EXPERIMENTAL TEST METHODOLOGY TO EVALUATE SOUND PROPAGATION PATHS BETWEEN INTERIOR SPACES OF BUILDINGS

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When is detected *in situ* the existence of poor sound insulation, typically the non-compliance with the acoustic requirements of buildings, between two spaces – source and receiver - and if we want to solve the problem, it is necessary to know which sound paths most contribute to the difference of sound levels between these spaces. However, the classical sound insulation measurement does not make this distinction, it only provides the difference in sound levels. In order to overcome this difficulty, a new test methodology is proposed to estimate the sound propagation paths between building rooms, generated by sound sources located in the interior. The proposed methodology is based on the use of vibration measurements of structural elements (slabs) and non-structural elements (partition walls) to estimate the sound field in the receiver space, together with sound measurements to estimate the sound field in the source space. With this alternative methodology to determine the sound insulation of a space, it is intended to obtain more rigorous results with respect to: i) determination of the contribution of each of the structural paths, in a certain sound isolation, in order to define the sound paths in which an acoustic rehabilitation intervention is most effective; ii) determining the possible existence of airborne paths that contribute to the reduction of sound insulation. In order to validate the proposed methodology, *in situ* sound insulation measurements were carried out, according to the applicable standards of ISO 16283 series, and vibration measurements of the separator elements (floor, ceiling, side walls) of interior spaces in existing buildings.

Keywords: flanking transmission; vibration measurements; radiation factor; acoustics rehabilitation.

1.   Introduction

The existence of noise causes the need to establish acoustic insulation requirements in the building elements of dwellings, in order to minimize the effects of discomfort between adjacent rooms. This minimization can be achieved most effectively by intervening in the sound transmission paths, restricting the sound propagation. This propagation can occur directly by the separating element or through some eventual weak point in insulation (air cavity or building defect), but it can also occur

through another existing transmission path, called flanking transmission. The propagation of the sound energy by the flanking paths occurs through the elements adjacent to the separating element and contributes to the increase of the sound level in the receiver room, thereby reducing the global acoustics insulation. That is to say, a constructive element, belonging to the enclosure of a room, with a poorer acoustics performance is enough to be able to significantly reduce the global sound insulation, no matter how well is the acoustical performance of the main (separating) element. The fact is that acoustic linings are sometimes ineffective because is forgeted the flanking paths. Therefore, it is only through the knowledge of the "sound pressure levels" of the different paths, between the source and the receiver, that we can know how to intervene in an efficient manner, namely whether it is sufficient to intervene only in the separating element, if it is necessary to intervene also in the flanking paths, or if there is a relevant aerial path.

The classical acoustics insulation measurements do not make this distinction, it only makes the difference in sound levels between the source and receiver rooms.

In order to overcome this difficulty, a new test methodology is proposed with the aim of estimating the paths of sound propagation between rooms.

For the development and validation of the proposed method it will be necessary to compare the average sound levels obtained through the direct sound pressure levels measurements, typical of acoustics insulation measurements, with the expected sound pressure levels resulting from the vibration measurements of the different elements of the receiver room (separating wall, exterior wall, interior wall, ceiling and floor).

Measurements will be made between adjacent rooms of different buildings, with the emission of noise in one of the rooms (source room). The different study cases were chosen to correspond to different architectural geometries and different constructive solutions, to allow the analysis of different situations.

2.   Vibration and sound pressure levels

For the accomplishment of this work the following standards were consulted and followed:
- ISO 16283-1 [1] which establishes methods for *in situ* measurements of sound insulation;
- ISO 717-1 [2] which addresses the procedures for determining the sound insulation index;
- ISO 12354-1 & ISO-12354-5 [3,4] describing the methods for predicting sound insulation and noise levels;
- ISO 10848-1 [5] which specifies measurement methods to characterize the flanking transmission of one or several construction components. These measurements are performed in laboratory or *in situ*.
- ISO 140-4 [6] wish specifies equations to transform vibration measurements in sound pressure levels.

