Building performance at low frequency range including flanking transmissions

Catherine GUIGOU CARTER[1]; Jordi POBLET-PUIG[2]

[1] Health and Comfort Department, Centre Scientifique et Technique du Bâtiment (CSTB), France

[2] Universitat Politècnica de Catalunya, Spain

ABSTRACT

Recent researches have proposed alternative formulas for the estimation of the vibration reduction index (K_{ij}) at junctions. Among other aspects, the new approaches propose different expressions for the low, mid and high frequency ranges; the current recommendation in the Annex E of EN 12354 standard provides a single value for the whole frequency range. Vibration reduction index can also be evaluated for specific junctions (dimensions, characteristics) representative of those in a particular building. This work analyses the potential effect that the use of the new vibration reduction index expressions can have in the prediction of global sound insulation outputs at low frequencies for different French traditional concrete based buildings. Measured acoustic performance is compared to predicted performance obtained following the EN 12354 approach.

Keywords: Sound, Insulation, Junction, Prediction, Building
I-INCE Classification of Subjects Numbers: 51.4 and 51.5

1. INTRODUCTION

Taking into account low frequencies for evaluating acoustic performances (down to 50 Hz) is developing or being considered in countries within Europe. Swedish regulation already has been imposing acoustic performance index integrating the 50 Hz one-third octave band for more than 15 years, and recently frequency bands starting at 20 Hz have even been included for high acoustic performance classes in dwellings (to improve comfort). Even if most European countries are not going to change their acoustic regulation to include low frequencies, it seems important that the various actors in the field of building design and construction, could have the necessary tools to understand the impact of their choices in terms of acoustic performance.

Recent researches have proposed alternative formulas for the estimation of the vibration reduction index (K_{ij}) at junctions [1,2,3]. Among other aspects, the new approaches propose different expressions for the low, mid and high frequency ranges; the current recommendation in the Annex E of Part 1 of EN 12354 standard series [4] provides a single value for the whole frequency range. Vibration reduction index can also be evaluated for specific junctions (dimensions, characteristics, etc…) representative of those in a particular building. In this work, the potential effect of using the new vibration reduction index expressions, in the prediction of global sound insulation outputs at low frequencies is investigated in the case of different French traditional concrete based buildings. Measured acoustic performance is compared to predicted performance obtained following the EN 12354 approach.

In this paper, the first section briefly present the building performance prediction method. A second section concentrates on evaluating K_{ij} values for different types of X- and T-junctions of various dimensions and characteristics. The K_{ij} values are evaluated using either a finite element approach or the tabulated expression from EN 12354 standard (2000) as well as the newly proposed frequency dependent K_{ij} (prEN 12354). Finally a third section compares measured acoustic performance to predicted performance for five French traditional buildings (concrete based) and the differences between prediction and measurement in performance rating including or not the low frequency range are discussed.

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[1] catherine.guigou@cstb.fr

[2] jordi.poblet@upc.edu

2. Building performance prediction method

2.1 General

Performance prediction of the flanking paths for traditional buildings (generally concrete based) are recalled in this section. Following the EN 12354 standard [1], the flanking sound reduction index R_{ij} and the normalized flanking impact sound level $L_{n,ij}$ between element i in the emission room and element j in the reception room are expressed as

$$R_{ij} = \frac{R_i + R_j}{2} + \frac{D_{v,ij} + D_{v,ji}}{2} + 10\log\frac{S_s}{\sqrt{S_i S_j}} \tag{1}$$

$$L_{n,ij} = L_{n,ii} - \frac{R_j - R_i}{2} - \frac{D_{v,ij} + D_{v,ji}}{2} - 10\log\sqrt{\frac{S_i}{S_j}} \tag{2}$$

where R_i and R_j are the sound reduction index of element i and j respectively, $D_{v,ij}$ is the vibration level difference between element i and j when element i is mechanically excited, S_i and S_j are the surface area of the elements (S_S for the separating element between emission and reception room), and $L_{n,ii}$ the impact noise level of element i. In order to simplify the expression, the effect of linings or floor covering are omitted.

The average of the junction velocity level difference is obtained based on the following equation

$$\overline{D}_{v,ij} = \frac{D_{v,ij} + D_{v,ji}}{2} = K_{ij} - 10\log\frac{l_{ij}}{\sqrt{a_i a_j}} \tag{3}$$

where a_i represents the equivalent absorption length of element i, l_{ij} the coupling length of the common junction between elements i and j. The vibration reduction index K_{ij} is related to the vibrational power transmission over a junction between structural elements; recommended value are tabulated in Annex E of EN 12354-1 standard, as a function of the junction type and mass per unit area of the connected elements. These values are independent of frequency for rigid junctions of heavy elements and were based mostly upon "in-situ" measurements, i.e. not independent junction and therefore most probably integrating more than the single path of interest. According to the results presented in [5-6], all the possible scenarios (isolated junction, junction tested in a real flanking laboratory and needing supports, junction tested in situ in the building) have potential sources of error due to undesired vibration transmission paths. This makes evident that evaluating K_{ij} is not a straightforward task

All those expressions can be applied starting at the 50 Hz third octave band.

