Criteria for vibration levels from Metro Lines to comply with acceptable noise inside residential buildings

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Abstract

Amongst all types of transportation means, the Metro generates high levels of vibration, which are transmitted to the structural elements of nearby buildings. The related energy reaches the foundations and the ground floor of buildings in the form of waves that excite floors and walls. By vibrating all the partitions of a room, a corresponding radiated noise field is established, thus disturbing the residents. To our knowledge, from the legislative point of view, there are no published legal limits for human comfort and criteria related to vibrations generated by railway traffic inside buildings.

This work is carried out in order to establish criteria to prevent or reduce the harmful effects and discomfort of the exposure to noise due to vibration inside housing. In this study, it is mainly intended to deepen the determination of criteria to be followed in the consideration of vibrations at low frequencies propagated through the foundations and structure of residential buildings. In situ measurements and calculation methods have been carried out taking into consideration different cases in order to analyse the transmission of those generated vibrations, to the different constructive elements linked to the floors, and in this way to be able to determine the overall noise established into the room.

Keywords: structural noise, flanking transmissions, low frequency sound, vibrations.

1. INTRODUCTION

In the field of investigation on noise evaluation and management, noise inside buildings is an important subject of study which should properly be taken into consideration. In cities, where Metro integrates their transportation network, residents have reported their discomfort because of the emitted noise due to vibrations generated by the traffic of Metro Lines. The vibrating energy produced in the interaction between the wheels and the rails are transmitted to the track platform, exciting the tunnel being then propagated through the surrounding soil to the foundations of nearby houses. These vibrations produce resonance phenomena [1] that generates an unwanted sound in the building rooms, known as radiated structural noise. The response of the building to this excitation depends on various aspects such as the natural frequencies of the whole structure, floors and walls, and of their internal damping. If suitable measures are not taken, the vibrations can reach unacceptable levels for the buildings inhabitants, which can lead to perceptible body vibration and noise levels in habitable rooms above the established limits.

Lower vibration amplitudes are usually associated with the concept of perception, that is to say, noticing events by users; however, the repetition of short events can lead to discomfort. Therefore, the result of the vibratory phenomenon can be extended from the induced discomfort for the building occupants, which should be studied in order to establish a common approach aimed at avoiding, preventing or reducing, as a priority, the harmful effects and nuisances of exposure to noise [1]. Nevertheless, it should be noted that the evaluation of the discomfort is difficult to quantify, since it is verified that it has an important subjective connotation, as well as a variability that depends on factors such as age, gender, health status, exposure time and duration of the vibrations [2].

From the legislative point of view, there is no general consensus on the admissible levels of vibrations in partitions (mainly floors), which are usually expressed in r.m.s. (sometimes peak) vibration velocity. However, due to an increase in public sensitivity there are relevant studies in academic literature relating to the human response to vibration, since this topic is becoming an important issue. Waddington et al. developed researches both focused on deriving exposure response relationships for annoyance due to vibration, as well as on determining mechanisms that explain the differences in user's responses to vibrations [2,3]. Klæboe et al. also studied exposure-effect relationships of vibrations generated by rail traffic in dwellings [4]. Moreover, it should be noted other studies that research on vibrations problems in structures [5,6,7]. Taking these works into consideration, it could be confirmed that the problems are generally confined at low frequencies, to the range between [8] 8 or less and 160 Hz. In relation to this and to our knowledge, there are no published legal limits of human comfort criteria related to noise generated by vibrations generated by railway traffic inside buildings. Consequently, due to the lack of national regulation on the subject, it is necessary to carry out an investigation capable of deepening the determination of criteria to be followed in the assessment of the discomfort induced by vibrations propagated by Metro Lines through the structure of dwellings.

As a starting point for the development of this work, the origin of the study has been based on the limits established by the Portuguese competent body - National Laboratory for Civil Engineering (LNEC) -, the works that gather the criteria that the scientific community accepts [9], the relevant mentioned

[1] Not always a resonance, but resonances increase the level of vibration.

bibliography [2-7] as well as the applicable international regulations [10,11,12]. To help defining those limits, in situ measurements were performed in order to determine the vibrational reduction index of various types of joints and to analyse the difference of vibration velocity level between the different constructive elements, essentially connected to the floors. Thus, calculation methods have been carried out considering different cases (rigid and non-rigid L-junctions and T-junctions) in order to confirm the values obtained from experimental technique and, in this way, to be able to determine both the total noise generated in the room and the limit value of the vibration velocity.

Based on the aforementioned problems, the purpose of this study arises where the concept of vibrations could be related to the emission of structural noise. The main aim of this work is to define limits of vibration velocity that should be generated in the base floor (first structural element), taking into consideration all the radiating elements (partitions) by flanking transmissions, thus increasing the existing noise field in the room. This limitation will be determined in order not to exceed the maximum noise established by national regulations, or defined by well-being criteria. Relevant conclusions from this work were extracted, which could help deepen the determination of criteria for noise at low frequencies inside residential buildings due to vibrations propagated through the foundations of residential buildings.

2. CURRENT REGULATIONS AND CRITERIA

Regarding structural noise, it has been used in Portugal a criterion that generally assures the non-emission by the vibrating floor of noise greater than 40 dB (A). This limit is translated into the maximum level of the vibration component of 0,03 mm/s above the octave band of 63 Hz.

