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EN EDIFICIOS**

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**VIBROACOUSTIC AND SOUND
INTENSITY STUDY OF
FLANKING TRANSMISSION
IN BUILDINGS**

By

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“Saber não ter ilusões é absolutamente necessário para se poder ter sonhos.”

“Knowing to have no illusions is absolutely necessary to have dreams.”

Fernando Pessoa

À minha mãe e à memória do meu pai.

To my mother and my father's memory.

RESUMEN

Esta tesis resume el esfuerzo que se ha realizado al estudiar las prestaciones acústicas de diversas topologías constructivas propias del sur de Europa, haciendo especial hincapié en el efecto de las transmisiones indirectas.

Inicialmente, se ha estudiado de una forma exhaustiva la bibliografía existente con el objeto de identificar y valorar los diversos métodos de medida experimentales relacionados con la estimación de las transmisiones indirectas. Asimismo, se han encontrado tres posibles métodos para aplicación:

- (i) El método de presión, utilizado en combinación con el aislamiento de tabiques o apantallamiento;
- (ii) El método de intensidad acústica, capaz de obtener resultados muy fiables sin recurrir al apantallamiento;
- (iii) El procedimiento de medida de vibraciones, cuyo fundamento radica en la relación entre la velocidad de vibración de cada uno de los elementos implicados y de los distintos caminos de flanco. Este tiene como base medidas de velocidad, midiendo las vibraciones transmitidas por estos elementos que después se convierten en estimación acústica.

De estos tres métodos de medida, el único estandarizado, que proporciona la contribución de cada camino de flanco por separado, es el método de intensidad. Por ello, este método ha sido utilizado como “método de referencia”. Se comparó con el método de presión, en lo que respecta a medida de aislamiento a ruido aéreo sin incluir transmisiones por flanco. Se comparó también con el método de vibraciones por velocidad, cuando se han tenido en cuenta las transmisiones por flanco.

Se han realizado diversas tandas de medidas experimentales para comparar los resultados de acuerdo a los tres métodos de medida, tanto en condiciones de laboratorio como en condiciones reales (*in situ*), así como para medidas de impacto y aéreas. En base a los resultados obtenidos, se plantea establecer el método de vibración como posible procedimiento de medida en la estimación del aislamiento sonoro de edificaciones con la estimación de las transmisiones de flanco.

En paralelo con estos experimentos, se calculó la predicción de la transmisión acústica incluida en la normativa EN 12354-1 (2000). Con esta información se añade otro conjunto de datos, comparables con los resultados experimentales, permitiendo concluir sobre la aplicabilidad, o no, de este método de predicción en los edificios del sur de Europa, más en concreto en los españoles.

Con el método de vibraciones solamente es posible obtener resultados mediante la aplicación de modelos matemáticos de estimación de la eficiencia de radiación acústica. Los autores de estos modelos se han escogido entre la bibliografía como los más conocidos y más novedosos, aplicados a las específicas condiciones de entorno elegidas y posibles para esta tesis. Los resultados de estos datos se expresan mediante gráficas de distribución espacial de niveles de velocidad de vibración.

El trabajo desarrollado experimentalmente implica un conocimiento profundo de todos los métodos de medición acústica referidos en esta tesis, permitiendo obtener datos que indiquen las ventajas y inconvenientes de cada uno de los métodos, así como los resultados comparados de las estimaciones obtenidas por cada uno de ellos.

Al final, se presentan las conclusiones y propuestas específicas, para el desarrollo de nuevos estudios.

ABSTRACT

This thesis summarises the work done to study the acoustical performance of several building construction types proper from the south of Europe. It was made special attention to the flanking contribution.

Initially, it was performed an exhaustive study of the existent bibliography with the aim of identifying and valuing the several acoustic experimental measurement methods related to the estimation of flanking contribution. Therefore, three possible applying methods were found:

- (i) Sound pressure method used in combination with elements shielding;
- (ii) Sound intensity method capable of obtaining the most reliable results without using the shielding process;
- (iii) Vibration velocity measurement procedure whose foundation lies on the relation between the vibration velocity of each element and the different flanking paths. This method is based on the velocity measures obtained from the transmitted vibrations by these elements, which are converted on acoustic estimation.

From these three measurement methods the sound intensity is the only standardized and allows quantifying the contribution of each flanking path separately. For that reason, the intensity method was used as reference. It was also compared with the sound pressure method, respecting the estimation of airborne sound insulation without including the flanking contribution, and with the vibration velocity method when considering the flanking transmission.

There were performed several experimental measurements to compare the results in laboratory and field conditions, for both structure and airborne sound transmission, through the three measurement methods. Taking the results obtained in consideration it is intended to establish a vibration velocity method as a measurement procedure on the estimation of airborne sound insulation with flanking contribution evaluation.

At the same time it was calculated the sound insulation prediction by means of the methods referred on the EN 12354-1 (2000). Gathering all this information and

comparing all the results, it is possible to conclude if the prediction methods are suitable for the south European countries, especially to the Spanish buildings.

It must be referred that the vibration velocity method is only capable of producing results through the application of mathematical models which simulate the radiation efficiency estimation. The authors of these models were selected, as the most recent and known, among the bibliography and their models were applied to the specific conditions found for this thesis. These results were expressed by means of graphics representing vibrational velocity levels spatially distributed.

The experimental work developed for this thesis implies a profound knowledge of all the measurement methods, and allowing obtaining data capable of concluding on the advantages and disadvantages of each method.

Finally, conclusions and specific proposals are presented in order to stimulate the development of new studies.

RESUMO

Esta tese resume o esforço que foi feito ao estudar as prestações acústicas de diversas topologias construtivas próprias do sul da Europa, com especial atenção no efeito das transmissões marginais de flanco.

Inicialmente, foi estudada de uma forma exaustiva a bibliografia existente com o objectivo de identificar e valorizar os diversos métodos de medida experimentais relacionados com a estimação das transmissões marginais, em concreto as de flanco. Com isto, foram encontrados três possíveis métodos para utilizar:

- (i) O método de pressão, utilizado em combinação com o isolamento independente de paredes;
- (ii) O método de intensidade acústica, capaz de obter resultados muito fiáveis e sem recorrer ao isolamento de paredes;
- (iii) O procedimento de medida de vibrações, cujo fundamento reside na relação entre a velocidade de vibração de cada uma das paredes implicadas e dos diferentes caminhos de flanco. Este procedimento tem como base medidas de velocidade, onde são medidas as vibrações transmitidas por estes elementos que posteriormente são convertidas em estimação acústica.

De entre estes três métodos de medida, o único normalizado, que proporciona a contribuição de cada caminho de flanco de forma separada, é o método de intensidade. Por isto, este método foi utilizado como “método de referência”. Este método foi comparado com o método de pressão, no que diz respeito a medida de isolamento a ruído aéreo sem incluir as transmissões de flanco.

Foram realizadas diversas séries de medidas experimentais para comparar os resultados para os três métodos de medida, quer em condições laboratoriais como em condições reais ou *in situ*, assim como para medições com excitação por percussão e aérea. Com base nos resultados obtidos pretende-se estabelecer um método de vibrações como possível procedimento de medida na estimação do isolamento sonoro dos elementos de compartimentação dos edifícios com a contabilização das transmissões de flanco.

Em paralelo com estes ensaios calculou-se a previsão da transmissão acústica através da norma EN 12354-1 (2000). Com esta informação é acrescentado um outro conjunto de dados, comparáveis com os resultados experimentais, permitindo concluir sobre a aplicabilidade, ou não, de este método de previsão aos edifícios do sul da Europa, mais concretamente aos espanhóis.

Com o método de vibrações isoladamente é possível obter resultados mediante a aplicação de modelos matemáticos que estimam a eficiência de radiação acústica. Os autores de estes modelos foram escolhidos de entre a bibliografia, como os mais conhecidos e também mais recentes, foram aplicados às condições do meio eleitas e possíveis para esta tese. Os resultados foram expressos mediante gráficos de distribuição espacial de níveis de velocidade de vibração.

O trabalho desenvolvido experimentalmente implica um conhecimento profundo de todos os métodos de medição acústica referidos neste tese, permitindo obter dados que indiquem as vantagens e os inconvenientes de cada um dos métodos, assim como os resultados comparados das estimações obtidas por cada um deles.

No fim, apresentam-se conclusões e propostas específicas para o desenvolvimento de novos estudos.

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NOTATION

a	vibration r.m.s. acceleration
a_i	equivalent absorption length of a structural element i
A_0	reference absorption area of 10 [m ²] (impact)
a_0	vibration reference acceleration 10 ⁻⁶ [m/s ²]
A_1	equivalent sound absorption area in the source room
A_2	equivalent sound absorption area in the receiving room
$a_{i,situ}$	equivalent absorption length of element i in the actual field situation
$a_{j,situ}$	equivalent absorption length of element j in the actual field situation
b	dimension of a square plate
b'	half length of a square plate
c_0	velocity of sound in the air
c_B	bending wave velocity
c_L	longitudinal wave velocity
d	vibration r.m.s. displacement
d_0	vibration reference displacement 1 [m] or 10 ⁻¹¹ [m]
d_M	distance between scan lines
$D_{n,e}$	element normalized level difference
$D_{n,s}$	normalized sound level difference for indirect transmission through a systems
$D_{v,ij}$	junction velocity level difference between excited element i and receiving element j
$\overline{D_{v,ij,situ}}$	direction-averaged junction velocity level difference
e	characteristic dimension of the panel
E_1	sound energy of sub-system S_1

E_2	sound energy of sub-system S_2
E_d	sound energy in sub-system d
$e_\varphi(\hat{I})$	estimation normalised systematic error associated with intensity
f	Frequency
f_c	critical frequency
f_m	central frequency band
$f_{m,n}$	natural frequencies of a plate
F_{pIn}	surface pressure intensity indicator
f_{ref}	reference frequency $f_{ref}=1000$ [Hz]
I_0	reference sound intensity 10^{-12} [W/m ²]
I_n	normal sound intensity
\bar{I}_{ni}	time and surface average normal sound intensity measured on the i^{th} sub-area
k	wave number
k_B	bending wave number
K_{Fd}	vibration reduction index for transmission path Df
K_{Fd}	vibration reduction index for transmission path Fd
K_{Ff}	vibration reduction index for transmission path Ff
K_{ij}	vibration reduction index for each transmission path ij over a junction
k_x	wave number in the x direction on a rectangular plate
k_y	wave number in the y direction on a rectangular plate
l_{ij}	common coupling length between element i and element j
L'_{nt}	apparent impact sound pressure level
l_0	reference coupling length 1 [m]
L_a	vibration acceleration level

L_d	vibration displacement level
l_f	common coupling length of the junction between separating element and the flanking elements F and f
L_I	sound intensity level
L_i	impact sound pressure level
$L_{I\delta}$	residual intensity level
l_k	length of the junction at the perimeter k
L_n	normalized impact sound pressure level
L_p	sound pressure level
L_{p1}	sound pressure level in the source room (1)
L_{p2}	sound pressure level in the receiving room (2)
L_v	vibration velocity level
L_W	sound power level
$L_{W,V}$	estimated sound power level radiated using surface average vibration velocity
L_{W1}	sound power level in the source room 1
L_{W2}	sound power level transmitted through a partition or element to room 2
L_x	panel dimension in x direction
L_y	panel dimension in y direction
$\bar{L}_{in,j}$	time and surface average normal sound intensity level for the flanking element j
$\bar{L}_{V,j}$	vibration velocity levels for elements j
\bar{L}_{In}	average normal sound intensity level
$L_{\bar{v}}$	time and space average vibration level of the radiating surface
m'	mass per unit area [kg/m^2]
m'_0	reference mass per unit area 1 [kg/m^2]
m'_i	mass per unit area of element i

n_1	modal density of sub-system 1
n_2	modal density of sub-system 2
P	sound pressure
p_{ref}	sound pressure reference 20 [μPa]
Q	directivity factor
r	receptor distance to sound source
R	sound reduction index
R' ; R_{situ}	apparent sound reduction index
$R'_{w,p}$	apparent weighted sound reduction index by pressure method
R'_I	apparent sound reduction index by intensity method
$R'_{w,I}$	apparent weighted sound reduction index by intensity method
R'_v	apparent sound reduction index by vibration velocity method
R'_w	apparent weighted sound reduction index
$R'_{w,12354\text{Sim}}$	apparent weighted sound reduction index by simplified model of EN 12354-1
$R'_{w,12354\text{Det}}$	apparent weighted sound reduction index by detailed model of EN 12354-1
$R'_{w,v\text{Rindel}}$	apparent weighted sound reduction index by vibration velocity method with Rindel equation
$R'_{w,v\text{Davy}}$	apparent weighted sound reduction index by vibration velocity method with Davy equation
R_{Dd}	sound reduction index for direct transmission
$R_{f,w}$	weighted sound reduction index of the flanking element f in the receiving room
$R_{F,w}$	weighted sound reduction index of the flanking element F in the source room
$R_{I Fj}$	sound reduction index for flanking element j by intensity method
R_{ij}	sound reduction index for flanking elements i and j
$R_{S,w}$	weighted sound reduction index of the separating element
R_w	weighted sound reduction index

S	partition or element surface area
S_0	reference area of 1 [m ²]
S_1	surface area of room 1; sub-system 1
S_2	sub-system 2
S_M	imaginary measurement surface area
S_{Mi}	sub-area of imaginary measurement surface area
SRI	sound reduction index
t	plate thickness
T_0	reference reverberation time 0,5 [s]
T_1	reverberation time in the source room
T_2	reverberation time in the receiving room
TL	transmission loss of an element or partition
T_s	structural reverberation time of an element i
$T_{S,i,situ}$	structural reverberation time of element i in the actual field situation
$T_{S,j,situ}$	structural reverberation time of element j in the actual field situation
$T_{S,lab}$	structural reverberation time in laboratory conditions
U	perimeter of a plate
v	vibration r.m.s. velocity
v_0	vibration reference velocity 5×10^{-8} [m/s]
V_2	receiving room volume
\bar{v}^2	average mean-square velocity of the radiating surface
W	radiated sound power
W_0	reference sound power 10^{-12} [W]
W_1	sound power in the source room 1

W_2	sound power transmitted through an element to room 2
W_3	sound power transmitted through flanking elements or by other components
W_a	sound power absorbed by the partition or element
W_d	sound power dissipated in a sub-system d
W_{ij}	sound power radiated from flanking element j due to element i
W_r	sound power in the reverberant field
W_{tot}	direct and flanking sound power transmission
W_{rad}^{piston}	sound power radiated by a piston
α	absorption coefficient of an element
α_k	absorption coefficient for bending waves, at the perimeter k
$\bar{\alpha}$	average absorption coefficient
$\bar{\alpha}_1$	average absorption coefficient in room 1
δ_{pI0}	pressure residual intensity index
$\Delta R_{Dd,w}$	weighted sound reduction index improvement by additional lining or layer on the source and/or receiving side of the separating element
$\Delta R_{Df,w}$	total weighted sound reduction index improvement by additional lining or layer on the separating element at the source side and/or flanking element at the receiving side
$\Delta R_{Fd,w}$	total weighted sound reduction index improvement by additional lining or layer on the flanking element at the source side and/or separating element at the receiving side
$\Delta R_{Ff,w}$	total weighted sound reduction index improvement by additional lining on the source and/or receiving side of the flanking element
ΔR_{situ}	sound reduction index improvement by additional layers in the actual field situation
$\eta_{12}; \eta_{21}$	loss coupling factors
η_d	dissipative internal factor of sub-system d
Θ	Angle

Λ	wave length
λ_B	bending wave length
λ_x	structural wave length in the x direction
λ_y	structural wave length in the y direction
ρ_0	density of air
σ	radiation efficiency
$\sigma_{i, \text{ situ}}$	radiation factor for element i on field conditions
$\sigma_{j, \text{ situ}}$	radiation factor for element j on field conditions
ν	Poisson coefficient
ω	circular velocity or angular frequency
τ'	ratio of the transmitted to the incident sound power in field or <i>in situ</i> conditions
τ	ratio of the transmitted to the incident sound power
τ_d	ratio of the radiated sound power in the receiving room by an element in the separating element due to direct airborne transmission
τ_e	ratio of the radiated sound power from components mounted in the separating element
τ_f	ratio of the radiated sound power in the receiving room by flanking elements f
τ_{ij}	ratio of the radiated sound power radiated from flanking element j due to incident sound on element i in the source room to the sound power W_1 which is incident on a reference area in the source room
τ_s	ratio of the radiated sound power in the receiving room by a system s due to indirect airborne transmission

Special characters

$\langle \overline{v_n^2} \rangle$	average mean square velocity
\overline{v}_n	normal vibration velocity distribution
\overline{v}_{pq}	vibration (time average) velocity complex amplitude for the vibration mode pq
\overline{E}	time average vibration energy
\overline{W}	time average radiated power
\tilde{P}	complex amplitude of pressure at a defined point
\tilde{B}	Complex amplitude
$\overline{W}_{\text{rad}}$	time-average radiated sound power
\overline{L}_{v_j}	vibration velocity levels for elements j
\overline{L}_{I_n}	average normal sound intensity level over the measurement surface or surfaces in the receiving room
$\overline{L}_{I_n j}$	average normal sound intensity level over the measurement surface for the flanking element j in the receiving room

Chapter 1

1 Introduction

1 Resumen de la introducción

Todo trabajo científico debe tener, en principio, hipótesis y suposiciones claras que conduzcan a un objetivo más fácil de realizar. En esta línea de pensamiento, el trabajo presente trata de alcanzar y clarificar esas hipótesis y suposiciones. La concepción de edificios, así como las técnicas de construcción empleadas, deben ser tales que el ruido percibido por sus ocupantes se mantenga a un nivel bajo, de forma que no amenace su salud ni unas condiciones satisfactorias de vida. El confort acústico es, en nuestros días, una de las razones que permiten la satisfacción e integración en la sociedad. Esto tiene más importancia en los países más desarrollados.

Existen muchos lugares donde la vida normal del ser humano se desarrolla: casa, trabajo, lugares de ocio, etc. Coexisten, así mismo, diversas fuentes de potencia sonora que perturban esos lugares. Sin embargo, si hay un lugar donde la perturbación del sonido no puede llegar a niveles intolerables (confort acústico) es en las viviendas particulares. En nuestros días, es conocido que el sonido puede transmitirse de una sala a la contigua, además de la vía aérea, a través del elemento de separación entre las salas, por vía directa de vibración estructural de este elemento de separación o por otros caminos indirectos. Estos caminos indirectos pueden aumentar el nivel de sonido en salas adyacentes bastante más de lo supuesto a hasta hace pocos años atrás. Este trabajo supone una contribución más para obtener mejores condiciones acústicas en los edificios y aportar nuevos conocimientos y “savoir faire” a la comunidad científica.

Durante el mismo, en primer lugar se realizó una búsqueda en las revistas, libros y artículos especializados en las áreas de conocimiento de acústica de edificios y transmisiones por flancos. Se trató la información recopilada, con el fin de resumir y conocer todo el trabajo científico efectuado hasta el momento y poder centrar en él la cuestión. El tema entonces se centró en estudiar lo que sucede cuando el sonido producido en una sala emisora hace vibrar todas las superficies alrededor. ¿Cómo viaja

esta vibración entre las superficies hasta la sala receptora, por qué caminos y cómo se estima el sonido?

Una vez centrado en este tema, se han realizado diversas estimaciones de aislamiento sonoro en laboratorio y en un edificio (medidas *in situ*), siguiendo el método de presión y el método de intensidad. A la par de estas mediciones, se implementó un procedimiento de medidas de vibraciones, de forma que se estimara el aislamiento sonoro estimado por medida directa de estas vibraciones. Todas estas medidas se han tratado, procesado, comparado y discutido con el fin de cumplir el principal objetivo de este trabajo, que consiste en comparar y validar distintos procedimientos de medida sonora, así como con las predicciones calculadas por los métodos expuestos por EN 12354-1 (2000).

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1.1 Preliminary remarks

The design of buildings and the construction techniques must be performed in such a way that the noise perceived by the occupants is kept down to a level that will not affect their health and satisfactory quality of life. The acoustical comfort is nowadays one of the most important items contributing for the family wellbeing. Protection against noise is one of the essential requirements that has been stated in the European Construction Product directive EEC (1989) amended further to EEC (1993) regarding the “CE” marking, among other issues¹. At the present time there are several endeavours and consults in order to upgrade this directive according the simplification established by the European Commission in Spring of 2005 according to the Lisbon Strategy².

Buildings in our time must be designed and built in such a way that the noise perceived by its occupants is kept at low levels, and does not threat their physical and psychological health, allowing them to work, rest or sleep in satisfactory conditions.

The demands of the building occupants intend to achieve levels of acoustic quality that comply with their needs. This aims to put more attention to a building acoustic project, and from the point of view of the investigation, seeking for a better understanding of the inherent physical behaviour phenomena. From the technological point of view it is intended to seek for appropriate solutions. The parameters that define the acoustical quality of a building are different and complex, but one can consider that both the airborne and impact sound insulation of the dividing elements, and as the reverberation time, give us an idea of the acoustical conditions of the dwellings. In fact, the demands of different countries can be very dissimilar and there is not an agreement for the parameters to consider or the limits to accomplish. The noise control starts from the definition of the target level. The target level in buildings is not standardized and varies from country to country legislation along the European Community. In northern European countries, in general, it is demanded and presented higher airborne sound insulation levels than in southern European countries.

