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Pressure Level Standard Deviation at Low Frecuencies: Effect of the Wall Vibrational Field

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Knowledge of the uncertainty of measurement of testing results is important when results have to be compared with limits and specifications. In the measurement of sound insulation following standards ISO 140-4 and 140-5 the uncertainty of the final magnitude is mainly associated to the average sound pressure levels L_1 and L_2 measured. However, the study of sound fields in enclosed spaces is very difficult: there are a wide variety of rooms with different sound fields depending on factors as volume, geometry and materials. A parameter what allows us to quantify the spatial variation of the sound pressure level is the standard deviation of the pressure levels measured at the different positions of the room. Based on the analysis of this parameter some results have been pointed out: we show examples on the influence of the microphone positions and the wall characteristics on the uncertainty of the final magnitudes mainly at the low frequencies regime. In this line, we propose a theoretical calculus of the standard deviation as a combined uncertainty of the standard deviation already proposed in the literature focused in the room geometry and the standard deviation associated to the wall vibrational field.

Keywords: building acoustic, uncertainty.

1. Introduction

The Building Acoustics Noise Codes of the different European countries establish values and limits for the different acoustic magnitudes. In this sense, an essential aspect of an "in situ" measurement is to give the measured magnitude and also its associated uncertainty. Normally, the uncertainty evaluation process encompasses a number of influence quantities that affect the result obtained for the measurand (International Organization for Standardization [ISO], 1995). On the other hand, the different parameters used to describe the acoustic insulation are based on the difference of sound pressure levels between the source and the receiving rooms. So, the measurement procedure following standards ISO 140 requires the measured of time-averaged sound pressure levels, L_1 and L_2, at a number of different points in the room and their averaged. The maximum uncertainty of the measurand is mainly coming from these averages.

Outside of the laboratory, in real situations there are a wide variety of rooms with different sounds fields. The transmission of sound between two contiguous rooms depends on multiple factors as the separation elements, as the connections between surrounding elements. In the same line, the change in level due to the presence of a façade depends on the sound propagation from the source, on the diffraction effects (Hopkins, 2007). There are some theoretical models for predicting the sound insulation of walls (Crocker, Price, 1969; Leppington *et al.*, 1987; Sewell, 1970; Villot *et al.*, 2001). The theory of Cremer for thin walls above the critical frequency is still in use (Cremer, 1942). In this line, J.L. Davy (2009a; 2009b; 2009c; 2009e; 2010) published several works which described the gradual development of a simple theoretical model for predicting the sound insulation of building partitions. In this model some of the approximations of the Cremer's theory are removed. The single sided radiation efficiency of an infinite panel is replaced with that for a finite panel. The experiments are performed on a finite size wall while the theory assumes a wall of infinite extent. Also the effect of the resonant response and radiation of the wall panels is included.

Furthermore it is difficult to establish general rules on the behaviour of the L_1 and L_2 averages mainly in the low frequency regime. In this sense, it is useful and necessary to look at the spatial variation of L_1 and L_2 time-averaged sound pressure levels, both in theory and in practice. We consider the standard deviation as an adequate parameter to describe the spatial variation of the sound pressure levels in a space. In the last years some theoretical models have been proposed in the literature to explain the frequency dependence of the standard deviation of the sound pressure levels in decibels (Davy, 1981; 1990; 2009d; Jacobsen, Rodriguez Morales, 2010). The equations are depending on the excitation noise, pure tone or continuous spectra, and on the distribution of the modal frequency spacing. In particular, in the region of low modal overlap, the formulas are not well established. In the regions where the modal frequency is almost constant is large for a pure tone and becomes smaller when the source band width increases. For pure tones, the existing theory is essentially due to Lyon (1969) and Davy (1981). Lyon assumed that the modal frequencies have a Poisson distribution. Some years later, Davy extended Lyon's theory by deriving a more general expression of the power transmission functions averaged over multiple source and receiver positions, assuming a "nearest neighbour" distribution of the modal frequencies. Weaver (1989) modified Davy's expression so as to take account of a modal frequency spacing described by the Gaussian orthogonal ensemble theory, which is now generally accepted. Finally, Davy (1990; 2009d) described and discussed the modified theory. For multitone excitation, in general, the probability density function is quite complicated (Hopkins, 2007).

