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Assessment of vibrations and structural noise at environmental impact studies: Current practices in Portugal and aspects to be improved for railway traffic in tunnels

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ABSTRACT

Currently there is no consensus for the assessment of the human response to indoor vibrations. Also, the methodology used by several countries is different, as can be seen from the publication and use of different normative documents. This paper presents a proposal for the evaluation of railway projects to be used in Portugal, through the calculation of transfer functions and their corresponding validation when the line begins operating. For this purpose, an eligibility criterion for vibrations and structural noise inside the buildings is presented. Additionally, this paper presents a proposal for the assessment of vibration mitigation measures.

Keywords: railway vibrations, vibration, structural noise

1. INTRODUCTION

With the improvement of the quality of the building, specifically its sound insulation, other aspects began to have a greater importance in the definition of the comfort within the dwellings. In urban areas, the effects of vibrations due to rail traffic have been of particular importance, for some years now. Effectively buildings occupants can directly perceive vibrations as mechanical oscillations (for frequencies between 1-80 Hz), or indirectly as re-radiated noise (in the frequency range 16-250 Hz). When the rail traffic is located in a tunnel, as is the case with the metro lines, the re-radiated noise can be particularly sensitive in houses with good sound insulation.

There is currently no consensus for the assessment of the human response to indoor vibrations, since the methodology used in several countries is very varied, as it can be seen from the national's standards published. Likewise, there is also no consensus on the single most appropriate descriptor for the assessment of vibration exposure, where RMS values vibration velocity, maximum vibration values and/or vibration dose values can be used (ELIAS and VILLOT, 2011).

The human response to vibrations in buildings varies from simple perception to a reaction of discomfort experienced by the individual in the presence of the vibratory stimulus (annoyance), which can lead to a deterioration of the quality of life and on the health of the occupants of buildings. Table 1 presents a possible relationship between amplitude of vibration and induced perception. Human response to vibration is very complex and, in many circumstances, the induced annoyance is not directly explained by the intensity and spectral content of the measured vibrations (ISO, 2003b). This response induced by vibratory events inside buildings is difficult to quantify, since it differs from individual to individual, depending on factors such as age, gender, health status, activity developed during its occurrence, and time exposure and duration of the vibratory phenomenon (ELIAS and VILLOT, 2011). In addition, human sensitivity to vibration levels varies according to the

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characteristics of the vibratory phenomenon, depending on its frequency, direction and amplitude content. For example, ISO 2631-1 (IPQ, 2007) suggests the values in Table 2 as indicative of the sensation of discomfort relative to vibration acceleration amplitudes.

Table 1 – Amplitude vs vibration (adapted from de ELIAS e VILLOT, 2011)

RMS value of the weighted acceleration (m/s^2)	Perceived perception
< 0,01	Not detectable
0,015	Threshold of perception
0,02	Rarely noticeable
0,08	Easily noticeable
0,315	Strongly perceptible
> 0,315	Extremely noticeable

Table 2 – Amplitudes of vibration and reactions caused by vibrations (adapted from IPQ, 2007)

RMS value of the weighted acceleration (m/s^2)	Human Sensation
< 0,315	not uncomfortable
0,315 - 0,63	little discomfort
0,5 - 1	reasonably uncomfortable
0,8 - 1,6	uncomfortable
1,25- 2,5	very uncomfortable
> 2	extremely uncomfortable

Another important aspect in the human response to vibration is related to the position in which the individual when he perceives the vibratory movement. However, and despite the difficulties mentioned above, ISO 2631-1 provides criteria for the evaluation of vibration taking into account the location of the individual. Also, in many circumstances, the induced annoyance is not directly explained by the amplitude and spectral content of the vibrations measured (ISO 2631-2), but by factors that are not directly related to exposure to vibrations, such as: i) sensitivity to vibrations ; ii) fear that the source of vibration causes damage in the housing; iii) understanding of the utility of the source; and, iv) future expectations regarding vibration levels (factors associated with attitudes). Likewise, factors associated with location (urban or rural area), visibility of the source, number of hours spent inside the dwelling, and socio-demographic factors, such as age, also contribute to this explanation.