The newly revised prEN 12354-1 (under inquiry at the time this paper is written) proposes in its Annex E in addition to previously described vibration reduction index K_{ij}, new junction characteristic values in terms structure-borne power transmission factor γ_{ij} from which K_{ij} can then be calculated. They were obtained from numerical simulations across L-, T- and X- junctions of homogeneous, isotropic plates and are given in three different frequency ranges: a low-frequency range (50 to 200Hz), a mid-frequency range (250 to 1000 Hz) and a high-frequency range (1.25 to 5 kHz). They are expressed in terms of the parameter PC defined as

$$PC = \log_{10}\left[\frac{m'_{\perp i}}{m'_i}\left(\frac{f_{c,i}}{f_{c,\perp i}}\right)^{3/2}\right] = \log_{10}\left[\frac{m'_{\perp i}}{m'_i}\left(\frac{h_{\perp i} c_{L,\perp i}}{h_i c_{L,i}}\right)^{3/2}\right] \tag{4}$$

where the subscript "⊥i" indicates the element perpendicular to element i in the junction, f_c is the critical frequency, m' is the mass per unit area, h the thickness and c_L the quasi-longitudinal phase velocity. For more details on these newly proposed frequency dependent junction characteristics denoted prK_{ij} in this paper, see reference [1].

The effect of modifying the vibration reduction index K_{ij} could therefore be of importance on the evaluation of the flanking path acoustic performance.

2.2 Correction at low frequencies

In order to compare building acoustic performance with measurements realized following ISO 16283-1 or -2 [7] for reception room below 25 m^3, it is recommended by the newly proposed EN 12354 to account for the higher energy density near the room boundaries using the Waterhouse correction given by

$$C_W = 10\log\left[1+\frac{c_0 S_t}{8fV}\right] \tag{5}$$

where c_0 is the sound speed in air, f the center frequency of the band, V the room volume and S_t the total surface area of the room.
This correction should be subtracted from the estimate of the in-situ airborne sound insulation in one-third octave bands below 250 Hz (or octave bands below 250 Hz). This correction is not exact for small rooms but in many cases the error leads to the safe side.

3. JUNCTIONS CHARACTERISTICS

In this section, the vibration reduction index (K_{ij}) of T- and X- type junctions are considered; values from EN 12354 standard, from under revision prEN 12354 standard [1] as well as SFEM (Spectral Finite Elements [8, 9]) calculations are compared.

The methodology and the numerical model used to study the specific junctions is the same as exposed in [3, 10]. The numerical model, based on shell SFEM, is an efficient alternative to solve the elastodynamic problem in structures composed of extrusion symmetry shells in the frequency domain. Point force excitation is used to obtain the junction velocity level difference. The SFEM model deals with finite size junctions. It means that the proper modal behaviour of the junction is reproduced in each frequency range: a more or less random behaviour at low frequencies controlled by particular modes, and almost SEA behaviour at mid frequencies when the modal overlap increases. Since SFEM results can be subject to a wide spread due to a strong modal response of the building elements under test, $D_{v,ij}$ values are smoothed by operating a moving average on 3 consecutive third-octave bands before computing K_{ij} values as previously proposed in [11]. This procedure is expected to yield values very close to the mean results obtained from a rather large number of measurements or calculations.

The specific X and T-type junctions considered in this section correspond to those (dimensions and materials) found in the real buildings considered in the next section.