During the last years, our laboratory has performed a considerable number of "in situ" measurements following the procedures described in the international standards ISO 140-4 (ISO, 1998a) and 140-5 (ISO, 1998b). These "in situ" measurements have been carried out in different volume ranges and geometry sites. We have analyzed these "in situ" measurements based on the standard deviation associated to the L_1 and L_2 sound pressure levels measured at the different microphone positions in a room. From the analysis of the frequency dependence of the L_1 and L_2 standard deviations some interesting aspects have been revealed. For example, although the international standard was applied the value of the final magnitude mainly at low frequencies is dependent on the microphone positions in the partition. This fact is associated to the existence of no exactly diffuse sound fields in the source and receiving rooms. Besides geometrical spacing properties the characteristics of the constructive elements are affecting to the standard deviation: we show results in which the L_2 pressure level standard deviation fits well to a standard deviation expression that combines the geometrical configuration of the room and the vibrational field associated to the wall across the main sound transmission is happening.

2. Experimental method and measurements

2.1. "In situ" measurement procedure

The standard ISO 140 describes how the "in situ" measurements of acoustic insulation of buildings and constructive elements must be carried out. In particular, the "in situ" measurements of airborne sound insulation between rooms have been performed following the procedure described in Part 4 of the international standard (ISO, 1998b). The L_1 and L_2 sound pressure levels have been calculated as the energetic average of the levels measured in ten microphone positions, five different positions for each position of the loudspeaker. The loudspeaker has been sited near the corners of the source room.

The façade sound insulation measurements have been performed according to ISO 140-5 (ISO, 1998a). This standard specified two methods for the measurement of the insulation of the façade elements and the façades. The L_2 values and so, the standard deviations, shown in this work correspond to the case of "in situ" measurements of façades following the loudspeaker procedure. In this case, the L_2 sound pressure level has been calculated as the energetic average of the levels measured in five microphone positions.

For both procedures, the microphone positions must be distributed uniformly in the maximum allowed space inside the room. Besides, these positions have to be spaced and fixed taking in consideration the limit distances specified in the standards. The distances must be higher than 0.7 m between microphone positions, higher than 0.5 m between any microphone position and the wall surfaces of the room or any object and higher than 1 m between any microphone position and the loudspeaker. Then, the average value of the sound pressure level calculated for the rooms combines corner microphone positions with positions in the central region of each room. In principle, this method provides a good estimate of the room average sound pressure level. The sound pressure levels at the different positions have been measured using a frequency range between 100 and 5000 Hz.

The results presented in this work are based on "in situ" measurements performed by different technicians of our laboratory following the procedures describe above. Most of the measurements have been carried out in partitions of various geometries and structural characteristics of houses of different Spanish cities. The volume of these partitions is ranging between 20 and 100 m^3. In this interval and in steps of 5 m^3 we have chosen around 50 partitions for each volume. In Fig. 1 we have shown the distribution of DnTw values of these partitions. Other results are derived from the analysis of repeatability test developed by our laboratory or from the participation in intercomparison activi-

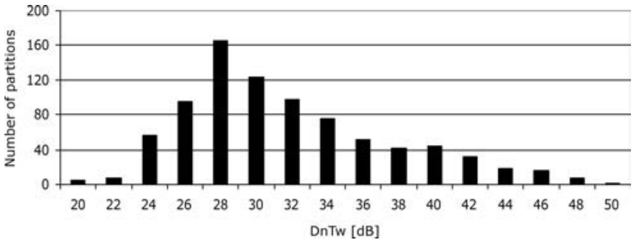


Fig. 1. Distribution of DnTw values of the partitions analyzed.

ties. For this type of activities, the microphone and the loudspeaker positions have been chosen again, in a random way for each new repetition of the "in situ" measurement (ISO, 1991).

2.2. Calculus of the standard deviation

The room average sound pressure level is defined as the energy average level that is calculated using all possible microphone positions, L_{1j} or L_{2j}, in the room following the equation:

$$\overline{L}_{1,2} = 10\log\left(\frac{1}{n}\right)\sum_{j=1}^{n} 10^{\frac{L_{1j},L_{2j}}{10}}. \tag{1}$$

From the average sound pressure level, the standard deviation of the L_1 an L_2 pressure levels measured at the different points of the source or receiving rooms has been estimated according to the next expression:

$$\sigma(L_{1,2}) = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(L_{1j,2j} - \overline{L}_{1,2})^2}. \tag{2}$$

For the next discussion, we consider this parameter as an appropriated descriptor of the characteristics of the room sound field.

