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ALARGAMENTO DO ÂMBITO DE APLICAÇÃO DA NORMA EN 12354-2 ÀS BAIXAS FREQUÊNCIAS

(EXTENSION TO LOW FREQUENCIES OF THE APPLICATION SCOPE OF THE STANDARD EN 12354-2)

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RESUMO ALARGADO EM INGLÊS

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1. INTRODUCTION

1.1. MOTIVATION

One of the problems that has remained without a simples solution in the area of building acoustics is the characterization and control of low frequency (20-200 Hz) impact sound transmission. Despite human capacity to detect sounds from 20 to 20000 Hz, current standards only apply to frequencies between 100 and 3150 Hz [1, 2]. This happens because standards used in building's acoustic to characterize sound transmission are based on traditional methods, which assume diffuse fields, either in terms of structural vibration or in terms of sound pressure distribution inside rooms. This hypothesis requires rooms with large volumes, typically above 50 m^3, whose dimensions are greater than the longest wavelength analyzed.

In the low frequencies range, construction elements and sound fields, with natural frequencies within the analyzed range (20-200 Hz), have a clearly modal behavior, thus not satisfying the hypothesis of diffuse fields mentioned above.

In the presence of modal behavior, the relationship between sound or vibration sources and construction elements or acoustic volumes characteristics acquires a great importance and may lead to resonance (amplification) phenomena, which origins severe discomfort in some cases. Mechanical equipments are usually the most problematic sources of low frequency noise, being footsteps identified as the most common source of low frequency impact sound in dwellings.

Since it is extremely common to find room volumes below 50 m^3 in dwellings, in addition to percussion actions in buildings representing significant energy content below 200 Hz, it becomes important to develop alternative prediction methods for low frequency impact sound transmission, in order to provide sound transmission analysis and correction tools to be used by designers. There are some methods available, which were introduced in relatively recent research [3-5]. These methods can be numeric, such as the Finite Element Method - FEM or analytical based on Natural Mode Analysis. As regards the analysis of noise transmission percussion, Neves e Sousa [4] proposed the modal analysis analytical method, which was validated numerically and experimentally for homogeneous heavy floors with different types of coating.

The modal analysis method has some limitations, such as being restricted to rectangular rooms and constant ceiling height. This is the typical configuration of dwellings, thus the method is valid to a significant proportion of current buildings. However, the method's implementation is theoric, thus unattractive for most designers. Therefore it would be useful to have a simpler method, possibly linked to the method already available in standards [1, 2].

1.2. OBJECTIVES

The purpose is to define a correction/adjustment criteria which allows the application of standard methods for predicting impact sound insulation at frequencies below 100 Hz. This will be accomplished using the modal analysis method on an extensive study of the impact sound level variance in the low frequencies range. The statistical analysis includes a significant sample of case studies, which considers the variation of parameters such as rooms' and floors' dimensions, floors' comprising material properties, or even the position of impact force application and sound receiver

1.3. OVERVIEW OF THE THESIS

In order to predict sound impact transmission in dwellings via modal analysis method, it is previously necessary to deduct two models. The first is the vibration field model generated in the pavement by a given impact force. The second model allows estimating the sound field generated in the lower compartment due to floor vibration.

Thus, the analytical method based on modal analysis for predicting vibration fields generated by point impact forces in simply supported uniform floors is described. The analytical method used to estimate sound pressure fields in rooms, which is also based on modal analysis, is described as well.

Once the previous models are defined, it is possible to create an analytic model of coupling between the room's sound field and the vibration field generated in the upper floor, due to an applied impact force.

The standard methods available for predicting sound transmission, whether airborne or direct impact force excitation are introduced. Reference to standard prediction methods of airborne sound transmission stems from the fact that they are related, in accordance to the principle of reciprocity, with the predicting methods of impact sound insulation.

A way of comparing the model described with the standard calculation method, which allows to define a measure of the error committed by the latter, is presented. The statistical analysis of the error based on a large sample of case studies, considering the variation of several factors, such as the impact and receiver position, the rooms' and floors' dimensions and the properties of the materials comprising the pavement is also described.

Based on previous statistical analysis, a correction criteria applicable at low frequencies to sound insulation values obtained with the standard predicting methods is proposed.

Concluding statements and suggested topics for further work are given in Conclusions.