Based on the mentioned standards, the present study focuses mainly on the determination of sound pressure levels related to sound power levels (vibration) of elements. In the area of acoustics these quantities are represented by decibel (dB), based on logarithmic scale. Using the decibel scale related to reference values that represent the hearing threshold, the size of the values scale is reduced.

Although the audible frequency range is between 20 Hz and 20 kHz, the analyzes performed in this work are restricted to the frequency range between 100 Hz and 3150 Hz, since it is the most worrying range in terms of human effects. The treatment of measurement records and the analysis of sound pressure levels are performed in 1/3 octave bands designated by their central frequency.

In the case of direct sound pressure levels measurement, for each frequency band i, the sound pressure levels, L_i, are determined from the mean energy of the values obtained in the n different positions of the microphone (L_{ij}), using expression [1]:

$$L_i = 10\log\left(\frac{1}{n}\sum_{j=1}^{n} 10^{L_{ij}/10}\right).[\text{dB}] \tag{1}$$

In the case of vibration measurement, the sound pressure levels are deduced for the different sound paths representing the different radiations between two rooms, associated with the different constituent elements. It is therefore important to determine radiation factors for each of them, and thereby ensure that the vibration-associated sound pressure levels are values that best reflect the behaviour of the building elements in order to be compared with the sound pressure levels of direct measurement. According to EN 12354, part 1 [3], the radiation factors can be calculated for a forced transmission (forced sound waves) or for a free transmission (free sound waves).

Figure 1 shows the different sound transmission paths, which arise from the various combinations of elements in the two rooms (separating element and elements adjacent to the separating element).
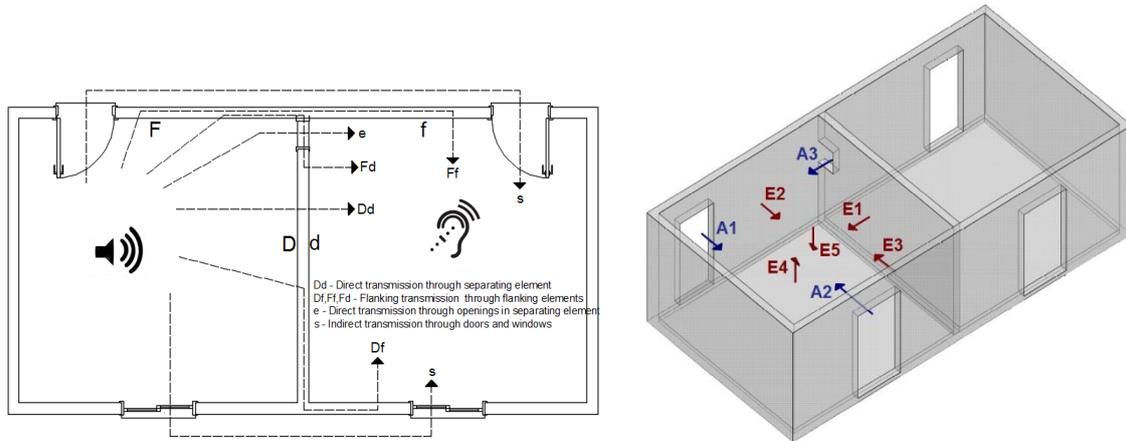
Figure 1: Definition of sound transmission paths between two rooms.
(a) in plan such as EN 12354-1 [3] (b) arrival paths in 3D.

The two images reflect the same paths, but with different notations, and can be divided into:
Structural Paths:
- E1 (Dd, Fd): irradiated in the receiver through the separating wall;
- E2 and E3 (Df, Ff): irradiated in the receiver through the side walls;
- E4 and E5 (Df, Ff): irradiated in the receiver through the floor and ceiling.

Aerial Paths:
- A1 and A2 (s): through windows and doors;
- A3 (e): through possible opening in the separating wall.