2. METHODOLOGY FOR PREDICTION OF VIBRATION LEVELS FROM RAILWAY LINES IN TUNNELS

2.1 Introduction

Detailed vibration predictions are usually performed during the final design phase of a project and when there are sufficient reasons to suspect adverse impact relative to the vibration descriptor. Effectively, it is considerably complex to develop detailed predictions of vibration propagation, using numerical methods, and is currently still a field of research. In this context, the International

Organization for Standardization published the standard ISO 14837-1 (2015), which establishes a general guide for the development of predictive models for vibrations and structural noise induced by rail traffic, having guidance in the steps of calibration, validation and verification of its implementation.

This standard includes a listing of the parameters to be considered for each step, as well as a checklist for the different modelling methods that can be used. In the case of environmental impact assessment, the standard provides the use of parametric models based on numerical analysis methods (EMF, FDM, BEM or hybrid), empirical methods, using extrapolation of measurement data, or the use of semiempirical methods, which are a combination of the previously referenced models. An example of such an operation would be the use of a numerical model for the characterization of the railway emission and corresponding tunnel response, combined with the use of empirical methods for the estimation of vibration propagation from the tunnel to the nearest buildings, by using transfer functions.

Given the difficulty of theoretical modelling of the phenomenology associated with the propagation of vibrations from the source to the receiver, and the uncertainty and variability of the characteristics of the materials and the constructive solutions, the methodological proposal presented is based on the use of an experimental determination of transfer functions.

2.2 Transfer functions calculation

On the basis of the map of urban network and the railway tunnel, plant and cuts, a visual inspection should be carried out to select the nearby buildings located on the tunnel and the points next to the respective foundations, where measurements will be taken at the level of the soil / surface. These points shall be kept vertical as far as possible from other correspondents, located on the tunnel wall, at the level of the railway, and the characteristics of the buildings must be written down (see illustration of figure 1).

Buildings located at distances less than 10 m from the axis of the future railway line must necessarily be chosen. When the soil type has characteristics of a medium soil, this limit value may be lower, if it is in the presence of loose soils, and extended if the soils are hard. Distances to the axis of the railway line between 10 and 30 m advise the choice of the building; particularly if it has reinforced concrete structure, the limit value of 30 m can be extended to 50 m in the case of hard soils. For distances greater than 50 m, there are usually no vibration problems.

The points selected in the tunnel (at track level) at the surface and on the upper floors of the building will constitute a set, in which the index J refers to the building, u to the tunnel, s to the surface, and kj to the selected floors. At this stage the tunnel must be already excavated, and preferably with the superstructure already concreted.

$$P_J = \left\{P_{Ju}, P_{Js}, P_{Jk_j}\right\} \tag{1}$$

For the calculation of vibration transmission from the tunnel to buildings, the line of points PJ (in each section considered for each chosen building) shall be set by placing accelerometers at the points selected on the tunnel wall (at track level), surface (in a floor solidly connected to the structure at the level of the threshold , outside or in the atrium of the building, next to a pillar), and on the upper floors (preferably half a span of the selected rooms).

Then, using a hydraulic drill hammer (see Figure 1), vertical vibrations are induced on the tunnel floor (by placing a small slab between the hammer and the ground, or tunnel floor) and the sensors are acquired the signals at the points PJ.

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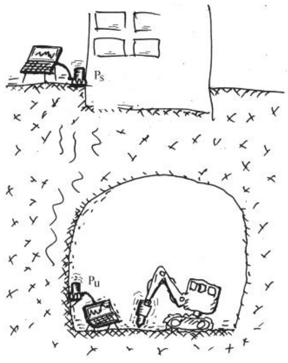

Figure 1 - Schematic determination of the vibration transfer from the tunnel to the surface

For each set of points, in the tunnel and at the surface and on the upper floors along the track development, and in the chosen buildings, the RMS values of the vertical velocity of vibration, $V_{S(fi)}$, $V_{u(fi)}$ e $V_{pK_{(fi)}}$ (S on the surface, u in the tunnel, and pk on the higher floors), and for each set of points P_J the transfer functions between the tunnel and the surface, and between the surface and the higher floors:

$$T_{u\to S_{(fi)}} = V_{S(fi)}/V_{u(fi)} \tag{2}$$

and

$$T_{u\to k_{j(fi)}} = V_{K_{j(fi)}}/V_{u(fi)} \dots\dots\dots j = 1, \dots \tag{3}$$

or

$$T_{u\to S_{(fi)}} = V_{S(fi)} - V_{u(fi)} \qquad \text{dBv} \tag{2a}$$

and

$$T_{u\to k_{j(fi)}} = V_{K_{j(fi)}} - \ V_{u(fi)} \dots\dots\dots j = 1, \dots \qquad \text{dBv} \tag{3a}$$