3.1 X-type junctions

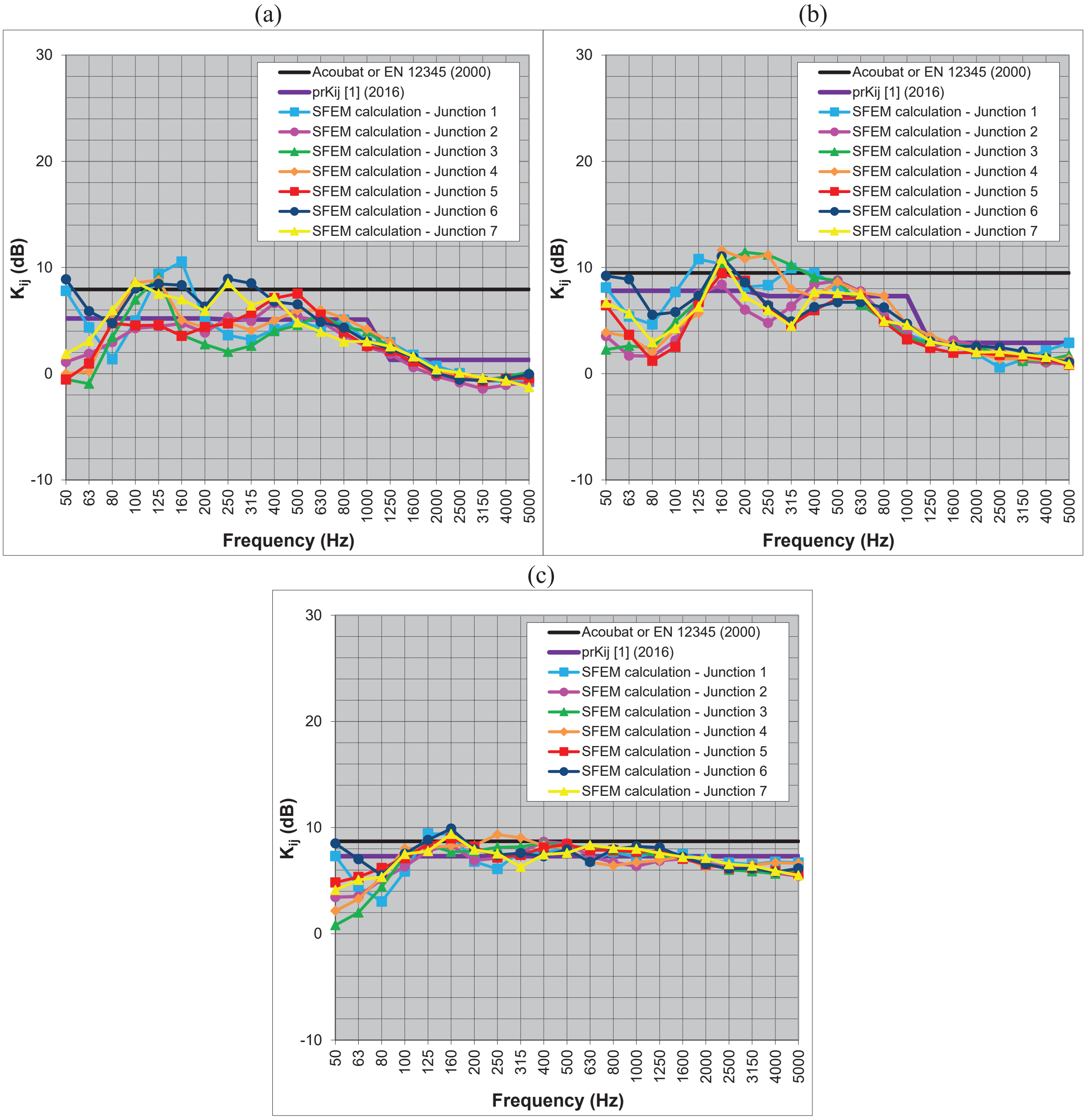
A number of 7 different X-junctions were modeled and SFEM calculations were performed; the horizontal elements are composed of 20 cm thick concrete (standard floor), while the vertical elements are 18 cm thick concrete (standard separating wall). Only the dimensions of the elements and therefore the junction length is changed (from 2.8 to 6.1 m).

Figure 1 presents the different K_{ij} obtained for the different paths (horizontal path or floor to floor path, vertical path of wall to wall path, and around the corner path). It can be seen that the SFEM calculation results fit relatively well with the proposed frequency dependent prK_{ij}; the K_{ij} values used in Acoubat (identical to those proposed in EN 12354 from 2000) appear to over-estimate the newly proposed K_{ij} as well as the SFEM based K_{ij} calculations. This is especially quite clear for the horizontal path (floor to floor) and more limited for around the corner path. This K_{ij} over-estimation could lead to an under-estimation of the flaking path influence of the building acoustic performance. As expected SFEM based K_{ij} calculations still show rather large variations in the low frequency range for the straight paths due to modal behavior of the elements. In the high frequency range (high model overlap), all SFEM based K_{ij} calculations converges.

3.2 T-type junctions

A number of 19 different T-junctions were modeled and SFEM calculations were performed; they represent either the junction between a floor and a façade wall, or a separating wall and a façade wall. As previously mentioned, the floors are composed of 20 cm thick concrete (standard floor), and separating walls are 18 cm thick concrete. The façade walls are also made of concrete with a thickness of either 15, 16 or 18 cm. Dimensions of the elements and therefore the junction length were changed according to the buildings considered; junction length varied from 2.5 to 5.4 m. In this section results are presented for two different types on T-junctions: the first one is composed of a 20 cm thick floor and a 15 cm thick façade wall and the second one of a 18 cm thick separating wall and a 16 cm thick façade wall. The straight path corresponds to the façade-façade path.

It should be noted that for the T-junctions the values for K_{ij} used by Acoubat are 1 dB higher than those suggested in EN 12354 standard (2000); this change was set in Acoubat due to comparisons between measured K_{ij} in French building performed in the 90's and the suggested EN 12354 standard K_{ij}.


(a)

(b)

(c)

Figure 1 – X-junctions; (a) Horizontal path, (b) Vertical path and (c) around the corner path.