The L_R sound pressure level measured in the receiver can be written as the energetic sum of the sound pressure levels associated with the structural paths (L_{Ei}) and the air paths (L_{Ai}) between the source and the receiver room, defined in Fig. 1:

$$L_R = 10\log\left(\sum_{i=1}^{n} 10^{L_{Ei}/10} + \sum_{i=1}^{m} 10^{L_{Ai}/10}\right) \tag{2}$$

For a diffuse sound field, the sound pressure level L_R in the receiver room due to the radiation of an element k can be obtained by the expression [4,7]:

$$L_{R,k} \approx L_{w,k} + 10\log\left(\frac{T}{V}\right) + 14 \tag{3}$$

where:
- T: reverberation time in the receiver room;
- V: volume of the receiver room.

The sound power level L_w of an element k is given by the expression:

$$L_{w,k} = 10\log\left(\frac{W_k}{W_{ref}}\right) \text{[dB]} \tag{4}$$

in which the power W_k emitted by an element k, with area S_k, in the receiver room, can be determined by the expression [6]:

$$W_k = \rho c S_k \overline{V_k^2} \sigma_k \tag{5}$$

where:
- V_k^2: spatial mean square of the value of the normal vibration velocity on the surface of the element.
- σ_k: radiation factor;
- ρc: characteristic air impedance.

The average level of the vibration velocity, L_v, of the separating wall and the remaining elements of the receiving room, when the structure is excited by air, can be given by [5]:

$$L_{v,k} = 10\log\left(\frac{v_1^2 + v_2^2 + \cdots + v_n^2}{n \cdot v_0^2}\right) [\text{dB}] \tag{6}$$

where:
- v_1, v_2 ... v_n: root mean square values of the normal vibration velocity at the surface for n different points;
- v_0: reference vibration velocity ($v_0 = 10^{-9}$ m/s).

It turns out that the sound power level L_w of an element k can take the form of the following equation:

$$L_{w,k} \approx L_{v,k} + 10\log(S_k \sigma_k) - 33 \tag{7}$$

Starting from Eq. (2) and admitting that:

$$L_{Ei} = L_{Rk} \tag{8}$$

It is assumed that the sound pressure level can be calculated by:

$$L_R = 10\log\left(\sum_{k=1}^{n} 10^{L_{Rk}/10} + \sum_{i=1}^{m} 10^{L_{Ai}/10}\right) \tag{9}$$

In order to measure sound pressure levels and vibration the following equipment was used:
- Sound level meter (class 1), brand "Larson Davis" model "SoundTrack LxT", with data processing through the software "G4 LD Utility V2.2";
- Sound amplifier, brand "Fender";
- Vibration analyzer (class 1), brand "Svantek" model "SVAN946A", with piezoelectric accelerometer, brand "Dytran" and model "3185D".

The procedure of the proposed method can be divided into three essential phases:
1) Vibration tests of the building elements constituting the receiver part, which involves:
   i. Vibration measurements made on the separating wall and other elements connected to the separating wall, inner wall, outer wall, ceiling and floor;
   ii. Deduce sound pressure levels from measured vibration velocities;
   iii. Compare values associated with each element, thus establishing the contributions of each of them;
2) Measurements of the sound pressure level directly in the source and receiver rooms;
3) Comparisons of the two types of measurements performed in the previous points.

In the following sections the proposed method will be applied to two study cases.

3. Study case I

The building of case study I corresponds to a school building, consisting of two raised floors. The room under study consists of slabs and walls in lightweight concrete blocks (thermal blocks and normal blocks). The separating wall has a thickness of 15 cm dividing two classrooms.

Figure 2 shows the results of the vibration measurements performed on the separating wall and the remaining elements of the receiver room in terms of the sound pressure levels generated (vibration) in the receiver room.
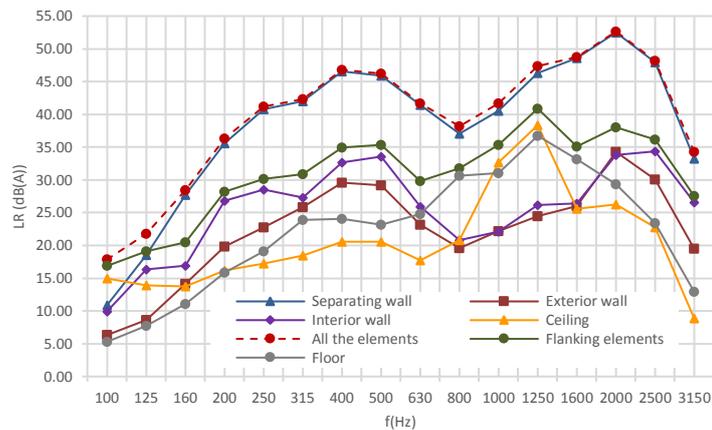
Figure 2: Sound pressure levels generated by the vibration – study case I.