Then, the vibration generated by similar trains on similar railway lines, on the tunnel wall or at the station, at the level of the track, vuc(t), is estimated or measured (preferred option), and the respective spectrum, Vuc (fi) is calculated. The estimate must be based on credible measurements taken on lines with similar characteristics «, and correctly transposed to the tunnel wall at the track level.

The predictable surface vibration (buildings, ground floor), $\mathrm{Vsc}_{(t)}$ and on the various floors $\mathrm{V}_{\mathrm{k}_{\mathrm{jc(t)}}}$ is:

$$\mathrm{Vsc}_{(\mathrm{fi})} = \mathrm{T}_{\mathrm{u}\to\mathrm{s}_{(\mathrm{fi})}} . \mathrm{V}_{\mathrm{uC(fi)}} \tag{4}$$

and

$$\mathrm{V}_{\mathrm{k}_{\mathrm{j(fi)}}} = \mathrm{T}_{\mathrm{u}\to\mathrm{k}_{\mathrm{j(fi)}}} . \mathrm{V}_{\mathrm{uC(fi)}} \dots \mathrm{j} = 1, \dots \qquad \text{mm/s} \tag{5}$$

or

$$\mathrm{Vsc}_{(\mathrm{fi})} = \mathrm{T}_{\mathrm{u}\to\mathrm{s}_{(\mathrm{fi})}} + \mathrm{V}_{\mathrm{uC(fi)}} \tag{4a}$$

and

$$\mathrm{V}_{\mathrm{k}_{\mathrm{jc(fi)}}} = \mathrm{T}_{\mathrm{u}\to\mathrm{k}_{\mathrm{j(fi)}}} + \mathrm{V}_{\mathrm{uC(fi)}} \dots \mathrm{j} = 1, \dots \qquad \text{dBv} \tag{5a}$$

If the measurements inside the buildings have been carried out on the common parts (atrium floors), the addition of +6 dBv is applied. An analogous procedure should also be used to account for future wear and degradation of wheel and rail surfaces (+10 dBv increase in all frequency bands).

The final spectra $\mathrm{V}_{\mathrm{k}_{\mathrm{jc(fi)}}}$ and $\mathrm{Vsc}_{(\mathrm{fi})}$ and the final global values obtained for the velocity v, are compared with the allowable limits. The global values are estimated from the spectra, according to the expression (6).

$$\mathrm{V}_{\mathrm{RMS}} = (\textstyle\sum_{\mathrm{i}} {\mathrm{V}_{\mathrm{RMS}_{\mathrm{i}}}}^{2})^{\frac{1}{2}} \tag{6}$$

This methodology is based on the use of the measurement procedures describe in ISO/TS 14837-31: 2017, in the frequency range of 1 to 80 Hz for vibration evaluation, and 16 Hz and 250 Hz for structural noise.

For each case there are 4 stages, namely: selection of buildings and corresponding measurement points; calculation of transfer functions between track and buildings; estimation of the vibration generated by trains pass by in the superstructure and buildings, and estimation of structural noise.

3.2.1 Estimation of the structural noise $Leq_{kjc}(t)$

Sound levels within buildings close to railways are often a combination of airborne noise and noise induced by the vibration transmitted by the building foundations (structural noise), and often arising from the same source. The vibrations induced by the railway pass by compositions are usually measured with accelerometers placed in the center of the compartment floors, mainly measuring the vertical component, while the measurement of structural noise is performed by microphones also located in the center of the compartment, in the range of audible frequencies, in this case between 16-250 Hz (ISO 14837-1, 2006).