Concerning international regulations, a bibliographical research was also carried out on the assessment of structural noise generated by the circulation of rail traffic. In USA, the applicable criteria depend on the quantification of the number of daily events related to the same source of vibration and with the type of buildings under evaluation. The limits for vibration inside residential buildings are presented as criteria in terms of the effective value of the vibration velocity originated essentially by rail traffic [10]. Another type of approach is the method from the Netherlands, whose principle is to verify if low frequency noise is audible or not, and thus identify possible problems. A Swiss directive [13], based on standard DIN 4150-2 [14], determined that the limit values assessment indicator, within residences, is the equivalent continuous sound level, which must not exceed 35 dB(A) during the day and 25 dB(A) during the night period. However, care must be taken with the A-weighted values of sound pressure level since some researches show how this parameter sometimes underestimates the prediction of nuisance, using a in situ based measurement technique [15,16].

On the other hand, with regard to the criteria of human comfort inside buildings related to the evaluation of human exposure to whole-body vibration, it could be highlighted the ISO 2631-1 [17], which has served as a basis to assess the levels of vibration in humans for a wide spectrum of situations; and the ISO 2631-2 [3] that determines the methodology for the measurement of suitable criteria for the evaluation of the discomfort induced by perceptible radiated noise emitted by vibrations in buildings.

In addition, it should be noted that the problems associated to the vibration, as well as the corresponding evaluation of its perception, are both a potential of discomfort that can be induced by the vibratory phenomenon inside the buildings. An audible noise is considered when the level, during the passage of the Metro, is significantly higher than the undisturbed environmental noise, +3 dBA. In this regard, the concept of human discomfort, when the noise is emitted, can be traduced in a penalty value of the equivalent sound level (L_{eq}(A)) that should be considered in order not to be exceeded. Therefore, another criterion to evaluate the discomfort of the noise generated by the vibration will be to establish a limit value of +5 dB penalty for the intermittent characteristic of the noise generated by the railway traffic. Therefore, taking into consideration the value determined by the municipal noise regulation [18], since the equivalent sound level L_{eq}(A) of 27 dB(A) should not be exceeded in a room during the night period, the criteria for assessing the discomfort of the noise generated by the vibration will be to establish as limit value 22 dB(A), since a penalty of 5 dB(A) was considered due to the repetition of the phenomena (circulation of Metro).

3. METHODOLOGY

Calculation methods have been carried out taking into consideration different cases in order to analyse the flanking vibrations transmitted to walls and partitions linked to the floors, and in this way to be able to determine the limit of vibration velocity that should be propagated in the floor. Firstly, with the aim of studying a real example, vibrations generated in the floor of a room will be determined from experimental technique. Secondly, a procedure will be followed based on the calculations of parameters determined in the International Standard in order to obtain the indirect transmission between structural elements. In this regard, this process will allow to determine both the difference in velocity level averaged and the index of vibrational reduction of the connections. Only L-junctions and T-junctions will be considered in the study as representatives of the most unfavourable cases, since vibrations in X-junctions, located in upper floors, can be determined as second order vibrations, thus the effect is not significant. Finally, once all the values of vibration have been obtained in floor and walls, it will be determined the total sound emitted in the room, which will allow the adjustment of the effective value of vibration velocity in order not to exceed the noise maximum value established by regulations, or pre-defined as acceptable. Figure 1 shows a scheme of propagations paths of vibrations that are transmitted between constructive elements.

Experimental technique based on the in situ measurement of the velocity level was conducted to analyse the vibrational reduction index of joints (floor-wall). In order to develop the study, three spaces were selected whose constructive elements can be classified into different types, which could be associated to normal building joints. The difference in velocity level that is transmitted between building elements were also investigated to confirm the reliability of calculation method procedure that was followed. Tests were carried out using the equipment of the National Laboratory of Civil Engineering (LNEC), in Lisbon (Portugal).

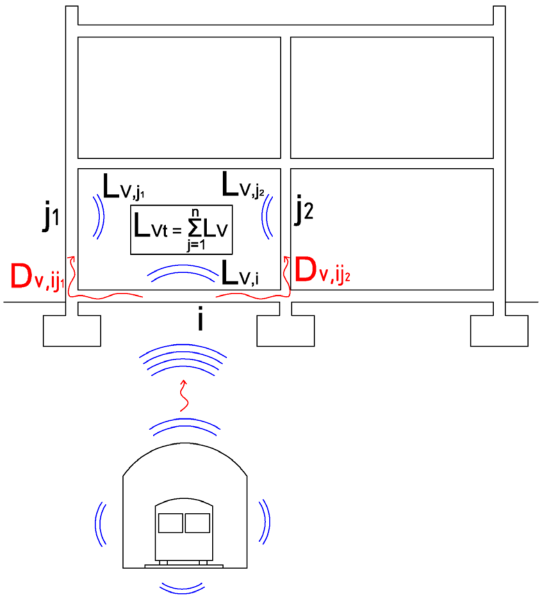

Figure 1. Scheme of propagation paths of vibrations. Lv = acoustic sound level generated by vibration of the surface - floor (i) or walls (j). Dv, ij = difference in velocity level of vibration, averaged in ij direction.

3.1 Noise due to vibrations

As previously indicated, the vibration of the floor of a dwelling can emit an audible noise, which can be harmful to the resident in terms of annoyance. Characteristic of emitted noise depends on different factors such as the composition of the structural elements and the type of joint between them.