Figure 3 shows the comparative analysis between the values of the sound pressure level obtained by the two methods of measurement, direct and indirect, through their overlap over the frequency range considered.
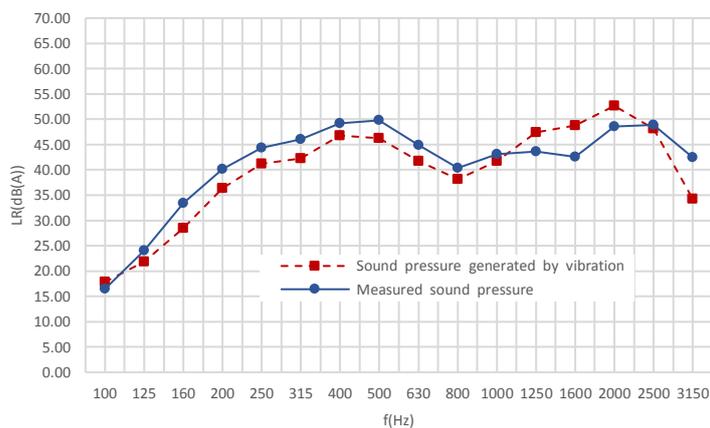
Figure 3: Expected sound pressure levels (vibration) and measured – case study I.

4. Study case II

Case study II corresponds to a building consisting of three upper floors. The room under study is composed of solid reinforced concrete slabs and bored ceramic brick walls. The separating wall consists of a single 15 cm dividing the two rooms.

Figure 4 presents the sound pressure levels determined from the vibration measurements and Fig. 5 shows the comparative analysis between the values of the sound pressure levels obtained by the two measurement methods (vibration prediction method and direct measurement method).
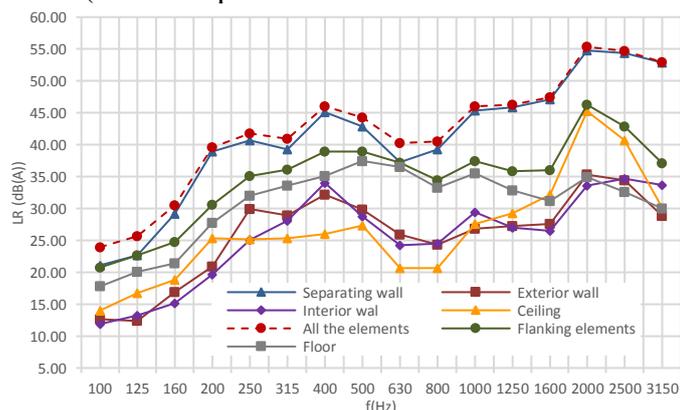
Figure 4: Sound pressure levels generated by the vibration – study case II.
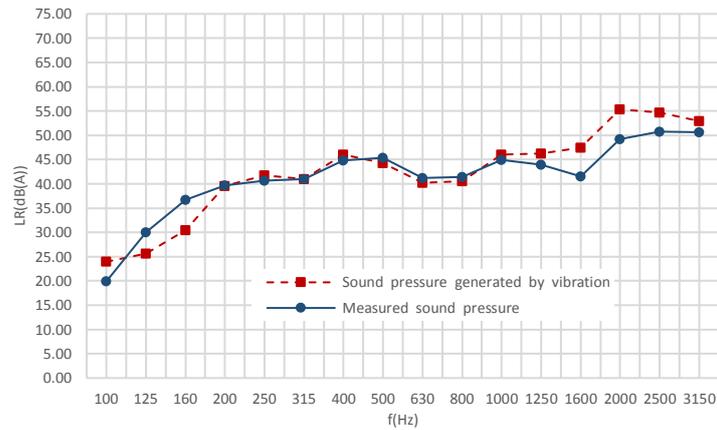
Figure 5: Expected sound pressure levels (vibration) and measured – case study II.