¹ <http://ec.europa.eu/enterprise/construction/internal/cpd/notecpd.htm>

² http://ec.europa.eu/enterprise/construction/cpdrevision/cpd_revision_intro_en.htm

Airborne sound insulation is one of the most important physical quantities related to the acoustical comfort of buildings and it can be measured *in situ*³ conditions as described in the standard EN⁴ ISO 140-4. Although this procedure is widely used and accepted, it does not give information about the flanking contribution in the receiving room. The flanking contribution can be defined as the structure borne and airborne sound paths to a receiving room. This type of transmission can only really be evaluated *in situ*, since laboratory, usually built as to prevent flanking transmission conditions, can not predict in real terms the flanking contribution. It is therefore especially important to develop procedures and prediction models that can be used to verify building project requirements before, during and after its construction. In most of the European countries, their respective legislation is leading towards verification after the construction and therefore it is imperative to discover methods during the project phase in order to quantify the flanking transmission in terms of verification after construction. The European standard EN 12354-1 is the first example of it and it was introduced in 2000, three years before this research work was started.

1.2 The state of the art

The acoustical quality of buildings is an object of study for many investigation groups of several countries. The research of bibliographic issues is aimed to the building acoustic developments and then sub-divided in the following main research subjects: initially, the standardized experimental methods, sound pressure and sound intensity; secondly, the prediction methods and/or computer simulation; thirdly, a different field measurement method, the vibration velocity.

The sound pressure method is based on the diffuse sound field theory. The first theoretical formulation to determine the sound transmission loss, between two rooms, was presented in the earlier 1920's by Sabine. The evolution was further continued by Morse, Newman, Hunt, Beranek, Cremer, etc. The current international standards in building acoustics are used in Europe (EN) and worldwide (ISO⁵). They can grossly be

³ Field or non laboratory conditions

⁴ European standard

⁵ International Standard Organization

divided in laboratory measurements and field or *in situ* measurements. The sound pressure method standardized by the EN ISO 140 is worldwide used on the evaluation of the acoustic performance and characterization of buildings and building elements.

Comparably, it is presented an additional standardized airborne sound insulation measurement method capable of performing the same task with more data information of the measures. The sound intensity method is now standardized by the EN ISO 15186. But the first main application of the sound intensity method was the direct determination of sound power by Burger et al. (1973) and Van Zyl and Anderson (1975). The sound intensity method presents the advantage of knowing the direction of the sound energy flow, since it is estimated using the velocity magnitude with information on the direction of sound.

Pavic (1977) presents an article proposing to measure the sound intensity making use of two microphones, and introducing the first discussion about the measure associated errors.

The sound intensity method found its first application on building acoustics by Vittor and Roland (1981) with the measurement of sound power radiated through panels and by Crocker et al. (1981) where the sound transmission loss of panels was determined. They also compared the insulation values obtained by the intensity method with the pressure method values. They find an acceptable agreement between both methods, differing only below the 500 [Hz]. A good agreement was also found for certain cylindrical structures for low frequencies.

Halliwell and Warnock (1985) compared the results obtained by the classical pressure method and by the intensity method and found that if the receiving room is reverberant, it is necessary to have in mind the interference phenomenon near the walls. They introduced to the insulation calculus a correction factor named as “Waterhouse correction factor K_c ”. Since then, this factor appears in several papers, some in favour of the applicability of this factor and others against, discussing his authentic meaning.

The most serious problem in building acoustics with intensity measurements is that it is not possible to accurately measure specimens which are sound-absorbing on the receiving room side. If the absorption coefficient of the specimen on the receiving room side is zero, which is the ideal case, the net intensity caused by extraneous noise, (i.e.

flanking sound, reverberant direct sound, and background noise) is zero Van Zyl et al. (1986). A sound absorbing specimen leads to the underestimation of the true intensity radiated by the specimen if the intensity of the background noise or by other sound sources is sufficiently high. Thus, the sound reduction index by sound intensity will be overestimated. If possible, the sound absorbing side should be towards the source room.

Mey and Guy (1987) performed an exhaustive investigation study with the intention of validating the sound intensity insulation measurements against the classical methods. It was demonstrated that the sound intensity method can be used to identify other indirect sound transmission paths.

Fahy (1989) published a monographic book about intensity. All the theoretical aspects, applications of sound intensity are collected in this book. The second edition Fahy (1995) introduces additional information about intensity associated errors as well as about the sound power transmission through walls.

Jonasson (1991) Publish the results from the Nordtest Project 746-88 with a Nordic standard proposal for measuring the sound insulation by sound intensity. Further has presented several corrections discussed during the work group revision of the 140 series from ISO (ISO TC 43/SC 2 WG 18).

Jonasson (1993) has shown that agreement with traditional measurements of the sound reduction index is excellent. If the Waterhouse correction is applied in the receiving room the weighted sound reduction index R_w is over-estimated by about 0.5 [dB] with a standard deviation of 1.0 [dB]. Without this correction there is a small underestimate. The investigation indicates that the sound intensity method is more reliable than the traditional method when measurements are carried out on windows with high sound insulation.

Jonasson (1994) presents a measurement of sound insulation using sound intensity method.

Jonasson and Andresen (1996) present the results for *in situ* conditions from the measurement of sound power levels using different standards.

Herráez (1996) studied the parameters that affect the sound power measurement procedure using the sound intensity method. The determination of sound power has proved experimentally that the estimation in the presence of background noise has presented very good results in different situations. Therefore, this confirms that the sound intensity method is the adequate direct measurement method to develop *in situ*, if always, as the background noise is stationary and the source is fully enclosure by the measurement surface.

The first international building acoustical measurement standard with possible application of the intensity method was initially published in 1995, and reviewed in 1998 as EN ISO 140-5 (1998) in Annex E, as a supplementary tool for façade measurements. The dedicated laboratory standard intensity measurement method appears in 1997 as ISO/DIS-15186-1 with its first final version in 1999 and further reviewed in 2003 to EN ISO 15186-1 (2003).

Machimbarrena (1999) showed, for sound insulation, that the differences between the sound pressure method and the sound intensity method can be smaller than 1 [dB] in the frequency range of 50 to 10.000 [Hz]. It is presupposed that the measurements were carried out in large test rooms and using adequate intensity measurement equipment (recent models of intensity analyzers and probes). They used only a 12 [mm] microphone spacer. The intensity analyzer was equipped with the possibility to improve the residual pressure-intensity index by correcting for phase mismatch.

Hongisto (2000) has studied the difference between the maximum sound reduction indexes obtained by the sound intensity method and by the sound pressure method and the influence of adding room absorption to the receiving room. The results obtained showed that it is possible to measure wall structures having better sound reduction index using the sound intensity method rather than the sound pressure method. The sound intensity method makes easy measurements of small and/or heavy specimen in the presence of flanking contribution.

Andrade (2003) has performed several *in situ* measurements making use of the sound intensity method, in order to enhance and survey the method for building acoustics.

Secondly, speaking in terms of prediction methods applied to building acoustics, the following exposed is supported in statistical energy systems and in the acoustic data tables of building elements.

The predict method “Statistical Energy Analysis” – SEA was introduced by Lyon (1975) and provides great opportunities on the estimation of the transmission of sound energy, in several points of a building, transmitted by airborne sound or structural sound paths, as showed by Craik (1996).

The mathematical model that supports this method consists in considering the building as a physical system and each rooms and respective separating specimens as sub-systems of the complete physical system. This allows the interaction between sound fields, in closed rooms and the transference of the mechanical vibration energy, by elastic connections, between several rooms and the propagation of the energy through themselves.

This method is of easy application, it needs few parameters considering the possible amount of information and results that can give and it allows the characterization of the acoustic behaviour of buildings.

At low frequencies, where there are few vibration modes, this method does not produce reliable results and there are other difficulties when the degree of coupling between the sub-systems is considered low.

This prediction method is widely used in investigations of building acoustics nowadays, such as these performed by Hopkins (1997); Patrício (1999); Kim (2001); Craik (2003).

Hopkins (1997) used the SEA model results to compare with a flanking laboratory conditions for sound transmission across a separating and flanking cavity wall construction. The results obtained by the SEA model were in good agreement with the measured data, validating the SEA predictions for the direct and flanking transmission paths that are dominant.

Recent investigations by Nightingale and Bosmans (2003) established expressions for the first order flanking path, derived using the SEA model. This expressions showed to

be identical to the expressions appearing in EN 12354-1 (2000) for airborne sound insulation, even though this standard was not derived using SEA.

The expressions used in the EN 12354-1 (2000) start to be derived with the work of Cremer and Heckl (1973) [re-edited as Cremer et al. (2005)] and by Gerretsen (1979) or even more recently in Gerretsen (1986). This model was adopted and developed by the CEN⁶ to achieve a final version in the year of 2000. This standard is of extreme significance due to the fact that it can give to engineers, architects and other project planners or schemers, a powerful tool to calculate, with some accuracy, the possible acoustical behaviour of a building during the project phase, enabling the correction or improvement of the building acoustical performance. Nowadays, this is even more important with the increasing country building acoustics legislation inside the European Union, as referred previously in section 1.1.

Thirdly, more recently a vibration velocity method has appeared. Foreman (1990) refers: “(...) To determine the relative contribution for the various vibrating surfaces to the over all noise field it is usually desirable to measure the vibration at specific location on a machine. (...)”. This thought is applied to machinery noise control; also the vibration measurement procedure could be applied to the building acoustics. When this work started, the procedure based on the vibrating surfaces, was not standardized. Nowadays, the EN ISO 10848-1 (2006) reveals a procedure and two methods for measuring quantities related to vibrations for acoustic laboratory conditions.

Cremer and Heckl (1973) were the first to study and publish the sound transmission by structural vibrations. Nowadays, their concepts are used as basic learning of sound radiation. The vibration velocity method involves the calculation of the sound field starting from the vibration velocity of his surface.

Craik et al. (1995) concludes that simple measurement techniques provide a useful method of measuring power flow in buildings.

Also the prEN ISO 10848-1 (1999), later edited as EN ISO 10848-1 (2006), dedicated to evaluate, in laboratory conditions, the flanking transmission in buildings through the estimation of the newest acoustical quantity called the vibration reduction index between element i and element j or K_{ij} . This standard is of major importance on

⁶ Comité Européenne de Normalisation

the base for the implementation of the vibration measurements. A new vibration concept, which is the structural reverberation time of an element, was introduced. Knowing all the structural reverberation times and the vibration velocities differences between the elements, in a room, it is possible to estimate the vibration reduction index for each transmission path ij , over a specific junction, for *in situ* conditions.

More recently, some experimental works were performed using the radiated power performed by Fausti and Secchi (2002) and Fausti et al. (2003).

In these two previously mentioned works, the sound insulation is calculated by the estimation of the radiation efficiency V \acute{e} r (1992). This calculated parameter characterizes the efficiency of a sound emitting element, function of his vibration. There are several mathematical models available to simulate this physical behaviour.

Kihlman (1970) presents an analytical model based on the ratio between the incident sound power and radiated sound power for the case of diffuse sound field and equal areas.

Sewell (1970) presents a simple analytical expression for square and rectangular plates with a low frequency correction.

Josse (1972) presents in his acoustic book a simple equation capable of mathematically expressing the radiation efficiency.

Ljunggren (1990) present an analytical model in which the sound transmission loss is calculated in similar manner as the used by Cremer and Heckl (1973) and taking as starting point the simple model proposed by Kihlman (1970) for equal areas. Ljunggren (1990) model presents the advantage of calculating the sound transmission loss for rooms with different size and respect to a diffuse sound field. The model also features for the case of equal sizes.

V \acute{e} r (1992) makes possible to understand the concept of the sound radiation, explaining the basic mathematic equation from which derives the radiation efficiency. Although this ratio is basically undisputable, it is possible to derive different mathematical functions to describe it.

Rindel (1993) presents a theoretical analytical model for the transmission loss based on the ratio of the energy densities instead of the ratio of the incident sound power with

the radiated sound power. It can be used for any angle of incidence and for diffuse sound field.

Novak (1995) presents a mathematical model where it is shown that the radiation efficiency for high frequencies is the same for both forced and free vibrations, but for low frequencies the shape of the curves is different. He also shows that for forced vibrations at low frequencies the radiation efficiency can be expressed as a single function of a suitable defined Helmholtz number.

Davy (2004) presents a simple analytical model based on a strip theory which agrees reasonably with Sato (1973) numerical results for a rectangular panel. It also concludes that it is the length of the panel in the direction of radiation, rather than its width, which is important in determining its radiation efficiency.

Andrade et al. (2004) report the results of the comparison between the sound intensity method and the vibration velocity method, to estimate the flanking sound transmission. The measurements take place on a laboratory with particular conditions (two suppressed junctions) and in field conditions. It concludes that the results obtained with the vibration velocity method are largely in good agreement with the intensity levels, principally the results obtained for the flanking path D-f. To evaluate the contribution of the flanking paths, this is a good quality result and gives excellent perspectives to use this method in replacement of intensity method, for structure borne excitation.

Andrade et al. (2005b) reports the first *in situ* results obtained by sound intensity and vibration velocity methods, estimates the overall flanking contribution for one type of junction in common Spanish buildings.

Andrade et al. (2005a) compares three different measurement methods used in building acoustics, sound pressure, sound intensity and vibration velocity method with flanking evaluation. These methods were compared with the two prediction models proposed on the EN 12354-1 (2000) and the main objective of this experimental work was the verification and applicability of the EN 12354-1. The results conclude that the prediction models can be applied with good agreement to the Spanish constructions for the case of single layer elements.

This thesis was performed under the group of acoustic and vibration of the University of Valladolid. This group presents several studies on the subject of building acoustics, on the particular case for Spanish constructions. These developed studies are shown by several publications regarding special attention to the flanking transmission: González et al. (2007a); González et al. (2006a); Lorenzana and Machimbarrena (2006); González et al. (2006b); González et al. (2007b); González et al. (2009); Lorenzana et al. (2007); Martín Bravo et al. (2008); Martín Bravo et al. (2005a); Martín Bravo et al. (2005b); Martín Bravo et al. (2006a); Martín Bravo et al. (2006b); Martín Bravo et al. (2006c).

Additionally, part of this thesis was carried out on collaboration with the Italian universities of Bologna and Ferrara, on the DIENCA and engineer department respectively. During the four months of residence in Italy the initial work of this thesis was performed. The work group of this two universities has a recognized experience on the issue of the flanking transmissions as shown here by some of the works presented: Fausti (1993); Fausti et al. (1999); Cocchi et al. (1999); Fausti and Secchi (2002); Smith et al. (1999); Fausti et al. (2003); Cocchi and Semprini (2003), Semprini et al. (2004); Bonfiglio and Fausti (2004).

Following this, it was a great opportunity to get near on the most recent developments on the flanking transmissions and vibration velocity measurements and making use of flanking transmission facilities to perform the desired experiments.

1.3 Thesis justification

In the classical sound insulation measurement methods of building acoustics the most important room element is the main separating wall. However, the other elements of the room, connected to the main wall, are also contributing to the sound transmission. This transmission is named as flanking sound transmission and includes many different paths.

In easy terms what happens is that the sound field existent in the source room produces a vibration in all surrounding surfaces, thus it includes a vibration movement

on the separating wall and on all the elements connected to it. This vibration travels between them to them by different paths and doing so they radiate sound. Therefore there are two main issues to regard.

One issue is to analyse which are the propagation paths. Inspiring on the Foreman (1990) idea previously cited, it seems that the vibration measure of each element (vibration velocity) can be a good parameter capable of identifying the most contributively vibrating element. The physical magnitude named as structural reverberation time of an element i , represents the time for a structure, use for velocity or acceleration, to decrease of 60 [dB] after the end of the structural excitation. This is similar to the traditional acoustic reverberation time. Also it is establishing the concept of path ij as the propagation medium between the element i and the connected element j . Through the velocity difference between both elements, it can be easily identified if the vibration of element i travels efficiently until element j . The physical parameter which expresses this information will be the magnitude defined by the velocities level difference.

The second issue will be characterizing the radiation phenomenon, which is the existent relation between the vibrations of an element i and the corresponding sound field generated by it. The radiation will be characterized by the radiated sound power level, as mentioned in several studies by Cremer and Heckl (1973) and Norton and Karczub (2003), element i and his function of the vibration velocity of the element i and by his radiation efficiency.

Related to the first issue, at the present time, the determination of the propagation paths is performed by the introduction of the magnitude named as vibration reduction index or K_{ij} .

For laboratory measurements, the physical connection between the main separating element i and the flanking elements j is characterized by the vibration reduction index or K_{ij} index, tabled on the EN 12354-1 (2000) for different types of typical building joints. To obtain this vibration reduction index it is necessary to have a specific flanking laboratory where it possible to measure two connected elements in a room, but physically disconnected from all other 4 elements. The K_{ij} can then be calculated based on the difference of the structural vibration velocities between them and the respective structural reverberation times. As mentioned, this measurement procedure is not easy to

perform *in situ* conditions. However, if the same source room scheme used in the classical sound pressure method is used for in field conditions, it is possible to measure the velocity vibration of the main element and correspondent flanking walls.

Related to the second issue, to obtain the vibration radiated power level on the room elements surface, it is necessary to have another physical quantity - the radiation efficiency, as mentioned in Cremer et al. (2005). This quantity can be obtained through theoretical mathematical models developed by several authors such as Kihlman (1970), Sewell (1970), Josse (1972), Rindel (1993); Novak (1995) and more recently by Davy (2004). With the calculated radiated power level it is promising to obtain comparable sound reduction indexes similar to the obtained by other building sound measuring methods, such as the sound pressure method and the sound intensity method.

In parallel, Gerretsen (1986) has developed a prediction method, described in the standard EN 12354-1 (2000). This model also makes use of the K_{ij} index. This prediction method allows the building acoustical engineer to have instruments for producing better building acoustical projects. This prediction method needs to be validated and verified in building constructions for many situations, type of materials and country realities.

In the beginning of the current research work one task was clear; the measurement *in situ* conditions of the K_{ij} index. With this index it is possible to verify the flanking contribution using the newest (at the beginning of this thesis) draft of the future ISO standard EN ISO 10848-1 (2006). This standard is of most importance because it introduces the possibility of adjusting laboratory measurement procedures to *in situ* conditions and estimating the flanking contribution of sound transmission between adjoining rooms. However the measurement *in situ* conditions of the vibration reduction index involves the need of physically separate the adjoined elements of a room. This necessity was not able to be achieved, because it is related to the destruction of the joints and respective reconstruction that is not feasible and the research would gain other direction. The measurement process used to measure the K_{ij} index can be applied for the *in situ* conditions, but only for measuring the vibrations of the distinct elements present in a room.

The standardized sound intensity method by ISO 15186-2 (2003) for field conditions gains now a new meaning, in such a way, of being a greatly tested measurement method

working as a inescapable reference in the acoustic medium. This method is capable, when well executed, of quantifying the contribution of each flanking element, likewise the sound reduction index.

Therefore, the implementation of the vibration velocity method was experimented as a third sound measurement method. After some initial fair results achieved in laboratory conditions during the stage in Italy at the “DIENCA- Dipartimento Ingegneria Energetica, Nucleare e del Controllo Ambientale” in the University of Bologna, the vibration velocity method has become one of the central matters of the thesis.

1.4 Objectives

The first objective is to implement the vibration velocity measurement method for *in situ* conditions measuring the vibration velocities of the room elements. First, it is necessary to analyse the methodology of the EN ISO 10848-1 (2006) designed for laboratory conditions, and then to perform the applicability and adaptation of this methodology to the *in situ* case. This study will be preferable primarily performed in a flanking laboratory, where the *in situ* conditions can be easily simulated.

The second objectives group of this thesis is related to different types of comparison between experimental methods and prediction model methods, for *in situ* conditions:

- (i) Initially, to compare the sound reduction indexes of the three measurement methods tested *in situ* conditions: the sound pressure method by EN ISO 140-4 (1998); sound intensity method by ISO 15186-2 (2003) and the vibration velocity based on the EN ISO 10848-1 (2006);
- (ii) These results are compared to the two sound transmission prediction models proposed on EN 12354-1 (2000): the simplified model and the detailed model for *in situ* conditions;
- (iii) Inside this second objective, the insulation information obtained from the intensity method and the vibration velocity method can also be separated by the main separating element contribution and the flanking elements

contribution. Through this, it is possible to quantify the differences with and without the flanking elements contribution.

Thirdly, another possible evaluation is, starting from the values previously referred, to compare the weighted levels obtained by EN ISO 717-1 (1996). In this case, the weighted levels in comparison are related to the sound pressure method, sound intensity method, vibration velocity method and EN 12354-1 (2000) prediction methods (simplified and detailed method).

1.5 Thematic distribution

The thesis is structured in eight chapters. Most of them refer, either directly or indirectly, to matters related to the results described on chapter six. The following paragraphs describe briefly the subject of each chapter. Each one contains a bibliography section allowing an enhanced indexing to the subjects.

The chapter 2 deals with building acoustic isolation theory, regarding the airborne sound insulation and structure born sound transmission; it also includes a description of the flanking transmission.

Chapter 3 contains the prediction models including a description of some commercial software used for acoustics building design. Also describes the correspondent airborne sound insulation standards by EN and ISO.

The chapter 4 describes all the rooms where measurements were carried out, that is, laboratory and *in situ* measurement rooms. A detailed description of hardware and software equipments is also included.

In chapter 5 all the explanations of experimental measurements in laboratory and *in situ* conditions can be found. The development and implementation of the vibration velocity method is well described.

In chapter 6 the results and comparison from all the measurement methods applied are shown. An exhaustive comparison between sound pressure, sound intensity, vibration velocity methods and prediction models is made.

Chapter 7 is a conclusions chapter and it includes discussion and future research work that can be prepared following this matter.

At last in chapter 8 is included all the bibliography useful in this thesis.

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Chapter 2

2 Acoustic insulation in buildings

2 *Resumen de aislamiento acústico en edificación*

Este capítulo se inicia con una introducción sencilla a las magnitudes de acústica y vibraciones utilizadas en el resto del trabajo. Se explica el concepto de radiación en estructuras sencillas y la relación entre vibración y campo sonoro radiado, mediante la magnitud de eficiencia de radiación. Posteriormente, se presenta el concepto de transmisión sonora entre dos salas, así como los parámetros acústicos asociados a su caracterización. Se explican los distintos caminos de transmisión del sonido, y se hace hincapié en los conceptos de caminos directo y camino de flanco, que son cruciales en el desarrollo de este trabajo.