2. VIBRATION FIELD MODEL OF THE FLOOR

The expression that describes the vibration field generated by a point impact force (F) acting on a plate, with dimensions b and c, at the frequency ω is given by

$$v_x(y,z) = j\frac{4\omega F}{m''bc}\left[\sum_{m1,n1=1}^{\infty}\frac{\varphi_{m1n1}(y,z)\varphi_{m1n1}(y_0,z_0)}{\omega^2{}_{m1n1}(1+j\eta)-\omega^2}\right]. \qquad (2.1)$$

where: m'' is the mass per unit area of a wall or floor (kg/m^2); φ_{m1n1} is the eigenfuntion for the vibration field of floors; ω_{m1n1} is the eigenfrequency of the floor vibration field (rad/s) and η is the loss factor;

3. SOUND FIELD MODEL

Sound radiation into a room from a vibrating plate-like structure can be derived from natural mode analysis as demonstrated by Kihlman [6]. This method can be applied to rectangular rooms with a vibrating floor at $x=a$. Floor dimensions along the y and z-axes are represented by b and c, respectively. Previous applications of the method have shown a good agreement with experimental results and with Finite Elements models [4]. The sound pressure (in Pa) at the frequency ω can be obtained by

$$p(x,y,z,t) = -j\omega\rho_0 \sum_{l,m,n=1}^{\infty} \frac{8{c_0}^2(-1)^{l} C_{mn}\varphi_{lmn}(x,y,z)}{abc[(\omega_{lmn}+j\delta)^2-\omega^2]} e^{j\omega t}\,, \tag{3.1}$$

where: ρ_0 is the static value of air density (in kg/m^3); c_0 is the phase speed of sound (in m/s) in the air; $\delta = 6.9/T_R$ is a global absorption coefficient given as a function of the reverberation time of the room T_R (in seconds) [4]; $\varphi_{lmn}(x,y,z)$ are the sound field eigenfuntions and ω_{lmn} are the corresponding eigenfrequencies; C_{mn} are coupling factors given by

$$C_{mn} = \int_0^b \int_0^c v_x(y,z) cos\left(\frac{m\pi y}{b}\right) cos\left(\frac{n\pi z}{c}\right) dydz, \tag{3.2}$$

where $v_x(y,z)$ is the transverse velocity field of the vibrating floor.

For a room topped by a thin rectangular plate of uniform thickness h (in m) and mass per unit area given by $m'' = \rho h$ (in kg/m^2), simply supported at all edges, subjected to a point impact force F (in N) at (y_0, z_0), the coupling factors for the acoustic modes (l,m,n) are

$$C_{mn} = j\frac{4\omega^2 F}{m''bc} \sum_{m_1,n_1=1}^{\infty} \left\{ \frac{\varphi_{m_1 n_1}(y_0,z_0)}{\omega^2{}_{m1n1}(1+j\eta)-\omega^2} \frac{[(-1)^{m_1+m}-1][(-1)^{n_1+n}-1]}{m_1 n_1\left[\left(\frac{m}{m_1}\right)^2-1\right]\left[\left(\frac{n}{n_1}\right)^2-1\right]} \right\}, \tag{3.3}$$

where η is the floor structural loss factor.

4. IMPACT SOUND PRESSURE LEVEL

4.1. DEFINITION OF THE IMPACT SOUND INSULATION LEVEL IN UNCOVERED FLOORS

The standard descriptor of impact sound insulation, L_n, is the sound level measured in the room below a tested floor excited by a standard tapping machine, normalised to the receiving room sound absorption area A_2, according to

$$L_n = 10\log\left(\frac{{p_2}^2}{{p_0}^2}\frac{A_2}{A_0}\right), \tag{4.1}$$

where p_2 is the sound pressure measured in the receiving room; p_0 is the reference sound pressure (p_0= 2 x 10^{-5} Pa) and A_0=10 m^2 is the reference absorption area.

4.2. NORMALISED IMPACT SOUND PRESSURE LEVEL - STANDARD METHOD

For average temperature and pressure conditions, L_n predictions obtained with the standard method described in EN 12354-2 [2], for homogeneous floors are given by

$$L_n \approx 134 + 10log\left(\frac{{F_t}^2 Y\sigma}{m''\eta f}\right). \quad (4.2)$$

In equation (4.2), the radiation factor for free bending waves (σ) and the floor total loss factor $\eta \approx 0.01 + m''/(485\sqrt{f})$ are calculated in accordance with annexes B and C of EN 12354-1 [1], respectively. The characteristic floor mobility is given by

$$Y = Re\{Y\} = \frac{1}{8\sqrt{B'm''}} = \frac{1}{2{,}3c_L\rho h^2} = \frac{1}{2{,}3c_L m'' h}. \quad (4.3)$$