Simultaneous measurements of noise and vibration have shown that the theoretical expression (p, sound pressure, ρ specific mass of air, c speed of propagation of sound waves in air, v velocity of vibration of an infinite plate that will generate sound waves), allow results similar with measurements (the effects of reflections and absorption in a division seem to be compensated).

$$p = \rho . c . v \tag{7}$$

Considering ρ = 1.205 kg / m3 and c = 343 m / s, the previous expression takes the following form, (velocity expressed in mm/s):

$$Lp = 20\log_{10} v + 146dB \tag{8}$$

The previous expression allows an approximation to the estimate of the structural noise level, from the measurement (or prediction) of the vibration velocity values in the center of the building floors. If it is of interest, the A-weighted sound level value can be obtained from the values of the sound pressure level for the octave third bands between 16 Hz and 250 Hz, using the expression:

$$Leq_A = 10.\log_{10}(\textstyle\sum_j 10^{0,1(Lpj+Cj)} \tag{9}$$

Where the coefficients Cj refer to the A weighted values.

In the European project Rivas a simplified expression based on the application of the statistical energy analysis method was obtained for the prediction of structural noise levels in the center of a compartment by measuring the vibration velocity level in that compartment and which for concrete slabs, takes the form:

$$Lp_{av} \approx L_{v\ \ pav} + 4 \qquad \text{v in m/s re. } 2x10^{-8} \tag{10}$$

This expression is valid for frequencies equal to or greater than 40-50 Hz and is also indicated in the ISO/TS 14837-31.

3.2.2 Estimation of insulation to propagation of vibrations

Where the expected values are higher than the admissible values, appropriate insulation must be provided to reduce the propagation of vibrations, either by introduction mitigation measures at vehicles and the track, under ballast mats, floating slab tracks, for example (see reference 3) with a sufficient insulation proprieties ΔVisol (fi) which allows to reduce the value of the spectra Vkjc (fi) and Vsc (fi) to below the admissible values.

In the case ballast tracks, the mass and elastic proprieties of the ballast and underlying materials shall provide the necessary insulation. It should be noted that the insulation, or vibration propagation cut, depends on the frequency. Its calculation must be done by modeling the whole source system of vibrations that will propagate in the tunnel, taking into account the masses of the compositions (carriages and bogies with wheels), with and without passengers, the track (rails and sleepers), and the underlying slab, as well as the elastic and damping characteristics of the carriage suspensions, under-sleeper pads, and the underlying mat. In a simplified way, the vibration source system can be modeled as a linear mass-spring system, or mass-spring-damper, with a degree of freedom, considering the total mass as the sum of the masses referred above, and the stiffness of the supporting. Indications for the developing, calibrating and validating the models used for the establishment of mitigation measures are published in Annex C in ISO 14837-1 (2015).

Thus the final prediction, for the isolated system, will have the form (x = s ou kj):

$$V_{XC_{isol(fi)}} = T_{XC_{(fi)}} + \Delta V_{isol(fi)} \tag{11}$$

3. ELIGIBILITY CRITERIA

Traditionally, the vibration velocity was used to establish limit values, taking into account that human sensitivity to vibration is constant between 8 and 80 Hz. In fact, ISO 2631-2 (1989 version) establish values for vibrations exposure in buildings from the determination of the frequency-weighted acceleration values. This standard presented the base curves of acceleration and velocity rms values for the different directions, which are used to establish the vibration target values, by using appropriate multiplicative factors. However, in the current version of this standard, there is no indication of limit values.

For vibration perception inside the buildings, in terms of the rms value of vibration velocity, the Portuguese criteria uses the reference values indicated in Table 3. These values are valid for the vertical or horizontal component of the velocity, if the latter is the more significant.

Regarding the perception of vibrations, the lower value presented (0,11 mm / s) is considered as perception threshold, however, values of rms vibration velocity of less than 0,28 mm / s, are still allowable for daytime and short duration vibrations of. This simplified approach, must be applied in terms of order of magnitude, being the duration of vibration an important parameter.

