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CHARACTERISATION OF LOW FREQUENCY IMPACT SOUND TRANSMISSION IN DWELLINGS

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Abstract

The present paper reports on a study of low frequency impact sound transmission in buildings that was sponsored by the Portuguese Foundation for Science and Technology (FCT). It is recognised that in general, building elements such as walls and floors fail to comply with performance standards at low frequencies. This problem is exacerbated by the modal behaviour of the pressure fields in small often rectangular rooms, and of the vibration fields of intervening walls and floors, which results in large spatial and spectral variations in impact sound level and airborne sound level difference. These variations are not taken into account in the present national and international standards and a measurement method has yet to be confirmed for very low frequency sound transmission. In this study of impact sound transmission, a parametric survey has been performed, using an experimentally validated analytical method, on the impact sound transmission between dwellings in the frequency range 40 – 200 Hz. Results are presented as narrow-band values and conclusions refer to the relative importance of factors such as the type of excitation (footfall, standard impact sources), the location of excitation, the type of floor (solid or with an isolated layer), the edge conditions, the room dimensions, the absorption and the listener position. The expected variances in impact sound pressure level, due to the range of room volumes encountered in dwellings, are given for typical floor types and a proposal is given on how the low frequency behaviour can be incorporated into present standards.

INTRODUCTION

A standard tapping machine consists of five hammers with $m = 500$ grams, which are dropped freely onto the test floor from a height $H = 4$ cm, each hammer twice per second [1, 14]. Therefore, the impact frequency is $f_s = 10$ Hz and the root-mean-square force produced at low frequencies by a tapping machine in floors with hard surfaces, *i.e.*, without soft layers such as rugs, can be obtained from the spectral distribution $F = 2\, f_s\, m \sqrt{2\, g\, H}$ of the series of equally time spaced force pulses [4, 13]. Thus, the vibration induced by a tapping machine can be predicted from the model for the point mobility of homogeneous floors, which was discussed in previous papers [12, 2]. The steady state forced response of the floor is given in terms of the transverse velocity as

$$v_x(y, z, t) = \mathrm{j}\, \frac{4\, \omega\, F}{m''\, b\, c} \sum_{m_1, n_1 = 1}^{\infty} \left[\frac{\varphi_{m_1 n_1}(y, z)\, \varphi_{m_1 n_1}(y_0, z_0)}{\omega_{m_1 n_1}^2 (1 + \mathrm{j}\, \eta) - \omega^2} \right] \mathrm{e}^{\mathrm{j}\omega t}, \tag{1}$$

where m'' is the floor mass per unit area; b and c are the floor dimensions along the y and z-directions, respectively; $\varphi_{m_1 n_1}$ and $\omega_{m_1 n_1}$ are respectively the eigenfunctions and eigenfrequencies corresponding to the floor mode (m_1, n_1); and η is the total loss factor of the floor [4]. The vibration field given by equation (1) can be used to assess the sound pressure field $p(x, y, z, t)$ in the room below by

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

where a is the room height; ρ_0 and c_0 are respectively the density and the speed of sound in air; δ is a coefficient that takes into account sound absorption of room surfaces; and C_{mn} is a coupling factor that was described in previous papers [12, 2, 15].

PARAMETRIC SURVEY

Equations (1) and (2) show that impact sound transmission depends on the impact force, floor and room characteristics, which will all be discussed in the following.

Force characteristics

The type of impact force and the location of impact will be discussed.

Type of impact force

The typical force spectrum of a tapping machine is constant within 20 to 200 Hz and therefore the floor velocity is proportional to the mobility in the entire frequency range [4, 13]. This does not hold for typical force spectra for footsteps [11]. The force exerted on a floor by a 70 kg adult walking, for example, decreases at a rate of approximately 10 dB/octave. This means that, in average, both the transverse velocity of the floor and the sound pressure in the room will decrease at the same rate.

Location of impact

The effect of force location is illustrated for a 200 mm concrete floor with a floor area of 3.50 m $\times$ 4.50 m = 15.75 m^2. The location of impact was varied over a mesh of 36 equidistant points defining one floor quadrant. Figure 1 shows the predicted point mobilities at $(y, z) = (b/3; c/3)$. Generally, the mobilities are -7/+3 dB around the average mobility, but the differences can go up to -13/+5 dB in certain frequencies.

