applied covering a frequency range up to 200 Hz. Usually experimental tests are repeated several times to achieve better quality results reducing the effect of residual vibrations that could be present in the environment. The experimental transfer functions obtained by measured responses and applied loads provide a complete characterization of the dynamic behavior of tunnel structure, soil, buildings and related interactions to acquire a comprehensive knowledge of vibrations propagation from tunnel to buildings.

The numerical phase, starting from the experimental measures, allows evaluating the effective disturbance level on surrounding buildings as the result of adding the loads simultaneously applied by different train boogies taking into account of train length. At the same way, further numeric evaluations are carried out to calculate the effects of contemporary transit trains and to evaluate attenuations provided by using advanced isolated track systems.

To suitably exploit experimental results, tests are usually carried out on typical sections characterized by different tunnel typology and dimensions, as well as different soil properties and building constructional features (materials, sizes, foundation types, number of floors, etc). Subsequent numerical evaluations enables thus to easily extrapolate the results to comparable situations.

For specific applications, the method can also be applied to check and validate short sections of trial track systems before laying the track on the entire railway line. In this case, the hydraulic exciter is usually mounted on the track that is equipped with the unsprung masses to suitably simulate the dynamic interaction with the train boogie.

The proposed numerical experimental combined approach has been successfully applied to forecast groundborne vibrations and noise of new underground lines (such as the new Brescia Metro or Bergamo Tramway) and high speed railways (such as Sesto Fiorentino crossing, close to Florence).

The paper deals with base notions of the proposed approach and describes real study cases showing details and problems related to practical carrying out of experimental tests and numerical analysis.

2 EXPERIMENTAL TESTS

The experimental phase is aimed at the characterization of the real mode of propagation of vibrations from the subway tunnel to sensitive buildings, taking into account the actual chain of transmission of vibrations in the site: tunnel, soil characteristics, building foundations, structures in elevation, decks, and their interactions / dynamic couplings (tunnel / soil and soil / foundations interactions).
Forced vibration tests are carried out by transient vertical loads applied on the tunnel base by a hydraulic exciter (hydraulic vibrodyne) that allows generating a time history derived from real load spectra due to trains transit. Induced vibrations are measured inside the tunnel, on the outside ground and at surrounding buildings by accelerometers, seismometers and sound level meters.
At this stage it is not strictly necessary to consider the real load spectra generated by the train. Usually load spectra provided by previous studies and relevant to comparable conditions are applied. Where appropriate, load spectra are suitably amplified to induce in buildings vibrational levels sufficiently high in order not to be influenced by the ambient noise.

Fig. 1 Hydraulic exciter on the tunnel base

2.1 Testing equipment

The load is applied by a hydraulic exciter (Fig. 1) that allows generating transient dynamic forces of the order of 100 kN in the frequency range up to 200 Hz. Applied forces are characterised by suitable values already starting at low frequencies.
The need to operate in the frequency range up to 200 Hz takes into account the characteristics of the vibration spectra of interest for developing vibrational projects for railway / metro. These spectra are usually characterised by not negligible contents up to about 200 Hz, that can induce possible vibrational effects on buildings and groundborne noise to users.
A wide network of accelerometers (Figg. 2, 3) is installed inside the tunnel (tunnel base and walls). Triaxial seismometers and sound level meters (Fig. 4) are located on surrounding buildings (typically at foundations level and centre of slabs).

Fig. 2 Accelerometer on tunnel base

Fig. 3 Accelerometers on tunnel walls

The sensors inside the tunnel are located close to excitation position and at defined sections to gather data related to vibration reduction with distance.

Fig. 4 Triaxial seismometers and sound level meters

2.2 Experimental procedure

The test procedure is developed through the following main phases:

a) Load spectra definition as force [kN] vs frequency [Hz]. Fig. 5 shows the graph of a typical load spectrum provided at 1/12 octave bands.