Después, se presentan los tres métodos de medida del aislamiento, de presión sonora, de intensidad sonora y el novedoso método de velocidad de vibración sonora, así como sus respectivas normativas internacionales asociadas, teniendo en cuenta tanto condiciones en laboratorio como condiciones *in situ*.

Por último, se comenta, aunque de manera somera, por no ser objeto principal de este trabajo, el concepto de transmisión sonora debido a impactos.

Parte de lo expuesto en este capítulo es una adaptación de lo expuesto en Cremer and Heckl (1973), Fahy (1985), Norton and Karczub (2003) y Patrício (1999) entre otros, y se trata de definiciones simples relativas a la acústica de edificios.

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2.1 Introduction

When a sound wave travels through the air or by other possible medium (fluid or solid) and impacts on a surface object, its energy is partially absorbed, partially reflected and other part is transmitted. The sound insulation, expressed by several physical magnitudes brings up to date an amount of energy transmitted, comparatively to the incident. The sound can travel through air or through a structure; in this manner, two kinds of transmission to a surface are defined: airborne sound transmission and structure borne sound transmission.

In building acoustics, one of the aspects of major assessment is the airborne sound insulation. This insulation is performed by the building elements, like the façade elements or inner walls. Thus, during the project stage it is convenient to evaluate the sound insulation performance of these parts, in conformity with regulation, to accomplish adequate comfort patterns levels inside the building.

The airborne sounds are originated by the direct excitation of air by a sound source, which, in the case of buildings, can be performed by road traffic, railway traffic or air traffic or by common machinery, collective or individual, even from normal conversation and common daily activity.

Nevertheless, the structure borne sounds can present more disturbing characteristics in the acoustic behaviour of a building against the airborne sounds.

The walk of people, falling objects, drag furniture or any type of action causing a hit, produces an excitation which is spread along the excited element and transformed in a radiating sound source to the structural coupled elements.

Having the attention that, in major cases, the hit actions occur with more probability in floors than in walls, the below room will present a higher sound field.

The sound fields inside building spaces have origin in noisy sound sources, with emission characteristics that can fluctuate with time, space, by type and spectral composition. Globally, in building acoustics and taking in consideration to its origin, we

can roughly classify the airborne sounds of interest in two major groups: Outer and inner sounds.

The outer sounds are usually road and railway traffic. However, in some cases they are generated by outer sound fields significantly disturbing to building occupants, such as: airports, industry installations, public fairs and markets.

The inner sounds are mainly due to the use of the building and respective occupants. From this point of view, it is easy to conclude that outer sounds will determine the type of sound insulation of the exterior building elements, and the inside sounds limit the sound insulation that is essential to ensure through the internal building elements, both vertical and horizontal.

In the present chapter, at first, several concepts related with acoustic insulation are exposed, referring how the sound moves, direct and flanking paths, respective physical acoustic transport and theoretical acoustic models used to predict sound insulation of simple layer walls.

Afterwards, three measurement methods are presented and respective international standards in use, relating to inside laboratory conditions and *in situ* conditions.

The propagation of sound energy acts as a wave form, for example, in a fluid environment or in a solid environment. Due to this, major measurement of sound procedures make use of extraordinary and sophisticated instrumentation, that in such way induct an abstraction of reality measurement of the propagation of impulses and induces to “forget” the wave characteristic of sound energy propagation.

Therefore, in this chapter some general aspects of sound transmission are present. Thus, for a better integration on the theme in study and at the same time new concepts for the study of sound propagation in buildings are introduced.

It is intended to refer the starting point of this work in order to show at the same time some background for better research and detailed information about this subject.

The following sections descriptions are a short review of the exposed in Cremer and Heckl (1973), Fahy (1985), Norton and Karczub (2003) and Patrício (1999), and are fundamental and simple definitions in building acoustics.

Notice: Building acoustics and respective international standards classify the sound transmission in airborne sound transmission and structure borne sound transmission. However the airborne sound transmission obviously presents a structural component. The main subject in this thesis is the airborne sound transmission with his structural component and flanking contribution, nevertheless in section 2.7 it is presented a resume of the sound transmission due to impact actions and corresponding flanking transmission.

2.2 Sound and vibration measurements

This section initiates a discussion on sound and vibration measurement units. The emphasis is on the fundamental principles involved in the selection of objective sound measurement scales, vibration measurement scales and frequency analysis bandwidths.

2.2.1 Sound measurement scales

Decibel scales are commonly used to quantify both sound and vibration levels and since they represent relative values, they have to be constructed with reference values which are universally accepted. Consider the sound power radiated by a sound source. Let W_0 be the reference sound power and W the radiated sound power. L_w is defined as the sound power level of a sound source relative to the reference sound power W_0 :

$$L_w = 10 \log \frac{W}{W_0} \quad [\text{dB re } W_0] \quad (2.1)$$

It is important to note that the sound power of a sound source refers to the absolute value of power in Watt [W], while the sound power level refers to the magnitude of the power in [dB] relative to a reference sound power. The same argument applies when describing sound intensity, sound pressure or even vibrations in terms of decibel.

Because of the relative nature of the decibel scale, it is critical that each magnitude has a unique reference value. The internationally accepted reference sound power is

$$W_0 = 10^{-12} \quad [\text{W}] \quad (2.2)$$

A 0,5 [W] sound source would thus have a sound power level, L_W of 117 [dB].

Like sound power, sound intensity can also be expressed in terms of a sound intensity level, by dividing $|I|$, by a reference value and taking logarithms. The sound intensity level, L_I , is defined as:

$$L_I = 10 \log \frac{|I|}{I_0} \quad [\text{dB re } I_0] \quad (2.3)$$

Where the internationally accepted reference value, it is:

$$I_0 = 10^{-12} \quad [\text{W} / \text{m}^2] \quad (2.4)$$

On the other hand, a sound pressure level is defined as L_p (inside the logarithm should appear a magnitude proportional to the energy, it is the square of the sound pressure):

$$L_p = 10 \log \frac{P^2}{P_{\text{ref}}^2} = 20 \log \frac{P}{P_{\text{ref}}} \quad [\text{dB re } P_{\text{ref}}] \quad (2.5)$$

Where p_{ref} is an internationally accepted value, it is the threshold audition limit at 1 [kHz]

$$p_{\text{ref}} = 2 \times 10^{-5} [\text{N} / \text{m}^2] = 20 [\mu\text{Pa}] \quad (2.6)$$

2.2.2 Vibration measurement scales

In the vibration measurements, depending on what is intend to study, there are three vibration measurement magnitudes: displacement, velocity and acceleration.

The vibration displacement level L_d , is:

$$L_d = 20 \log \frac{d}{d_0} \quad [\text{dB re } d_0] \quad (2.7)$$

where d_0 is the most internationally accepted value and it is:

$$d_0 = 10^{-11} \quad [\text{m}] \quad (2.8)$$

Sometimes is used $d_0=1$ [m].

The vibration velocity level, L_v , is:

$$L_v = 20 \log_{10} \frac{v}{v_0} \quad [\text{dB re } v_0] \quad (2.9)$$

The reference velocity v_0 , according to the sound measurement scales, can assume different values. The internationally recommended value is $v_0=10 \times 10^{-9}$ [m/s] according to the ISO/DIS 1683 (2007). The one used in this thesis is $v_0=5 \times 10^{-8}$ [m/s]. Sometimes other values are used as 10×10^{-8} [m/s] or 0,1 [m/s]. It is useful to note that 10^{-9} [m/s] corresponds to 10^{-6} [mm/s] - vibration velocity levels are often quoted in [dB re 10^{-6} mm/s].

The vibration acceleration level L_a is:

$$L_a = 20 \log \frac{a}{a_0} \quad [\text{dB re } a_0] \quad (2.10)$$

Where a_0 is the most internationally accepted value, and used in this thesis is:

$$a_0 = 10^{-6} \quad \left[\text{m/s}^2 \right] \quad (2.11)$$

Sometimes is used: $a_0=1$ [m/s²]; $a_0=10^{-5}$ [m/s²] and $a_0=9.81$ [m/s²].

This clearly illustrates the point that decibels are only relative values; when comparing different vibration levels in [dB], one should always ensure that they are all relative to the same reference value.

In the bibliography and insulation standards, usually the vibration levels are expressed in velocity levels while, experimentally, the measurements are performed with piezoelectric accelerometers, which obtain values in acceleration levels.

During this research work, for each one third octave band, experimental measurements were performed in acceleration levels L_a re $a_0=10^{-6}$ [m/s²], and velocity levels L_v re $v_0=5 \times 10^{-8}$ [m/s] were obtained from the equation (2.12), where f_m represents the central frequency band in [Hz].

$$L_v = L_a - 20 \log f_m + 10 \log \left(\frac{a_0^2}{4\pi^2 v_0^2} \right) \quad (2.12)$$

The previous equation is deduced in the annex A.

2.3 Radiation of a plate

When the sound in a source room hits the separating element, this element starts to vibrate and this bending vibration generates a sound field on the receiving room. In order to understand how this sound field is radiated, at first it is presented a single model of the radiation of an infinite plate; and secondly the explanation theory for the sound radiation from a finite plate. Due to the fact that our measurements took place between rooms separated by single layer and homogeneous walls, it is fundamental to explain the theory behind the finite plate sound radiation.

2.3.1 Sound radiation from an infinite plate

The theory here presented is a short resume from the authors Norton and Karczub (2003).

In supposition, it is possible to have an infinite plate separating two rooms and assuming that the propagating medium is the air in both sides. Therefore, if this plate is acoustically excited in one side, the plate starts to vibrate, and in the other side a sound wave is generated, as represented in the Figure 2.1, for a planar bending wave of constant amplitude and propagation speed of c_B :

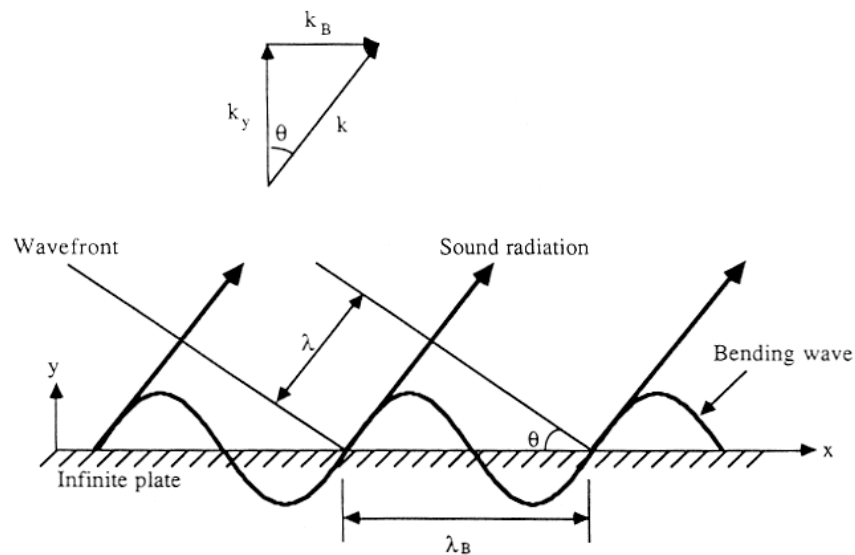


Figure 2.1 - Sound radiation from an infinite plate

In consequence, there are acoustical waves in the air, produced by the structural waves in the plate. Therefore, it is useful to introduce the concept of wave number, equation (2.13), in the analysis of a structure borne sound.

$$\mathbf{k} = \frac{2\pi \cdot \mathbf{f}}{c_0} \quad (2.13)$$

Where f is the frequency in [Hz] and c_0 is the velocity of sound in the air in [m/s].

The wavelength in [m] of the air is:

$$\lambda = \frac{c_0}{f} \quad (2.14)$$

The bending wavelength λ_B in [m], of the plate is:

$$\lambda_B = \frac{c_B}{f} = \left(\frac{1,8c_L \cdot t}{f} \right)^{\frac{1}{2}} \quad (2.15)$$

Where c_B is the bending wave velocity in [m/s], t is the thickness of the plate in [m], f is the frequency in [Hz] and c_L is the longitudinal wave velocity in [m/s].

The wave length ratio between a structural wave and a sound wave at the same frequency is:

$$\frac{\lambda_B}{\lambda} = \left(\frac{1,8c_L \cdot t \cdot f}{c_0^2} \right)^{\frac{1}{2}} \quad (2.16)$$

Therefore, different efficiencies of sound radiation are expected from the structure depending on whether $\lambda_B/\lambda > 1$ or < 1 . Radiation ratios will be discussed further in section 2.3.3.

In equation (2.16) it can be seen that $\lambda_B = \lambda$ when $c_B = c_0$, i.e. when the bending wave velocity in the structure equals the speed of sound in the air. The frequency at which this occurs can be obtained from c_B equation and by equating c_B to c_0 . Thus:

$$f_c = \frac{c^2}{1,8c_L t} \quad (2.17)$$

Where f_c is the plate critical frequency.

2.3.2 Sound radiation from a finite plate

In an infinite plate only occurs sound radiation above the critical frequency f_c . Considering a more realistic model of a finite plate shows how the major part of the radiation has origin above the critical frequency f_c , but also there is radiation below f_c with the called edge modes and corner modes.

Sound radiation from free bending waves (bending waves which are not restricted by some structural discontinuity) in a structure, can be categorised as: (i) modal sound radiation at any given arbitrary frequency, including non-resonant frequencies, and (ii) frequency band averaged sound radiation. Finite structural elements always allow the existence of natural frequencies and their associated mode shapes. Thus, when a structure is excited by some broadband force, this generally results in the resonant excitation of numerous structural modes. Therefore, frequency band averaged sound radiation is necessarily dominated by resonant structural modes whereas modal sound radiation is not. It is essential remind that a resonance occurs when an excitation frequency coincides with a structural natural frequency.

Specialists, such as Fahy (1985), Cremer and Heckl (1973), provide analytical expressions for the sound radiation, for finite planar surfaces; and for arbitrary single frequency excitation. The solutions are generally restricted to the far field. Cremer and Heckl (1973) also provide analytical expressions for the near field sound power radiated, at regions in proximity to the excitation point.

In practice, when structures are technically excited by some broadband force they respond in a multi-mode resonant form, natural frequencies are excited and they resonance with the applied force. In this instance it is often, but not always, the case that these resonant modes are responsible for most of the sound radiation. It is not always the case because radiation ratios of finite structures generally increase with frequency - a situation could arise where the higher frequency, but non-resonant, modes (i.e. modes above the excitation frequency band) with their associated higher radiation ratios generate more sound than the lower frequency, but resonant, modes. Generally, however, while these higher frequency modes have higher radiation ratio their vibrational levels are significantly reduced, because they are non-resonant, thus the net effect is that they radiate less sound than the lower frequency, lower radiation ratio

resonant modes which are within the excitation band. Hence, as a general rule, resonant structural modes tend to dominate the sound radiation from mechanically excited structures.

The situation is somewhat different for acoustically excited structures. It is worth noting that the vibrational response of finite structures to acoustic excitation (i.e. incident sound waves) comprises:

- (i) a forced vibrational response at the excitation frequency;
- (ii) a vibrational response due to the excitation of the various structural natural frequencies.

The previous is associated with a wave that propagates through the structure at the trace wavelength $\lambda/\sin\theta$, of the incident sound wave (see Figure 2.1). The latter is associated with the structural waves that are generated when the trace wave interacts with the boundaries; these structural waves are, in effect, free bending waves, with corresponding natural frequencies. The important point to be noted is that the structural response is now both resonant and forced, and the transmission of sound through the structure (i.e. a partition between two rooms) can be due to either one of the mechanisms or both.

For the infinite plate, it is clear that sound is only radiated for those structural waves where $f_{m,n} > f_c$. Unfortunately, the situation is not so simple for finite plates. Firstly, the problem is now two-dimensional and secondly the plate boundaries generate standing waves. Because of this, sound can be radiated at frequencies both below and above the critical frequency.

In practice, the mechanical excitation of plates or panels results in most of the radiated sound being produced by resonant plate modes – the sound radiated by non resonant forced modes tends not to be very significant. With acoustic excitation, however, it is the non-resonant forced modes, driven by the incident sound field, which match the wavelengths of the sound waves thus transmitting sound very efficiently through the structure at frequencies below the critical frequency (but above the fundamental resonance). At frequencies above the critical frequency, both forced and resonant modes, contribute to the radiated sound.

The sound radiation characteristics of finite plates are somewhat complex, especially at frequencies below the critical frequency. It is, however, obvious that the sound radiation (below and above the critical frequency) depends upon the number of possible vibrational modes that can exist within a given frequency bandwidth. Hence, the concept of ‘modal density’ is relevant to the radiation of sound from vibrating structures. Modal density is defined as the number of vibrational modes per unit frequency. For any plate of arbitrary shape, surface area S , and thickness t , it can be approximated in Vér (1992) by:

$$n(f) = \frac{\sqrt{12} \cdot S}{2 \cdot c_L \cdot t} \quad (2.18)$$

Equation (2.18) allows for a rapid estimation of number of resonant modes to be expected, the vibrational response and the sound radiation from a structure can be directly related to this. Modal density concepts play an important role in the analysis of sound and vibration from complicated structures.

It is fairly instructive to qualitatively analyse the radiation of sound from plate modes in some detail and to try to understand how the sound is radiated. The mode shape of a typical mode on a rectangular plate is illustrated in Figure 2.2.

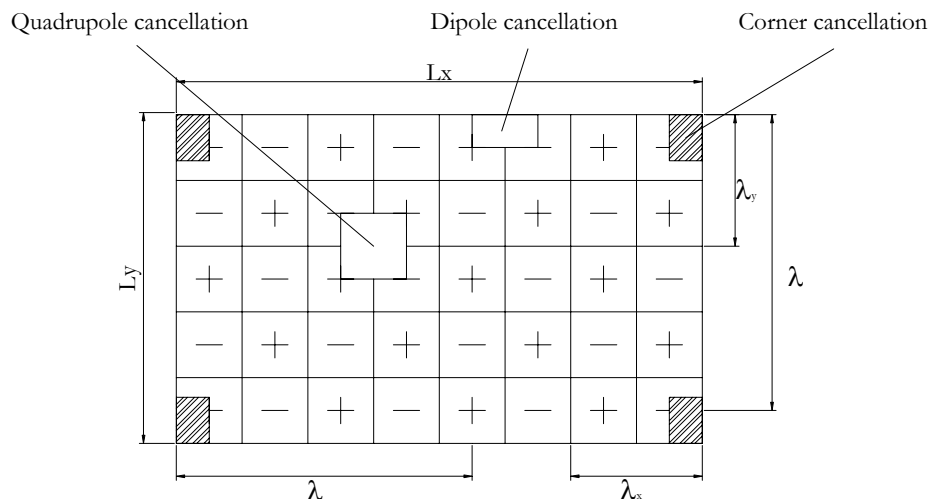


Figure 2.2 – Schematic illustration of corner radiation for a finite plate

For this particular example, the bending wave numbers k_x and k_y are greater than the corresponding acoustic wave number k , at the same frequency. Hence, k_x and k_y are both smaller than λ . This situation is representative of the corner modes in Figure 2.2. For this example, the bending wave numbers k_x and k_y are greater than the corresponding acoustic wave number k , at the same frequency. Hence λ_x and λ_y are both smaller than λ . The structural wavelengths in both the x and y directions are less than a corresponding acoustic wave length at the same frequency and, as such, the fluid which is displaced outwards by a positive sub-section is transferred to an adjacent negative sub-section without being compressed. The consequence of this is that very little sound is radiated. The radiated sound can be modelled in terms of monopole, dipole and quadrupole sound sources. The central regions of the plate are quadrupole sound sources (groups of four sub-sections that essentially cancel each other as they oscillate). The edges of the plate comprise a line of dipole sources (groups of two sub-sections oscillating out of phase and cancelling each other), and the uncanceled oscillating volumes of fluid in the corners are monopole sources. From fundamental acoustics, quadrupole sound sources are the least efficient and the monopoles the most efficient. Thus only the corners of the plate radiate sound efficiently.

In the above example, if the lengths of the plate are much less than an acoustic wavelength (L_x and $L_y < \lambda$) then the four corner monopoles will interact with each other. This interaction will be dependent upon their respective phases. For instance, for odd values of m and n , the four corners will radiate in phase with each other and behave like a monopole. For m even and n odd, adjacent pairs will be in phase but out of phase with the opposite pair, and behave like a dipole. For both m and n even, all four corners are out of phase with each other and the behaviour is quadrupole like. When L_x and $L_y > \lambda$ the four corners radiate like individual, uncoupled monopoles.