3. Results and discussion

To understand the results derived from the "in situ" measurements is fundamental to know the sound field inside a room. However, outside of the laboratory we found a wide variety of sound fields whose analysis is complicated and from a theoretical point of view mainly supported by two ideal models, diffuse and modal sound fields. In this work, we propose to analyze the spatial variations of the sound field inside a room based on the standard deviation of the pressure levels, L_2 and L_1, measured at the different microphone positions. This parameter, easy to calculate (see Subsec. 2.2), is directly derived from the "in situ" measurements, so the geometrical and structural characteristics of the partition are reflected or captured in its value. Continuing with this approach, it would be necessary to consider also the sound pressure level temporal variations. Nevertheless, it has been assumed that the uncertainty related to the temporal average associated to the sound pressure level at one microphone position is depreciable compared to the spatial variations between microphone positions.

Previously we have analyzed in detail the behaviour of the L_2 standard deviation as frequency function for a wide range of partition volumes (Navacerrada *et al.*, 2010) and reverberation times. At intermediate frequencies, ranging between 400 and 4000 Hz, the L_2 standard deviation is independent on the room volume and practically independent on the reverberation time so, on the geometrical and structural qualities of the partition. For this frequency range, the standard deviation is in the majority of the "in situ" measurements analyzed close to 1 dB. The highest values of the L_2 standard deviation have been calculated at low frequencies, below 400 Hz. In this regime, the standard deviation values are clearly dependent on the frequency and the frequency tendencies observed are not completely explained by the theoretical models actually published in the literature. In particular, at medium and high frequencies where the modal overlap is high, Jacobsen and Rodriguez-Morales (2010) based on a simple model of sums of waves from random directions having random phase relations predict that, above the Schroeder frequency, the relative variance of the mean-square sound pressure approaches unity. However, below this frequency, the relative variance is much larger, particularly if the source emits a pure tone.

Furthermore the frequency dependence of the standard deviation requires our attention to understand the low frequency uncertainty associated to the final magnitudes derived from the "in situ" measurements. In the next sections we will analyze the influence on the standard deviation frequency dependence of the two followings factors: the microphone positions chosen inside the room and the structural characteristics of the constructive elements that constitute the partition.

3.1. Microphone positions

The standard deviation calculated for "in situ" measurements carried out by different operators in the same partition and following the standard procedures has been compared. An example is shown in Fig. 2: the L_2 standard deviation as frequency function calculated for five "in situ" measurements following ISO 140-4 has been plotted. The "in situ" measurements were carried out for three different operators in the same partition and under the repeatability conditions describe in Subsec. 2.1. The standard deviation is independent on the microphone positions chosen for the "in situ" measurement above the 400 Hz. However, their values can be very different in the frequency range between 100 and

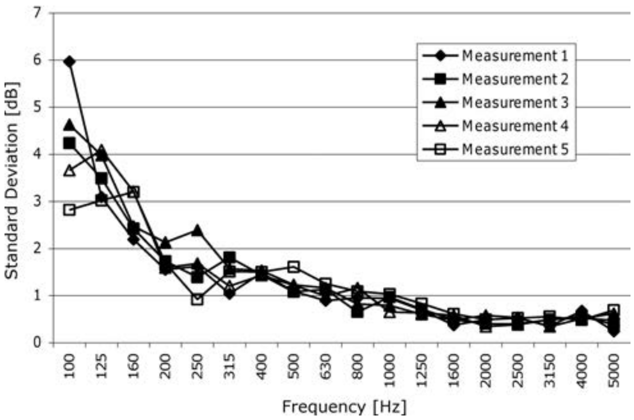


Fig. 2. L_2 standard deviation following ISO 140-4 corresponding to five "in situ" measurements carried out by three operators under repeatability conditions.

400 Hz. These differences can be traduced in differences of 2–4 dB on the value of the final magnitude in this region. The operator has to know that these differences can be happening depending on the microphone positions chosen although the standard procedure has been followed.

3.2. *Influence of partition structural characteristics*

In this section, some representative examples of "in situ" measurements have been shown to illustrate the effect on the standard deviation of the characteristics of the constructive elements across the main sound transmission is taking place during the measurement.

We have compared the L_2 and L_1 standard deviation values versus frequency of "in situ" measurements following ISO 140-4. Basically two different behaviours have been found: 1) the values of the L_2 standard deviation calculated for the receiving room are smaller than the L_1 standard deviation values calculated for the source room, or 2) the standard deviation values calculated for L_2 and L_1 are almost coincident. In Fig. 3 an example of these two general behaviours has been plotted. The curves plotted in Fig. 3a correspond to the case 1, an example of the case 2 has been represented in Fig. 3b.