It should be noted that, sometimes, the order of magnitude of the vibrations originated inside dwellings (equipment, walking, running or domestic activities) can be higher [19] than the magnitude of the vibration generated by external sources of vibration, such as railway traffic. However, it is necessary to analyse the result of external vibrations since they can generate discomfort to the users. The structural vibration in buildings generated by this type of excitation could be determined as intermittent, that is, a sequence of incidental vibrations of short duration, separated by intervals of time in which vibrations of much lower levels occur.

For the characterization of the vibratory phenomenon as an oscillatory movement of a surface, two descriptive quantities are at least necessary in the spectrum: the amplitude of the movement, characterized by velocity or sometimes acceleration, and the content in frequency of the vibration, distributed in third octave bands. There are various metrics that can be used to assess vibration: such as Root Mean Square (r.m.s.), which must be used in all calculations regarding power or energy in a waveform; Root Mean Quad (r.m.q.), whose averaged weight is more appropriate to short periods at high magnitude; Vibration Dose Value (VDV), which should be used when assessing a cumulative measurement of the vibration level.

In this work, effect of vibrations on comfort within dwellings will be based on the effective values of the velocity (r.m.s time averaged, and r.m.s frequency spectrum) during a representative period. However, for situations in which the vibration signal can be significantly influenced by peak values, the use of the effective r.m.s. value may underestimate the induced discomfort.

On site measurements were carried out by members of the LNEC (Lisbon) in order to determine the vibration velocity in a floor slab of a residence whose users complained due to the discomfort of the noise generated by vibrations during the night-time. For this purpose, two measurement sites were selected. The first site was located in the tunnel of the meter, in the vertical closest to the residence where the discomfort is perceived. Two accelerometers were placed in this zone: one of them in the railway track and the other in the wall of the tunnel. The second measurement site selected was the interior of the residence identified above, and measurements were taken at ground level in the living room and on the first floor in a bedroom. In this work, only the measurements carried out in the residence will be evaluated, since this research has the purpose of determining the maximum vibration velocity that should be generated in the floor of the dwelling to not exceed regulation limits.

In this regard, measurements were carried out taking into account the points and rooms where the discomfort reported and felt by the occupants were greater. One of the measurement equipment was the accelerometer IMI 626A04, serial number 6061, which made continuous measurements of vibrations. The purpose of use of this accelerometer was focused on the confirmation of the results obtained by the rest of the equipment. The second measuring system, model Pulse 3560-D, Bruel and Kjaer brand and serial number 2487454, recorded the values of amplitude of acceleration of the vibration of the slab of the living room, according to the directions vertical, perpendicular and parallel to the development of the layout of the railway. In order to perform the measurements, three accelerometers PCB model 393A03, serial numbers 9287, 9288 and 9289 were used, which were screwed to a stainless steel hub. This steel hub was fixed by means of polymerized glue to the central area of the living room floor. Figure 2 shows the installation of the measurement systems.

Figure 2. Installation of the measurement systems on the floor of the living room (left picture) and the bedroom on the 1st floor (picture on the right) [14].

3.2 Indirect transmission between elements

3.2.1. Calculation methods

The indirect (flanking) transmission of vibrations to the different structural elements, such as walls, should be taken into account, since they may increase the level of noise generated by the vibration of the proper floor.

In the interior walls (partitions), reflection, damping or absorption of the sound waves are also produced, depending on the type of constructive solution as well as the type of joint between structural elements (floor - wall).

In order to calculate how much vibration is transmitted from the floor to other connected structural elements, such as walls, it is necessary to determine which is the difference of vibration between both elements, taking into account the type of junction between them. The ISO10848-1 standard [20] presents the theoretical Eq (1), which allows to estimate approximately the difference of vibration velocity level averaged in ij direction ($D_{v,ij}$), obtained from the vibrational reduction index (K_{ij}).

$$D_{v,ij,situ} = K_{ij} - \frac{l_{ij}}{\sqrt{a_{i,situ} a_{j,situ}}} \; ; \quad D_{v,ij,situ} > 0 \text{ dB} \qquad (1)$$

where l_{ij} is the common coupling length between the element i (floor) and the element j (wall or partition), and $a_{i,situ}$, $a_{j,situ}$ are the equivalent absorption lengths in the real situation, obtained from the surface of the element as well as from the structural reverberation time. However, taking into account the construction elements of this study, the equivalent absorption length is considered numerically equal to the surface of the element divided by the reference length, said being equal to 1 m.

The vibrational reduction index of the connections (K_{ij}) is defined as an inalterable

Table 1. Constructive solutions and types of coupling between elements/partitions for the case studies considered.

CASE	COMPOSITION					TYPE OF CONECTION			
	i	j1	j2	j3	j4	ij1	ij2	ij3	ij4
1	CS 20	BF 24	BW 14	BW 14	BW 14	LJ	TJ	TJ	TJ
2	CS 20	BW 14	BW 14	BW 14	BW 14	TJ	TJ	TJ	TJ
3	CS 14	BW 14	BW 14	BW 14	BW 14	LJ	TJ	TJ	TJ
4	CS 14	BW 14	BW 14	BW 14	BW 14	TJ	TJ	TJ	TJ
5	CS 14	BW 24	BW 14	BW 14	BW 14	LJ	TJ	TJ	TJ
6	CS 20	CPW 12	CPW 12	CPW 12	CPW 12	LJ	TJ	TJ	TJ
7	CS 20	CPW 12	CPW 12	CPW 12	CPW 12	TJ	TJ	TJ	TJ
8	CS 14	CPW 12	CPW 12	CPW 12	CPW 12	L	TJ	TJ	TJ