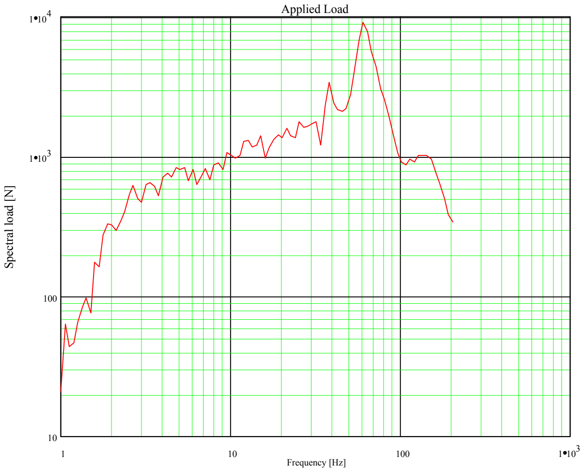

Fig. 5 Example of load spectra applied on tunnel base by hydraulic exciter

b) Generation of the time history (TH) derived from the load spectra to be applied on tunnel base (fig. 6) by hydraulic exciter. Forces can be applied in different positions to achieve a better characterisation of the transfer functions which relate tunnel excitation to vibrations induced on buildings.

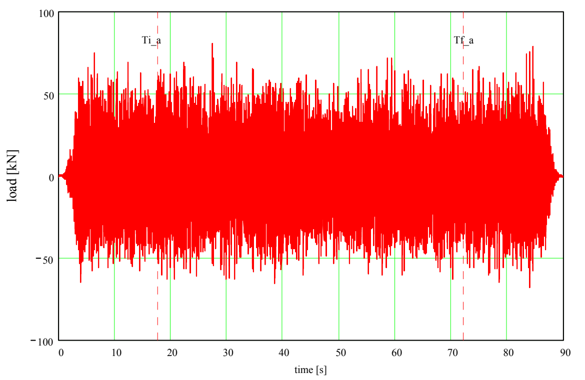

Fig. 6 Example of a TH provided by the vibrodyne

c) Simultaneous recording of vibrations generated in the different measuring points within the infrastructure and on surrounding buildings.

Fig. 7 Example of in situ measurements

d) Repetition several times of dynamic force application and subsequent measure of vibration generated (Figg. 7, 8). In this way, through a statistical process, uncertainties associated with the possible presence of residual environmental vibration are minimized (optimization of noise / signal ratio).

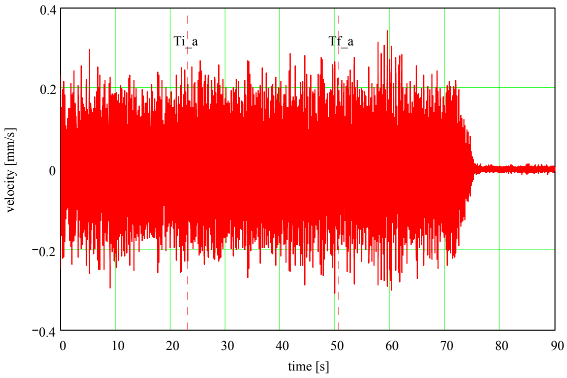

Fig. 8 Example of Response Time History measured at buildings

e) From applied forces and related response measurements, transfer functions between the excitation and measuring points are evaluated. These functions completely characterize the mode of transmission of vibrations through the tunnel and the ground up to different points on buildings. Transfer functions are defined as follows:

Accelerometers inside the tunnel (Fig. 8)

$H_{i,j}^{Rif}(f) = A_{i,j}^{Rif}(f) / F_i^{App}(f)$

where:

$F_i^{App}(f)$: Load spectra generated by the vibrodyne at i-th excitation position with i=1÷n (n = number of excitation positions) [N – Hz]

$A_{i,j}^{Rif}(f)$: Acceleration spectra measured inside tunnel at j-th position with vibrodyne applied at i-th excitation position [mm/s² – Hz]

$H_{i,j}^{Rif}(f)$: Transfer functions between applied load and accelerometers inside tunnel [mm/s² / N – Hz]