4.3. NORMALISED IMPACT SOUND PRESSURE LEVEL - NATURAL MODE ANALYSIS

In order to assess the variance of impact sound transmission in the range 20-200 Hz, equation (3.1) was used to calculate the narrowband sound pressure response near a room corner, at (x, y, z)=(0.4,0.4,0.4) m, for point impact forces of intensity equal to unity at all frequencies. These transfer functions were converted into one-third octave bands and then used to calculate the corner sound pressure response for the floor excited by the five hammers of a standard tapping machine, each weighting 500 grams, which are dropped freely, twice per second, onto the test object from a height H=4 cm [7]. For hard floor surfaces, the mean-square value of the force acting on the floor can be obtained from the spectral distribution F_n of equally time spaced force pulses as

$${F_t}^2 = \frac{\Delta f}{f_S}\frac{{F_n}^2}{2} \approx 0.910f, \quad (4.4)$$

where: f_S=10 Hz is the impact frequency; $\Delta \mathrm{f} \approx 0.232\mathrm{f}$ is the bandwidth of one-third octave band with central frequency f; $F_n \approx 2f_S(m\sqrt{2gH})$; and g(m/s^2) is the acceleration of gravity [7]. If equation (4.4) is simplified to $F \approx 0.953\sqrt{f}$, then the one-third octave band sound pressure response in the room corner is given by the corresponding transfer function multiplied by $0.953/\sqrt{0.232} \approx 2$.

4.4. COMPARISON OF THE NORMALISED IMPACT SOUND PRESSURE LEVEL PREDICTION METHODS

The comparison between the impact sound pressure levels prediction methods (described in 4.2 and 4.3) was made for a point near a corner room (referred in the previous section) in order to obtain a more complete spectral response.

A correction of 9 dB [8-10] should be added to equation (4.2) in order to estimate the room response in the corner ($L_{n,c}$). The error (ε) associated to the standard method, which derives from parameter uncertainties and modal behavior of acoustic volumes and floors, will be evaluated as the difference from predictions of $L_{n,c}$ obtained with modal analysis for a large number of cases.

5. PARAMETRIC STUDIES ON THE VARIANCE OF IMPACT SOUND TRANSMISSION

5.1. STUDY PARAMETERS

Calculations of impact sound transmission, performed as described above, were used to assess variance of impact sound levels for 168750 cases, where the following parameters were combined:

1. Location of impact - 25 positions (y_0, z_0) for each floor/room combination;

2. Floor mass per unit volume ρ - 3 cases including an average value with a ±10% variation;

3. Floor elasticity modulus E – 3 cases including an average value with a variation of ±5%;

4. Floor dimensions - 5 combinations with ratios b/c equal to 1/1.00, 1/1.25, 1/1.50, 1/1.75, and 1/2.00, complying with a minimum floor dimension requirement [11] defined as $b,c \leq$ 2.1, 2.4, and 2.7 m for floor areas below 9.5, 12.0, and 15.0 m^2, respectively;

5. Room height - 5 cases with a equal to 2.4, 2.5, 2.6, 2.7, and 2.8 m;

6. Room volume - 5 cases with V equal to 20, 30, 40, 50, and 60 m^3;

7. Floor thickness – 6 cases with h equal to 0.15, 0.20, 0.25, 0.29, 0.34, and 0.39 m.

Three layers were considered for all floors: plaster (E=10 GPa; ρ=1800-2000 kg/m^3); reinforced concrete (E=28-36 GPa; ρ=2400 kg/m^3); and mortar (E=15 GPa; ρ=1000-2000 kg/m^3). The thickness of the plaster layer was assumed as 2 cm for the three thickest floors, and 1 cm for the three thinnest floors. For the concrete layer, thicknesses of 15, 20, and 25 cm were assumed for the thickest floors, and 7, 11, and 15 cm for the thinnest floors. Finally, a constant thickness of 12 cm was assumed for the mortar layer in the three thickest floors, whereas a variable thickness of 7, 8 and 9 cm was assumed for the thinnest floors. Through a process of section homogenisation and further calculation of the equivalent elasticity modulus and density of a unity width homogeneous section of the same overall thickness, the floor properties indicated in Table 1 were defined.

Table 5.1 – Floor properties.