Code: CS = concrete slab / BF = brick facade / BW = brick wall / CPW = cardboard-plaster wall / nº = thickness of the element (slab, wall or sheet) in cm / LJ = L- junction / TJ = T-junction

quantity to characterize a union between elements. It is based on considerations of power transmission as a simplification of the theory of statistical energy analysis (SEA). It should be noted that the main calculation hypothesis of this indicator is that the vibration fields in the elements are diffuse. In principle, this analysis implies that the basic assumption of the SEA is met. In this work, the error generated by the non-fulfilment of this hypothesis is assumed since a frequency range between 16 and 160 Hz is considered. K_{ij} has been calculated according to Annex E of the standard 12354-1 [21]. In order to calculate K_{ij}, a primary classification of the type of connections was established. The lower limit of the K_{ij} value should result in $D_{vij,situ}$ = 0 dB. For the usual types of unions considered, the K_{ij} value depends on the surface densities of the elements connected to the joint, denoted by m_1 and m_2. The relations for K_{ij} in the annex E of the mentioned standard are given as a function of the magnitude M, defined as Eq. (2):

$$M = log\frac{m'_i}{m'_j}\ ; \quad (2)$$

In relation to the rigid coupling between elements, in some cases compliance with inequality Eq.(3) has been proven, since it is essential for heavy elements. In this work an equal value of Dv_{ij} and K_{ij} was assumed for all the frequency bands considered.

$$D_{v,ij,situ} \geq 3 - 10\ log\frac{m_i f_{ci}}{m_j f_{cj}}\ \text{dB} \quad (3)$$

where f_{ci} and f_{cj} are the critical frequencies of the elements, determined by Eq.(4), being ν as the Poisson coefficient of material of the element, *E* is the modulus of elasticity of the material and *h* the thickness of the element.

$$f_c = \frac{c^2}{2\pi h}\sqrt{\frac{12\rho(1-\upsilon^2)}{E}}\ \text{Hz} \quad (4)$$

Then, a group of case studies have been established. The different constructive solutions have been classified as well as the different types of connections between elements/partitions (floor and wall). Table 1 shows the cases that have been considered.

3.2.2 *In situ* measurements

In order to verify the reliability of the calculation procedure that was followed and to confirm the correspondence of values obtained from calculation methods, in situ measurements were performed selecting various types of joints of constructive solutions (L-junctions and T-junctions) in different situations.

The procedure was based on the vibrational reduction index (K_{ij}) that was obtained between coupling elements, that is to say, joints between floor and walls. An excitement was generated by the impact of a harmer in the floor in the most unfavorable area located between two joists, in order to determine the average of the difference of vibration that is transmitted between both elements. Two Bruel & Kjaer 4383 accelerometers were located in each of the coupling surfaces and vibration velocity of the different constructive elements was acquired from the voltage values registered by an oscilloscope. Figure 3 shows the measurement set-up described.

The results obtained in the measurements were obtained by processing the signals acquired through the accelerometers. The obtained values were compared to the voltage values determined from the Fast Fourier Transform (FFT) by processing the signals acquired through the accelerometers. The conversion of voltage units to acceleration units was possible to determine thanks to the knowledge of sensitivity of the accelerometer (3,14ρC/ms^{-2}).

a) b) c)

Figure 3. Measurement set-up: a) LNEC Office; b) Dwelling; c) LNEC laboratory.

3.3 Sound pressure emitted

As mentioned in previous sections, an infinite vibrating plate emitted an audible noise, that is to say, sound pressure in the air due to the waves of sound overpressure. This pressure is related to the normal velocity of the plate (v). The acoustic noise level relative to the reference ($(p\ v)_o = 10^{-12}$ N m^{-1} s^{-1}) can be calculated by the following Eq. (5):

$$L_v = 20 * log_{10}(v) + 146\, dB \quad \text{dB} \quad (5)$$

If the effective value of vibration velocity v is decomposed into third-octave bands, each component v_i produces a L_v sound level Eq(6).

$$v^2 = \Sigma_i\, v_i^2 \quad \text{m/s} \quad (6)$$

The final sound level weighted A, L(A) in dB(A), could be calculated by Eq. (7), where C_i are the A weights for the various third-octave bands.

$$L\,(A) = 10 * log_{10}\left(\Sigma_i\, 10^{0,1\,(Lvi+Ci)}\right) \quad \text{dB(A)} \quad (7)$$

Finally, the value of maximum vibration velocity generated in the floor can be obtained since the parameter D_{vij} determined the difference in velocity level averaged in ij direction Eq. (8).

$$D_{v,ij} = L_{vi} - L_{vj} \rightarrow v_j = \frac{v_i}{10^{\frac{D_{vij}}{20}}} \quad \text{dBv} \quad (8)$$

4. RESULTS

4.1 Vibrational spectrums

As previously stated, the house under study was selected due to the users' complaints because of the noise generated by vibrations. The row house was located less than 200 m from the line. Measurements were taken at ground level in the living room and on the first floor in a bedroom. For the development of the calculation, six types of spectrum have been taken into consideration: four real vibrational spectrums whose values were obtained from measurements, a white noise spectrum and a pink noise spectrum.

4.1.1 Real vibrational spectrum based on measurements

Regarding the real vibrational spectrums, it should be noted that all of them were measured experimentally in a room of a building located in the vicinity of a Metro Line. Figure 4 shows two examples of spectrums for the amplitude of vibration velocity.