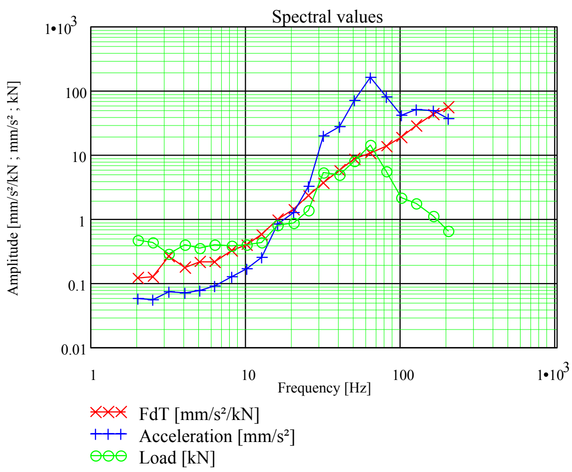

Fig. 8 Accelerations – Load - Transfer Functions

Measuring positions on surrounding buildings (Fig. 9)

$H_{i,j}^{Ric}(f) = V_{i,j}^{Ric}(f) / F_i^{App}(f)$

where

F_i^{App} (f): Load spectra generated by the vibrodyne at i-th excitation position with i=1÷n (n = number of excitation positions) [N – Hz]

$V_{i,j}^{Ric}$ (f): Velocity spectra measured at buildings at j-th position with vibrodyne applied at i-th excitation position [mm/s – Hz]

$H_{i,j}^{Ric}$ (f): Transfer functions between applied load and seismometers on buildings [mm/s / kN – Hz]

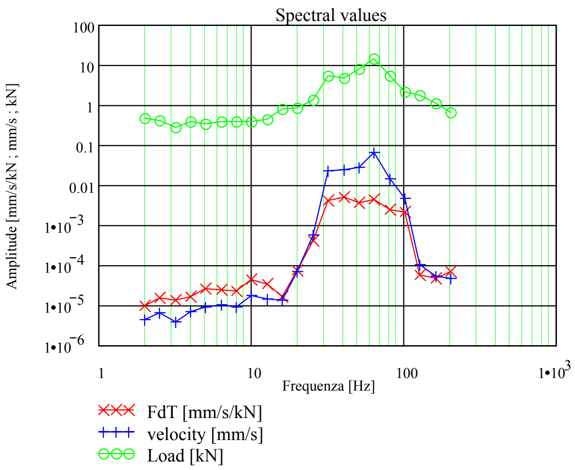

Fig. 9 Velocity – Load - Transfer Functions

Transfer functions are the main result of the experimental tests and represent the input data for the subsequent numerical analysis.

3 NUMERICAL ANALYSIS

The numerical phase, starting from the experimental measures, allows evaluating the effective disturbance level on surrounding buildings as the result of adding the loads simultaneously applied by different train boogies taking into account of train length.

3.1 Load spectrum definition

For the numerical analysis is necessary to know the load spectrum induced on the tunnel base by the train in transit. This spectrum can be estimated from experimental measurements carried out on lines in service with the same type of train, similar infrastructure and type of track bedding known (reference track bedding).

The load spectrum is then derived in force from the effects in terms of acceleration spectrum produced by the transit of trains running in similar tunnels by measurements on walls or tunnel base.

The load spectrum is often to be modified to take into account of the actual transit speed to be considered for the underground line. Typical relations give increasing load spectra with growing speeds. At the same way greater load spectra can be related to alterations in the time of the wheel-rail contact through suitable correction factors of the type shown in Fig. 10

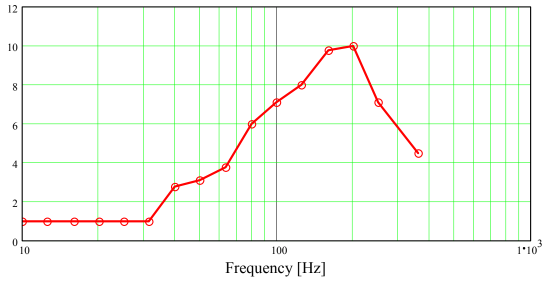

Fig. 10 Corrections due to alteration of the wheel rail contact

To consider the design isolated track system, which generally differs from the track bedding related to in service measurements, the following transmissibility function TR is used:

$$S(A)_{pf,p}(f) = \frac{TR_p(f, f_p, \nu_p, k_p)}{TR_o(f, f_o, \nu_o, k_o)} \times S(A)_{pf,o}(f)$$

where

$S(A)_{pf,o}$ (f) load spectrum at rail, measured on in line service with related track bedding (reference track)

$S(A)_{pf,p}$ (f) load spectrum at rail level modified on the base of the design isolated track system

f_o = first natural frequency of the reference track bedding;