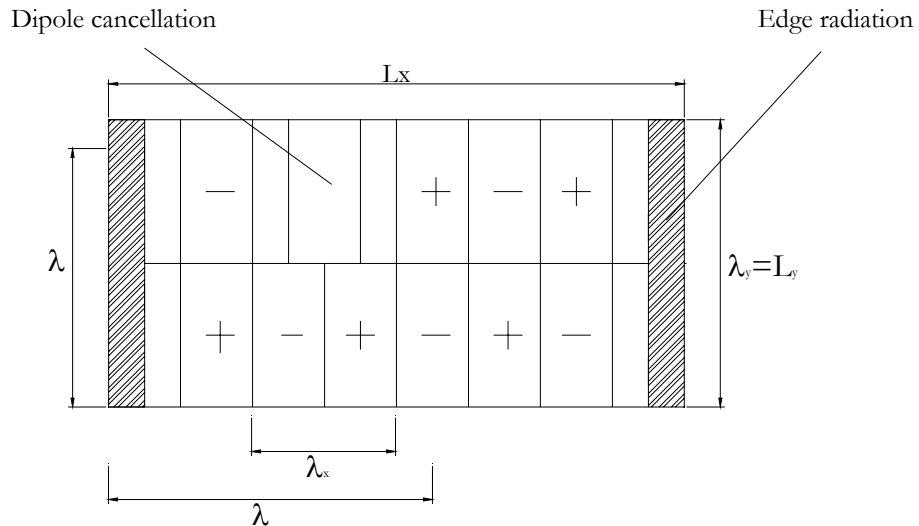


Figure 2.3 – Schematic illustration of edge radiation for a finite plate

Figure 2.3 illustrates the case where one of the bending wave number k_y , is less than the corresponding acoustic wave number k , at the same frequency. Hence, λ_x is smaller than λ , but λ_y is greater than λ . In this case, the central regions of the plate form long narrow dipoles which cancel each other, but the edges along the y -direction do not cancel. The structural wavelength in the y -direction is greater than a corresponding acoustic wavelength at the same frequency and, as such, the fluid which is displaced outwards by the positive sub-section (in the y direction) is compressed when it is transferred to the adjacent negative sub-section. Sound is radiated as a consequence of this. These edge modes are more efficient radiators than corner modes.

As the exciting frequency approaches the critical frequency, the cancellation in the central regions starts to reduce. This is because the separation between sub-sections approaches $\lambda/2$. The cancellation breaks down totally at and above the critical frequency and the whole plate radiates sound. These modes are called surface modes, and both λ_x and λ_y are greater than the corresponding acoustic wavelength λ , at the same frequency (or k_x and $k_y < k$). The fluid which is displaced outwards by positive sub sections (in both the x - and y -directions) is compressed as it is transferred to adjacent negative subsections since all the sub-sections are greater than a fluid wavelength. Surface modes are very efficient radiators of sound.

As a result of the preceding discussions relating to flat plates, it is clear that while at frequencies above the critical frequency finite plates behave in a similar manner to infinite plates, but this is not the case at lower frequencies. Above the critical frequency, the radiation ratio σ , is the same in both cases, but it is clear that the radiation ratio of finite plates is not zero below the critical frequency; there is sound radiation which in some instances is very efficient. It should by now be very clear that radiation ratios have a very important role to play in engineering sound and vibration control.

In the following section it is explained the concept of radiation efficiency of a surface.

2.3.3 The radiation efficiency and vibration velocity method

To establish a relation between a vibrating surface of area S , vibrating at a time average mean square velocity $\langle \bar{v}^2 \rangle$ and the sound field radiated by it, the concept of radiation efficiency is introduced. It is considered as a reference sound source a rigid piston, which generates a planar wave and the sound power radiated by one surface will be compared against the radiated sound power radiated by a piston, both from the same surface of area S and vibrating at the same time average mean square velocity $\langle \bar{v}^2 \rangle$. Having in attention the relation for a planar wave, the radiated power by a piston is:

$$W_{\text{rad}}^{\text{piston}} = S \cdot \rho_0 c_0 \langle \bar{v}^2 \rangle \quad (2.19)$$

Where ρ_0 is the air density [kg/m^3], c_0 is the velocity of sound in the air [m/s], S is the plate surface area [m^2] and $\langle \bar{v}^2 \rangle$ is the time and space average mean-square velocity of the radiating surface [m^2/s^2].

The radiation factor for a vibrating element is the ratio of the radiated power by the surface W_{rad} and the radiated power by the piston $W_{\text{rad}}^{\text{piston}}$ and is usually designated by the symbol σ and is defined by the equation (2.20) in Vér (1992):

$$\sigma = \frac{W_{\text{rad}}}{\langle \bar{v}^2 \rangle \rho_0 c_0 S} \quad (2.20)$$

Where W_{rad} is the sound power radiated by the surface in [W],

The radiation of a surface $\sigma > 1$ represent that is higher than the radiation of a piston, when $\sigma = 1$ is the same as a piston and when $\sigma < 1$ is inferior to the piston radiation.

Rewriting the equation (2.20) in logarithm terms and after a mathematical reorder, in Cremer and Heckl (1973), it is obtained the estimated sound power level radiated using surface average velocity vibration values $L_{w,v}$, respective to the radiation efficiency and the value of his surface area, represented by the equation (2.21):

$$L_{w,v} = L_{\bar{v}} + 10 \log(S) + 10 \log(\sigma) \quad (2.21)$$

Where $L_{\bar{v}}$ is the time and spatial average velocity level [dB re 5×10^{-8} m/s] and σ is the radiation efficiency.

This equation (2.21) represents the estimation of the radiated power from a surface in [dB re 10^{-12} W]. The measurement of his velocity and estimation of his radiation efficiency it will be identified in this thesis by vibration velocity method.

It must be noticed that only with the previous equation is not possible to estimate the radiated power by a surface, unless it is also estimated, by mathematical models, the radiation efficiency of that surface.

There are several modelling approaches in terms of mathematical formulation usable to estimate the radiation efficiency. These prediction equations are developed for determined shapes, i.e.: spheres, cylinders, thin plates, single and double layer walls, etc.

One of the first works presented within this subject refer to Kurtze and Watters (1959) and some years after Sewell (1970) presents an expression for a square plate, including a low frequency correction.

$$\sigma = \frac{1}{2} \left(0,16 + \ln 2kb + \frac{1}{16\pi \cdot k^2 b^2} \right) \quad (2.22)$$

Where b is the dimension of the square plate and k is the sound wave number defined in equation 2.13:

Few years later, Sato (1973) presents an extensive numerical calculations for different size plates, where the plate wavelength is longer then the wavelength in air. Also numerically calculated, the radiation efficiency averaged over all possible directions of sound incidence. These numerical results obtained by Sato are often used as reference values to validate new approaches to the radiation efficiency behaviour, as was used by Davy (2004).

Also Josse (1972) present a simple equation for the evaluation of the radiation efficiency.

$$\sigma = \frac{1}{\sqrt{1 - \frac{f_c}{f_m}}} \quad (2.23)$$

Rindel (1993) developed an expression (2.24) for single layer elements based on the angle of incidence and was corroborated by Sato numerical results.

$$\sigma = \frac{1}{2} [0, 20 + \ln(k \cdot e)] \quad (2.24)$$

The main difference to the previous equation (2.22) is the rearrangement for non square plates introduced by the constant e ,

$$e = \frac{4S}{U} \quad (2.25)$$

and what Rindel identifies as the characteristic dimension of the plate. With this constant introduced in equation (2.22), it was concluded that the results obtained are equal. Where e is the characteristic dimension of the surface, S is the area [m^2] and U is the perimeter [m].

More recently Davy (2004) has presented an expression (2.26),

$$\sigma = \log\left(\frac{q+1}{q+g}\right) + 2\log\left(\frac{2q+3g}{2q+2g}\right) \quad (2.26)$$

Where q and g are:

$$q = \frac{\pi}{2k^2 b'^2} \quad \wedge \quad g = \sqrt{\frac{\pi}{2kb'}} \quad (2.27)$$

And b' is half length of a square plate and k the wave length.

Easier of implement then the one used by Rindel, extended to the low frequencies. The purpose of Davy is deriving an analytic approximation (2.26) to Sato's numerical results, using a simple two dimensional strip model, explained in Davy (2004).

2.4 Sound transmission between rooms

The sound transmissions that occur between two rooms or dwellings, with a sound source in the source room (airborne excitation), can be of two types: airborne transmission and structure borne transmission. For the two room's case, the sound transmission arrives by several different paths, the direct path and the flanking paths, as shown in the following Figure 2.4.

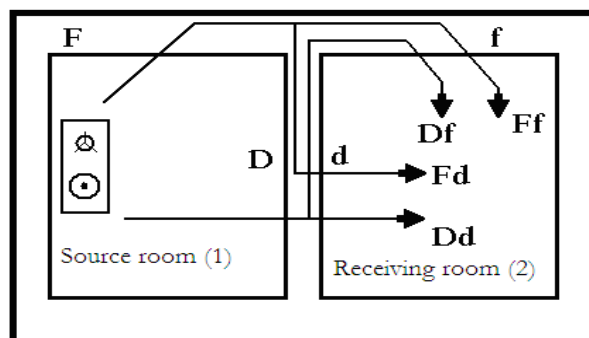


Figure 2.4 – Sound transmission paths between two rooms, Gerretsen (1979)

The Figure 2.4 describes two adjoining rooms and the correspondent four identified paths of sound transmission for two rooms. It is represented a source room (upper case letters) and a reception room (lower case letters).

If we have in the source room a sound source producing airborne excitation, the **Dd** path is the transmission due to direct airborne sound transmission path, because the transmission is performed through the separating element. The other three paths are identified by flanking sound transmission paths, due to the airborne excitation of the source room elements. The sound transmission is due to an airborne and structure borne transmissions of the correspondent connected elements, producing sound emission by the receiving room elements. These transmissions paths are:

- (i) through flanking and direct element **Fd**;
- (ii) direct emission element through flanking receiving element **Df**;
- (iii) through flanking to flanking elements **Ff**.

The acoustic behaviour of building structural separating elements or partitions and respective characterization, can be performed in acoustic laboratories test facilities with two rooms, separated by the plate in study, following the requirements of EN ISO 140-1 (1997). These laboratories facilities do not consider the contribution of flanking transmission. Only the **Dd** path is considered.

By this reason, it becomes imperative to establish the requirements for a flanking laboratory facility, which is expressed in the EN ISO 10848-1 (2006). These flanking sound laboratory facilities present an approach to the *in situ* conditions, having in attention the contribution of the flanking sound transmission paths **Fd**, **Df** and **Ff**.

There are numerous building constructions which can present specific structural differences, which tend to change the predictable acoustic behaviour of the construction.

In that way, the certification of acoustic project requirements must be made after the building construction. It comes useful at the beginning of the building design, having measurement methods to estimate contribution of flanking transmission, in terms of the established in the building insulation acoustic project as a direct correlation after the building construction.

The applicability to building acoustics and determination of transmission loss or sound reduction indexes must obey to a diffuse sound field in the source room with single layer walls (studied in this thesis) or double layer walls as separating element. The angle of incidence is between 0° and 90° degrees and the equation approach must be integrated in this range of incidence.

In practical engineering works it is fundamental to understand how the sound waves are transmitted through plates or panels and partitions. Most practices of engineering applications involving sound and vibration control make use of panels or partitions. Wall partitions, machine covers, windows, all of them transmit vibrations and sound. Typical examples are:

- (i) Wall homogeneous partitions with single leaf panels;
- (ii) Double leaf panels including, or not, sound absorbing materials;
- (iii) Stiffened panels;
- (iv) Mechanically coupled panels, etc.

Because of the vast variety of panels, no single theory describes their sound transmission characteristics. Many basic theories are available, but limited to describe correctly the real practical problems, although they serve to illustrate the physical characteristics that are involved.

Due to the fact that partitions are connected between each other in a building, they provide the presence of flanking transmissions. These flanking transmissions can have origin in airborne or structure borne sounds, interacting with the sound transmission in a one.

In the following section 2.4.1 it is defined the concept of transmission loss in both situations: (i) laboratory conditions and (ii) *in situ* or field conditions.

Further in section 2.4.2 it is analysed the frequency behaviour of the sound transmission loss for finite and clamped (fixed) single leaf panels.

The section 2.4.3 shows practical suggestions for the evaluation of R and R'.

2.4.1 Transmission loss for a single panel in a diffuse sound field

For the case represented in the previous figure 2.4 with acoustical excitation, the terms airborne “transmission loss” - TL, airborne “Sound Reduction Index” level – SRI represented by R, are commonly used to describe the reduction in sound that is being transmitted through a separating element or a panel.

When only the direct transmission is considered, the transmission loss TL for an element is defined as:

$$\mathbf{TL = SRI = R = 10\log\left(\frac{1}{\tau}\right)} \quad (2.28)$$

where τ is the ratio of the transmitted sound power, to the incident sound power.

$$\tau = \frac{W_2}{W_1} \quad (2.29)$$

Where W_1 is the sound power which is incident on an element under test and W_2 is the sound power transmitted directly through this element.

$$\mathbf{R = 10\log\left(\frac{W_1}{W_2}\right)} \quad (2.30)$$

For a simplest reference in this thesis, the transmission loss TL or sound reduction index SRI, commonly represented by R, will be referred during this text as is referred by the EN ISO organizations, which is sound reduction index – R, for laboratory condition and direct transmission.

When the weighted value of sound reduction index is represented, it will be referenced as R_w .

When the transmission loss is obtained *in situ* conditions (direct and flanking transmissions considered) it will be referenced as R' and called as apparent sound reduction index.

R' is defined as “ten times the logarithm to the base 10 of the ratio of the sound power W_1 which is incident on a partition under test to the total sound power transmitted into the receiving room if, in addition to the sound power W_2 transmitted through the separating element (direct) and the sound power W_3 , transmitted through flanking elements or by other components, it is expressed in decibel” EN ISO 140-4 (1998):

$$R' = 10 \log \frac{W_1}{W_2 + W_3} = 10 \log \frac{W_1}{W_{\text{tot}}} \quad (2.31)$$

Where the W_{tot} is the total sound power transmitted through the separating element plus the flanking elements. The following Figure 2.5 shows different contributions of sound power transmission, considered valid scheme previously the more precise actual scheme in Figure 2.4.

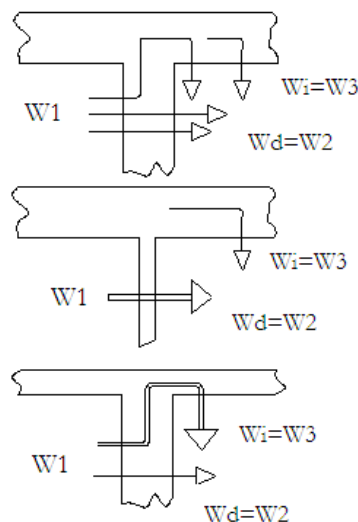


Figure 2.5 – Example of a flanking transmission scheme, in Warnock and Fasold (1998) or Patrício (2001)

In the previous Figure 2.5 W_3 represents the sound transmission (energy passing through) that occurs by indirect paths, and W_2 represents the direct path. This criterion was considered more precise, earlier, than the presented by Gerretsen (1979), because it can illustrate the influence of this kind of sound transmission, starting in the dimension elements (mass law criterion or law of theoretic mass) contributing to the direct and flanking transmission.

2.4.2 Graphical representation of R in function of frequency

Several theoretical models have been developed using mathematical expressions, which allow the calculation to predict direct airborne sound reduction indexes levels for several standard partitions or elements, as Cirillo (1987); Byrne (1988) and Recuero (1992), Vér (1992); Grèhant (1996), to mention a few.

The frequency behaviour of the sound reduction index level R of a clamped homogeneous single leaf panel is schematic illustrated in Figure 2.6 by Norton and Karczub (2003). There are four general regions of interest, and they are:

- (i) Stiffness controlled;
- (ii) Resonance controlled;
- (iii) Mass controlled;
- (iv) Coincidence controlled.

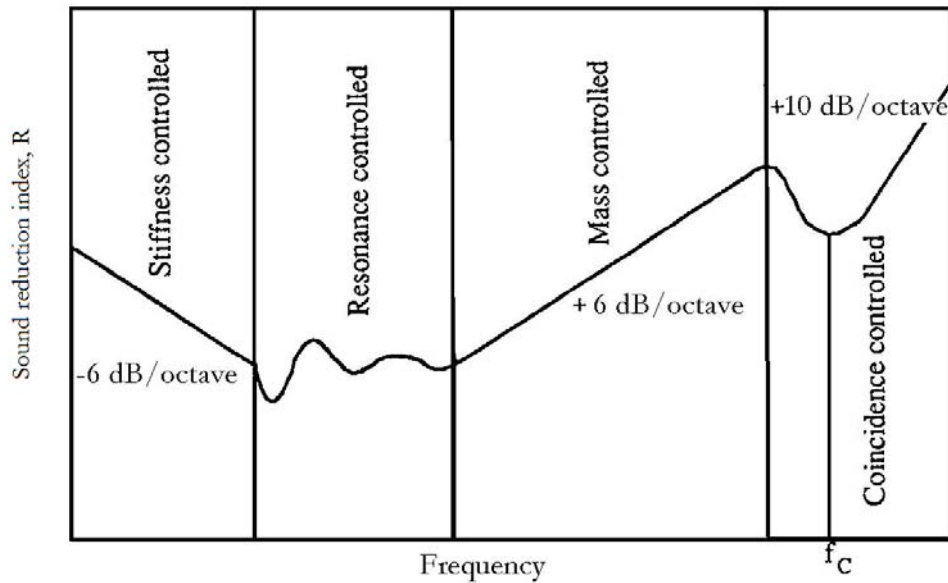


Figure 2.6 - Typical sound reduction index level of a clamped, homogeneous, single leaf panel, Norton and Karczub (2003)

These four regions are explained as follows:

- (i) **Stiffness controlled:** At frequencies below the first fundamental natural frequency of the element, it is the stiffness of the panel which dominates its sound transmission characteristics. In this region there is a 6 [dB] decrease in sound reduction index R per octave increase in frequency. Also, in this region, the addition of mass or damping will not affect the sound reduction index R characteristics. Doubling the stiffness would increase the transmission loss by 6 [dB];
- (ii) **Resonant controlled:** Because the panel is finite and clamped, it has a series of natural frequencies and it is important to note that these natural frequencies can be relevant to sound transmission. If the panel is acoustically excited below the critical frequency equation (2.17) and the incident sound field is diffuse, then the forced bending waves at the excitation frequencies (diffuse sound field) dominate the sound transmission through the panel and the resonant structural modes are relatively unimportant;

- (iii) Mass controlled: At frequencies above the first natural frequencies but below the critical frequency, the response is mass controlled. In this region there is a 6 [dB] increase in sound reduction index R per octave increase in frequency. There is also a 6 [dB] increase in sound reduction index R if the mass is doubled. Damping and stiffness do not control the sound transmission characteristics in this region. It is important to note that, although doubling the mass increases the sound reduction index, it also reduces the critical frequency;
- (iv) Coincidence controlled: Finally, at regions in proximity to and below the critical frequency, there is a sharp drop in the sound reduction index R . In these regions, the structural modes are coincident ($\lambda_B = \lambda / \sin\theta$) and their resonant responses are damping controlled. At frequencies above the critical frequency all the resonant structural modes have wavelengths greater than the corresponding acoustic wavelengths and they radiate sound very efficiently. The sound reduction index increases at about 10 [dB] by octave in this region; the resonant response is damping controlled and the non-resonant response is stiffness controlled.

Above the critical frequency a single layer partition does not verify the mass law, starting again with similar spring behaviour. In this area the main control factor of insulation variations is the internal damping, by other means, is the ability for acoustic absorbing energy of bending waves.

2.4.3 Practical suggestions for the evaluation of R and R'

The flanking airborne sound transmission was treated till a few years ago with the knowledge of the insulation features of the separating element and the correspondent connected elements; originally to establish contribution transmission categories and consequently the correction to laboratory values (according EN ISO 140-1 (1997)) or simplified evaluation models Figure 2.5. These categories were established as followed for homogeneous elements, as according to Patrício (2001):

- (i) For airborne direct weighted sound reduction index levels values with $R_w \leq 35$ [dB] the flanking transmission contribution is considered irrelevant, and the single number rating, obtained in laboratory conditions (direct), is considered equal to the *in situ* conditions (direct plus flanking), being $R_w = R'_w$;
- (ii) For airborne weighted sound reduction index levels values that are in the condition of $35 < R_w \leq 45$ [dB] the flanking transmission contribution become in the reduction of the direct sound reduction index of 3 [dB], $R'_w = R_w - 3$ [dB];
- (iii) For airborne weighted sound reduction index levels with $R_w > 45$ [dB] the flanking contribution could have a much bigger influence in lowering the levels and is not easy to estimate the R'_w .

2.5 Airborne sound insulation standards

Sound reduction index, R is the most usual acoustical quantity determined in laboratory or *in situ* measurements. The first theoretical formulation to determine sound transmission loss, between two rooms, was presented in the earlier 1920's and the first standard was proposed by ASTM¹, in 1951. The principle of this method was remained the same over the years.

The current international standards in building acoustics used in Europe (EN) and worldwide (ISO) can be grossly divided in laboratory measurements and field or *in situ* measurements, and it could be classified in function of the physical magnitude measured: sound pressure and sound intensity methods.

The further sections are a resume of each acoustic measure type and procedure, sound pressure and sound intensity methods. At the moment, the standard consists in

¹ American Society for Testing and Materials

several parts and can be confirmed in the respective web pages of the EN² and ISO³ organizations. The airborne sound excitation is accomplished by a loudspeaker and used the same setup in the source room (1) for sound pressure method, sound intensity method and also for vibration velocity method.

2.5.1 Introduction to the sound pressure method by

EN ISO -140

The EN ISO 140 is a collection of international standards applied to building acoustics – measurement of sound insulation in buildings and of building elements, where the experimental measured magnitude is L_p equation. The series consists in eighteenth parts, starting in EN ISO 140-1 (1997).

The applied method in this work and show next, is an *in situ* or field method, which is the described in EN ISO 140-4 (1998).

The general concepts of the method are described in the EN ISO 140-3 (1995).