For the development of the procedure, it should be noted that a calculation factor has been applied to the measured velocity values in order to determine the effective velocity of vibration that should be considered so as not to exceed in the room the total sound pressure 22 dB (A). In addition, it is necessary to determine the coupling lengths (l_{ij}) between structural elements (floor and walls). Thus, a general room type has been considered whose dimensions are 4 x 3 x 3 m^3.

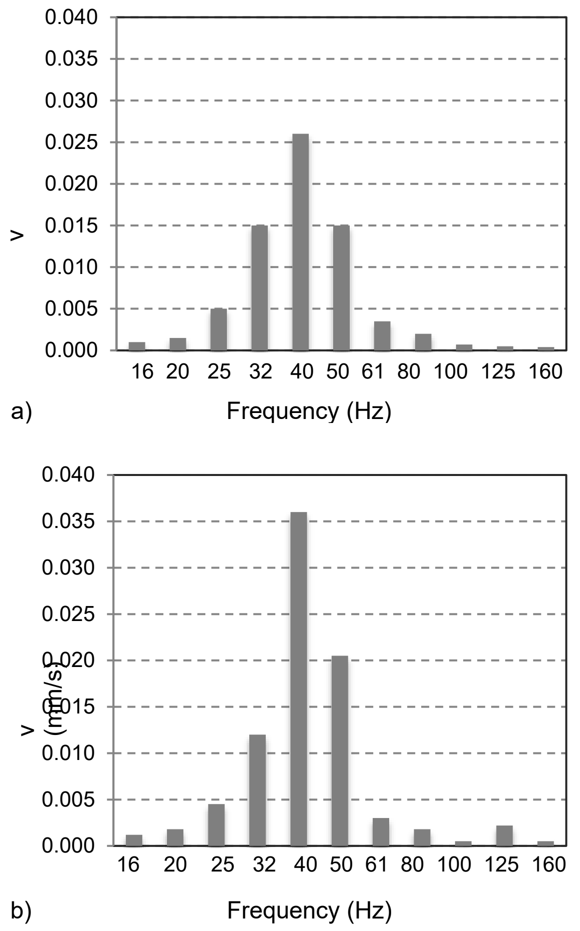

Figure 4. Real examples of vibrational spectrums (type 1 and type 3) in bands of octave thirds for the amplitude of vibration velocity measured in the floor slab of the room (effective value), according to the direction z, for the first passage of the Metro.

4.1.2 White and pink noise spectrum

In signal processing, white noise is a random signal having equal intensity at different frequencies, showing a constant power spectral density since the noise level increases +1 dB at each 1/3 frequency band. On the other hand, pink noise is a signal with a frequency spectrum where the power spectral density is inversely proportional to the frequency of the signal, so that each octave band carries an equal amount of noise energy. Figure 5 shows two examples of spectrums corresponding to white noise and pink noise.

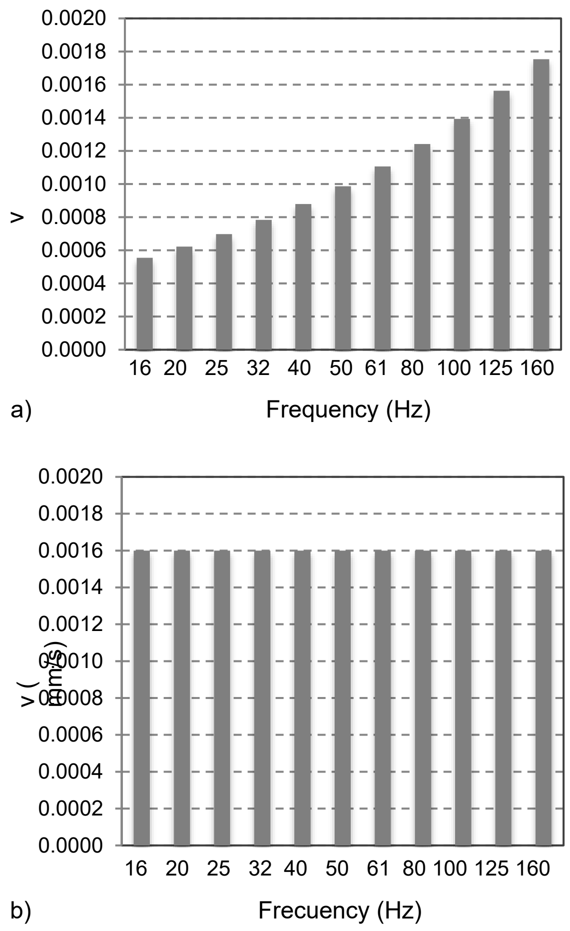

Figure 5. Examples of vibrational spectrums: a) white noise ; b) pink noise.

4.2 Vibrational reduction index of the connections

In situ measurements and calculations were carried out in order to obtain both the vibrational reduction index of the connections (K_{ij}) and the difference in velocity level averaged in *ij* direction ($D_{v,ij}$). It was taken into account the composition of the constructive elements as well as the type of connection of all the cases considered in the study. As it can be seen below, a relationship between measured and calculated values was observed since three groups of ranges of values could be set mainly depending on the degree of rigidity of the connection.