5. Results analysis

For each of the study cases, of the previous section, were calculate the broad band sound pressure levels related with each path, as shown on Table 1, related with the frequency values shown on Figs. 2 and 4.

Table 1: Sound levels of the flanking elements for the two study cases

Constructive element	Sound Pressure Levels [dB(A)]	
	Study case I	Study case II
Exterior wall	39	41
Interior wall	41	42
Ceiling	41	45
Floor	40	47
Total flanking	**46**	**51**
Separating wall	57	60
Global	**57**	**60**

From the Table 1 we can see that the great contribution for the global value comes, as usual, from the separating wall. Knowing the contribution of each path allows to decide better where we need to intervene to achieve a certain global sound reduction.

For example, if we want to reduce 10 dB on the global value, it is enough to intervene on the separating wall, but it is not enough to reduce just 10 dB on the separating wall (we need to reduce 16 dB in the study case I and 27 dB on the study case II). Once the difference between the total flanking values and the global values are 11 dB in the two cases, it is impossible to reduce in more than 11 dB the global value just reducing the separating wall value.

In Table 2 is shown different reductions examples to achieve reductions of 5 dB, 10 dB, 20 dB and 25 dB on the global value, showing the type of intervene needed on each path.

Table 2: Examples of global sound reductions from different element sound reduction

Constructive element	Sound Pressure Levels [dB(A)]									
	Study case I					Study case II				
Global reduction intended	5	10	15	20	25	5	10	15	20	25
Exterior wall	39	39	39-4= 35	39-18= 21	39-22 = 17	41	41	41-3 = 38	41-18 = 23	41-22 = 19
Interior wall	41	41	41-6 = 35	41-20 = 21	41-24 = 17	42	42	42-4 = 38	42-19 = 23	42-23 = 19
Ceiling	41	41	41-6 = 35	41-20 = 21	41-24 = 17	45	45	45-7 = 38	45-20 = 25	45-24 = 21
Floor	40	40	40-5 = 35	40-19 = 21	40-23 = 17	47	47	47-9 = 38	47-20 = 27	47-24 = 23
Separating wall	57-6 = 51	57-16 = 41	57-20 =37	57-20 =37	57-26 = 31	60-7 = 53	60-27 = 33	60-20 = 40	60-20 = 40	60-26 = 34
Global	**52**	**47**	**42**	**37**	**32**	**55**	**50**	**45**	**40**	**35**

6.   Conclusions

In this work, an alternative method was proposed to determine the noise generated in a building room due to sound sources in adjacent room. The objective of the method is to estimate not only the sound pressure levels in the receiver room but also and mainly to understand the contribution of each sound propagation path. Only with this knowledge is possible to intervene on the right way for acoustic space rehabilitation situations.

From the analysis of the results presented in the previous sections it can be affirmed that the alternative method proposed in this work leads to acceptable results in both study cases. It should be noted that the analyzed buildings have different structural elements: one is composed of slabs and walls of lightweight concrete blocks and the other by solid reinforced concrete slabs and walls in bored ceramic brick. In both cases the sound pressure levels predicted by the proposed method (vibration measurements) fit reasonably well to direct sound pressure levels measurements.

The small discrepancies between the two methods may be due to the existence of air transmission paths.

Although the acceptable results obtained in this work, it is important to study exhaustively the problem of the most appropriate radiation factor to be considered for predicting the sound pressure levels from vibration measurements: free regime radiation, forced regime radiation or simply consider a radiation factor of 1.

As a final conclusion, it should be noted that, although it is necessary to analyze more study cases, the proposed methodology was adequate for the analyzed buildings. In this way it is possible to perceive in which elements there will be a greater transfer of sound energy, and so rehabilitate the space acoustically in a more effective way.

REFERENCES

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7   International Standard, ISO 3382-2, *Acoustics: Measurement of room acoustic parameters; Part 2: Reverberation time in ordinary rooms*. 2008.