Thickness h (m)	Equivalent elasticity modulus E (GPa)	Equivalent density ρ (kg/m^3)
0.15	17.7-19.5	1800-2200
0.20	18.3-20.4	1850-2250
0.25	18.9-21.4	1900-2300
0.29	17.7-19.5	1800-2200
0.34	18.3-20.4	1850-2250
0.39	18.9-21.4	1900-2300

5.2. VARIANCE ANALYSIS OF IMPACT SOUND TRANSMISSION AND COMPARISON WITH THE STANDARDS

5.2.1. Uncertainty associated to the location impact

The spectra of 6750 samples of 25 cases each exhibit strong variation with frequency and confirm the process of modal selection described in section 3. For small room volumes, coupling between structural floor modes (1,1) and acoustic room modes (1,0,0) is stronger for thin floors than for thicker floors, where coupling between modes (1,1) and (2,0,0) becomes more important. The standard method underestimates $L_{n,c}$ at frequencies corresponding to strong modal coupling, where the error can reach approximately 12 dB. On the other hand, the standard method generally overestimates $L_{n,c}$ below 50 Hz, regardless of room volume and floor thickness. The standard deviation of $L_{n,c}$ decreases from 3-20 dB (with average around 9 dB) at 20 Hz to 2-14 dB (with average around 4-6 dB) at 200 Hz. The standard deviation of the error also decreases with frequency. For higher room volumes, both the error and standard deviation of $L_{n,c}$ increase near 20 Hz, due to decreasing acoustic natural frequencies, and decrease for higher frequencies. Near 200 Hz, $L_{n,c}$ maxima obtained with modal analysis for the largest room volumes tend to be closer to the average values of L_n obtained with the standard method. Separated statistical analyses of average and maxima $L_{n,c}$ showed that standard deviations for maxima never exceed those obtained for average $L_{n,c}$.

5.2.2. Uncertainty associated to the floor mass

The analysis of 2250 samples of 75 cases each confirmed most of the conclusions drawn above and indicated a standard deviation of L_n (or $L_{n,c}$) obtained from equation (4.2) around 1-2 dB. In this case, the standard deviation of $L_{n,c}$ obtained with equation (3.1) decreases from 5-18 dB (with average around 9 dB) at 20 Hz to 2-11 dB (with average around 4-6 dB) at 200 Hz.

5.2.3. Uncertainty associated to the floor equivalent modulus of elastic

The analysis of 750 samples of 225 cases each confirmed most of the conclusions drawn in previous sections and indicated a decrease of the standard deviation of $L_{n,c}$ from 6-17 dB (with average around 9 dB) at 20 Hz to 3-9 dB (with average around 5-6 dB) at 200 Hz. The error associated to the standard method reaches approximately 17 dB for the thinnest floors at frequencies where strong modal coupling occurs.

5.2.4. Uncertainty associated to the floor dimensions

The analysis of 150 samples of 1125 cases each confirmed most of the above conclusions and indicated an increase of the standard deviation of $L_{n,c}$, which varies from 7-18 dB (with average around 10-11 dB) near 20 Hz to 3-8 dB (with average around 5-6 dB) at 200 Hz. The error associated to the standard method also increased to approximately 20 dB for the thinnest floors at frequencies where strong modal coupling occurs. Contrarily to the behaviour described in previous sections, separated statistical analyses of average and maxima $L_{n,c}$ indicated higher standard deviations for maxima than for average $L_{n,c}$.

5.2.5. Uncertainty associated to the room height

The analysis of 30 samples of 5625 cases each indicated an increase of the dispersion of $L_{n,c}$, with maxima about 6 dB higher than in the cases described in section 5.2.1. The standard deviation of $L_{n,c}$ decreases from 9-15 dB (with average around 10-12 dB) near 20 Hz to 4-8 dB (with average around 5-7 dB) at 200 Hz. The error associated to the standard method also increased, exceeding 20 dB in some cases due to strong modal coupling. When room height and the four previous parameters vary together, some of the conclusions drawn in previous sections are difficult to confirm.

5.2.6. Uncertainty associated to the room volume

The analysis of 6 samples of 28125 cases each indicated that the standard deviation of $L_{n,c}$ decreases from 12-17 dB near 20 Hz to 6-7 dB at 200 Hz. The error associated to the standard method always exceeds 20 dB at the 63 Hz one-third octave frequency band, where strong modal coupling occurs, regardless of floor thickness. The standard deviation of the error decreases from 12-18 dB near 20 Hz to 6-8 dB at 200 Hz.