4.2.1 Values obtained from measurements

Amongst the spaces in which measurements have been performed, a classification of three main cases can be determined:

i) robust and L-junction connection between heavyweight constructive elements (dwelling – heavyweight façade and concrete slab connection, $D_{v,ij}$ = 3,9 and K_{ij} = -0.25);

ii) rigid on T-junction between regular types of building solutions, mainly heavyweight (office – brick wall partition and concrete slab connection, $D_{v,ij}$ = 8 and K_{ij} = 4); and

iii) a non-rigid connection between floor and lightweight walls (office – lightweight non homogeneous wall and concrete slab connection, $D_{v,ij}$ = 13 and K_{ij} = 9).

Thus, three groups of ranges of vibrational

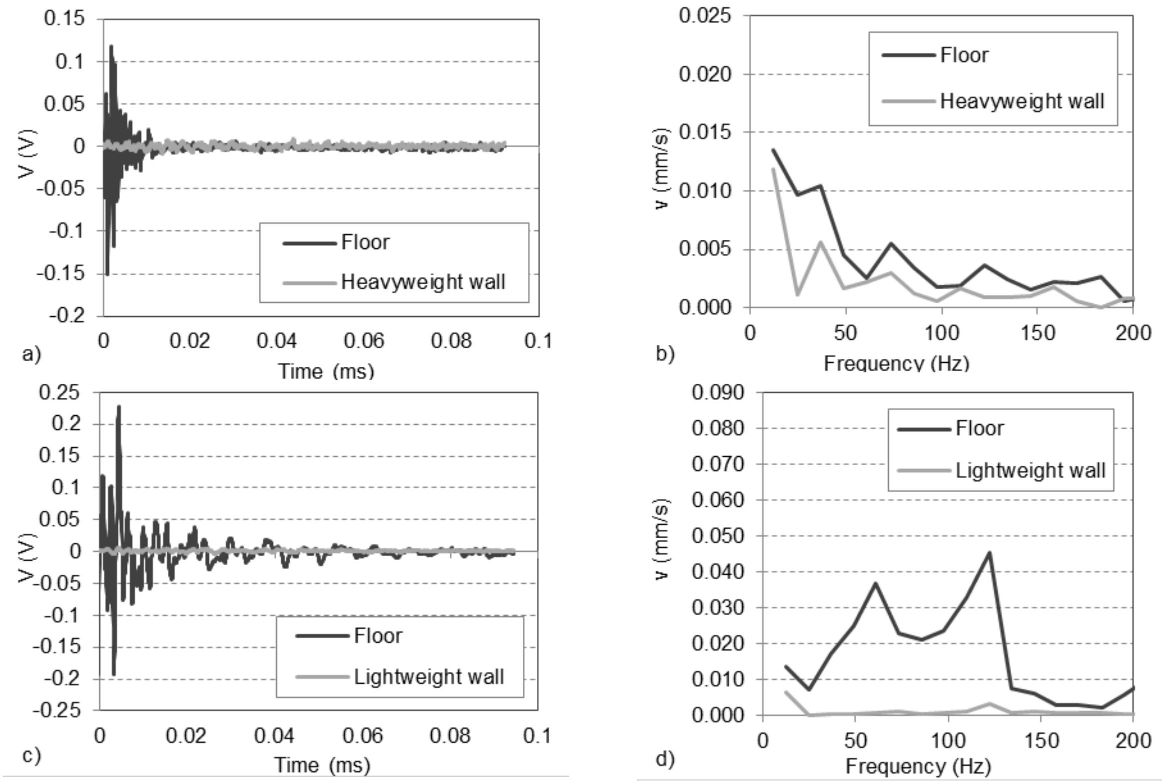

Figure 6. Registered values of vibrations in the two connected elements of two cases: a-b) Joint between concrete slab and a heavyweight wall rigidily connected; c-d) Joint between concrete slab and a lightweight wall non-rigidily connected; a-c) Voltage values of vibration; b-d) Vibration velocity values after FTT.

reduction index could be established. The higher is the value of the index (K_{ij}), the less vibration is transmitted between both elements.

4.2.2 Values obtained from calculations

In the light of the results, the values of D_{vij} determine a greater transmission between heavy elements connected by rigid union in corner, and a smaller transmission in those situations in which the partitions are lightweight, with a rigid coupling in T. As it can be seen in Table 2, again three groups of ranges of values are contained:

i) values between 1 to 6 for $D_{v,ij}$ and -3.5 to 2 for Kij;
ii) values between 9 to 12 for $D_{v,ij}$ and 5.5 to 7 for Kij;
iii) values between 13.5 to 15 for $D_{v,ij}$ and 8.5 to 10 for Kij.

In addition, this classification is directly related to the degree of rigidity of the union, being i) the largest rigidity and the lowest rigidity. Thus, it can be confirmed there is a direct correspondence between these groups of values and the classification of results measured *in situ*.

Table 2. Vibrational reduction index of the connections (K_{ij}) and difference in velocity level averaged in ij direction ($D_{v,ij}$), obtained for all the cases considered in the study (see Table 1)

CASE	GROUP (section 4.2.1)	ij1		ij2-3-4	
		K_{ij}	$D_{v,ij}$	K_{ij}	$D_{v,ij}$
1	i	-1.4	3.3	6.6	11.7
2	ii	6.4	11.1	6.3	11.7
3	i	0.3	5	5.9	11.2
4	ii	5.9	10.6	5,9	11.2
5	i	-3,7	1.04	5.9	11.2
6	iii	8.8	13.6	9.2	14.6
7	iii	9.2	14	9.2	14.6
8	iii	6.5	11.2	7.9	13.3

4.3 Calculation of maximum level of vibration

Firstly, taking into account the composition of the constructive elements as well as the type of connection between them (Table 1), it was possible to determine the values of K_{ij} and Dv_{ij} for each element, in the different frequency bands, following the method specified in the Methodology section. Then, a vibration spectrum, which is measured on the floor surface of the dwelling room, has been selected. It was determined the value of the sound pressure emitted by the vibration propagated by the floor L_{vi}, and, subsequently, it was obtained the vibration value transmitted to each of the coupled elements, which has allowed to determine the effective value of the vibration velocity. Once all the indicated parameters have been obtained, it has been possible to calculate the level of sound pressure emitted by each surface, and consequently the overall weighted sound level L(A) inside the room.