Michelsen (1982) and Olesen (1992) have investigated the standard deviation of sound pressure levels in the source and receiving rooms for sound insulation measurements in both, the laboratory and the field. From a theoretical point of view they suggest that we had to consider different ways of excitation of the source and receiving room modes. While in the source room we have excited with a single point source, all the room surfaces radiate sound into the receiving room: one or more room surfaces, separating and flanking elements, are acting as the sound sources. Radiating surfaces in the receiving room can be represented as an equivalent number of uncorrelated point sources, hence the larger the surface, the larger the number of point sources. In principle, that would imply a more diffuse field in the receiving room because of the increased number of uncorrelated point sources and standard deviation values lower than in the source room. This argument would explain the behaviour of the example represented in Fig. 3a. However, in practice, the standard deviation measured for the receiving room is not always smaller than for the source room. As we have previously mentioned in this section, in a lot of situations the behaviour plotted in Fig. 3b has been found: we have calculated values very similar for L_1 and L_2 standard deviation versus frequency. We believe that this similarity observed between the standard deviation curves calculated for the source and receiving rooms could be attributed to a strong coupling between both rooms via the separating wall. When two or more rooms are joined together in such a way that energy can be transmitted between them, the rooms can constitute a coupled system. A measurement of this coupling, so of the transmitted energy, could be the sound pressure level difference, $L_1 - L_2$, between

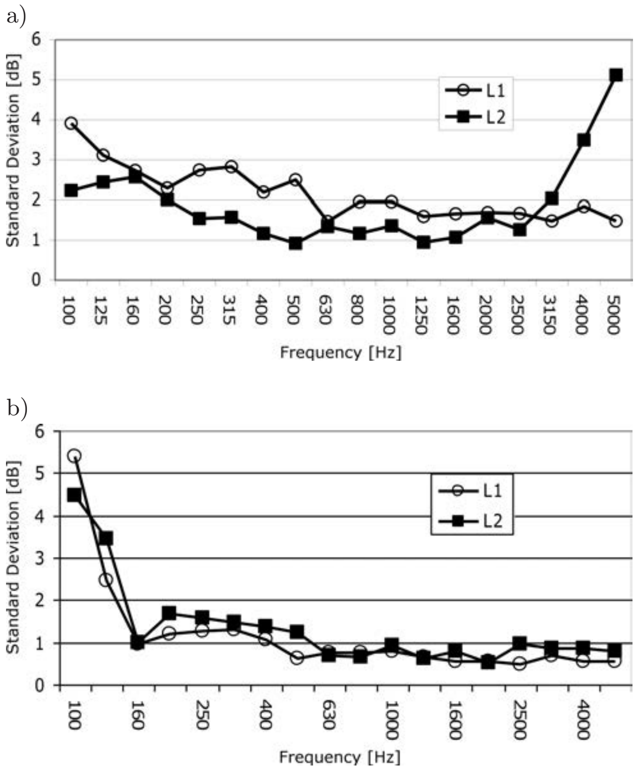


Fig. 3. Two examples in which the L_2 and L_1 standard deviations measured versus frequency following ISO 140-4 are compared. In example (a) the L_2 standard deviation values in the receiving room are smaller than the L_1 standard deviation values in the source room. In Fig. 3b the standard deviation in both, source and receiving rooms, are almost coincident.

rooms. In Fig. 4 we have plotted such difference for the two examples shown in Fig. 2. The smaller $L_1 - L_2$ difference corresponds to the Fig. 3b. The higher the energy transmitted between rooms, the higher the coupling and so similar behaviour of the L_1 and L_2 standard deviation versus frequency is calculated.

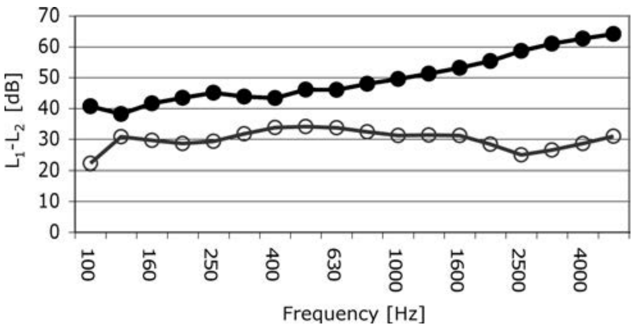


Fig. 4. Difference of sound pressure levels $L_1 - L_2$ for the two examples of Fig. 3: full circles correspond to Fig. 3a and open circles to Fig. 3b.