EN ISO 140 Acoustics -- Measurement of sound insulation in buildings and of building elements:

Part 1: Requirements for laboratory test facilities with suppressed flanking transmission;

Part 2: Determination, verification and application of precision data;

Part 3: Laboratory measurements of airborne sound insulation of building elements;

Part 4: Field measurements of airborne sound insulation between rooms;

Part 5: Field measurements of airborne sound insulation of façade elements and façades;

² http://www.cen.eu/cenorm/standards_drafts/index.asp

³ <http://www.iso.ch/iso/en/CatalogueListPage.CatalogueList>

- Part 6: Laboratory measurements of impact sound insulation of floors;
- Part 7: Field measurements of impact sound insulation of floors;
- Part 8: Laboratory measurements of the reduction of transmitted impact noise by floor coverings on a heavyweight standard floor;
- Part 9: Laboratory measurement of room-to-room airborne sound insulation of a suspended ceiling with a plenum above it;
- Part 10: Laboratory measurement of airborne sound insulation of small building elements;
- Part 11: Laboratory measurements of the reduction of transmitted impact sound by floor coverings on lightweight reference floors;
- Part 12: Laboratory measurement of room-to-room airborne and impact sound insulation of an access floor;
- Part 13: Guidelines;
- Part 14: Guidelines for special situations in the field;
- Part 16: Laboratory measurement of the sound reduction index improvement by additional lining;
- Part 18: Laboratory measurement of sound generated by rainfall on building elements

2.5.1.1 EN ISO 140-4, sound pressure method: field or *in situ* measurements of airborne sound insulation between rooms

This fourth part is one essential issue in this thesis, which specifies a field method for measuring the airborne sound insulation properties of inner walls, floors and doors between two rooms, under diffuse sound field conditions in both rooms.

The sound pressure method provides values for airborne sound insulation which are frequency dependent. They can be converted into a weighted value (as previously referred at the final of section 2.4.1), rating the acoustic performance, by application of EN ISO 717-1 (1996).

The results obtained can be used to compare sound insulation between rooms and to compare actual sound insulation with specific requirements.

2.5.1.2 Equations and field conditions

Starting with the expression of the sound pressure p_1 of room (1) at a general position at a distance r from the sound source (with a sound power of W and directivity factor Q) can be found deduced in Irwin and Graf (1979), which is:

$$p_1^2 = W\rho_0c \left(\frac{Q}{4\pi r^2} + \frac{4}{\left(\frac{\bar{\alpha}_1 S_1}{1 - \bar{\alpha}_1} \right)} \right) \quad [\text{Pa}^2] \quad (2.32)$$

Where S_1 is the surface area of the source room and $\bar{\alpha}_1$ is the average absorption coefficient of room 1.

The total pressure is the addition of direct and reverberant components, described, respectively, by the first and second terms in parenthesis of equation (2.32).

Rewriting the previous equation (2.32) in terms of levels and by equation (2.1) and (2.5), and assuming that we are operating near the normal conditions of pressure and temperature, yields:

$$L_{p1} = L_{w1} + 10 \log \left(\frac{Q}{4\pi r^2} + \frac{4}{\left(\frac{\bar{\alpha}_1 S_1}{1 - \bar{\alpha}_1} \right)} \right) \quad [\text{dB}] \quad (2.33)$$

The EN ISO 140 standard has the foundations on the diffused sound field theory. This theory, also known as Eyring theory, is widely applied because of its simplicity, and the conditions to achieve diffuse sound field are:

- (i) at any position in a room, energy is incident from all directions with equal intensities;
- (ii) The sound pressure of the sound field does not vary with receiver position.

After these conditions, the direct field in equation (2.33), is considered despicable, and becomes:

$$L_{p1} = L_{w1} + 10 \log \frac{4}{\left(\frac{\bar{\alpha}_1 S_1}{1 - \bar{\alpha}_1} \right)} \quad [\text{dB}] \quad (2.34)$$

For an equivalent scheme as represented in Figure 2.4, and assuming the reverberant field is achieved in the source room (1).

The sound power of the reverberant field W_r which is absorbed by the partition from room (1) W_a and is described in Irwin and Graf (1979) by the following expression:

$$W_a = W_r \left(\frac{S \cdot \alpha}{S_1 \cdot \bar{\alpha}_1} \right) \quad [W] \quad (2.35)$$

Where W_r is the sound power in the reverberant field in [W]; S is the area of the wall in [m^2]; α is the absorption coefficient of the element; $\bar{\alpha}_1$ average absorption coefficient and S_1 is the surface area of room (1) in [m^2].

If is assumed that all the power which is incident upon the wall will be absorbed, that is saying $\alpha = 1$. The sound power in the reverberant field may be expressed in terms of the sound power, W_1 of the source:

$$W_r = W_1 (1 - \bar{\alpha}_1) \quad [W] \quad (2.36)$$

This upon substituting in equation (2.35) yields:

$$W_a = W_1 \frac{1 - \bar{\alpha}_1}{S_1 \cdot \bar{\alpha}_1} S = \frac{W_1 S}{A_1} \quad [W] \quad (2.37)$$

This combined with equation (2.29) yields,

$$W_2 = \frac{W_1 S \cdot \tau}{A_1} \quad [W] \quad (2.38)$$

Where W_2 is the sound power transmitted by the separating element; τ is the ratio of the transmitted sound power to the incident sound power; and A_1^4 is the equivalent sound absorption area in the source room (1).

Substituting this equation (2.38) in equation (2.33) to obtain:

$$p_2^2 = W_1 \rho_0 c \frac{S \cdot \tau}{A_1} \cdot \frac{4}{A_2} \quad [Pa^2] \quad (2.39)$$

⁴ $A_1 = \bar{\alpha}_1 S_1 / (1 - \bar{\alpha}_1)$

Rearranging:

$$L_{p2} = L_{p1} + 10 \log \frac{S}{A_2} - TL \quad [\text{dB}] \quad (2.40)$$

Where the term TL is defined in equation 2.28.

Becoming the apparent sound reduction index R' as presented in equation (2.41):

$$R' = 10 \log \frac{W_1}{W_{\text{tot}}} = L_{p1} - L_{p2} + 10 \log \frac{S}{A_2} \quad (2.41)$$

Where, L_{p1} is the spatial average sound pressure level in the source room (1), L_{p2} is the spatial average sound pressure level in the receiving room (away from the wall), S is the area of the element and A_2 is the equivalent sound absorption area in the receiving room (2).

In all situations, the measurements take place in rooms without furniture or other type of elements, capable of changing the diffuse sound field.

2.5.1.3 Test procedure

The standard does not specify an exact procedure, except in the experimental determination of reverberation time measurements, reporting to the existing standard EN ISO 354 (2003) and determined using Sabine's formula:

$$A_2 = \frac{0,16 \cdot V_2}{T_2} \quad (2.42)$$

Where A_2 is the equivalent absorption receiving room area in $[\text{m}^2]$, V_2 is the receiving room volume in $[\text{m}^3]$ and T_2 is the reverberation time in the receiving room in [s].

The field measurements of airborne sound insulation were made in one third octave bands. The sound generated in the source room shall be steady and have a continuous spectrum in the frequency range considered. If broad-band noise is used, the spectrum may be shaped to ensure an adequate signal-to-noise ratio at high frequencies in the receiving room (white noise was used). In either case, the sound spectrum in the source room shall not have differences in level greater than 6 [dB] between adjacent one-third-octave bands of L_{p1} .

The sound power should be sufficiently high for the sound pressure level in the receiving room L_{p2} , to be at least 10 [dB] higher than the background noise level in any frequency band.

The spatial average sound pressure levels of source room and receiving room can be obtained by using a single microphone moved from position to position or by a moving microphone. The microphone positions or moving radius were in accordance with the minimum separating distances, as specified in the standard.

2.5.2 Sound intensity method by EN ISO 15186

The series EN ISO 15186 Acoustics - Measurement of sound insulation in buildings and of building elements using sound intensity, presents three standards where L_i is measured in order to obtain the sound reduction index estimation. The description of parts is the following:

ISO 15186 Acoustics - Measurement of sound insulation in buildings and of building elements using sound intensity:

Part 1: Laboratory measurements (EN and ISO);

Part 2: *In situ* measurements;

Part 3: Laboratory measurements at low frequencies.

At the present instant, the first part EN ISO 15186-1 (2003) is referred by the two standard organizations and according to their web sites.

The part used in this thesis is the second part. The ISO 15186-2 (2003) is a standard that specifies a sound intensity method to determine, *in situ* conditions, the apparent sound reduction index of building elements. This method can be used in alternative to the EN ISO 140-4 (1998) standard, with an expected equal or even better reproducibility as demonstrated by Machimbarrena (1999) and Hongisto (2000).

These standards have some definitions in the previous standards ISO 9614-1 (1993), second ISO 9614-2 (1996) and third part ISO 9614-3 (2002), also some definitions are obtained from the EN ISO 140 standards.

For field standards, the presence of strong flanking sound transmission EN ISO 140 standards have serious problems to obtain reproducible results shown by Van Zyl et al. (1986). The ISO 15186-2 (2003) can solve that problem. The following section resumes the second part, in respect to the *in situ* or field measurements.

2.5.2.1 ISO 15186-2, sound intensity method: field or *in situ* measurements

ISO 15186-2 (2003) specifies a sound intensity method to determine the *in-situ* sound insulation of walls, floors, doors, windows and small building elements. It is intended for measurements that have to be made in the presence of flanking transmission. It can be used to provide an exhaustive study of flanking transmission or to measure flanking sound insulation parameters.

2.5.2.2 Terms and equations

One of the most important magnitude describing airborne sound insulation, defined in this standard for comparison with the sound pressure method, is the apparent sound reduction index by sound intensity method R'_I or simply R' for a building element or partition that divides one source room and a receiving room. Considering the equation (2.30), presented by the differences of sound power levels in the source room and in the receiving room, to estimate the apparent sound reduction index:

$$R'_I = L_{w1} - L_{w2} \quad (2.43)$$

The sound power level in the source room can be obtained from the expression (2.28) and considering the reverberant field in the source room, taking a similar equation to (2.34), for source room. The sound pressure level in the source room, under reverberant conditions, is:

$$L_{p1} = L_{w1} + 10 \log \left(\frac{4}{A_1} \right) \quad [\text{dB}] \quad (2.44)$$

Where L_{w1} is the sound power level in the source room and A_1 is a similar equation to (2.42). Rearranging equation (2.44) for the area S of the separating element, yields:

$$L_{w1} = L_{p1} - 6 + 10 \log \left(\frac{S}{S_0} \right) \quad [\text{dB}] \quad (2.45)$$

The sound power through intensity $W_{S_M}^I$ can thus be obtained by integrating the components of sound intensity normal to an imaginary control surface S_M enclosing the sound source, mathematically expressed by:

$$W_{S_M}^I = \int_{S_M} I_n \, dS \quad (2.46)$$

The measurement surface or control surface S_M in the receiving room side defines a measurement surface that totally comprises the building element under test. The partition surface may be divided into a number of smaller sub-areas S_{Mi} , and the measurement surface is located in the vicinity, as represented in the following Figure 2.7 with six sub-areas for the building element under test.

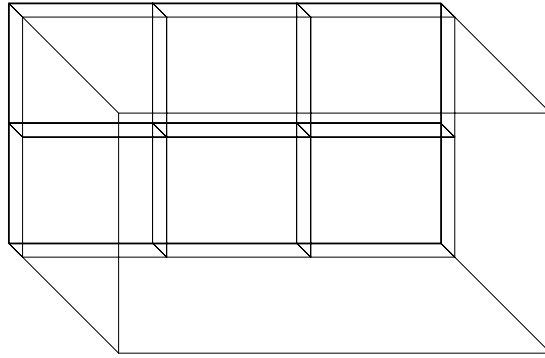


Figure 2.7 – Measurement surface created from a series of sub-areas, all of which parallel to the element under test

If the control surface S_M is divided in several smaller control areas S_{Mi} becomes:

$$\bar{L}_{in} = 10 \log \left(\frac{1}{S_M} \sum_{i=1}^n \frac{S_{Mi} \bar{I}_{ni}}{I_0} \right) \quad (2.47)$$

\bar{I}_{ni} is the surface signed normal sound intensity measured on the i^{th} sub-area S_{Mi} and where there are N sub-areas having a total area of S_M .

Starting from the previous equation the sound power level in the receiving room is L_{w2} :

$$L_{w2} = \left[\bar{L}_{in} + 10 \log \left(\frac{S_M}{S_0} \right) \right] \quad (2.48)$$

Combining the equations (2.43), (2.45), and (2.47), and considering the control surface area of separating element, is obtained the equation which calculates the sound

transmission, or sound reduction index, considering only the direct sound power W_2 transmission.

$$\mathbf{R}'_I = \left[\mathbf{L}_{p1} - 6 + 10 \log \left(\frac{\mathbf{S}}{\mathbf{S}_0} \right) \right] - \left[\bar{\mathbf{L}}_{in} + 10 \log \left(\frac{\mathbf{S}_M}{\mathbf{S}_0} \right) \right] \quad (2.49)$$

Where the first term relates to the incident sound power on the separating element, for a diffuse sound field in the source room, and the second term, relates to the sound power radiated from the building element or elements, contained within the measurement control volume in the receiving room. L_{p1} is the sound pressure level in the source room; S is the area of the separating building element under test. \bar{L}_{in} is the average normal sound intensity level over the measurement surface or surfaces in the receiving room; S_M is the total area of the partition measurement surface or surfaces and S_0 is $1 \text{ [m}^2\text{]}$.

To estimate the sound power contribution W_3 related with the flanking elements contribution, a similar equation could be obtained for a flanking element $j=1, \dots, 4$.

R'_{IFj} is identified as apparent intensity sound reduction index for flanking element j :

$$\mathbf{R}'_{IFj} = \left[\mathbf{L}_{p1} - 6 + 10 \log \left(\frac{\mathbf{S}}{\mathbf{S}_0} \right) \right] - \left[\bar{\mathbf{L}}_{inj} + 10 \log \left(\frac{\mathbf{S}_{Mj}}{\mathbf{S}_0} \right) \right] \quad (2.50)$$

Where \bar{L}_{inj} is the average normal sound intensity level over the measurement surface for the flanking element j in the receiving room; S_{Mj} is the total area of the imaginary measurement surface for the flanking element j . The same equation is used for each flanking element.

In sound intensity method, there are some terms or indicators related with measurement verification of a correct choice of the measurement surface and correct equipment verification. For the equipment, the verification or indicator term is the pressure residual intensity index δ_{pI0} , obtained during the calibration procedure, as well explained in Fahy (1995), and is the “difference, in decibels, between the indicated

sound pressure level, L_p and the indicated sound intensity level, L_I when the intensity probe is placed and oriented in a sound field such that the sound intensity is zero”:

$$\delta_{pI_0} = L_p - L_{I_0} \quad (2.51)$$

Where L_{I_0} is the level of the residual intensity and is given by:

$$L_{I_0} = 10 \log \frac{|I_0|}{I_0} \quad (2.52)$$

For a correct choice of the measured surface related to the measurement environment, it is provided by the measurement surface indicator F_{pIn} . In a very diffuse sound field is very difficult to achieve accurate measurement intensity results. For that reason, the direct component of the element is important in the measurement surface.

A satisfactory environment is defined as being one that assures the criterion for reflective test specimen. The difference between the term δ_{pI_0} and F_{pIn} for any field is a measure of the normalized error, in Fahy (1995):

$$\delta_{pI_0} - F_{pIn} = 10 \log \left(1 + \frac{1}{e_\varphi(\hat{I})} \right) \quad (2.53)$$

Where $e_\varphi(\hat{I})$ is the estimation normalised systematic error associated with intensity.

If it is intended to have a systematic error of ± 0.25 or an estimation intensity level error of ± 1 [dB], the equation must obey to the following:

$$F_{pIn} < \delta_{pI_0} - 7 \quad (2.54)$$

If a precision of ± 0.5 dB is desired the difference between both indicators must be higher than 10 [dB].

2.5.2.3 Instrumentation and test procedure

The sound intensity instrumentation shall be able to measure sound intensity levels in [dB re 10^{-12} W/m²] in one third octave bands.

The generation of the sound field by the loudspeaker and the generated input signal, shall meet the requirements of the EN ISO 140-4 (1998).

The probe orientation shall be normal to the measured surface and the sound intensity \bar{I}_n shall be positive for energy flowing from the building or wall element under test.

The manual scanning procedure of the measured surface was the only used and the velocity proportional to the respective dimension sub-area was kept constant at low velocities between 0,1 and 0,3 [m/s], with interrupted measurements when going from one sub-area to another.

To scan each sub-area, parallel (vertical and horizontal) lines were used, turned at each edge, back to front with approximately the same distance between scan lines d_M , till the sub-area is all scanned.

This is a recommended procedure for this method, and in order to achieve good results, it is fundamental the requirement of an experimented and skilled equipment operator.

Machimbarrena (1999) showed that the differences between the sound pressure method and the sound intensity method, can be smaller than 1 [dB], in the frequency range of 50 to 10.000 [Hz]. Hongisto (2000) studied the difference between the maximum sound reduction indices, obtained by the sound intensity method and by the sound pressure method, and the influence of adding room absorption to the receiving room. The results obtained showed that it is possible to measure separated elements structures, having better sound reduction index, using the intensity method in opposition to the classic sound pressure method.

Also Hongisto et al. (2001) enhanced the capabilities of this method in the presence of strong receiving room absorption.

2.6 Sound reduction index by vibration velocity method

The apparent airborne sound reduction index for *in situ* conditions R'_v or simply R' can be calculated through vibration velocity levels in one test element using the following equation (2.55),

$$\begin{aligned} R'_v &= \left[L_{p1} - 6 + 10 \log \left(\frac{S}{S_0} \right) \right] - [L_{\bar{v}} + 10 \log(S) + 10 \log(\sigma)] \\ \text{or} & \\ R'_v &= \left[L_{p1} - 6 + 10 \log \left(\frac{S}{S_0} \right) \right] - L_{w,v} \end{aligned} \quad (2.55)$$

Where L_{p1} is the pressure level in the source room in [dB]; S is the surface area [m^2]; S_0 is the reference area of 1 [m^2] and $L_{w,v}$ is the estimated sound power level according to equation (2.21), in [dB]. The radiation efficiency can be calculated according one of the four mathematical models, previously referred.

This information has only interest to the main separating element. The sound reduction index for the flanking elements has only interest in association with all the flanking elements contribution. To add the flanking transmission contribution, was applied an equation (2.56) similar to the one used by the sound intensity measurement method, equation (2.50) in ISO 15186-2 (2003) and consequently the field apparent sound reduction index with flanking contribution, becomes:

$$R'_v = \left[L_{p1} - 6 + 10 \log \left(\frac{S}{S_0} \right) \right] - 10 \log \left[\sum_j S_{M_j} \cdot \sigma_j \cdot 10^{\frac{\bar{L}_{v_j}}{10}} \right] \quad (2.56)$$

Where L_1 is the sound pressure level in the source room [dB]; S is the surface area [m^2]; S_0 is the reference area 1 [m^2]; S_{M_j} is the surface area of elements j [m^2] and σ_j is the radiation efficiency for element j ; \bar{L}_{v_j} is the vibration velocity levels for elements j in [dB].

For a better understanding of this measurement and calculus procedure, see chapter 6 of this thesis, where the comparison figures of sound intensity method and vibration velocity method are presented.

2.7 Sound transmission due to impact actions

The sound produced in a building due to impact actions are in major cases of difficult resolution. This type of sounds results of the direct excitation of any building element and can be easily propagate, due to the existence of rigid connections trough all the building structural frame, establishing eventually high sound fields in dwellings far away from the excitation point.

The walk of people on floors, object falling, furniture drag, or generally speaking, the impact action at a determined point of a structural element in a building produces an excitation which is propagated to overall element, with elastic waves transforming it on a sound source to all attached structural elements.

Due to the fact that all these situations occur on floors with much higher regularity than would be expected, the dwelling immediately below will present a much higher sound field. Therefore the verification of direct and flanking transmission due to impact sound fields are made in dwellings vertically and directly disposed.

The research in progress at the DIENCA laboratory, involving the evaluation of floors to impact actions according to the EN ISO 140-8 (1997) is of major influence and because of that, the measurement conditions during this thesis were set-up to evaluate of impact actions, as further revealed by Semprini et al. (2004). Therefore, it was only possible to carry out sound intensity and vibration velocity measurements with the source room (1) conditions, which will be described in the section 4.2.1, and consecutively to reproduce the specified by EN ISO 140-7 (1998). The measurements in the laboratory conditions at DIENCA facility were only structure borne excitation (impact machine) and performed in special conditions, as described further on chapter 5. Due to these conditions, these measurement procedures are not standardized and will be named in this thesis as “impact sound intensity method” and “impact vibration

velocity method”. The source and receiving room conditions are the described and explained in the further section 4.2.1. The mentioned impact methods make use of the same scheme for the reception room, explained for field procedures by sound intensity method in section 2.5.2.1 and vibration velocity method in section 2.6 and the receiving room measurement procedures will be explained in section 5.3.1 and section 5.4.1, respectively.

In the following Figure 2.8 it is represented a scheme of the flanking transmission path from direct excitation of a floor.

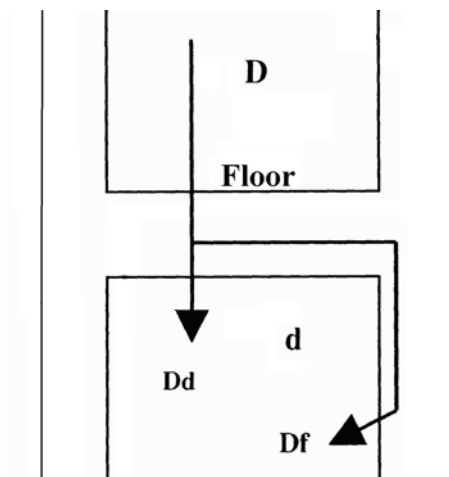


Figure 2.8 – Direct and flanking sound transmission paths present in a floor

The ISO CEN method (the method adopted by ISO and CEN organizations) or also identified as Gerretsen (1986) method, reveals the impact insulation of floors characterization according the standards EN ISO 140-6 (1998) for laboratory conditions and EN ISO 140-7 (1998) for *in situ* conditions.

The pressure levels used in impact sound sources are usually referred by L_i and are described in the EN ISO 140-6 (1998) as ‘impact sound pressure level L_i ; and defined as “average sound pressure level in one third octave band in the receiving room when the floor under test is excited by standardized impact sound source, expressed in decibels”.