4.3.1 Real vibrational spectrum based on measurements

On the one hand, measured vibrational values were considered to determine the limit level of vibration that should be generated on the floor and not to exceed the maximum level of sound pressure. Table 3 shows the values of one Type 1 spectrum of vibration propagated to the floor surface (i), as well as the values of vibrations transmitted to the remaining surfaces (s_1, s_2, s_3 and s_4).

Table 3. Spectrum Type 1 : Vibration values (mm/s), in a range of one third octave bands between 16 and 160 Hz, propagated to the floor (i), as well as the values of vibrations transmitted to the surfaces connected to floor (s_1, s_2, s_3 and s_4).

	Frequency band (Hz)											
	16	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**Σ**
i	0,0007	0,001	0,0033	0,0099	0,017	0,0099	0,0023	0,0013	0,0005	0,0003	0,0003	**0,023**
s_1	0,0004	0,0007	0,0022	0,0067	0,0116	0,0067	0,0016	0,0009	0,0003	0,0002	0,0002	0,015
s_2	0,0002	0,0003	0,0009	0,0026	0,0044	0,0026	0,0006	0,0003	0,0001	9E-05	9E-05	0,006
s_3	0,0002	0,0003	0,0009	0,0027	0,0048	0,0027	0,0006	0,0004	0,0001	6E-05	7E-05	0,006
s_4	0,0002	0,0003	0,0009	0,0026	0,0044	0,0026	0,0006	0,0003	0,0001	9E-05	9E-05	0,006

Table 4. Spectrum Type 1 : Sound pressure values (dB) in a range of 1/3 octave bands between 16 and 160 Hz, emitted by the floor (i), as well as the values of sound levels emitted by the surfaces connected to floor (s_1, s_2, s_3 and s_4).

	Frequency bands (Hz)											
	16	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**Σ**
i	22,4	25,9	36,4	45,9	50,7	45,9	33,3	28,4	19,3	16,4	14,4	53,1
s_1	22,4	25,9	36,4	45,9	50,7	45,9	33,3	28,4	19,3	16,4	14,4	49,7
s_2	19,0	22,5	33,0	42,5	47,3	42,5	29,9	25,0	15,9	13,0	11,1	41,3
s_3	10,6	14,2	24,6	34,2	38,9	34,2	21,5	16,7	7,5	4,6	2,7	41,9
s_4	11,3	14,8	25,2	34,8	39,6	34,8	22,1	17,3	8,2	5,2	3,3	41,3

As stated in section 2, it should be pointed out that although it is commonly used 27 dB, a penalty of 5 dB(A) was considered due to the repetition of the phenomena (circulation of Metro). For the development of the study, a calculation factor has been applied to the vibration spectrum that has made it possible to proportionally reduce all the frequency bands. Therefore, in order to adjust the weighted sound level L(A) to 22 dB(A), these values correspond to that decreased by 44% of a real vibration spectrum measured in the dwelling. Table 4 shows the sound pressure values emitted by the vibrations propagated by the floor surface (i), as well as the sound levels emitted by the vibrations transmitted to the rest of surfaces (j_1, j_2, j_3 and j_4), whose values are shown in Table 2.

Figure 7 shows the values of equivalent sound pressure for the third octave bands between 16 and 160 Hz, obtained by adding the levels emitted by each of the connected surfaces (Table 4). In addition, the values of weighted sound pressure level in dB(A) are also shown, being determined the limit at 22 dB(A).

Finally, Table 5 shows the effective limit values of vibration velocity obtained for each case study.

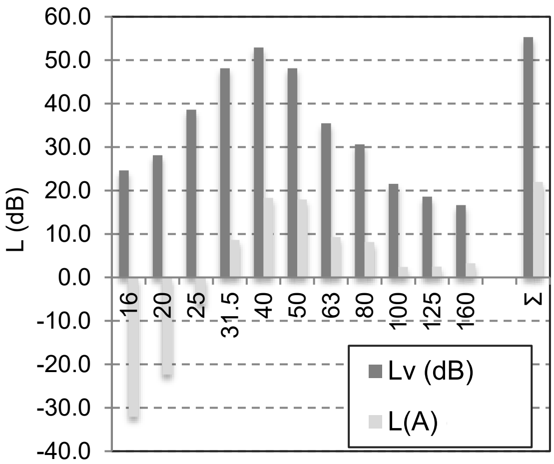

Figure 7. Spectrum Type 1: Equivalent sound pressure values (Lv) and weighted sound pressure levels L(A), for the third octave bands between 16 and 160 Hz.

Table 5. Effective limit values of vibration velocity obtained for each case study (mm/s).