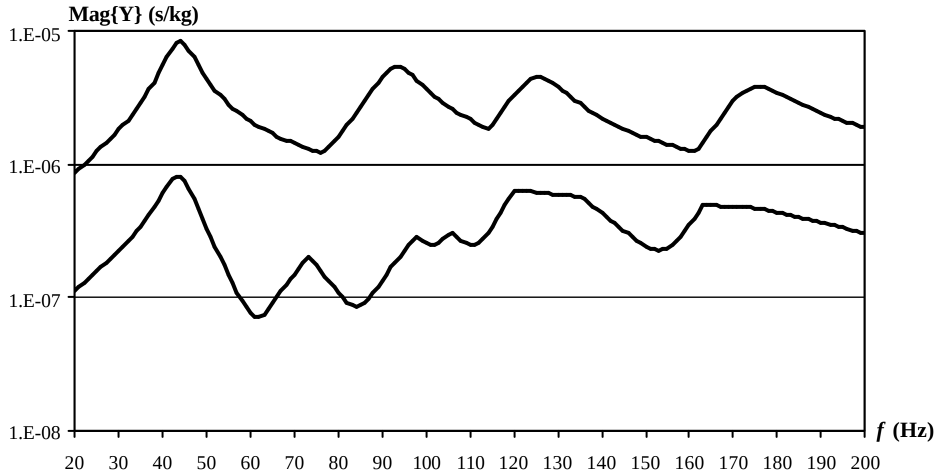

Figure 1 – Variability of point mobility at (y, z) = (b/3; c/3)

Figure 2 shows the predicted variability of the transfer function between the impact force and the sound pressure at $(x, y, z) = (0.2, 0.2, 0.2)$. The height of the room was assumed as $a = 2.50$ m. In general, impact sound transmission is -18/+8 dB around the average, but the differences can go up to -54/+19 dB for some frequencies above 40 Hz. The sound pressure obtained with an equivalent point sound source is also shown in Figure 2. As pointed out in previous papers [12, 2], the shape of impact sound transmission spectra is mainly controlled by the modal behaviour of the room.

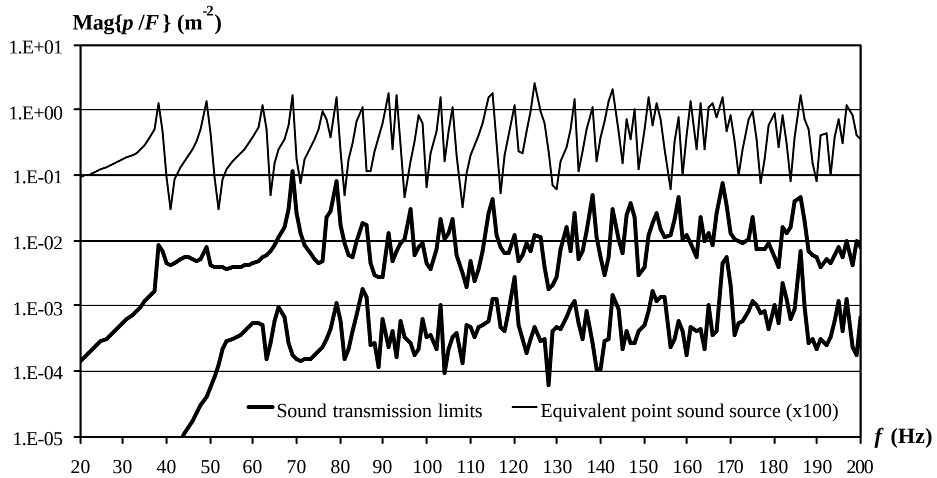

Figure 2 – Variability of the transfer function between the impact force and the sound pressure at (x, y, z) = (0.20; 0.20; 0.20)

Floor Characteristics

In the following, floor dimensions will be discussed as well as the influence of material properties, such as the elasticity modulus E, the density r and the Poisson's ratio n. The effect of edge conditions and floating floors will also be considered.

Floor dimensions

The effect of floor dimensions was studied for a 200 mm concrete floor by calculating the floor mobility at (4b/13; 4c/13) for a force applied at the same point. The study considered 99 different floors which were assumed in rooms with volumes varying from 20 to 100 m^3, but with a constant height a = 2.50 m. The variability of the point mobility obtained for the 99 floors is shown in Figure 3.