Other example on the influence of the constructive elements has been plotted in Fig. 5. In this figure, it has been shown the standard deviation as frequency function for "in situ" measurements performed in the same partition following the standards ISO 140-4 and 140-5. Both curves are compared. A first difference between both curves is the smaller standard deviation for the "in situ" measurement following ISO 140-5. This difference can be associated to the distance between the loudspeaker and the receiving room, this distance is higher in the 140-5 measurement and so, higher the contribution of the reverberant field to the sound field inside the room. However, the main difference is the dependence shape of the standard deviation. Again, we believe this different dependence is related to the characteristics of the wall across the sound transmission is mainly taking place. In the same figure it has been plotted the level difference $L_1 - L_2$ for each one of the measurements. The difference between both walls is the glazed surface that constituted the façade across the sound transmission is taking place for the measurements according to 140-5. This fact could explain the insulation decrease at 160 Hz (see level difference of Fig. 5) and so, the different frequency dependence of the standard deviation.

a)

b)

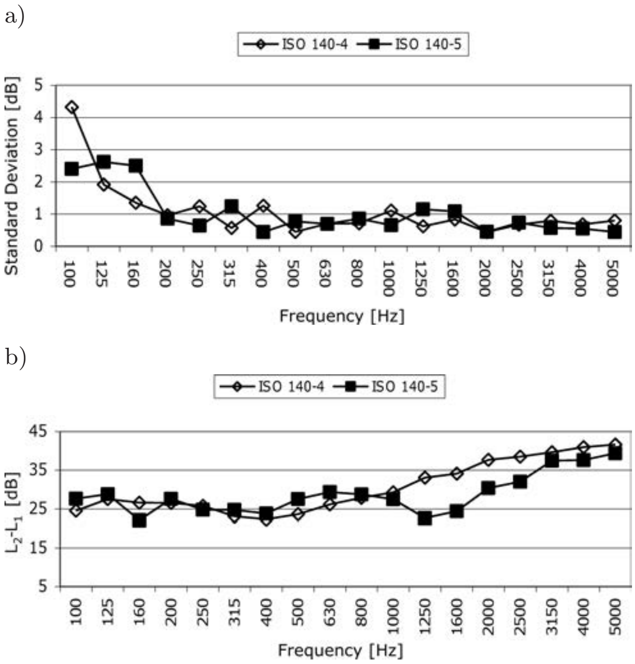


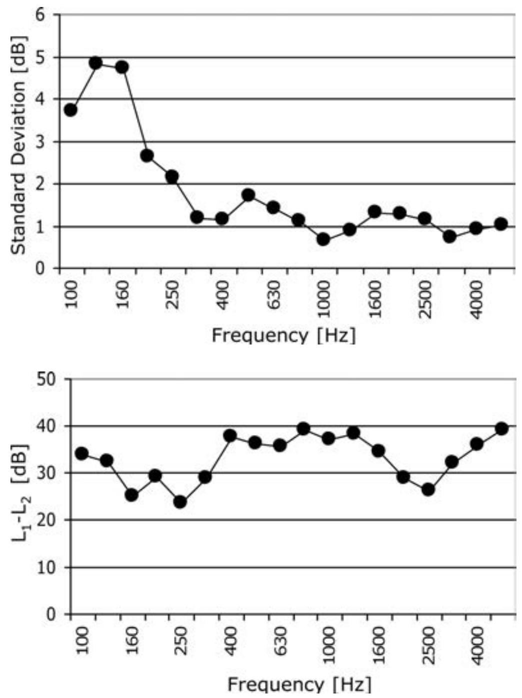
Fig. 5. Standard deviation for measurements following standards ISO 140-4 and 140-5 carried out in the same partition. The level difference $L_2 - L_1$ has been represented for both measurements.

These examples from Figs. 2 to 5 reveal that, independent on the type of "in situ" measurement, 140-4 or 140-5, the standard deviation low frequency dependence is strongly determined by the element across the transmission is happening. In general, for frequencies ranging between 100 and 400 Hz two different standard deviation frequency dependences can distinguish: a) the standard deviation decreases with the frequency or b) its maximum value is reached for a frequency ranging between 125 and 200 Hz. These two different behaviors have been illustrated in Fig. 6 for measurements following standard ISO 140-5. The façade measurements have been performed in rooms of different geometries and façade structural characteristics, however we believe the frequency dependence is associated to the different glazed percentage of the façade surface, or even if the window is double or simple glazed. In fact the stud borne transmission via the window frames has to be included when modeling the sound insulation of double glazed windows (Davy, 2010). This stud borne transmission via the window frames is particularly important for windows with wide air gaps.