ν_o = damping of the reference track beddings;

k_o = stiffness of the reference track bedding;

f_p = first natural frequency of the design isolated track system;

ν_p = damping of the design isolated track system;

k_p = stiffness of the design isolated track system

$$TR_o(f, f_o, \nu_o, k_o) = \frac{\frac{1}{k_o}}{\sqrt{\left[1-\left(\frac{f}{f_o}\right)^2\right]^2 + \left[2\times\nu_o\times\left(\frac{f}{f_o}\right)\right]^2}}$$

$$TR_p(f, f_p, \nu_p, k_p) = \frac{\frac{1}{k_p}}{\sqrt{\left[1-\left(\frac{f}{f_p}\right)^2\right]^2 + \left[2\times\nu_p\times\left(\frac{f}{f_p}\right)\right]^2}}$$

To transfer the load spectrum from rail level to wall or tunnel base the following transmissibility function T_p is used:

$$S(A)_{pp,p}(f) = S(A)_{pf,p}(f) \times T_p(f, fp, \nu p, kp)$$

where

$S(A)_{pp,p}$ (f) load spectrum at wall or tunnel base

$S(A)_{pf,p}$ (f) load spectrum at rail level

$$Tp(f, f_p, \nu_p, k_p) = \sqrt{\frac{\left(H^{Vib}(f)\times k_p\right)^2 + \left(H^{Vib}(f)\right)^2 \times \left[2\times\nu_p\times k_p\times\left(\frac{f}{f_p}\right)\right]^2}{\left[-(2\times\pi\times f)^2 + H^{Vib}(f)\times k_p\right]^2 + \left(H^{Vib}(f)\right)^2\times\left[2\times\nu_p\times k_p\times\left(\frac{f}{f_p}\right)\right]^2}}$$

H^{Vib} (f): Experimental transfer function between exciting load and acceleration measured at the excitation point [mm/s² / N – Hz]

Having defined the target acceleration spectrum at wall or tunnel base and evaluated the experimental transfer functions inside the tunnel, it is then possible to calculate the load spectrum able to produce the target acceleration spectrum through the following relations:

$$A^{Rif,tg}(f) = \Sigma_k H_k^{Rif}(f) \times F_k^{Rif}(f)$$

where

$A^{Rif,tg}(f)$: target acceleration spectrum [mm/s² – Hz]
$F_k^{Rif}(f)$: load spectrum at the k-th excitation point with k =1÷n (where n represents the number of boogies capable of produce vibration effects on wall or tunnel base) [kN – Hz]
$H_k^{Rif}(f)$: Transfer function between target acceleration spectrum and load spectrum [mm/s² / kN – Hz]

Assuming $F_k^{Rif}(f)$ keeping constant while varying excitation point, i.e. the train generates the same load spectrum in all positions, it is possible to write:
$F_k^{Rif}(f) = F^{Rif}(f)$
thus determining the load spectrum $F^{Rif}(f)$:

$$F^{Rif}(f) = A^{Rif,tg}(f) / \Sigma_k H_k^{Rif}(f)$$

3.2 Vibrations and noise disturbance forecasting

Starting from the load spectrum $F^{Rif}(f)$ and taking into account of the experimental transfer functions between dynamic excitation inside tunnel and vibration measurements on surrounding buildings, it is possible to evaluate vibrations due to train transits at buildings, using the following relation:

$$V_j^{Ric}(f) = F^{Rif}(f) \times \Sigma_k H_{k,j}^{Ric}(f)$$

where

$V_j^{Ric}(f)$: Velocity spectra at different j-th positions on buildings (foundation level, centre of slabs, etc.) [mm/s – Hz]
$H_{k,j}^{Ric}(f)$: Experimental transfer function at the j-th measurement position on buildings due to vibrodyne applied at the k-th excitation position [mm/s / kN – Hz], being k =1÷ m (where m represents the number of boogies capable of produce vibration effects on surrounding buildings).