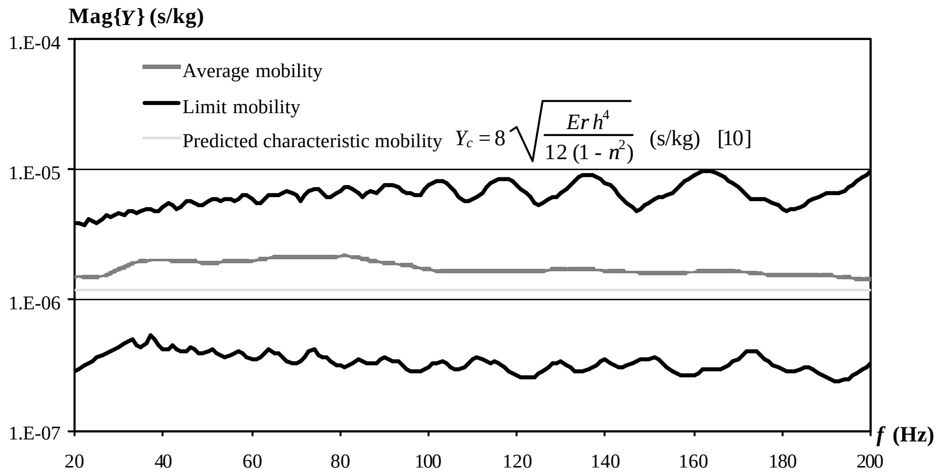

Figure 3 – Variability of point mobility at (y, z) = (y_0, z_0) = (4b/13; 4c/13)

Generally, the floor mobility is -7/+6 dB around the average mobility, but the differences can go up to -10/+9 dB for some frequencies. If the floors are grouped in terms of floor area, then the variability reduces in general to -3/+3 dB around the average. Again, there are frequencies for which the variability can be as high as -10/+5 dB. If the floors are grouped by aspect ratio, then the variability is generally -7/+5 dB around the average mobility, but the differences can go up to -10/+8 dB for square floors or -10/+6 dB for b/c = 0.50, 0.67, 0.75, 0.80 and 0.90. The variability in impact sound transmission was also assessed for the 99 floors (Figure 4). Since all studied rooms had the same height, a peak occurs in all spectra at 68 Hz, which is the frequency that corresponds to the room mode (1,0,0). Generally, impact sound transmission varied -20/+18 dB around the average. The maximum differences to the average were -80/+30 dB. Again, if the floors are grouped in terms of floor area, then impact sound transmission variability decreases to -14/+9 dB around the average with maximum differences of -48/+15 dB for frequencies below 50 Hz and -40/+18 dB for frequencies above 50 Hz. Grouping floors by aspect ratios gives a general variability of impact sound transmission of -20/+13 dB with differences as high as -80/+22 dB.

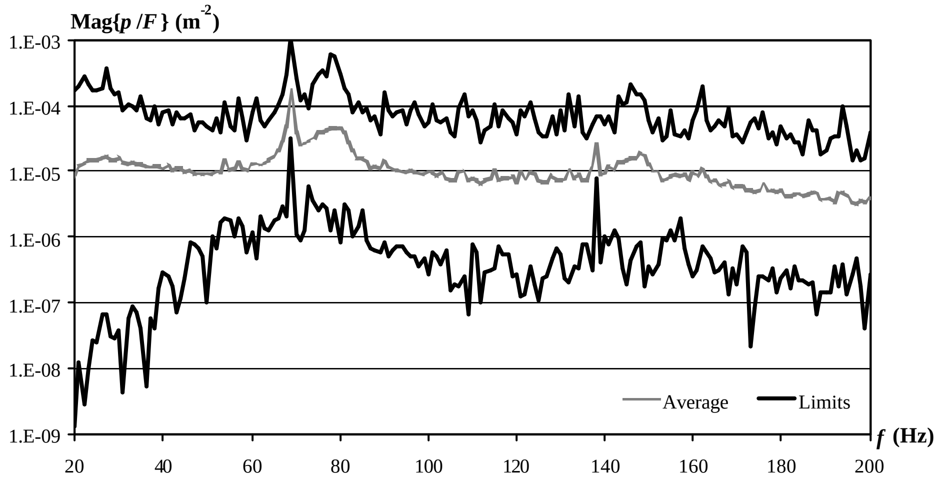

Figure 4 – Variability of the transfer function between the impact force and the sound pressure at (x, y, z) = (0.20; 0.20; 0.20)