All these characteristics fix the façade insulation at low frequency and in general, the maximum of the standard deviation shown coincidence with the decrease of the insulation. For thermal comfort and energy saving reasons usually the windows are constituted by a double glass separated by an air chamber. In the practice the width of this chamber is ranging between 6 and 16 mm, and the mass-air-mass frequency of the system is situated at low frequencies. The level difference $L_2 - L_1$ of the examples of Fig. 6 has been also plotted.

3.3. Fitting of the experimental results

For establishing a theoretical expression for the standard deviation it is necessary to know the probability distribution for the mean square pressure, or identify one that gives a reasonable representation of the distribution. It would be desirable to make a direct determination of the distribution of modal frea)



b)

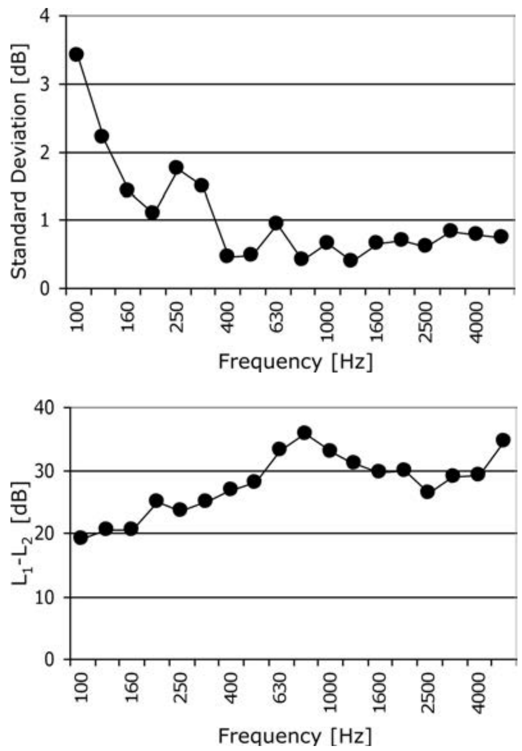


Fig. 6. Standard deviation and level difference $L_2 - L_1$ as frequency function for two measurements following ISO 140-5. In the case (a) the partition volume is 60 m^3 and 40 m^3 in the case (b).

quency spacings in order to apply the adequate equation. For sound insulation we almost always use broad-band noise and measure in frequency bands; although sound insulation against pure tones is occasionally of interest with environmental noise sources.

We will assume that the sound pressure is sampled at stationary microphone positions located at random points in the room, these positions are away from the room boundaries and at positions where the direct field from the source is insignificant. In this situation, the spatial variation of the mean-square pressure is represented by a gamma probability distribution for either modal or diffuse sound fields (Hopkins, 2007). Under these conditions, the expression proposed for the standard deviation is the following (Schroeder, 1969):

$$\sigma = \frac{5.57}{\sqrt{1 + 0.238BT}}, \tag{3}$$

where B is the filter bandwidth and T the reverberation time.

In this same line, and mainly at low frequencies Lubman (Craik, 1990) proposes the next expression where the modal character of the sound field has been considered:

$$\sigma = \frac{4.34}{-0.22 + \sqrt{1 + 0.319N}}, \tag{4}$$

where N is the number of normal modes for each band.

Concerning the sound transmitted into the receiving room is not always broad-band in nature. It may contain peaks in the sound pressure level at single frequencies, for example at the critical frequencies of walls/floors/windows or the mass-spring resonances of wall linings. So, the gamma probability distribution may not be a reasonable representation of the actual distribution for mean-square sound pressure in a receiving room. The sound pressure level will be the sum of a large number of random quantities and the central limit theorem can be used to infer that the sound pressure level in decibels will have a normal probability distribution. Despite these complexities, empirical evidence suggests that reasonable estimates for receiving rooms can be found using the same equations as for source rooms (Hopkins, 2007).

The experimental results fit to the proposed models only for some frequency intervals, normally at intermediate frequencies. Some examples have been show in Navacerrada *et al.* (2010; 2011). In this line, it would be interesting to modify these models to improve the fitting of the standard deviation curves principally at low frequencies. As a starting point, in this section a model for the fitting in the case of the standard deviation decreases with the frequency has been suggested.