The number of significant boogies can be evaluated by means of the experimental results, or through empirical relationships depending on train length and distance between tunnel and buildings.
The simultaneous transit of trains is evaluated considering adding the effects at buildings of spectra generated by the passage of each train.
The rms values of vibration allows the evaluation of vibrational annoyance to people, whereas possible vibrational damage to building is concerned reference has to be made to velocity peak values of vibration.
Groundborne noise is evaluated by the use of empirical rules whose reliability has been experimentally checked. These rules consider vibration levels and the main dimensions and acoustical properties of building rooms.

Finally, it is worthwhile citing that the described experimental numerical combined approach can be applied to optimise the choice of advanced isolated track systems. To contain construction costs isolated track systems are to be used only where it is strictly necessary and their design must be exactly sighted to limit disturbance under allowable values.

4 RESULTS EXTRAPOLATION

Generally it is not possible to extensively apply the accurate and detailed procedure previously described. It is therefore necessary to exploit the results obtained trying to extend them to the greatest number of buildings with similar characteristics.
To suitably exploit experimental results, tests are usually carried out on typical sections characterized by different tunnel typology and dimensions, as well as different soil properties and building constructional features (materials, sizes, foundation types, number of floors, etc).
Subsequent numerical evaluations enables thus to easily extrapolate the results to comparable situations.
The numerical extrapolation is based on typical analytical formulations mainly available in literature regarding the various parameters that come into play in the transmission of vibrations.
The main parameters to be taken into account are:
a) tunnel characteristics in terms of shape, main dimensions and wall thickness
b) soil properties related to waves propagation
c) buildings features in terms of foundation typology, floors number, deck characteristics, materials, dynamic behaviour, etc.
The numerical extrapolation based on analytical formulations can be conveniently verified and calibrated using the results provided by the experimental numerical combined approach previously described.
This operating method allows to perform groundborne vibrations and noise forecasting by a relatively easy and quick way, keeping at the same time a good accuracy level.
The following Fig. 11, which refers to vertical vibrations forecast at the centre of a slab of a building, compares values obtained by the experimental numerical combined approach with the results provided by the calibrated numerical extrapolation.

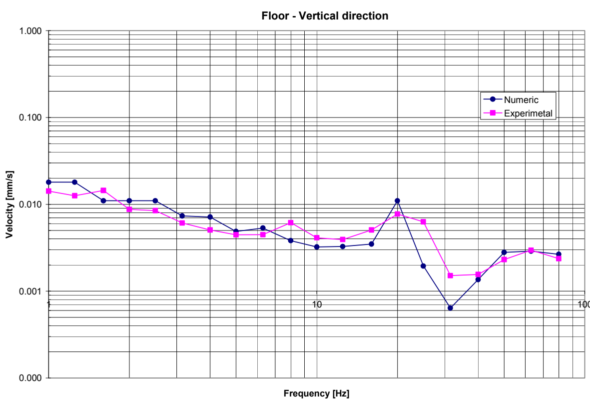

Fig. 11 Calibration of the numerical extrapolation

5 DIRECT VALIDATION OF TRIAL TRACK SYSTEMS

For specific applications, the method also can be applied to check and validate short sections of trial track systems before laying the track on the entire railway line. In this case, the hydraulic exciter is usually mounted on the track that is equipped with the unsprung masses to suitably simulate the dynamic interaction with the train boogie (Fig. 12).
The method is profitably employed to test on site the actual dynamic behaviour of isolated track system which should assure high vibration isolation performance.

Fig. 12 – Vibrodyne on track and unsprung masses

The method requires to directly applying the load spectrum of the train in transit. This load spectrum can be derived from the draft standard UNI U21020691 "Numerical and Experimental Evaluation of static and dynamic behaviour of track systems for railway applications - Part 1, Appendix C.
In the following are shown some Figures which refer to a real study case regarding the validation of a new massive (40 kN/m) isolated track system with low resonance frequency. The track was composed by separate massive slabs with elastomeric mats interposed between slab and tunnel base (Fig. 13).