The normalized impact sound pressure level L_n is the term used in the reports and it is defined as “impact sound pressure level L_i increased by a correction term which is given in decibels, being ten times the logarithm to the base ten of the ratio of the

measured equivalent absorption area A_2 of the receiving room to the reference absorption area A_0 , expressed in decibels.” See equation (2.57).

$$L_n = L_i + 10 \log \frac{A_2}{A_0} \quad (2.57)$$

Where the reference absorption area A_0 is 10 [m²].

For the *in situ* conditions in EN ISO 140-7 (1998) there is an additional definition called the “standardized impact sound pressure level” defined as “ L'_{nT} ; impact sound pressure level L_i reduced by a correction term which is given in decibels, being ten times the logarithm to the base 10 of the ratio of the measured reverberation time T_2 of the receiving room to the reference reverberation time T_0 and expressed in decibels”. See the equation (2.58):

$$L'_{nT} = L_i - 10 \log \frac{T_2}{T_0} \quad (2.58)$$

Where T_0 is 0,5 [s], considered a reference value for a room.

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Chapter 3

3 Prediction methods for sound transmission in buildings

3 Resumen de métodos de predicción para aislamiento sonoro en edificaciones

La formulación teórica de los métodos de predicción en transmisión sonora se centra en el comportamiento vibratorio de los elementos que componen los edificios. Este tipo de métodos se aplican habitualmente en la fase de proyecto y en la definición de los elementos de la edificación.

En concreto, en este capítulo se describe, en primer lugar, de manera somera, el método de Análisis Estadístico de la Energía, conocido como SEA (Statistical Energy Analysis) Lyon (1975). Y posteriormente, el método propuesto por la Comisión Europea de Normalización, también conocido como CEN, que fue introducido inicialmente por Gerretsen (1986) y que forma parte de la Normativa Europea en la EN 12354-1 (2000).

Esta Normativa se explica de forma detallada, ya que es de gran importancia en el desarrollo de este trabajo. El método de predicción que introduce permite pronosticar el aislamiento sonoro entre salas con una aproximación bastante adecuada, que se podrá, posteriormente, validar in situ, tras la construcción del edificio. Este es uno de los objetos de esta tesis, en el caso de edificaciones españolas, como se verá en el capítulo 6.

Por último, se comenta brevemente cual es el software de aplicación que en la actualidad se encuentra en el mercado.

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3.1 Introduction

The theoretical formulation of the sound transmission prediction methods is based on the vibrational behaviour of building elements. These types of methods are usually applied during the project phase and definition of the building elements.

The methods described further are: The Statistical Energy Analysis (SEA) by Lyon (1975) and the CEN method of Gerretsen (1986) introduced in the EN 12354-1 (2000) standard.

The standards series EN 12354, previously referred, are explained here in detail because it is of major significance within the development of this thesis. The predictions methods allow forecast airborne sound insulation between dwellings, with a significant accuracy as can be seen further in chapter 6. Consequently, *in situ* validations after construction are intended for the trustiness of the model and apply it in our study for Spanish buildings.

3.2 The SEA method

The method known as “Statistical Energy Analysis” – SEA in Lyon (1975), enables the chance to estimate the sound energy, in several points of a building, transmitted by airborne or structural paths, as mentioned by Craik (1996).

The mathematical model supporting this method consists of studying the building as a physical system and each dwelling and separating element as sub-systems of the whole physical system. The interaction between sound fields in rooms and the transition of vibrational mechanical energy by the elastic connections is present between several dwellings and consequently the corresponding energy propagation through them.

To a given considered sub-system, it is necessary that the geometric dimensions must be sufficient large in comparison to the sound wavelength passing through the sub-system.

Because this method is based on energetic balance between a range of sub-systems in all building, incident sound power must be equal to the sound power dissipated, in steady conditions and for each sub-system. Thus, the building has at each moment a total vibration energy, which is distributed in all constituted sub-systems, in such a way that the transmitted sound is concentrated on the energy transferred between the sub-systems referred previously.

If η_d is the dissipative internal factor of a certain sub-system d and E_d is its sound energy, one verifies that the sound power dissipated at this sub-system W_d , Lyon (1975), is equal to:

$$W_d = \omega \cdot \eta_d E_d \quad (3.1)$$

Thus, considering two sub-systems S_1 and S_2 , with sound energy E_1 and E_2 ($E_1 > E_2$), the sound power internally handles between them W_{12} is:

$$W_{12} = \omega \cdot \eta_{12} E_1 - \omega \cdot \eta_{21} E_2 \quad (3.2)$$

Where η_{12} and η_{21} are the loss-coupling factors, related by n_1 and n_2 , which are the modal density of the subsystem 1 and 2, respectively in the following expression:

$$n_1 \cdot \eta_{12} = n_2 \cdot \eta_{21} \quad (3.3)$$

One of the main problems for the correct application of the method appears with the definition of the sub-systems. In some cases these could be the proper separating elements or the volumes defined by them (rooms) and in other cases a collection of vibration eigen-modes.

Another allusion is that SEA method take advantage of the total (time and spatial average) vibrational energy, as a dynamic variable to estimate the response of each sub-system, and the total vibrational (time and spatial average) energy. Beginning with in the information of the value of that energy, it is possible to calculate all the values associated with the other dynamic variables (velocities, accelerations, displacements, on the separation element) specifically concerning the sound transmission estimation.

This method is of easy application, it needs few parameters compared to the possible amount of information and results that it can provide, and it allows the characterization of the acoustic behaviour of buildings.

At low frequencies, where there are few vibration nodes, this method has not reliable results and there are others difficulties, namely when the degree of coupling between the sub-systems is considered low, it could present some difficulties to go on.

This prediction method is widely used in investigations of building acoustics nowadays by Craik (1996).

Hopkins (1997) has used the SEA model results to compare with flanking laboratory measurements for sound transmission across a separating and flanking cavity wall construction. The results obtained by the SEA model were in good agreement with the measured data, validating the SEA predictions for the direct and flanking transmission paths that are dominant.

Recent investigations by Nightingale and Bosmans (2003) established expressions for the first order flanking path, derived using the SEA model. This expressions showed to be identical to the expressions appearing in EN 12354-1 (2000) for airborne sound insulation, even though EN 12354 was not derived using SEA.

3.3 The EN 12354 standard series

In this section it is explained how the standard is organized and further the flanking sound paths and the characterization of the vibrational energy, with explanation of the magnitudes involved, are described. Then, two method calculus are presented has simplified model and detailed model, with correspondent description of equations involved.

3.3.1 Standard series description

The European standard series EN 12354 is, till the moment, divided in six parts, which are the following:

Part 1: airborne sound insulation between rooms;

Part 2: impact sound insulation between rooms;

Part 3: airborne sound insulation against outdoor sound;

Part 4: transmission of indoor sound to the outside;

Part 5: sound levels in rooms due to technical equipment and installations;

Part 6: reverberation time in rooms and other enclosed spaces in buildings.

One of the standards in attention in this thesis is the EN 12354-1. This standard describes two calculus methods (simplified and detailed method) for estimating the airborne sound insulation between rooms in buildings. These methods make use of measured data, which characterise direct or indirect flanking transmission by the participating building elements. As a result, derive theoretical methods for sound propagation in the building elements.

A simplified calculus model for structure borne transmission (further explained in section 3.3.4), with a restricted field of application is deduced, calculating directly the single number rating for the separating element between dwellings (including flanking contribution), using the single number ratings of the elements.

The detailed calculus model for structure borne transmission (explained in section 3.3.5) is described for calculation in octave bands, and it can also be adapted to one third octave bands. The single number rating can be determined from the calculation results. The document describes the principles of calculation scheme, lists the relevant quantities and defines its applications and restrictions. It is intended for acoustical

experts and provides the framework for the development of application documents and tools for other users in the field of building construction, taking into account local circumstances.

The calculation models described use the most general approach for engineering purposes, with a clear link to measurable quantities that specify the performance of building elements.

The models are based on experience with predictions for rooms or dwellings; they could also be used for other types of buildings, providing that the construction systems and dimensions of elements are not too different from those in rooms.

3.3.2 Flanking paths and magnitudes

Previously in chapter 2, in section 2.4, several different paths for flanking sound transmission were represented, showed in figure 2.4 and again represented here by Figure 3.1, adding the reference of the standard in attention.

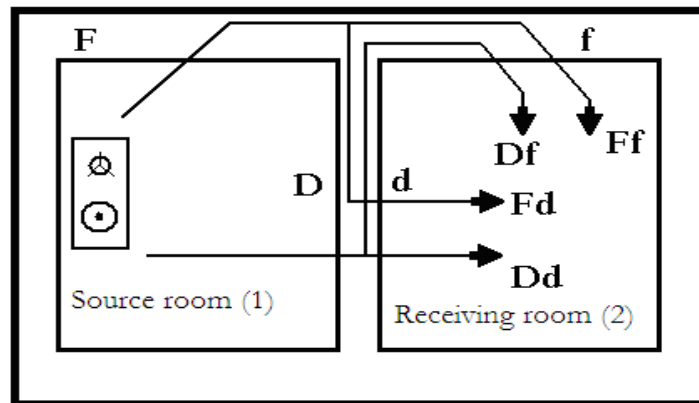


Figure 3.1 - Definition of sound transmission paths ij between two rooms; EN 12354-1 (2000)

The previously represented scheme in Figure 3.1 is a simplified scheme including only the direct and flanking sound contribution against the following Figure 3.2, representing extended contributions with addition of mounted components in the elements and the indirect transmission.

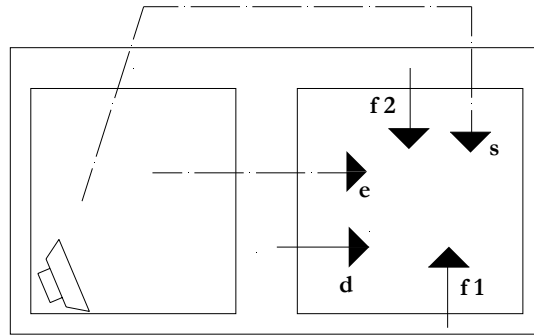


Figure 3.2 - Different contributions to the total sound transmission to a room: d – radiated directly from the separating element; f ($f1$ and $f2$) – radiated from flanking elements; e - radiated from components mounted in the separating element; s – indirect transmission; in EN 12354-1 (2000)

τ_e is the sound power ratio of radiated sound power in the receiving room by an element in the separating element due to direct airborne transmission of incident sound on this element, relative to incident sound power on the common part of the separating element, such as ventilation grids.

τ_s is the sound power ratio of radiated sound power in the receiving room by a system s due to indirect airborne transmission of incident sound on this transmission system, relative to incident sound power on the common part of the separating element; n is the number of flanking elements usually $n=4$ (two lateral elements; ceiling and floor), but can be smaller or larger; m is the number of elements with direct airborne transmission; k is the number of systems with indirect airborne transmission.

The sound radiated by a structural element can be considered to be the summation of the structure-borne sound transmission through several paths. Each path can be identified by the element i on which the sound is incident in the source room and the radiating element j in the receiving room. The paths for a flanking element and the separating element are shown in Figure 3.1, where in the source room the elements i are designated by \mathbf{F} for the flanking element and \mathbf{D} for the separating element. In the receiving room the elements j are designated by \mathbf{f} for a flanking element and \mathbf{d} for the separating element.

The sound power in the receiving room $\tau' = W_{tot}/W_1$ is due to sound radiated by the separating element and by the flanking structural elements present in the room. The total transmission factor can be divided into transmission factors, related to each

element in the receiving room and the elements and systems involved in the direct and indirect airborne transmission:

$$\mathbf{R}' = -10 \log(\tau') \quad (3.4)$$

$$\tau' = \tau_d + \sum_{f=1}^n \tau_f + \sum_{e=1}^m \tau_e + \sum_{s=1}^k \tau_s \quad (3.5)$$

Where the sub-indices d, f, e and s refer to:

d – radiated directly from the separating element;

f – radiated from flanking elements;

e - radiated from components mounted in the separating element;

s – indirect transmission.

The different contributions to the sound transmission, as illustrated in the previous Figure 3.2, and where τ' is the sound power ratio of total radiated sound power in the receiving room relative to incident sound power on the common part of the separating element; τ_d is the ratio between the sound power radiated by the separating element in the receiving room and the incident sound power in the source room.

The transmission factor for the separating element τ_d consists in contributions from the direct transmission and n flanking transmission paths.

$$\tau_d = \tau_{Dd} + \sum_{F=1}^n \tau_{Fd} \quad (3.6)$$

The transmission factor for each one of the four flanking elements f present in the receiving room consists in contributions from two flanking transmission paths.

$$\tau_f = \tau_{Df} + \tau_{Ff} \quad (3.7)$$

The transmission factors for these structure-borne transmission paths are related to the SRI for direct transmission R_{Dd} and the flanking SRI, R_{ij} as follows:

$$\tau_{Dd} = 10^{-\frac{R_{Dd}}{10}} \quad (3.8)$$

$$\tau_{ij} = 10^{-\frac{R_{ij}}{10}} \quad (3.9)$$

Where $\tau_{ij} = W_{ij}/W_1$.

The transmission factors for the direct and indirect airborne transmission are related to the element normalized level difference $D_{n,e}$ and the normalized level difference for indirect airborne transmission $D_{n,s}$ as follows:

$$\tau_e = \frac{A_0}{S_s} 10^{-\frac{D_{n,e}}{10}} \quad (3.10)$$

$$\tau_s = \frac{A_0}{S_s} 10^{-\frac{D_{n,s}}{10}} \quad (3.11)$$

Where S_s is the area of the separating element in $[m^2]$ and A_0 is the reference equivalent sound absorption area in $[m^2]$.

3.3.3 Characterization of the vibrational loss energy

In this section are described the magnitudes, terms and equations involved in the transmission of the vibrating energy, between the elements present in two adjoined rooms.

The most important assumptions in this approach are that the transmission paths described can be considered to be independent and that the sound and vibrational fields behave statistically. Besides these restrictions this approach is quite general, in principle allowing for various types of structural elements, i.e. monolithic elements, cavity walls, lightweight double leaf walls and different positioning of the two rooms. However, the available possibilities to describe the transmission, by each path, impose restrictions in this respect. The models presented are therefore limited to adjacent rooms, while the type of elements are mainly restricted by the available information on the vibration reduction index K_{ij} to monolithic and lightweight double elements.

The vibration reduction index K_{ij} is defined here as a quantity related to the vibrational power transmission over a junction between two structural elements i and j , normalized in order to make it an invariant quantity. It is determined, according to EN ISO 10848-1 (2006), by normalizing the direction average velocity level difference d_{ij} over the junction, to the junction length l_{ij} and the equivalent sound absorption length a_i , if relevant, of both elements in accordance with the following equation:

$$K_{ij} = \frac{D_{v,ij} + D_{v,ji}}{2} + 10 \log \frac{l_{ij}}{\sqrt{a_i a_j}} \quad (3.12)$$

Where:

$D_{v,ij}$ is the velocity level difference between element i and j , when element i is excited in [dB];

$$D_{v,ij} = K_{ij} - 10 \log \frac{l_{ij}}{\sqrt{a_i a_j}} \quad [\text{dB}] \quad (3.13)$$

l_{ij} is the common length of the junction between element i and j in [m];

a_i is the equivalent sound absorption length of element i in [m];

a_j is the equivalent sound absorption length of element j in [m].

These last two terms are defined by the following equation:

$$a_i = \frac{2,2\pi^2 S_i}{c_0 T_{S,i}} \sqrt{\frac{f_{ref}}{f_m}} \quad (3.14)$$

Where S_i is the area of element i in $[m^2]$; $T_{S,i}$ is the structural reverberation time of element i in $[s]$; f_m is the centre band frequency and f_{ref} is the reference frequency; $f_{ref}=1.000$ [Hz].

The reverberation time can be evaluated from the total loss factor, which follows from the internal loss plus losses due to radiation (normally neglected) and losses at the perimeter of the element.

$$T_s = \frac{2,2}{f \cdot \eta_{tot}} \quad (3.15)$$

The total loss factor is:

$$\eta_{tot} = \eta_{int} + \frac{2\rho_0 c_0 \sigma}{2\pi f m'} + \frac{c}{\pi^2 S \sqrt{f f_c}} \sum_{k=1}^4 l_k \alpha_k \quad (3.16)$$

η_{int} is the internal loss factor of the material, roughly 0.01;

m' is the mass per unit area in $[kg/m^2]$;

α_k is the absorption coefficient, for bending waves, at the perimeter k , and varies when taken in laboratory or field conditions;

l_k is the length of the junction at the perimeter k .

3.3.4 The proposed models for structure borne and airborne transmission

The simplified model calculates the building performance for a single number rating, based on the single number ratings of the performance of the elements involved, considers only the structure-borne transmission.

The detailed model calculates the building performance in octave bands (also it can be calculated in one-third octave bands), based on acoustic data for the building elements. As a minimum, the calculation has to be performed for octave bands from 125 [Hz] to 2000 [Hz] or one-third octave bands from 100 [Hz] to 3150 [Hz]. The calculations can be extended to higher or lower frequencies if element data are available.

The detailed model for airborne transmission involves the determination from measured direct transmission for small elements (τ_e) directly determined from the element normalized level difference from equations (3.10) and (3.4).

The determination from measured total indirect transmission (τ_s) does not have, at the moment, a standardized measurement method available to characterise the indirect airborne transmission $D_{n,s}$. For more information, see EN 12354-1 (2000).

The application of the simplified model is restricted to direct and flanking transmission with primarily homogeneous elements. The influence of the structural damping of elements is taken into account in an average way. Each flanking element should be essentially the same on the source and receiving side. If the values for the vibration reduction index K_{ij} depend on frequency, the value at 500 [Hz] may be taken as a good approximation, but the result can then be less accurate.

The apparent weighted SRI or R'_w is calculated in [dB] according to the following equation (3.17).

$$R'_w = -10 \lg \left[10^{\frac{R'_{D,d,w}}{10}} + \sum_{F=f=1}^n 10^{\frac{R'_{F,f,w}}{10}} + \sum_{f=1}^n 10^{\frac{R'_{D,f,w}}{10}} + \sum_{F=1}^n 10^{\frac{R'_{F,d,w}}{10}} \right] \quad (3.17)$$

Where $R'_{Dd,w}$ is the apparent weighted SRI for direct transmission, $R'_{Ff,w}$ is the apparent weighted flanking SRI for transmission path **Ff**, $R'_{Df,w}$ is the apparent weighted flanking SRI for transmission path **Df**, $R'_{Fd,w}$ is the apparent weighted flanking SRI for transmission path **Fd**, all in [dB] and n is the number of flanking elements, usually $n=4$.

For each element i the SRI is calculated using the mass law equation (3.18).

$$R_{w,i} = 37,5 \lg \left(\frac{m'_i}{m'_0} \right) - 42 \quad (3.18)$$

Where m'_i is the mass per unit area of the element i and m'_0 is the reference mass per unit area [1 kg/m²]

This equation is inserted in the standard as an informative equation to give examples of applicability of the simplified model. The equation used could be another with a best fit slope to the particular conditions and material characteristics of the single layer walls encountered in the Spanish buildings. However, our intention is to verify if the simplest equation given in the standard (as informative) can be applied to our elements under test.

The weighted SRI considering only the direct transmission $R_{Dd,w}$ is determined from the input value for the separating element according to the following equation (3.19).

$$R_{Dd,w} = R_{S,w} + \Delta R_{Dd,w} \quad (3.19)$$

Where $R_{S,w}$ is the weighted SRI of the separating element and $\Delta R_{Dd,w}$ is the variation of the weighted SRI improvement by additional lining or layer on the source and/or receiving side of the separating element, all in [dB].

The weighted flanking SRI's are determined from the inserted values according to the following equations (3.20).

$$\begin{aligned}
R'_{Ff,w} &= \frac{R'_{F,w} + R'_{f,w}}{2} + \Delta R'_{Ff,w} + K_{Ff} + 10 \log \frac{S_s}{l_o \cdot l_f} \\
R'_{Fd,w} &= \frac{R'_{F,w} + R'_{d,w}}{2} + \Delta R'_{Fd,w} + K_{Fd} + 10 \log \frac{S_s}{l_o \cdot l_f} \\
R'_{Df,w} &= \frac{R'_{D,w} + R'_{f,w}}{2} + \Delta R'_{Df,w} + K_{Df} + 10 \log \frac{S_s}{l_o \cdot l_f}
\end{aligned} \tag{3.20}$$

Where:

$R_{F,w}$ is the weighted SRI of the flanking element **F** in the source room;

$R_{f,w}$ is the weighted SRI of the flanking element **f** in the receiving room;

$\Delta R_{Ff,w}$ is the total weighted SRI improvement by additional lining on the source and/or receiving side of the flanking element;

$\Delta R_{Fd,w}$ is the total weighted SRI improvement by additional lining or layer on the flanking element at the source side and/or separating element at the receiving side;

$\Delta R_{Df,w}$ is the total weighted SRI improvement by additional lining or layer on the separating element at the source side and/or flanking element at the receiving side;

K_{Ff} is the vibration reduction index for transmission path **Ff**;

K_{Fd} is the vibration reduction index for transmission path **Fd**;

K_{Df} is the vibration reduction index for transmission path **Df**, all in [dB];

S_s is the area of the separating element, in square meters [m²].

l_f is the common coupling length of the junction between separating element and the flanking elements **F** and **f**, in meters [m];

l_o is the reference coupling length; $l_o = 1$ [m].

The acoustical data of the elements should be taken primarily from standardized laboratory measurements. This may also be deduced by other ways, using theoretical calculations, empirical estimations or measurement results from field situations. The

acoustical inputted data consist on weighted SRI of the elements $R_{S,w}$; $R_{F,w}$; $R_{f,w}$ and the vibration reduction index for each junction and path: K_{Ff} ; K_{Fd} ; K_{Df} . Information on this and for additional layers is given in annexes of the standard, as a data base.