Table 3 – Portuguese criteria for the perception of the continuous vibration inside buildings

vrms (mm/s)	Sensation
vef < 0,11	Nula
0,11 <vef< 0,28	Perceivable, supportable for short duration
0,28 <vef< 1,10	Discernible, annoy, can affect labor conditions
vef> 1,10	Very discernible, very annoying, work conditions reduced

For the continuous or intermittent vibrations inside the buildings, the Portuguese criteria use the following values:

- RMS vibration velocity less than 0.28 mm / s;
- Application of the base curve of ISO 2831-2 (1989 version), with multiplicative factors corresponding to intermittent vibrations for residential buildings. In this case, the spectrum of rms of vibration velocity values for third octave bands shall be less than 0,14 mm / s for central frequencies between 8 and 80 Hz (night period), limit value that increases to 0,4 mm / s at 2 Hz, and 0,8 mm / s at 1 Hz. For the daytime period, the rms velocity value vrms <3 mm / s, for the central frequency bands between 8 and 80 Hz, and increases for 8,8 mm / s for 2 Hz, and 17,2 mm / s for 1 Hz.

For the purposes of predicting structural noise inside the exposed dwellings, taking into account the specificity of the situation under consideration (noise and vibrations induced by rail traffic), the following criteria was proposed.

In accordance with the General Noise Regulation (Decree-Law no. 9/2007, of 17 January), it is considered acceptable that there are not noise annoyance assessments if the equivalent continuous sound level, LAeq, is less than or equal to 27 dB (A), for each reference period. This consideration is made by analogy, taking into account the comfort within sleeping or living compartments, in accordance with the legislation referred above, since the annoyance criteria is not applicable to transportation noise. Assuming that trains pass by can be associated with noise event emergence of 5 dB (A), it was establish a limit value of 22 dB (A), calculated in the relevant frequency range beginning in the 16 Hz band, for noise inside the compartments referred to.

Therefore, with the objective of mitigation measures implementation, the target value of 22 dB (A) inside living and sleeping rooms should be accomplished. Starting from the field of vibrations established in the floor slab in contact with the building foundations, and making use of the vibrations propagation by marginal transmission to the rigid flat elements connected to the slab, as well as to the infinite plate radiation process, the rms value of the vibration velocity, bands between 16 Hz and 200 Hz, the following values should be observe (ALONSO et al., 2018):

- be less than 0,02 mm/s, in the most unfavorable situations where the vibrational reduction index of the connection (Kij) are very low and transmission between the elements is high. This case occurs when the constructive solutions are very heavy and most of the connections considerer are rigid in corner;
- be in the range of 0.02-0.025 mm/s, in the intermediate situations where the vibrational reduction index of the connection (Kij) have medium values. This case corresponds to the common Portuguese buildings;
- be in the range 0,25-0,03 mm/s, in the most favorable situations where where the vibrational reduction index of the connection (Kij) hare very hight,, and the transmission between the elements is very low. This case occurs when the constructive solutions for the walls are very lightened.

4. ASSESSEMENT OF VIBRATION MITIGATION MEASURES

For the assessment of vibration of mitigation measures, measurements can be made at the emission, transmission or reception sites. In this case it is preferable to select the emission sites because the number of influencing parameters is smaller and the signal-to-noise ratio is higher. Some factors may help to further reduce the number of influence parameters, especially if both sections are adjacent and if the same trains are used. For the insertion loss determination based on the difference of the vibration levels with and without the implemented mitigation measure, during the railway pass by compositions, the vibration velocity level is measured along the rail, and two protocols can be used (STIEBEL et al., 2012): Comparison of vibration velocity levels obtained in adjacent sections with and without measurement; or the comparison of vibration velocity levels before and after the installation of a measurement. To reduce measurement uncertainties it is highly recommended to use both procedures in parallel (combined procedure). In this case, the test and reference section can be considered as comparable if vibration levels are identical before the measurement installation.

Equally important is the dynamic characterization of the railway track and all the subsystems, after installation, by means of an experimental approach, in order to be able to better identify the natural frequencies of each subsystem, as well of the whole complete system. This procedure enables to verify whether the natural frequencies identified coincide or not it the natural modes of vibration of the compartmental elements of the building being evaluated.

5. CONCLUSIONS

Nowadays here are several descriptors for the assessment of vibration exposure, distinguishing between the descriptors based on energy means (rms values and dose of vibration), and those based on the maximum value. So far, it has not been shown which type of descriptor is preferred. In this communication, a methodology is presented for vibration prediction inside the dwellings, using experimental determination of transfer functions, alternatively, or in combination with the use of numerical simulation models. It is expected that the application of the methodology described will contribute to the harmonization of the assessments of the environmental impact projects due to rail traffic, especially those dedicated to subway lines.

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