Figures 2 and 3 present the different K_{ij} obtained for the different paths (straight path and around the corner path) and for the different T-junctions considered. For the first T-junction, the junction length varies from 2.7 to 4 m. It can be seen that the SFEM calculation results fit relatively well with the frequency dependent prK_{ij}; the K_{ij} values used in Acoubat (1 dB higher than those proposed in EN 12354 from 2000) appear to under-estimate slightly the SFEM based K_{ij} calculations in the low frequency range. The frequency independent Acoubat K_{ij} clearly appear to over-estimate the results from SFEM calculation in the high frequency range for the straight path and in the low frequency range for the around the corner path. They indeed present a quite different trend. As expected SFEM based K_{ij} calculations still show rather variations in the low frequency range for the straight and around the corner paths due to modal behavior of the elements.

For the second T-junction, the junction length is constant and equal to 2.5 m (standard floor to ceiling height) but the dimensions of the façade and separating walls varies. For the straight path, the SFEM calculation results fit relatively well with the behavior of frequency dependent prK_{ij}. In the low frequency range, the SFEM calculation results are higher than the Acoubat and frequency dependent prK_{ij}. As previously observed the frequency independent Acoubat K_{ij} clearly appear to over-estimate the results from SFEM calculation in the high frequency range for the straight path. For the around the corner path, the SFEM based K_{ij} calculations do not present a strong behavior with respect to frequency; they appear on average rather frequency independent.

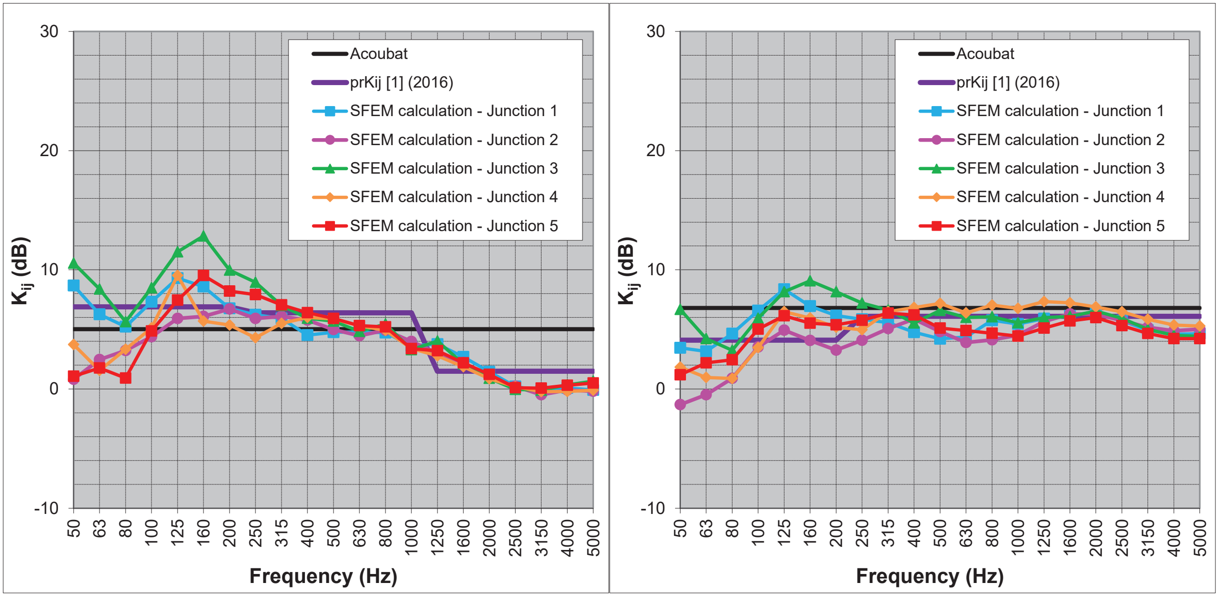

(a) (b)

Figure 2 – T-junctions 20 cm floor – 15 cm façade ; (a) Straight path and (b) around the corner path.