This simplified version of the calculation model for structured borne transmission also predicts for the two global sound reduction indices (weighted pink noise and weighted urban traffic noise) mentioned in EN ISO 717-1 (1996) with only one correction factor of $C=-1$.

3.3.5 Detailed model for structure borne transmission

The detailed model in comparison with the simplified model has a different calculus approach. This model is more exhaustive in the calculus procedure, and the acoustical input data are dependent on the path for each element:

The transmission for each path can be determined from the SRI of the separating element R_S ;

SRI for element i in source room R_i ;

SRI for element j in receiving room R_j ;

SRI improvement by additional layers for separating element in the source and/or in the receiving room Δ_{RD} , Δ_{Rd} ;

SRI improvement by additional layers for the element i in the source room and/or element j in the receiving room Δ_{Ri} , Δ_{Rj} ;

Structural reverberation time for an element in the laboratory T_s , lab;

Vibration reduction index for each transmission path from element i to element j K_{ij} ;

Area of the separating element S_S ;

Area of element i in source room S_i ;

Area of element j in receiving room S_j ;

Common coupling length between element i and element j , as measured from surface to surface l_o .

As in the simplified model, the acoustic data of the elements involved should be taken primarily from standardized laboratory measurements; however, they may also be deduced in other ways, using theoretical calculations, empirical estimations or measurement results from field situations.

The acoustic data of the elements has to be converted into *in situ* values before the determination of the sound transmission.

For the separating element and each of the flanking elements the *in situ* value of the SRI R_{situ} follows from equation (3.21):

$$R_{\text{situ}} = R' = R - 10 \log \frac{T_{\text{S,situ}}}{T_{\text{S,lab}}} \quad (3.21)$$

Where $T_{\text{S,situ}}$ is the structural reverberation time of the element in the actual field situation in [s]; and $T_{\text{S,lab}}$ is the structural reverberation time of the element in the laboratory in [s].

For each flanking transmission path the SRI of the involved elements should relate to the resonant transmission only. It is correct to apply the laboratory SRI above the critical frequency. Below the critical frequency this can be considered a reasonable estimation which errors on the low side, due to non-resonant transmission. If the values of the SRI are based on calculations from material properties, it is best to consider only resonant transmission over the whole frequency range of interest.

For the following building elements the structural reverberation time $T_{\text{S,situ}}$ shall be taken as being equal to $T_{\text{S,lab}}$ which leads to a correction term of 0 [dB]:

Lightweight, double leaf elements, such as timber framed or metal framed stud walls;

Elements with an internal loss factor greater than 0,03;

Elements which are much higher than the surrounding structural elements;

Elements which are firmly connected to the surrounding structural elements.

Otherwise the structural reverberation time, both for the laboratory and for the actual field situation, is taken into account.

For the additional layers the laboratory value can be used as an approximation for the *in situ* value of the improvement ΔR_{situ} in [dB]:

$$\Delta R_{\text{situ}} = \Delta R \quad (3.22)$$

For each flanking transmission path the SRI improvement ΔR of the involved elements should relate to the resonant transmission only. However, measurement methods to determine this are not readily available and there is some evidence, to indicate that the improvement for direct transmission is also reasonable, as an estimate for the improvement for flanking transmission is too.

For the junctions the *in situ* transmission is characterized by the direction-averaged junction velocity level difference $\overline{D_{v,ij,situ}}$. This follows from the vibration reduction index:

$$\overline{D_{v,ij,situ}} = K_{ij} - 10 \log \left(\frac{I_{ij}}{\sqrt{a_{i,situ} \cdot a_{j,situ}}} \right) ; \quad \overline{D_{v,ij,situ}} \geq 0 \quad (3.23)$$

With

$$a_{i,situ} = \frac{2.2 \pi^2 S_i}{c_0 T_{s,ij,situ}} \sqrt{\frac{f_{\text{ref}}}{f}} \quad (3.24)$$

$$a_{j,situ} = \frac{2.2 \pi^2 S_j}{c_0 T_{s,ij,situ}} \sqrt{\frac{f_{\text{ref}}}{f}} \quad (3.25)$$

Where, $a_{i,situ}$ is the equivalent absorption length of element i in the actual field situation and $a_{j,situ}$ is the equivalent absorption length of element j in the actual field situation, in [m]; f is the centre band frequency in [Hz]; f_{ref} is the reference frequency; $f_{ref}=1000$ [Hz]; c_o is the speed of sound in air in [m/s]; l_{ij} is the coupling length of the common junction between elements i and j , in [m]; S_i is the area of element i , in [m²]; S_j is the area of element j , in [m²]; $T_{S_i,situ}$ is the structural reverberation time of element i in the actual field situation and $T_{S_j,situ}$ is the structural reverberation time of element j in the actual field situation, both in [s].

For the following building elements the equivalent absorption length a_{situ} is taken as numerically equal to the area of the element, so $a_{i,situ}=S_i/l_o$ and/or $a_{j,situ}=S_j/l_o$, where the reference length $l_o=1$ [m]:

Lightweight, double leaf elements, such as timber framed or metal framed stud walls;

Elements with an internal loss factor greater than 0,03;

Elements which are much higher than the surrounding structural elements (by a factor of at least three);

Elements which are firmly connected to the surrounding structural elements.

Otherwise the structural reverberation time for the actual field situation has to be taken into account.

The SRI for direct transmission is determined from the adjusted input value for the separating element according to the following:

$$\mathbf{R}_{Dd} = \mathbf{R}_{s,situ} + \Delta\mathbf{R}_{D,situ} + \Delta\mathbf{R}_{d,situ} \quad (3.26)$$

The flanking SRI is determined from the adjusted input values according to the following, with $ij=\mathbf{Ff}$, \mathbf{Fd} and \mathbf{Df} :

$$\mathbf{R}_{ij} = \frac{\mathbf{R}_{i, \text{situ}}}{2} + \Delta\mathbf{R}_{i, \text{situ}} + \frac{\mathbf{R}_{j, \text{situ}}}{2} + \Delta\mathbf{R}_{j, \text{situ}} + \overline{\mathbf{D}_{v, ij, \text{situ}}} + 10 \log \left(\frac{\mathbf{S}_s}{\sqrt{\mathbf{S}_i \mathbf{S}_j}} \right) \quad (3.27)$$

If as a first approximation the terms with the structural reverberation time are taken as 0 [dB] and the equivalent absorption lengths are taken as $a_{i, \text{situ}} = S_i / l_o$ and/or $a_{j, \text{situ}} = S_j / l_o$, for all types of elements, equation (3.27) can be written as:

$$\mathbf{R}_{ij} = \frac{\mathbf{R}_i}{2} + \Delta\mathbf{R}_i + \frac{\mathbf{R}_j}{2} + \Delta\mathbf{R}_j + \mathbf{K}_{ij} + 10 \log \left(\frac{\mathbf{S}_s}{l_o l_{ij}} \right) \quad (3.28)$$

Equation (3.27) is identical to the following equation:

$$\mathbf{R}_{ij} = \mathbf{R}_{i, \text{situ}} + \Delta\mathbf{R}_{i, \text{situ}} + \Delta\mathbf{R}_{j, \text{situ}} + \mathbf{D}_{v, ij, \text{situ}} + 10 \log \left(\frac{\mathbf{S}_s}{\mathbf{S}_i} \right) + 10 \log \left(\frac{\sigma_{i, \text{situ}}}{\sigma_{j, \text{situ}}} \right) \quad (3.29)$$

However, since the junction velocity level difference is not an invariant quantity and the radiation factors are often not known, this relation is less suited for predictions. It could be used in existing field situations to estimate flanking transmission if appropriate data (measured or estimated) on the junction velocity level difference $\mathbf{D}_{v, ij}$ and the radiation factors $\sigma_{i, \text{situ}}$ and σ_j for that field situation are available.

The sound transmission by the separating element and by the flanking elements can be calculated in accordance with equations (3.6) and (3.7) applying the equations (3.8), (3.10) to (3.27) inclusive. The total sound transmission or apparent SRI can afterwards be calculated with equation (3.5).

To perform the calculations for this detailed model, it was applied the algorithm suggested in the informative Annex B1 of EN 12354-1 (2000). The algorithm was programmed in Visual Basic[®] editor for make use in an Excel[®] sheet software. In the Annex B of this thesis is listed the code used for this algorithm.

3.4 Commercial application software

Nowadays the presence of computers and software in any type of profession is vital and common. After the approval of the EN 12354-1 (2000), several software was developed in accordance with this standard. This kind of software is very useful in the project phase of building acoustics. However, it requires a data base for each type of material. Therefore, his applicability is dependent of the existence of laboratory results for each type of material. The data bases of these commercial softwares are consequently one of the main points of interest of their wide usage. Also, they can predict the SRI using the flanking contribution.

The two commercial software's presented are the most popular and deserve a special attention, because they can improve the quality of acoustic building projects and step up the applicability of the most recent developments in building acoustics predictions models. The intention of reference in this thesis is only to describe the main features of the two applications. It is not our intention to evaluate them qualitatively.

3.4.1 AcoubatSound_2008 Building Acoustics

The AcoubatSound_2008 building Acoustics software application developed by VCSTB (2008) is one of the top instruments of the building acoustic project engineers. It was developed in parallel with the French building code and now, it has a modulus of the predicted models of the European standards EN 12354-1 (2000).

Thanks to a data base of typical products, it is easy to determine an optimal acoustic solution for multifamily apartments, offices, classrooms, hospital rooms, etc.

AcoubatSound is software application that allows the calculation of airborne sound and impact sound insulation in buildings. In this software, the acoustic performances for the building are calculated from its component properties based on the standards EN 12354-1 (2000) and EN 12354-2 (2000). Even though the European method is fixed, a certain number of choices are available regarding the calculations, as well as choices for the presentation of results. After modelling the geometry, the software

allows the selection of components from a very rich data base. This data base includes most of the products to simulate residential buildings for the French building code. The results can be visualised in graph form representing the weighted insulation, or in the form of a series of curves detailing each transmission path. Examples of sound transmission between two rooms are: the direct path through the separating wall, including the physical phenomena of sound excitation in the emission room and sound radiation in the reception room; the flanking paths, including the physical phenomena of sound excitation in the emission room, vibration transmission at junctions between the separating wall and the lateral wall (in the number of 4), and sound radiation from these lateral walls in the reception room. There are three paths per junction, and so, twelve flanking paths in total; the indirect paths corresponding to an acoustic path such as an air opening in the separating wall, or a ventilation duct, or chimney exhaust between two rooms (interphony phenomenon). Therefore, it can directly appreciate the influence of the direct transmission and of the various other different paths to modify its calculation and find a solution that complies with regulation. Furthermore, for an acoustician, the calculation detail is given up to the vibration reduction index at the junction. This index is not included in the data base, is calculated from the characteristics of the walls considered.

3.4.2 BASTIAN[®]

Bastian[®] is an advanced software developed by Datakustik (2008) for predicting the sound insulation in buildings based in the European standards series EN 12354. Bastian[®] calculates the sound insulation regarding the airborne sound insulation between rooms according the EN 12354-1 (2000); calculates the impact sound insulation between rooms according the EN 12354-2 (2000), and calculates the airborne sound insulation against outdoor sound according the EN 12354-3 (2000).

Some of the most important features of this software are the calculation of the sound insulation based on data on the sound insulation of the transmitting elements and systems; doors and also windows as well as air intakes can be inserted into the separating elements in construction; additional flanking elements or sound transmission systems are added, such as ventilation and cable ducts. Junction types for combinations

of heavy single and double-walls, lightweight walls, floors and flanking cavity walls. Calculation of the structural reverberation time *in-situ*, correction of the radiation factor for flanking elements, calculation of the interior sound pressure levels for sound transmission from the outside. The database is filled with more than one thousand and five hundred constructions. Furthermore, this database can be expanded by the user.

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Chapter 4

4 Facilities and instrumentations

4 Resumen de medios físicos y técnicos utilizados

En este capítulo, se describen los medios físicos y técnicos utilizados al largo de las medidas experimentales. Refleja los medios utilizados durante un largo periodo de investigación en España y en Italia, adaptándose a los equipos utilizados de manera habitual por las Universidades correspondientes y sus respectivos laboratorios. Con el objeto de permitir un seguimiento mejor de este capítulo, se ha realizado una clasificación en función de los métodos de medidas acústicas utilizados, de presión sonora, de intensidad sonora y de velocidad de vibración. Además, este capítulo se divide en dos partes: (i) medios físicos; (ii) explicación de la cadena de medida y su puesta a punto.

En primer lugar, se realizó una primera tanda de medidas in situ en Valladolid, España. Estas medidas son las que recoge el trabajo tutelado del doctorando Andrade (2003), que fue el inicio del estudio del aislamiento aéreo de sonido y sus contribuciones de flanco. Ya que en ese estudio las condiciones de entorno estaban poco controladas, surgieron algunas dificultades para conseguir resultados con la fiabilidad deseada. Por ello, se planteó la necesidad de hacer ensayos en un laboratorio de transmisiones de flanco, donde las condiciones están más controladas. Dado que en España no existían laboratorios adaptados al estudio de las transmisiones por flancos, se optó por efectuar dichos ensayos en el laboratorio conocido como “D.I.E.N.C.A.- Dipartimento Ingegneria Energetica, Nucleare e del Controllo Ambientale” y situado en Italia, en la Universidad de Bolonia, mediante una estancia que realizó el doctorando en el mismo. Allí se realizó una segunda tanda de ensayos.

Tras ella, la fase siguiente fue realizar, siguiendo los mismos procedimientos de medida, ensayos en condiciones reales ó in situ. Esta posibilidad surgió en una edificación de la Universidad de Valladolid construida en los años 70 y conocida como

Magisterio, donde posteriormente se realizaron más tandas de medidas, tanto en aulas vacías como todo el edificio. De esta fase han surgido los resultados relevantes y novedosos de este trabajo.

En concordancia con lo expuesto, la instrumentación utilizada en Italia es parte del laboratorio de DIENCA y, consecuentemente de la Universidad de Bolonia, pero algunos de los instrumentos utilizados son también de la Universidad de Ferrara.

En España, las medidas *in situ* se realizaron con equipos de la Universidad de Valladolid.

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4.1 Introduction

This chapter exposes the technical resources and facilities used along the experimental measurements. During the period of several months of investigation in Spain and Italy it was necessary to make use of hardware instrumentations, as well as other instrumentation in use by the universities and their laboratories. For a better understanding of the subject, and considering the measurement methods related with sound pressure, sound intensity and vibration velocity, this chapter is divided in two parts: (i) facilities description and (ii) chain measurement explanation, with measurement setup.

A first set of measurements were performed in Valladolid, Spain, *in situ* conditions, and they are described in the MPhil dissertation of Andrade (2003), where the study of the flanking contribution of airborne sound insulation was prepared. Due to the several doubts, related with uncontrolled boundary conditions, some difficulties to achieve reliable results have emerged. These difficulties are associated with the measurement procedure in question. To accomplish the objectives that we had proposed, it came out the possibility to perform experiments in a flanking sound laboratory, in Italy, in the University of Bologna at “D.I.E.N.C.A.- Dipartimento Ingegneria Energetica, Nucleare e del Controllo Ambientale”.

The necessity to perform similar experimental procedures *in situ* conditions, gained attention. The possibility to make use of an existing building, to perform similar experiments, appeared in Spain, in a building built in the seventies and identified as “Magisterio” or old education faculty building, of the University of Valladolid. Consequently, further accomplished researches *in situ* conditions were performed in empty and available rooms of the referred “Magisterio” building.

According to the exposed, the instrumentations used in Italy on laboratory conditions are from the DIENCA laboratory, and consequently of Bologna University. Also some of the useful instrumentations are from the University of Ferrara.

In Spain, where the experiments *in situ* conditions were performed, the instrumentation and materials applied are from the University of Valladolid.

4.2 Description of measurement facilities

The description of measurement facilities and surroundings are directly related, in some way, to the results obtained and respective conclusions. Therefore, it is fairly significant to report the main characteristics of these places. First, it is presented the description of DIENCA laboratory, where the measurements were performed by an impact machine producing a structure borne excitation. These measurements were made by sound intensity method and vibration velocity method. Then, it is presented the description of “Magisterio” building and its respective rooms.

4.2.1 DIENCA laboratory

This facility was built in accordance with requirements of prEN ISO 10848-1 (1999), that more recently become EN ISO 10848-1 (2006), for flanking transmission of airborne and impact noise between adjoined rooms. It must be referred that the laboratory was not yet finished during the current work test period, but it was already possible to carry out several research experiences. The laboratory consists of two adjoined chambers (further the two upper chambers will be built), as it can be seen on a three dimensions virtual view of the laboratory, in Figure 4.1.

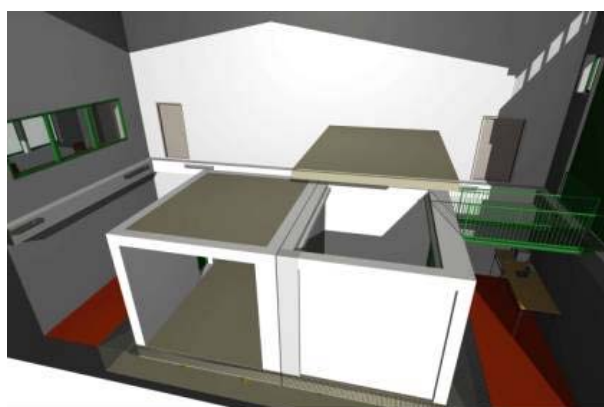


Figure 4.1 The necessity to perform similar experimental procedures *in situ* conditions

The dimensions of the upper source room (not yet built), are obviously not specified. The noise generated by the tapping machine was maintained closed in a wood box isolated with rock wool, with similar dimensions to the tapping machine itself (B&K Type 3204).

The receiving room dimensions are 4,50 x 3,50 x 3,40 [m] which makes a volume of more than 53 [m³]. This room is made of a structure of armed concrete, supported by a group of four spring-damping elements to perform a passive isolation from ground vibrations.

Because the superior chamber of the laboratory is not build, to isolate the noise produced by the tapping machine, a layer of high density sound absorbing material was laid on the superior part of the floor (not directly). To prevent the airborne noise produced by the tapping machine on the floor, from reaching the lateral elements of the receiving room, the tapping machine is maintained inside a wood box isolated with rock wool, as previously mentioned.

Two borders of the floor are structurally disconnected of the lateral walls and between them a sound absorbing material was applied. All the perimeter of the floor connected with the walls (elements) was acoustic isolated.

The floating floor in its surface, comprise a layer of shock absorbing material (expandable polystyrene, EPS) with 22 [mm] of thickness, that covers the entire surface and is finalized with a final layer of concrete of 5 [cm] of thickness, which is armed with a steel frame, as it can be seen in Figure 4.2. This last surface acts as a floating floor and is completely disconnected from the lateral surfaces to prevent structure borne transmissions.

On the ceiling of this room, a test floating floor of 12 [m²] was laid. The floor is made of 14 [cm] of armed concrete with volume density of approximately 2300 [kg/m³], that is laid in two structural longitudinal beams.



Figure 4.2 - Final concrete layer of floating floor of DIENCA

Figure 4.3 shows a schematic sketch of the laboratory receiving room, where the front view is shown with the entrance to the test room and the correspondent top view represented by section B-B, and left view, represented by section A-A. The facility allows testing different types of floors. These floors are previously built and then laid on two sides, on proper supports in the ceiling. The other two sides are structurally connected or disconnected according to the experience requirements. All the represented dimensions are in [m].

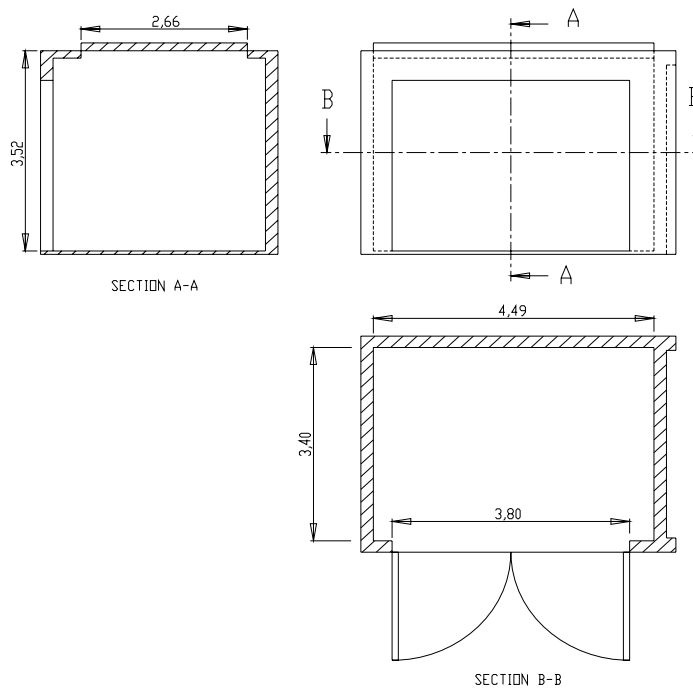


Figure 4.3 – Schematic drawing of DIENCA laboratory

4.2.2 “Magisterio”

The experiments made *in situ* conditions were carried out in a building facility, known as “Magisterio”. This building was previously used as a school and when the experiments were performed, this building was waiting for proper recondition for further use. By this reason, it was possible to carry out experiments without interference of any kind and during a relatively long period. A three dimension virtual view of the test rooms can be seen in the following Figure 4.4.