Material properties and floor thickness

The effect of material properties was studied for concrete floors with thicknesses *h* between 100 and 300 mm, *E* between 27 GPa and 37 GPa, *r* between 2,300 and 3,700 kg/m^3 and *n* between 0.15 and 0.25. The variables were combined in order to provide 81 different floors with dimensions identical to those used for studying the effect of impact location. The obtained results are similar to those described in a previous paper [2]. In general, the variability of the point mobility is -10/+6 dB around the average mobility, but the differences can go up to -15/+8 dB for certain frequencies. If the floors are grouped by thickness, then the variability reduces to -4/+3 dB, with maximum differences as high as -5/+5 dB for *h* = 100 mm or -10/+6 dB for *h* = 300 mm. The influence of the Poisson's ratio in mobility variability is less than 1 dB and therefore its effect is more evident in shifting eigenfrequencies. In general, the density can alter the floor mobility by -3/+2 dB, although for certain frequencies, the floor mobility can be altered by -7/4 dB. The elasticity modulus has an effect on floor mobility that is analogous to that of the density.

Edge conditions

Laboratory and *in situ* experimental validation of equation (1) for floors with different combinations of clamped and simply supported edges indicated that if the floor is considered with the dimensions of the room below, then a simply supported edge condition is appropriate for low frequencies. This conclusion, which is in agreement with other works [3], simplifies significantly the floor models.

Floating floors

The model for the amplitude of the steady state forced velocity response of floors with floating floors was derived from natural mode analysis [4, 5] and is given by

$$v_{x,2}(y, z, t) = \mathrm{j}\,\frac{4\omega F}{m_1'' bc} \sum_{m_1 n_1 = 1}^{\infty} \left[\frac{\omega_{20}^2\, \varphi_{m_1 n_1}(y_0, z_0)\, \varphi_{m_1 n_1}(y, z)}{\left(\omega_{\mathrm{I},m_1 n_1}^2 - \omega^2\right)\left(\omega_{\mathrm{II},m_1 n_1}^2 - \omega^2\right)} \right] \mathrm{e}^{\mathrm{j}\omega t}, \tag{3}$$

where $\left(\omega_{\mathrm{I},m_1 n_1}^2 - \omega^2\right)\left(\omega_{\mathrm{II},m_1 n_1}^2 - \omega^2\right)$ is given by

$$\begin{aligned} &\left[\omega_{1,m_1 n_1}^2 \left(1 + \mathrm{j}\,\eta_1\right) + \omega_{10}^2 \left(1 + \mathrm{j}\,\eta_0\right) - \omega^2\right] \times \cdots \\ &\cdots \times \left[\omega_{2,m_1 n_1}^2 \left(1 + \mathrm{j}\,\eta_2\right) + \omega_{20}^2 \left(1 + \mathrm{j}\,\eta_0\right) - \omega^2\right] - \omega_{120}^4 \left(1 + \mathrm{j}\,\eta_0\right)^2, \end{aligned} \tag{4}$$

with $\omega_{1,m_1 n_1}$ and $\omega_{2,m_1 n_1}$ being respectively the eigenfrequencies of the base and floating floors alone; $\omega_{10} = \sqrt{s''/m_1''}$ and $\omega_{20} = \sqrt{s''/m_2''}$ with s'' being the stiffness of the resilent layer; and m_1'' and m_2'' being the masses per unit area of the base and floating floors, respectively. The eigenfrequencies $\omega_{1,m_1 n_1}$ were determined for a free plate as proposed by Warburton [6, 16]. Equation (3) was experimentally validated in laboratory and *in situ* for concrete floors with different types of floating floors. The improvement in impact sound transmission occurs only for frequencies well above

$$f_{12} = \frac{1}{2\pi} \sqrt{s'' \left(\frac{1}{m_1''} + \frac{1}{m_2''}\right)} \quad \text{(Hz)}. \tag{5}$$

For frequencies in the vicinity of f_{12} there actually occurs an amplification of floor vibration which will lead to higher sound pressure levels in the room below. In the cases studied, f_{12} was generally in the range 20 – 200 Hz and the amplification of vibration in the vicinity of f_{12} reached values as high as 7 dB.