It is obvious that for the fitting of the standard deviation is essential to consider the modal composition of the sound field in the source and in the receiving room. Fundamental characteristics in what expressions (3) and (4) are based on. However, the non-uniform sound field in the receiving and the source room could also be attributed to the mass-spring-mass resonance frequency, to the radiation from local modes of walls or floors, to the modes due to the source room-separating wall-receiving room system (Santos, Tadeu, 2003). To calculate accurately all these contributions, so all the mode frequencies and mode shapes the material properties of the wall and floors and their boundary conditions have to be known. Nevertheless, this is rarely the case. Taking into account this difficulty, in principle we have considered only the wall vibrational field contribution based on that at low frequencies the dominant sound transmission path is through the separating wall (Summers *et al.*, 2004). In fact, it has been seen that there is significant spatial variation of the vibration velocity over the wall surface (Hopkins, 2007). In fact, mainly in the low frequency range to predict the sound insulation of a wall it is fundamental to include the effects of the resonant response and radiation of the wall panels.

Now it is crucial to choose the standard deviation frequency dependence curve what represents a reasonable estimation of the wall vibrational field. The majority of the walls at the partitions and buildings are rectangular with straight junctions that from the point of view of the calculus it is assumed are uniform. The diffuse reflections are few probable in these junctions, more when in the walls exist additional frontiers constituted by the perimeters of the doors and of the windows. So, it is difficult to assume diffuse vibrational fields on walls and on floors. The diffuse vibrational fields on surfaces represent an ideal situation more that the reality and few experimental results have been found. So, we have used as reference the curve measured (Hopkins, 2007, p. 399) for concrete walls. This curve reproduces the standard deviation frequency dependence shape of different surfaces although their exact values are depending on the surface finish, on the properties of the material, on the wall dimensions and on the type of excitation source. As an example we have shown the standard deviation curves of Fig. 7:

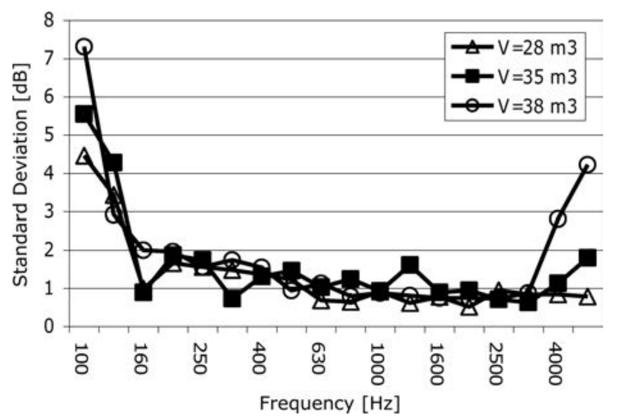


Fig. 7. Standard deviation as function of the frequency for three examples in which a different effect of the wall vibration is observed. The partition volume for each example is specified in the figure.

the standard deviation versus frequency curves measured reproduces the shape of the generalized curve chosen for the fitting but differences exist between the values of the three examples at low and high frequencies. Then the factors affecting the exact values of the reference curve can be interpreted as a different contribution of the wall vibrational field to the standard deviation measured and be included as a sensitivity coefficient in the fitting expression.

So, after this discussion and on the basis of the results shown in Fig. 7, as theoretical expression for the standard deviation has been considered a combined uncertainty of the standard deviation describe by expression (Crocker, Price, 1969) and the standard deviation associated to the wall vibrational field:

$$u_C = \sqrt{c_1^2(g)u_1^2(g) + c_2^2(w)u_2^2(w)}, \tag{5}$$

where g – geometry and w – wall.

As mentioned above, the sensitivity coefficients c_1 and c_2 associated to each input variable have been included in the expression (5) to consider their different contribution to the final value of the uncertainty or standard deviation. The sensitivity coefficients have been left as free parameters during the fitting. In Figs. 8 and 9 it has been shown examples of fittings for stan-