CASE	SPECTRUM OF VIBRATION			
	Type 1	Type 2	Type 3	Type 4
1	0,023	0,019	0,025	0,021
2	0,026	0,021	0,028	0,024
3	0,025	0,02	0,027	0,023
4	0,026	0,022	0,028	0,024
5	0,024	0,02	0,026	0,022
6	0,024	0,02	0,026	0,021
7	0,028	0,023	0,03	0,026
8	0,029	0,024	0,03	0,027

4.3.2 White and pink noise spectrum

It is also important to consider other types of spectrum to determine the maximum level of vibration that should be generated on the floor if the noise would be white or pink. The calculation procedure is the same as in the case of real vibrational spectrum produced by the passage of the Metro. However, since it is unknown the values of vibration for white or pink noise by frequency, the procedure must be developed in an inverse way in this case, by setting in first place the noise limit that should not be exceeded.

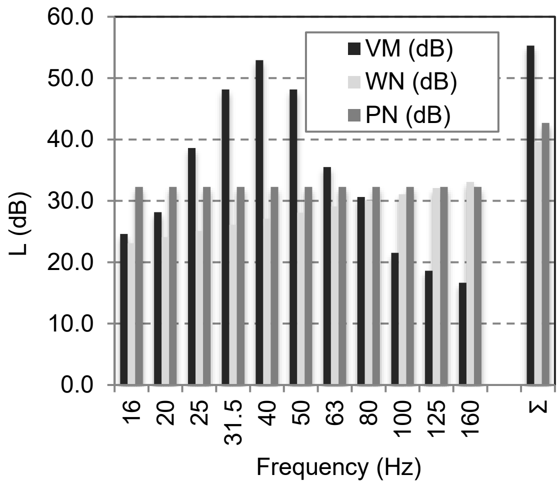

Figure 8. Equivalent sound pressure values (dB) for the third octave bands between 16 and 160 Hz, setting L(A) limit at 22 dB(A). VW = Vibration generated by the passage of Metro; WN = white noise; PN = Pink noise

Figure 8 depicts the values of equivalent sound pressure for the third octave bands between 16 and 160 Hz, obtained by adding the levels emitted by each of the connected surfaces, being the weighted sound pressure level limit at 22 dB(A). Table 6 shows the effective limit values of vibration velocity obtained for case study 1 (see Table 1), considering three types of spectrum: a real vibrational spectrum based on measurements, a white noise spectrum and a pink noise spectrum.

Table 6. Effective limit values of vibration velocity (mm/s) obtained for case study 1, considering real vibrational spectrum generated by Metro, white noise and pink noise.

	Frequency bands (Hz)										
CASE 1	**16**	**20**	**25**	**32**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**Σ**
VM	0,0007	0,0010	0,0033	0,0099	0,0172	0,0099	0,0023	0,0013	0,0005	0,0003	0,0003	**0.023**
WN	0,0006	0,0006	0,0007	0,0008	0,0009	0,0010	0,0011	0,0012	0,0014	0,0016	0,0018	**0.0037**
PN	0,0016	0,0016	0,0016	0,0016	0,0016	0,0016	0,0016	0,0016	0,0016	0,0016	0,0016	**0.005**

*VW = Vibration generated by the passage of Metro; WN = white noise; PN = Pink noise

As mentioned before, white noise shows an increasing constant power spectral density and pink noise shows an equal amount of noise energy at each octave band. In this regard, it is assumed that the vibration limit will be lower in the case that excitation is caused by white noise, since the noise level increases +1 dB at each 1/3 frequency band.

5. CONCLUSIONS

The passage of rail traffic has become one of the main sources of external vibrations that most often lead to complaints from users due to the low frequency noise propagated inside dwellings, which is perceived as an inconvenience and disturbing effect. In this work different case studies were analysed in order to determine the total noise generated in the room, and therefore, to obtain the limit of vibration velocity that should be generated in the floor to not exceed the maximum noise established by national regulations or acceptable living conditions.

In the light of the results, the values of D_{vij} determine a greater transmission between heavy elements connected by rigid union in corner, and a smaller transmission in those situations in which the partitions are lightweight, with a rigid T coupling. Based on the limit of noise level that could be generated in the room, it is possible to determine vibrations levels propagated to the different constructive elements linked to the floors.

Therefore, the higher is the value of the index (Kij), the less vibration is transmitted between both elements. In this regard, three groups of ranges of limit vibration values could be established depending on the type of connection as well as on the composition of the construction elements:

- 0,015 – 0,02 mm/s in the most unfavourable situations where vibrational reduction index of the connections (K_{ij}) are very low and the transmission between elements is very high. This case will occur when the constructive solutions are very heavy and most of the connections considered are rigid in corner.
- 0,02 – 0,025 mm/s in the intermediate situations where vibrational reduction index of the connections (K_{ij}) are medium values. This case corresponds to the regular cases and may be generalized for most of the situations analysed.
- 0,025 – 0,03 mm/s in the more favourable situations where vibrational reduction of the connections (K_{ij}) are very high, and the transmission between elements is very low. This

case will occur when the constructive solutions of the walls are lightweight.

Moreover, when analysing different types of spectrum, including white noise and pink noise spectrum, it is observed that the white noise spectrum is the strictest case when evaluating the maximum limit of vibration generated in the floor. Up to 6 times lower should be the effective value of the speed of the vibration with respect to a spectrum of real vibration generated by the passage of the Metro. In the case of pink noise, the vibration velocity should be 4.5 times smaller in order to obtain the weighted sound pressure level, which is set in 22 dB(A) in this study, the weighted sound level that should not be exceeded in a room during the night period.

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