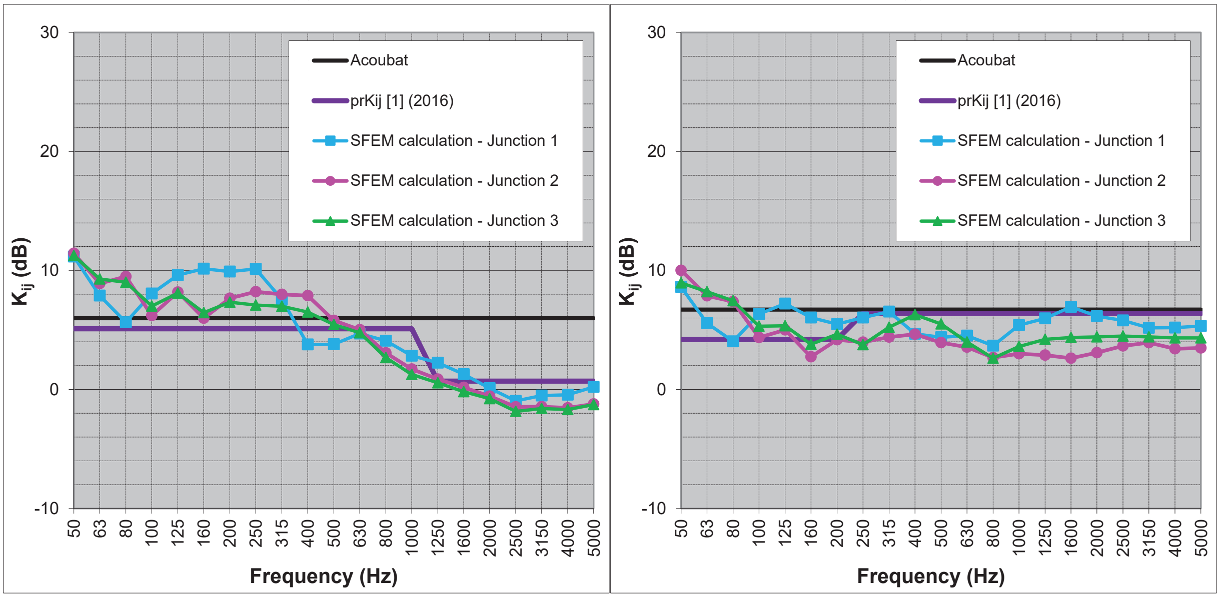

(a) (b)

Figure 3 – T-junctions 18 cm separating wall – 16 cm façade ; (a) Straight path and (b) around the corner path.

3.3 Summary

The results obtained with SFEM calculations demonstrate than in general the newly proposed frequency dependent prK_{ij} are in better agreement with the different junction cases considered and the different evaluated paths. It is indeed not possible to perform calculation for each junction cases encountered in a building; therefore tabulated K_{ij} value, frequency independent or frequency dependent, are of great importance. In the next section, K_{ij} values from Acoubat software and the proposed frequency dependent prK_{ij} are used in order to evaluate building acoustic performance in terms of airborne and impact sound insulation.

Finally, since the considered junctions tend to have mass ratio around 1, it was expected that the different K_{ij} evaluation would be in relatively good agreement. Indeed in this range of mass ratio, less differences were found between the newly proposed frequency dependent formulas and the current formulas in Annex E of the EN 12354 [1].

4. BUILDING ACOUSTIC PERFORMANCE

A package of 5 French traditional multi-apartment buildings is considered in this work. The walls and floors are in concrete respectively of thickness 18 and 20 cm; the façade walls are generally in concrete (80% of the cases). All façade walls having interior thermo-acoustic linings. The floor covering consists in plastic flooring. The acoustic performances of the different elements (walls, floors, etc…) required to perform building performance prediction are taken from the Acoubat database. Acoubat [12] is a commercially available software developed and distributed by CSTB based the EN 12354 standard series.

4.1 Airborne sound insulation

A total number of 23 airborne sound insulation measurements were carried out in the 5 considered French traditional buildings. These measurements were performed following ISO 16283-1 standard and therefore the Waterhouse correction C_w (see Section 2.2) for comparing measurement and prediction can be applied if appropriate (reception room below 25 m^3). An example of comparison between measurement and prediction (with and without Waterhouse correction) is shown in Figure 4(a) in the case of vertical transmission. It should be noted that taking into account the Waterhouse correction C_w decreases as expected the D_{nT} values between 50 and 250 Hz (in the order of 3 dB at the one-third octave band 50 Hz for the two cases presented). A difference in airborne sound insulation is obtained in the low frequency range when using the Acoubat software and when introducing proposed frequency dependent prK_{ij}.

Figure 4(b) presents measured and predicted airborne sound insulation for vertical transmission (no Waterhouse correction required in this case). No difference in airborne sound insulation is obtained when using the Acoubat software and when introducing the frequency dependent prK_{ij}.

In general, comparisons between measurement and prediction are acceptable. For the considered cases, the frequency dependent prK_{ij} do not introduce any discontinuity in the predicted airborne sound insulation.