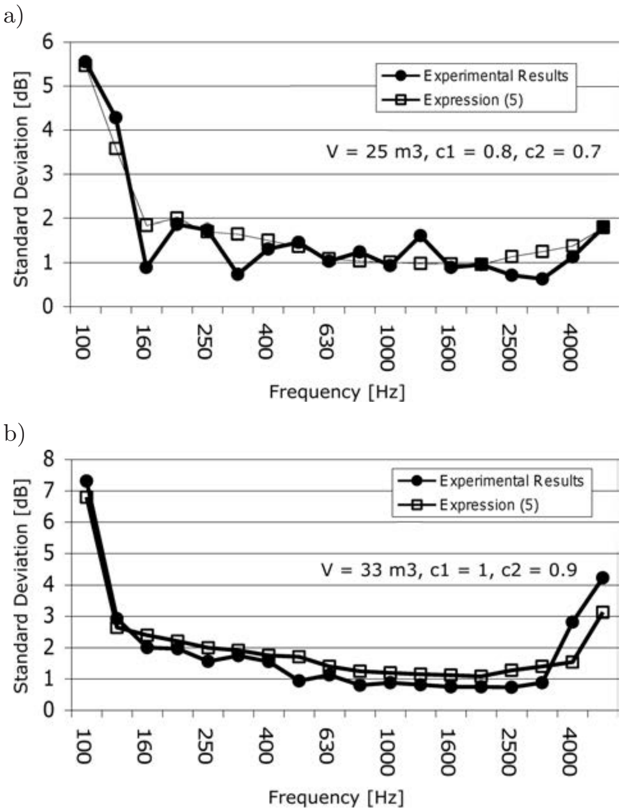
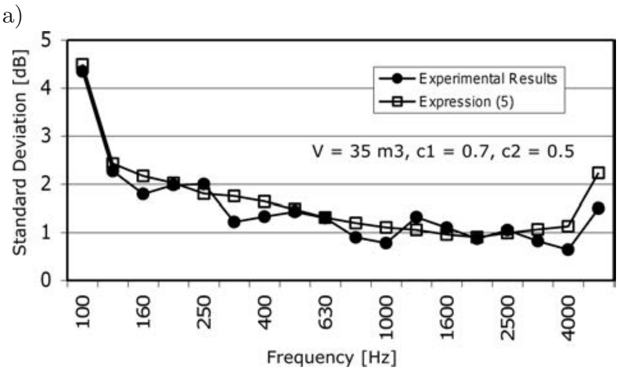


Fig. 8. Fitting of the standard deviation measured following standard ISO 140-4 to expression (Davy, 1990). The volume and the sensitivity coefficients values are indicated at the figures.

a)



b)

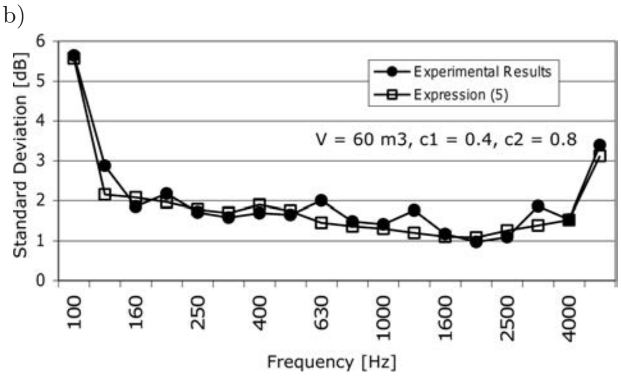


Fig. 9. Fitting of the standard deviation measured following standard ISO 140-5 to expression (Davy, 1990). The volume and the sensitivity coefficients values are indicated at the figures.

dard deviations derived from "in situ" measurements following standards ISO 140-4 and 140-5 respectively.

Several fittings were possible for different values of the sensitivity coefficients: the values of these coefficients that provide the small quadratic medium for the fitting have been chosen. It is clear, that this model need more refinement and does not explain all the standard deviation frequency dependences measured. Nevertheless, it serves as a starting point and it reveals than other contributions besides the geometrical configuration of the partition must be considered to explain the standard deviation frequency dependence.

4. Conclusions

Based on the analysis of the standard deviation calculated for "in situ" measurements following standards ISO 140-4 and 140-5 some important aspects related to the uncertainty of "in situ" measurements have been pointed out:

- Under repeatability conditions and following the standard procedures at low frequencies the results are dependent on the microphone positions chosen. The operator must be known that these differences can be producing.
- Different examples have served to illustrate the effect of the structural characteristics of the wall across the main sound transmission is taking place on the standard deviation. So, as a starting point besides the geometrical configurations, the wall vibrational field must be considered in the analysis of the standard deviation. In fact, we have shown examples in which data fit well to a standard deviation that combines these two effects. However, this model does not explain all the situations measured and a more refinement of this method is required taking into account the construction details of the source-receiving room system.

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