6. CORRECTION FUNCTION APPLICABLE FOR THE STANDARD PREDICTION METHOD

6.1. DEFINITION OF $L_{n,c,st}$ CORRECTION FUNCTION

Assuming a normal probability distribution of $L_{n,c}$ at each frequency due to parameter uncertainties, the 95 % percentile can be defined as $L_{n,c,95\%} = L_{n,c,av} + 1.645\sigma,$ where $L_{n,c,av}$ is the average and $\sigma = \sigma_{st} + \sigma_{\varepsilon}$ is the standard deviation of $L_{n,c}$. Assuming a similar behaviour for the error ε, predictions of $L_{n,c,95\%}$ can be obtained from average values obtained with the standard method ($L_{n,c,st}$) as

$$L_{n,c,95\%} = L_{n,c,st,av} + [\varepsilon_{av} + 1.645(\sigma_{st} + \sigma_{\varepsilon})] = L_{n,c,st,av} + \Delta, \tag{6.1}$$

where ε_{av} and σ_{ε} are, respectively, the average and standard deviation of the error.

As described previously, the variation of $L_{n,c}$ predictions obtained with the standard method for floors of the same thickness is low. Thus, the floor dimensions which lead to the least variations from average values can be found for the six floor thicknesses considered: b=3.0 to 3.4 m and c=4.5 to 5.1 m. In this work, average values b=3.15 m and c=4.70 m, together with the average values of E and ρ obtained from Table 1, were used for estimation of $L_{n,c,st}$. Calculation of the standard correction factor Δ for each floor thickness according to equation (6.1) and further logarithmic regression on $Re\{Y\}$ and polynomial regression of the logarithmic regression parameters on f leads to

$$\Delta \approx \sum_{i=1}^{6} A_i f^{6-i}.\ln(Re\{Y\}) + \sum_{i=1}^{6} B_i f^{6-i}, \tag{6.2}$$

where A_i and B_i are constants with the values indicated in Tables 6.1 and 6.2, respectively.

Table 6.1- Constants A_i.

Parameter uncertainties	$A_1\ (\times\ 10^{-10})$	$A_2\ (\times\ 10^{-8})$	$A_3\ (\times\ 10^{-5})$	$A_4\ (\times\ 10^{-3})$	$A_5\ (\times\ 10^{-1})$	$A_6\ (\times\ 10^{1})$
(y_0, z_0)	-0.575	-16.107	6.184	-7.420	1.419	1.018
$(y_0, z_0),\rho$	-2.223	-0.419	3.025	-4.724	0.514	1.144
$(y_0, z_0),\rho, E$	-2.102	-0.900	3.074	-4.711	0.481	1.153
$(y_0, z_0),\rho, E,(b, c)$	-12.811	57.098	-8.279	4.930	-2.791	1.412
$(y_0, z_0),\rho, E,(b, c),a$	-6.204	21.993	-1.571	-0.590	-0.988	1.241
$(y_0, z_0),\rho, E,(b, c),a,V$	4.200	-23.731	4.275	-1.268	-3.476	2.035

Table 6.2 – Constants B_i.

Parameter uncertainties	$B_1\ (\times\ 10^{-9})$	$B_2\ (\times\ 10^{-6})$	$B_3\ (\times\ 10^{-4})$	$B_4\ (\times\ 10^{-2})$	$B_5\ (\times\ 10^{0})$	$B_6\ (\times\ 10^{2})$
(y_0, z_0)	-2.308	-0.934	7.251	-11.191	3.963	0.689
$(y_0, z_0),\rho$	-6.218	1.259	2.835	-7.429	2.709	0.880
$(y_0, z_0),\rho, E$	-6.072	1.206	2.874	-7.387	2.656	0.895
$(y_0, z_0),\rho, E,(b, c)$	-17.985	7.631	-9.609	3.071	-0.802	1.155
$(y_0, z_0),\rho, E,(b, c),a$	-10.510	3.663	-2.037	-3.146	1.216	0.975
$(y_0, z_0),\rho, E,(b, c),a,V$	8.803	-5.377	11.538	-9.012	-0.401	1.923

Equation (6.2) is valid for floors with characteristic mobility in the range 5x10^{-7}-3x10^{-6} s/kg.