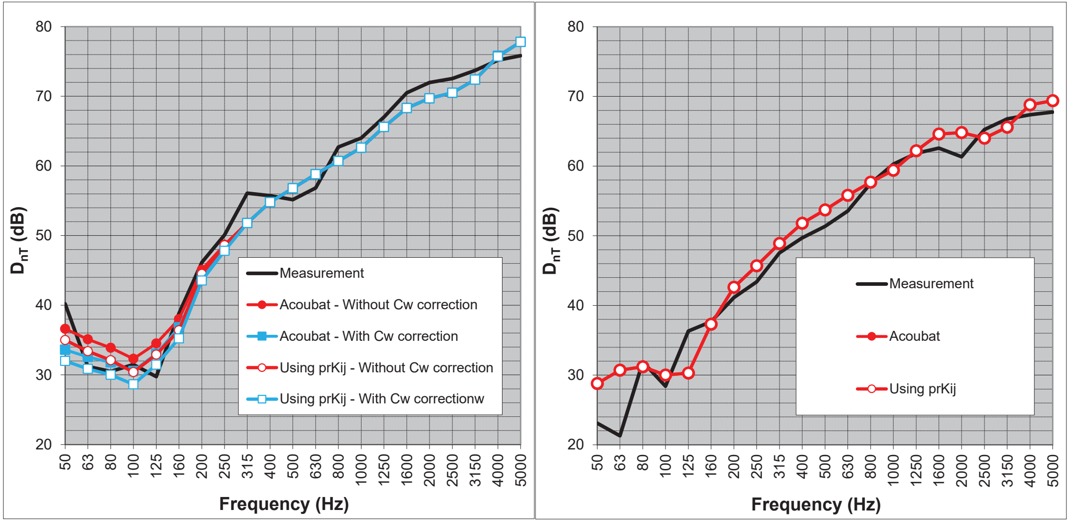

(a) (b)

Figure 4 – An example of measurement and prediction comparison – Airborne sound insulation; (a) Vertical transmission and (b) horizontal transmission.

Figure 5 presents the difference obtained in terms of $D_{nT,w}$+C and $D_{nT,w}+C_{50\text{-}3150}$ between measurement and prediction (integrating Waterhouse correction if appropriate) for vertical airborne sound insulation. A negative value indicated that the prediction over-evaluates the measured performance. First, it should be noted a spread around 0 dB of the predicted and measured performance difference; the spread is not increased when low frequencies are taken into account. Using the Acoubat software, for the standard frequency range (100-3150 Hz) the difference between prediction and measurement is on average of -1 dB (standard deviation of 2 dB); the same values are obtained when the frequency range is extended to low frequencies. When using the frequency dependent prK_{ij}, the difference between prediction and measurement is on average of 0 dB with a standard deviation of 3 dB for the standard frequency range; the same values are obtained when the frequency range is extended to low frequencies. Therefore, for the considered cases, there is little difference between the global predicted performance rating using the Acoubat software and the one using the proposed frequency dependent prK_{ij}.

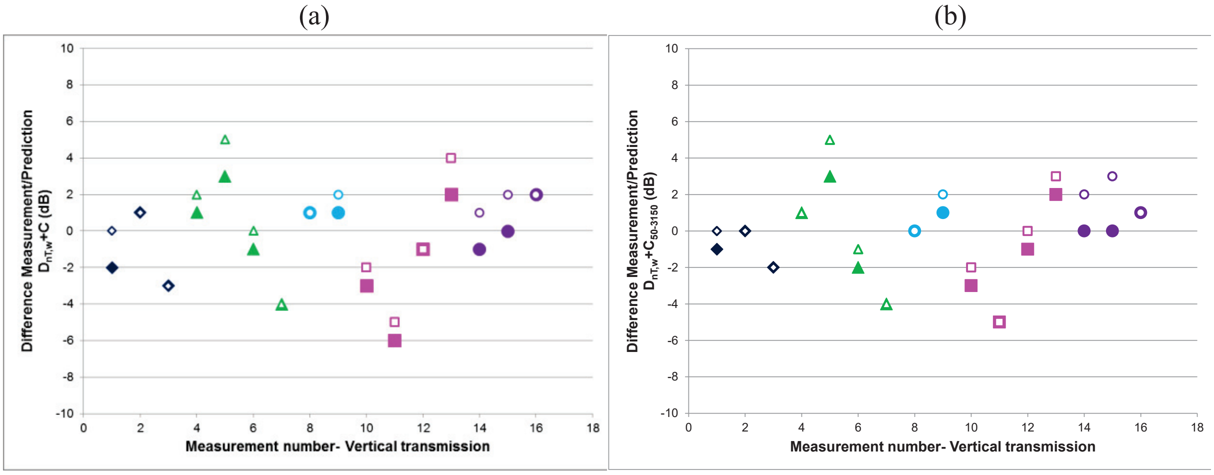


Figure 5 – Vertical transmission – Difference between measured and predicted performances – Airborne sound insulation; (a) 100-3150 Hz and (b) 50-3150 Hz (hollow marker are predicted results using prK_{ij}).

4.2 Impact sound insulation

A total number of 16 impact sound insulation measurements were carried out in the 5 considered French traditional buildings. These measurements were performed following ISO 10052 standard [13] and therefore the Waterhouse correction C_w (see Section 2.2) for comparing measurement and prediction is not applicable. An example of comparison between measurement and prediction is shown in Figure 6 in the case of vertical and horizontal transmission. In general, comparisons between measurement and prediction are acceptable. It should however be noted that the comparisons in the low frequency range are in general not as good as in the mid frequency range; the predicted impact sound insulation generally over-evaluates the measured one. Using the frequency dependent prK_{ij} for the prediction, has an influence: the impact sound level is increased by around 2 dB with respect to the standard Acoubat prediction below 200 Hz for vertical transmission considered and on the complete frequency range for the horizontal transmission presented. Note that this increase is larger (almost 5 dB) in the high frequency range (starting at 1250 Hz) for the horizontal transmission; the prediction is therefore closer to the measurement but this has no effect on the global performance rating. Since for horizontal transmission there is no direct path, it was expected that the change in K_{ij} could have an important effect; however, no discontinuity in the predicted impact sound insulation that could be associated to the frequency dependent prK_{ij} can be observed. This remains true for all the considered cases in this work.