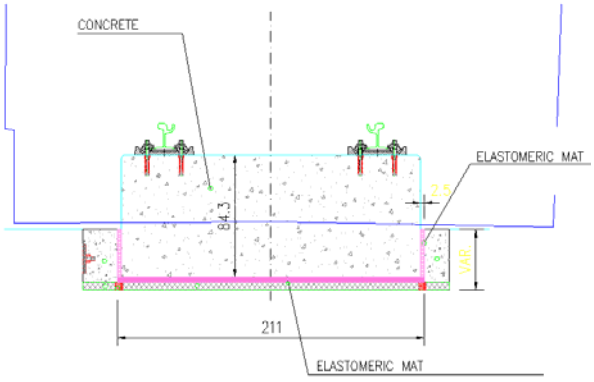

Fig. 13 Massive isolated track system - section

The applied load spectrum, derived from the mentioned UNI draft standard, is shown in Fig. 14.

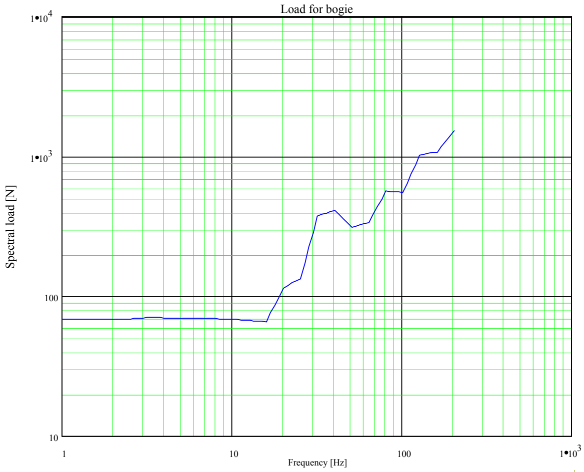

Fig. 14 Load spectrum – train boogie

By accelerometers mounted on the slabs, the dynamic behaviour of the isolated system was evaluated in terms of first natural frequency and related damping, as described in Fig. 15.

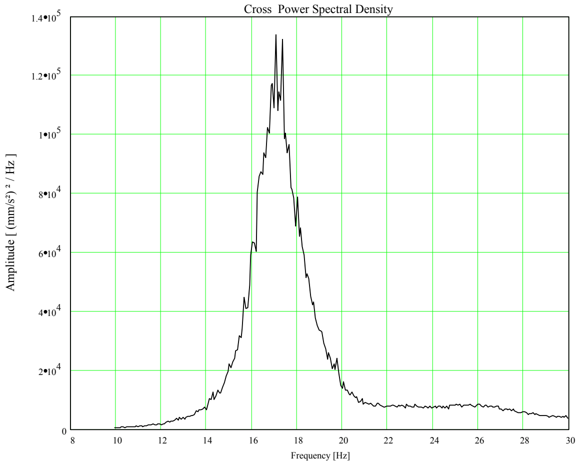

Fig. 15 First natural frequency

Adding the effects due to the different boogies of the train, vibrations levels and groundborne noise expected on the surrounding buildings were evaluated (Fig. 16 shows an example of expected velocity spectra).

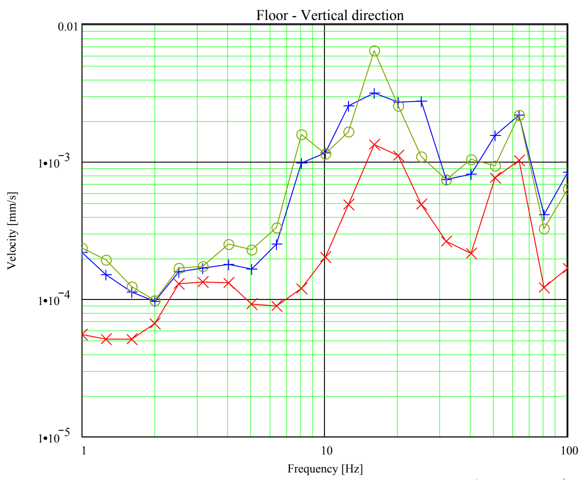

Fig. 16 expected velocity spectra on buildings

6 CONCLUSIONS

A numerical experimental combined approach to forecast groundborne vibrations and noise due to trains in underground lines has been presented.
The base notions of the proposed approach have been described, and the experimental and numerical phases have been illustrated making also reference to operational aspects.
The method can support the design of new isolated track systems, as well as can be applied to check and validate short sections of trial track systems before laying the track on the entire railway line.
The described approach enables to achieve good quality results. It represents an effective tools to contain construction costs allowing to use isolated track systems only where is strictly necessary, addressing their design to the right performances.

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