6.2. VALIDATION CASES

In order to validate equation (6.2), three case studies were done. In this section the first case is presented. In this case a homogeneous floor with thickness h=23 cm and $Re\{Y\}$=1.3x10^{-6} s/kg was considered. Figure 6.1 shows a prediction of $L_{n,c,st}$, obtained with equation (4.2) with a correction of 9 dB for the following average values of material properties: E=17.5x109 GPa; ρ=2190 kg/m^3; and ν=0.2. Uncertainty is yet associated to these values. Predictions of $L_{n,c,95\%}$ are also shown in Figure 6.1, with values increasing with the number of considered parameter uncertainties. In order to illustrate the validity of the method, particular solutions of the room response $L_{n,c}$ at coordinates (0.4,0.4,0.4) m, obtained with the natural mode analysis, also are shown in Figure 6.1 for a room with volume $V_1 = abc$ =2.45x4.40x3.65=39.35 m^3, considering the tapping machine located at (1.40,1.20) m and (1.95,1.60) m, and for a room with volume V_2=2.75x2.75x3.35=25.33 m^3, with the tapping machine located at (1.05,1.25) m and optimal coupling conditions with the floor

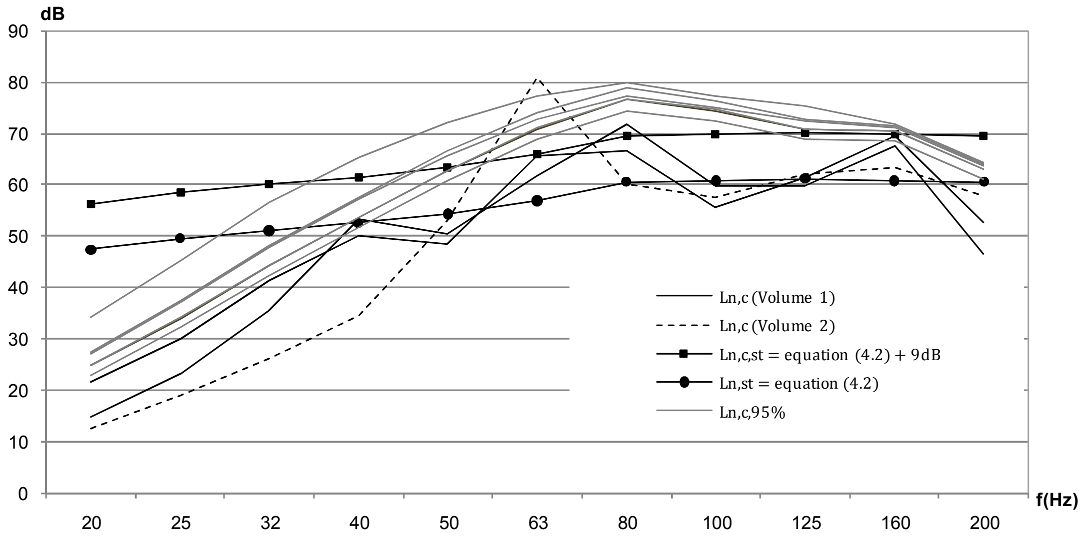

Figure 6.1 – Predicted spectra of $L_{n,c}$ for case study.

6.3. CONCLUSIONS

Figure 6.1 shows that predictions of $L_{n,c,95\%}$ are in good agreement with L_n predictions obtained with equation (6.2) at 200 Hz, where the diffuse field conditions start to apply. Below 200 Hz, predictions of $L_{n,c,95\%}$ are, in general, a good estimate of maxima $L_{n,c}$. Maxima $L_{n,c}$ are expected to exceed $L_{n,c,95\%}$only for cases of optimal coupling conditions.

7. CONCLUDING REMARKS

7.1. CONCLUSIONS

The results of the statistical analysis established a correction criteria, that can be applied at low frequencies to the impact sound insulation predicted with the standard methods. It was possible to define a correction function, that only depends on the characteristic mobility of the floor, which is known with the application of the standard method. Once the dimensions of the room where the floor will be installed are unknown, it is recommended the application of the standard method with reference dimensions of b=3.15 m and c=4.70 m.

The application of the normalized impact sound correction function is possible when the characteristic mobility of the floors range between 0.5x10^{-6} and 3.0x10^{-6} s/kg, This function provides an estimate of the sound level near a bottom corner of the room, in a position potentially occupied by a receiver. This estimate is likely to be exceeded only in 5% of the cases.

The estimates were validated by three case studies where pavements were tested in conditions of optimum modal coupling with the enclosed spaces below.

7.2. PROPOSED FURTHER WORK

Once the correction function of the normalized impact sound standard method was estimated based only on simply supported floors, it is suggested the extension of the analysis, to floors with other support conditions.

In order to make the correction function proposed in this paper of generalized application, the method provided in EN 717-2 [12] for calculating the single normalised impact sound level should be changed to include low frequencies.

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