Room Characteristics

In the following, the effects of room dimensions, indoor air conditions and absorption by room surfaces on impact sound transmission will be discussed. The effect of the listener position will also be considered.

Room dimensions

The influence of room dimensions was studied for small rooms. Volumes of 15 and 20 m^3 were considered. A total of 63 room configurations were considered. The height of the rooms was varied from 2.15 to 2.85 m. If the rooms are grouped in terms of volume, then the variability of impact sound transmission is -13/+8 dB and -22/+12 dB around the average for the 15 and 20 m^3 rooms, respectively. Maximum differences are respectively -40/+18 dB and -55/+25 dB. If the rooms are grouped in terms of floor area (or room height), then impact sound transmission variability decreases to -10/+6 dB around the average for 15 m^3 rooms with a = 2.15 m and to -7/+5 dB for a = 2.30 m. The same trend is observed for 20 m^3 rooms, for which the variability of impact sound transmission is -13/+7 dB for a = 2.15 m and -7/+4 dB for

a = 2.85 m. These results are in agreement with those obtained when studying the effect of floor dimensions. Differences to the average impact sound transmission can reach -48/+14 dB for both room volumes. Grouping floors by aspect ratios gives a variability of impact sound transmission of -8/+5 dB with differences as high as -38/+13 dB for 15 m^3 rooms. For 20 m^3 rooms, the variability of impact sound transmission is in general -12/+7 dB around the average but can go up to -40/+15 dB.

Indoor air conditions

The velocity of sound propagation in air, c_0, depends on the air temperature q. Standards and regulations dealing with thermal comfort in dwellings consider comfort air temperatures between 20 and 25 ºC. Assuming that thermal comfort requirements are not always satisfied, q can be assumed to vary within 15 to 30 ºC, with the average being q_m = 22.5 ºC, and therefore $c_0 = 331.5\sqrt{1 + q/273.15}$ varies within 340.5 to 349.2 m/s. The resulting variation of impact sound transmission is ±0.1 dB and therefore can be neglected for practical applications. However, the eigenfrequencies of the sound field also depend on c_0. Consequently, the impact sound transmission spectra can be shifted 1.3 % around the average (obtained for q_m). This shifting is only important for the higher frequencies. In the present study, the highest frequency of interest is 225 Hz, which means that a 225 Hz room eigenfrequency can vary between 222 and 228 Hz. The air density, r_0, depends on q and on the relative humidity *RH*. Comfort requirements generally consider *RH* around 50 % but as ventilation conditions in dwellings are not always complying with requirements, *RH* is assumed to vary within 20 to 80 %. Therefore, the variability of r_0 is ±3 % around the average density $r_{0,m}$ = 1.188 kg/m^3. Thus, the variability of impact sound transmission is ±0.3 dB around the average, which is negligible.

Absorption by room surfaces

According to Vieira de Melo [7], absorption below 100 Hz in dwellings is very small. It has been shown that although furniture might shift room eigenfrequencies, changes in the room frequency response are lower than 5 dB [7, 10]. In the present study, a global absorption coefficient of 0.02 was assumed for all cases studied.

Listener position

Present standards [14, 9] recommend that impact sound pressure levels are averaged for microphone positions in the middle of the rooms. However, the sound field in small rooms exhibits a modal behaviour at low frequencies and therefore those averages become meaningless. In the present study, it was assumed that sound pressure levels should be always measured at one of the room corners, (x, y, z) = (0.20, 0.20, 0.20) because that is the position at which the response generally contains a contribution from every room mode. This approach also has been suggested by other authors [8].

SUMMARY

A parametric survey has been conducted on the factors affecting low frequency impact sound transmission. It was proved that the same floor, when installed in different rooms, can lead to impact sound pressure levels that differ as much as 20 dB from the average. The height of the room has less influence in the variability of impact sound transmission because it is generally within 2.40 – 2.70 m. However, a peak will always occur in impact sound transmission at frequencies corresponding to the first vertical (normal) room mode, which generally occur between 60 and 75 Hz.

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