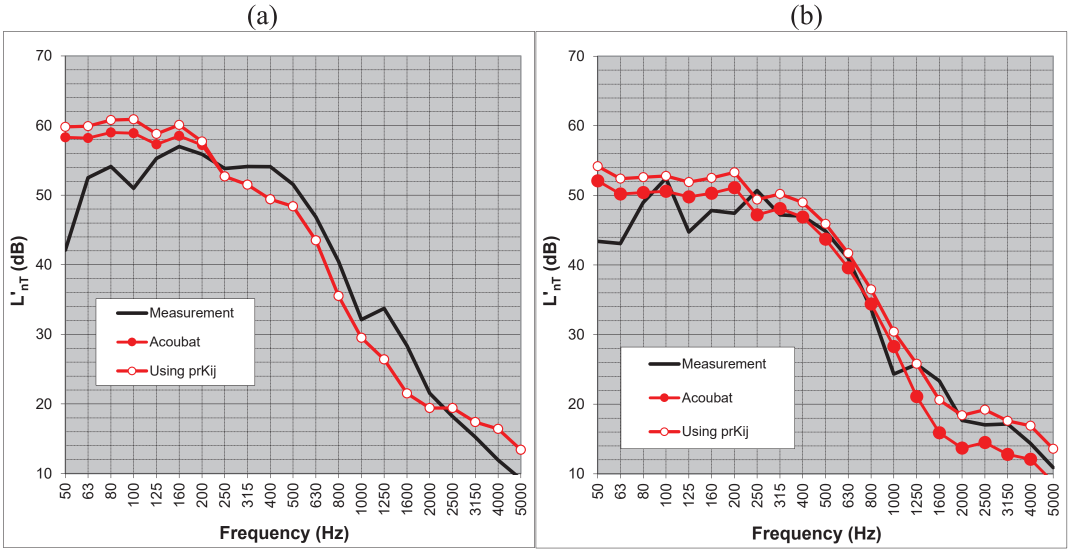


Figure 6 – An example of measurement and prediction comparison – Impact sound insulation; (a) Vertical transmission and (b) horizontal transmission.

Figure 7 presents the difference obtained in terms of $L'_{nT,w}$ and $L'_{nT,w}+C_{I50\text{-}2500}$ between measurement and prediction for vertical airborne sound insulation. A positive value indicated that the prediction over-evaluates the measured performance. Using the Acoubat software, for the standard frequency range (100-3150 Hz) the difference is on average of 0 dB (standard deviation of 3 dB); this difference is on average 2 dB with a standard deviation of 3 dB when the frequency range is extended to low frequencies. When using the frequency dependent prK_{ij}, the difference between prediction and measurement is on average of 0 dB with a standard deviation of 3 dB for the standard frequency range; this difference is on average 3 dB with a standard deviation of 3 dB when the frequency range is extended to low frequencies. Obviously it can be expected that for horizontal transmission the difference between prediction and measurement would be larger on average; this is presented in the next section.

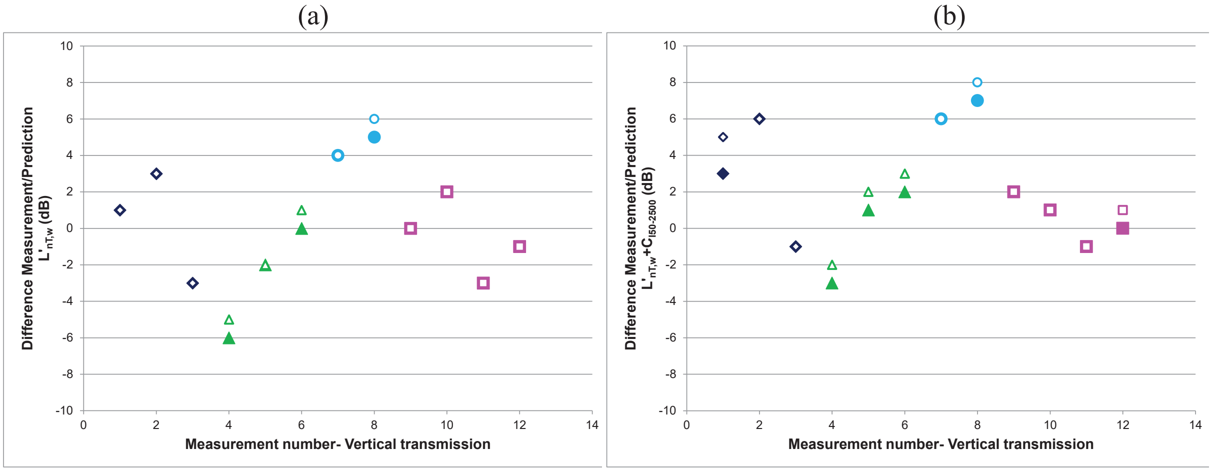


Figure 7 – Vertical transmission – Difference between measured and predicted performances – Impact sound insulation; (a) 100-3150 Hz and (b) 50-3150 Hz (hollow marker are predicted results using prK_{ij}).

4.3 Summary

Table 1 presents a summary of the differences between measurement and prediction for the different cases of transmission considered. First, for the traditional buildings considered cases, there is little difference between the global predicted performance rating using the Acoubat software and the one using the proposed frequency dependent prK_{ij} for airborne sound insulation as well as for impact sound insulation.

For airborne sound insulation, the average of the difference between measured and predicted performances is more important for horizontal transmission than for vertical transmission. This averaged difference remains identical when low frequencies are taken into account in the performance index. For the impact sound insulation, the average of the difference between measured and predicted performances is more important for horizontal transmission than for vertical transmission; this is due to the fact that there is not direct path for horizontal transmission. Furthermore, the average of the difference between measured and predicted performances is increased when low frequency are taken into account for the vertical or horizontal sound transmission.

Globally for airborne sound insulation, the integration of the low frequencies does not modify the comparison between measured and predicted performance rating; the measured performance is on average the same as the one predicted. For impact sound insulation, the effect of integrating the low frequencies is more important. The measured performance rating is on averaged quite similar to the predicted one for the standard frequency range; it is however 3 to 4 dB higher when the low frequencies are taken into account (this value is therefore rather on the security side).

Therefore, for all the considered cases, there is little difference between the global predicted performance rating in terms of airborne and impact, using the Acoubat software and the one using the proposed frequency dependent prK_{ij}.

Table 1 – Difference between measured and predicted performances: Average (standard deviation)

	Acoubat		Newly proposed frequency dependent K_{ij}	
	$\Delta(D_{nT,w}+C)$	$\Delta(D_{nT,w}+C_{50\text{-}3150})$	$\Delta(D_{nT,w}+C)$	$\Delta(D_{nT,w}+C_{50\text{-}3150})$
Horizontal transmission	1 dB (1 dB)	1 dB (1 dB)	2 dB (2 dB)	2 dB (2 dB)
Vertical transmission	-1 dB (2 dB)	-1 dB (2 dB)	0 dB (3 dB)	0 dB (3 dB)
All transmission types	0 dB (2 dB)	0 dB (2 dB)	1 dB (3 dB)	1 dB (3 dB)
	$\Delta(L'_{nT,w})$	$\Delta(L'_{nT,w}+C_{I50\text{-}2500})$	$\Delta(L'_{nT,w})$	$\Delta(L'_{nT,w}+C_{I50\text{-}2500})$
Horizontal transmission	2 dB (3 dB)	3 dB (4 dB)	3 dB (4 dB)	3 dB (5 dB)
Vertical transmission	0 dB (3 dB)	2 dB (3 dB)	0 dB (3 dB)	2 dB (3 dB)
All transmission types	1 dB (4 dB)	3 dB (4 dB)	2 dB (4 dB)	4 dB (4 dB)

5. CONCLUSIONS

In this paper, vibration reduction index (K_{ij}) at junctions was first investigated. Comparisons of different vibration reduction indexes for X- and T-junctions were presented. The vibration reduction indexes were evaluated from the current tabulated formulas in Annex E of the EN 12354 [4], from newly proposed frequency dependent formulas [1] as well as from SFEM based calculation on a number of specific junctions (representative of those found in the buildings considered in this work). Since these considered junctions tend to have mass ratio around 1, it was expected that the different K_{ij} evaluations would be in relatively good agreement. Indeed in this range of mass ratio, less differences were found between the newly proposed frequency dependent formulas and the current formulas in Annex E of the EN 12354 [1].

In a second part of the paper, the potential effect of using the new vibration reduction index expressions, in the prediction of global sound insulation outputs at low frequencies is investigated in the case of five different French traditional concrete based buildings. Measured acoustic performance was compared to predicted performance obtained following the EN 12354 approach using the Acoubat software. The differences between prediction and measurement in performance rating including or not the low frequency range was discussed. For all the considered cases, little difference was found between the global predicted performance rating in terms of airborne and impact, using the Acoubat software and the one using the proposed frequency dependent prK_{ij}. Since the different K_{ij} evaluations were relatively close (considered junctions with mass ratio around 1), it was more or less expected not to find very large differences between the acoustic outputs computed by means of the two different formulations. It remains as a future task to perform similar analysis of building acoustic performance for buildings with different junction typologies that could have a mass ratio quite different from 1.

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