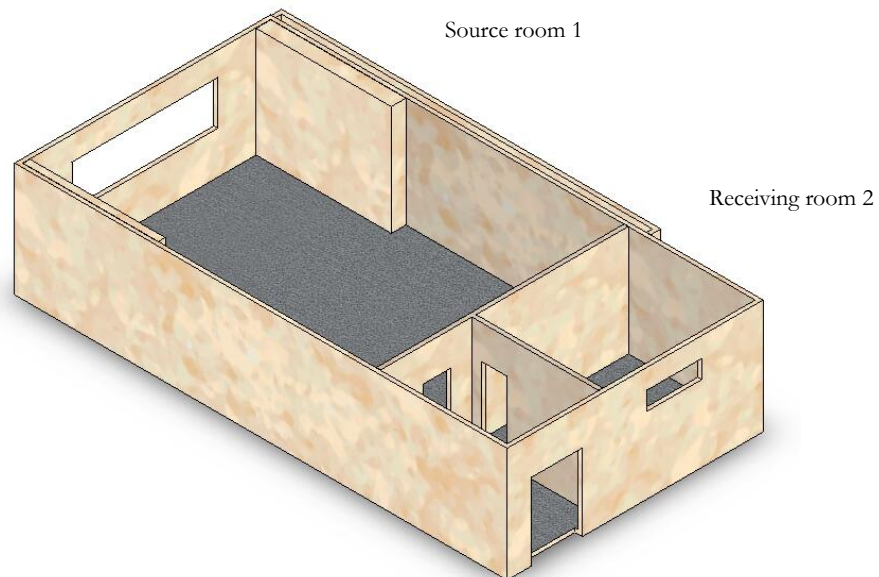


Figure 4.4 – The three dimension virtual view of “Magisterio” tested rooms.

The source room (1) dimensions are 6,80 x 9,70 x 3,01 [m] corresponding to a volume of 181 [m³]. The receiving room (2) dimensions are 4,18 x 3,47 x 3,02 [m] corresponding to a volume of 43,8 [m³]. All lateral walls are built of bricks and furnished with a concrete (mortar or plaster) layer on each side. Their total thickness is 115 [mm] with a surface density of approximately 120 [kg/m²].

The main transmission path or direct path is the separating element between the two rooms. The wall dimensions are 4,18x3,01 [m] corresponding to an area of 12,6 [m²] and a thickness of 0,115 [m].

The separating element critical frequency, previously defined in section 2.3.1 by equation 2.17, is estimated has approximately 175 [Hz], obtained for a estimated longitudinal velocity of 3.200 [m/s] and from the previously referred correspondent thickness and surface density.

The ceiling is composed by beams, compression layer and is finalized with a paving-tile on the superior part, with an overall thickness of about 0,370 [m] and a surface density of approximately 450 [kg/m²], corresponding to a critical frequency less than 100 [Hz].

The connections between the source room (1) and the receiving room (2) are simple rigid T junctions in vertical and horizontal connections.

Figure 4.5 represents a schematic drawing of the two rooms used during *in situ* experiments; the dimensions represented are in [m].

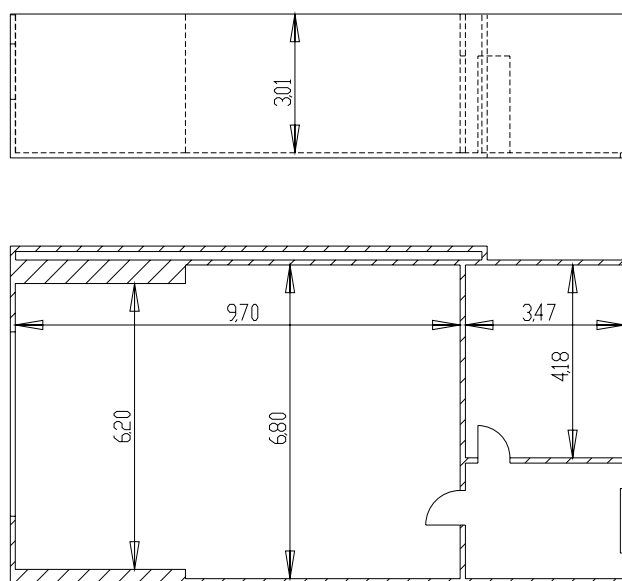


Figure 4.5 - Schematic sketch of “Magisterio” test room

In the plant sketch it is represented a double exterior wall that finishes in a T junction, approximately at the distance of 1 [m] on the out side wall of our receiving room. Because of this double wall, the results obtained by the different measurement methods express this influence and more accurately the flanking contribution can be

evaluated by the vibration velocity method as further discussed on chapter 6 and well illustrated in Figure 6.21.

4.3 Hardware and software

The instrumentation used can be divided in the hardware, for physically perform measurements; and in the software, for compute the data generated, acquired by the hardware. The results are divided in three groups, corresponding to three main measurement methods and also to three different procedures and respective measurement chains.

Therefore, in the following sections the three measurement chains are described and in each sub-heading the measurement chain for laboratory conditions and for *in situ* conditions are classified.

4.3.1 Sound pressure method, instrumentation and measurement setup

The sound pressure method, explained in section 2.5.1, was performed according to the specified on the standard EN ISO 140-4 (1998) for *in situ* conditions and was only carried out in “Magisterio”, Spain.

To perform sound pressure method measurements *in situ* conditions it is necessary at least six basic elements in a measurement chain, to be known: (i) source excitation with a sound source; (ii) response at source and receiving rooms (calibrator and pre-amplified microphones); (iii) real-time frequency analyser processing; (iv) post processing software; (v) connection cables and (vi) tripods.

The reverberation time for the receiving room T_2 is obtained by equation 2.41 and performed according to EN ISO 354 (2003).

In the source room (1) and receiving room (2) it was used a pre-amplified microphone (B&K type 4190) and a dual-channel real time frequency analyser (B&K type 2144). The data was post-processed by the software B&K “Building acoustic program” WT9343 version 1.71 (1992). A sound pressure level calibrator (B&K type 4231) was used before each measurement process.

In Figure 4.6 a partial view of source room (1) can be seen, where it is visible, at the bottom, the separating element.



Figure 4.6 – Separating element view in “Magisterio” source room surface

The measurements by means of sound pressure method, took in consideration the pre-established in the EN ISO 140-4 (1998). In some situations, the recommend measure lower limits (i.e. measurement scan time) are raised in opposition to the minimum values referred in the standard.

The generation of the sound field in the source room was maintained steady and diffusing a continuous spectrum of white noise, in the frequency range of interest. The sound power radiated was raised to a sufficiently high level, for the sound pressure level measured in the receiving room be at least 10 [dB] higher than the background noise level, and verifiable at any frequency band of interest.

The sound pressure level in the source room L_{p1} was measured using a moving microphone with an averaging time period of 30 [s], in one-third-octave band filters, from 50 [Hz] to 10.000 [Hz]. Three different measurements were performed, corresponding to a total measured time of 90 [s], averaged separately.

The treatment of these levels depends on the manifestation of overload situation, in reverberation time measurements, predominantly verified at lower frequency bands.

4.3.2 Sound intensity method

The sound intensity method was taken in Italy, described in section 2.5.2, by equation 2.49, in a flanking laboratory, and also in Spain, *in situ* conditions at the “Magisterio” facilities. The instrumentation used in each experiment, DIENCA and “Magisterio”, has the same basic structure, but differ in the instrumentations references.

The instrumentations were in accordance with class 1 requirements of IEC 61043 (1993).

4.3.2.1 Instrumentations useful in laboratory, DIENCA

For impact sound intensity method or sound intensity method experiments using as source an impact sound, the instrumentation used was: as a sound source a tapping machine (B&K type 3204); a sound intensity p-p probe, (B&K type 3595) with a 12 [mm] spacer linking a microphone pair (B&K type 4197); real time frequency analyzer (B&K type 2260); software (B&K Noise Explorer™ type 7815) and Microsoft Excel™ sheet to post-process the data acquired. The sound intensity probe was calibrated before each measurement with the sound intensity calibrator (B&K type 4297).

Figure 4.7 represents a partial view of DIENCA laboratory receiving room (2), where the experiments took place.



Figure 4.7- Partial view of DIENCA laboratory receiving room, showing ceiling and flanking elements

4.3.2.2 Instrumentations useful *in situ*, “Magisterio”

For sound intensity method performed *in situ* conditions, also the same arrangement for the source room were applied: an octahedral sound source (the same used in sound pressure method) and cable connected to an amplifier which is connected to a white noise signal generator. In the receiving room a sound intensity p-p probe (B&K type 3520) modified to a more recent model and with one sound intensity microphone pair (B&K type 4181) combined with a 12 [mm] spacer is connected to the real time frequency analyser (B&K type 2144). For the calibration procedure, the sound intensity calibrator (B&K type 3541) was applied.

4.3.2.3 Sound intensity measurement setup

The experiments took in consideration the pre-established in the ISO 15186-2 (2003) and described in section 2.5.2.

The generation of the sound field in the source room was maintained steady and consist of a continuous spectrum of white noise in the frequency range of interest.

Sound intensity levels were measured but the source sound power levels were the same used for the sound pressure method measurements.

The sound power was sufficiently high for the sound pressure level in the receiving room to be at least 10 [dB] higher than the background noise level at any frequency band of interest.

On the receiving room side, a measurement surface was defined, which totally encloses the building element under test and subsequently it was divided in smaller sub-areas. These sub-areas were divided allowing a convenient measurement time for each one, to preventing arduous work and consenting a good practice in scan measurements.

These sub-areas allow measurement velocities of 0,2 to 0,3 [m/s], reproducing measured times of 60 [s], in each scan direction, performing a total measured time of 120 [s], in one-third-octave bands. The previously mentioned sub-areas have the following frequencies starting from 50 [Hz] to 10.000 [Hz] and comprising linear averaging.

4.3.3 Vibration velocity method

The vibration velocity method performed in Italy, previously referred in section 2.6, using equation 2.55, in laboratory conditions and in Spain, *in situ* conditions, show correspondent instrumentation applied in each trial and presents similar arrangement, but differs in brands and respective references. Next it is presented the sub-heading division: instrumentation applied in laboratory and instrumentation applied *in situ* conditions.

4.3.3.1 Instrumentations useful in laboratory, DIENCA

For impact vibration velocity method, a tapping machine was used as a sound source. In the receiving room an amplifier of two channels from (B&K Nexus), shown in Figure 4.9, is cable connected with two charge accelerometers (B&K type 4371V) and with a real time frequency analyser (Larson Davis 2900B) shown in Figure 4.8. All the

data were acquired and stored in the personal computer and post-processed with a Microsoft Excel™ sheet.



Figure 4.8 – Real time frequency analyser (Larson-Davis 2900B) used at DIENCA

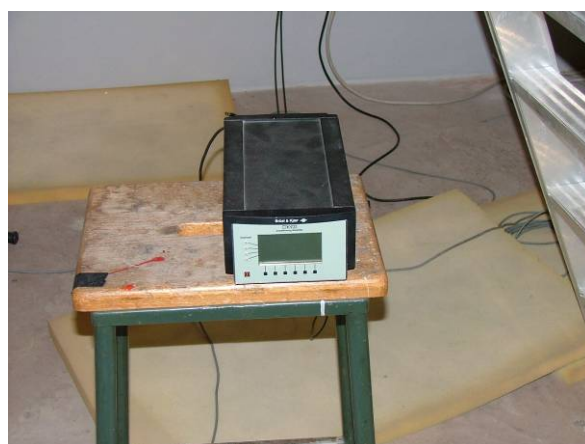


Figure 4.9 - Amplifier of two channels (B&K model Nexus) used at DIENCA

The acceleration transducers were screwed to a metal support that was glued on the wall with Pattex®, as can be seen in Figure 4.10.



Figure 4.10 – Support for acceleration transducer, glued on the DIENCA elements

4.3.3.2 Instrumentations useful *in situ*, “Magisterio”

The instrumentations applied for vibration experiments in the source room were composed by: an octahedral sound source cable connected to an amplifier which is connected to a noise signal generator. In the receiving room two charge acceleration transducers (B&K type 4384) were used connected with a real-time frequency analyser (B&K type 2144) useful in both source and receiving rooms. The acceleration transducers were coupled with bee wax to the elements and calibrated before each measurement with an accelerometer calibrator (B&K. type 4294).

4.3.3.3 Vibration velocity measurement setup

The experiments took in consideration what is pre-established in the prEN ISO 10848-1 (1999) and prEN ISO 10848-1 (2004), being now the EN ISO 10848-1 (2006).

The sound power generated in the source room (1) is similar to the one used in the sound pressure and sound intensity measurements.

The vibration values were measured by two acceleration transducers, on twelve randomly distributed positions, over the four flanking building elements surfaces,

according to EN ISO 10848-1 (2006) and also taking in attention some considerations from Craik et al. (1995).

The measurement time was of 60 [s], in one-third-octave band, having the following centre frequencies starting from 50 [Hz] to 10.000 [Hz].

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Chapter 5

5 Measurement layout

5 Procedimiento de medidas

De forma a ejecutar las medidas en condiciones laborales y fundamentalmente también *in situ*, fueron realizados diversos esfuerzos de forma a cumplir el mismo objetivo, a saber: mejorar el procedimiento de medida y consecuentemente los resultados obtenidos.

Este capítulo se encuentra organizado por los tres métodos de medida utilizados: método de presión sonora (apartado 2.5.1); método de intensidad acústica (apartado 2.5.2) y método acústico por velocidad de vibración (apartado 2.6). Para cada método, es descrito el procedimiento de medida de acuerdo con las especificaciones de la normativa correspondiente, tanto en condiciones laborales como *in situ*, con excepción para el métodos de acústica por velocidad de vibración.

Este capítulo permite al lector una mejor comprensión de los resultados mostrados en el capítulo 6 y al mismo tiempo comprender de que forma las medidas fueron efectuadas.

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5.1 Introduction

In order to accomplish the measurements both under laboratory and *in situ* conditions, especially for last one, several tests were performed. Each one aims to accomplish the same objective: improve the measurement procedure and subsequently the results obtained.

This chapter is organized according to the three measurements methods used: sound pressure method (section 2.5.1); sound intensity method (section 2.5.2) and vibration velocity method (section 2.6). For each method, the measurement layout is described according to the respective standard specifications, in laboratory or *in situ* conditions, exception made for the vibration velocity method.

This chapter allows the reader to better understand the results expressed in chapter 6, and to become familiar with the measurements procedures used.

5.2 Sound pressure measurement layout

The sound pressure method was only performed for airborne sound, and for *in situ* conditions in “Magisterio”.

The sound pressure method was performed in accordance with the requirements of the standard EN ISO 140-4 (1998). The expression of the SRI is given by equation (2.40).

$$R' = 10 \log \frac{W_1}{W_{tot}} = L_{p1} - L_{p2} + 10 \log \frac{S}{A_2}$$

In the source room (1) a white noise sound field is produced by a dodecahedral sound source, located at the centre of the source room. The spatial average sound pressure level in the source room (1) L_{p1} was evaluated by means of a moving microphone, with an arm radius of approximately 0,7 [m], averaged for at least sixty seconds, in two positions, referenced in Figure 5.1 as position A and position B.

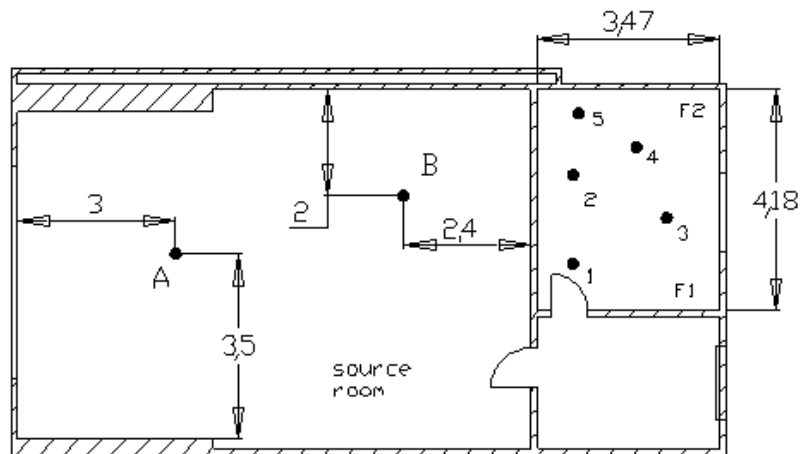


Figure 5.1 – Schematic drawing of “Magisterio” source/receiving room, dimensions in [m]

The spatial average sound pressure level in the receiving room (away from the wall) L_{p2} , was also performed using a moving microphone, averaged by sixty seconds, in the centre of the room, and it was only performed for this position, due to the small volume of the receiving room (2).

The area of the separating element is $12,6 \text{ [m}^2\text{]}$, as referred in the previous section 4.2.2.

In order to evaluate the equivalent sound absorption area in the receiving room (2) A_2 , the reverberation time in the receiving room T_2 was measured and then A_2 was determined using equation (2.41).

The reverberation time measurements can be performed according to the two following standardized methods. In this thesis both methods were used.

(i) EN ISO 354 (2003) - Measurements were performed for two loud speaker positions (F1 and F2) and for five microphone positions in each case as shown in Figure 5.1 (with the number one to five). In total eleven T_2 measurements were made since position number one was performed twice. The measurements were performed at almost the maximum loudspeaker output sound power levels, measuring seventy five spectra, collected for each position, for an exponential averaged time of $1/32 \text{ [s]}$ on a bandwidth between $0,40 \text{ [Hz]}$ to 20.000 [Hz] . The reverberation time obtained presents reliable results above the 200 [Hz] (B&K 2144). The room excitation is achieved by a

white noise sound, emitted by the loudspeaker and then abruptly interrupted. After several measurements attempts it was confirmed that the reverberation time obtained for frequencies below the 160 [Hz] (where the T_{60}^1 is not verified), results were consistent, and consequently, were considered for the corresponding calculations;

(ii) EN ISO 3382 (2000) - the reverberation time measurement procedure is achieved by means of full air balloons burst. These balloons were exploded, to provoke an impulse excitation in the room, and subsequently, to determine the respective sound decay by EN ISO 354 (2003) and EN ISO 3382 (2000). This technique is also called the integrated response method.

This type of procedure has advantages in terms of making use of a moving microphone: (i) it performs quickly, against the fixed microphone positions (usually at least four positions); (ii) in terms of the type of room excitation, for evaluation of the reverberation time, it has the advantage of not installing the sound equipment in the receiving room. On the other hand, numerous burst for several microphone positions must be carried out to average the decays.

The calculation of the reverberation time T_2 was performed by two possible means. First, a software known as WinMLS 2004 in a thirty days evaluation copy version of the software by Morset (2004) was used combined with the EN ISO 354 (2003) and with EN ISO 3382 (2000) standards procedures. Nevertheless, due to several difficulties in accomplish reliable results along the evaluation period; the applicability of this utility tool was discarded. However, several measurements to establish the reverberation time were still performed.

The other possible resource was to use the real time frequency analyser (B&K 2144) combined with the procedure of the EN ISO 354 (2003).

The reverberation times obtained by Win MLS 2004 software, are further compared with other reverberation times, obtained from classical procedures (using a real time frequency analyser), as it can be seen in Table 5.1, where the results obtained are expressed.

¹ in EN ISO 354 (2003)

Table 5.1 – Reverberation times by EN ISO 354 (2003) for “Magisterio” receiving room

Frequency [Hz]	Reverberation time (B&K 2144) [s]	Reverberation time (WinMLS 2004) [s]
100	1,75 o ²	2,69
125	2,16 o	2,50
160	1,71 o	1,81
200	1,69	1,67
250	1,54	1,62
315	1,44	1,24
400	1,32	1,49
500	1,13	1,12
630	1,02	1,16
800	0,98	1,17
1000	1	1,06
1250	0,98	1,05
1600	1	1,03
2000	0,95	0,94
2500	0,96	0,86
3150	0,9	0,80

As it can be seen, the reverberation times obtained by the Win MLS software are probably more accurate in the lower frequencies, compared to the values obtained from the real time frequency analyser (B&K 2144), and in general slightly higher for almost all one-third octave bands.

The background noise level was measured in the receiving room, using a one minute average for one central room microphone position.

5.3 Sound intensity measurements layout

The sound intensity method (section 2.5.2), was performed following the recommendations of ISO 15186-2 (2003), for two possible environments, *in situ* and laboratory.

The next section presents the layout for the measurements using sound intensity method in laboratory conditions at DIENCA and *in situ* conditions at “Magisterio”.

² T60 not verified

5.3.1 In laboratory, DIENCA

The intensity measurements were performed according to ISO 15186-2 (2003), explained in section 2.5.2 but using a procedure named in this thesis as “impact sound intensity method”. The measurement method was by means of a scan procedure of the surfaces under test. The type of excitation was a tapping machine (B&K Type 3204), as an alternative to the usual acoustical airborne excitation with white noise, emitted by a loudspeaker. The standardized impact measurements, for sound pressure method, are explained in section 2.7.

The excitation was performed by a tapping machine for one transverse position, as required by the EN ISO 140-6 (1998). The sound field generated and transmitted to the receiving room, was measured and then averaged for the sound intensity power levels, put on the air by the element floor and lateral element.

All the measurements were carried out in one-third octave bands, between 50 and 10.000 [Hz]. The sound intensity probe was calibrated between each laboratory element scan. Measurement conditions were satisfactory, in accordance with the requirements of ISO 15186-2 (2003).

The power level was calculated averaging between each sound probe intensity scan (vertical and horizontal) and then over the corresponding element surface area.

The surfaces were divided in sub-areas and for each measured sub-area, the scanning time was about one minute each (maximum).

The floating floor element has the dimensions of 4,49x2,66 [m] and it was divided in twelve sub-areas with approximately 1,12x0,88 [m] each one. The lateral element of 4,49x3,39 [m], was also divided in twelve sub-areas and each one presents approximately 1,12x1,13 [m] as shown in Figure 5.2.

At low frequencies, for some of the floor sub-areas, negative intensity levels tend to appear. In the flanking element, this also happens both at high and low frequencies. The reason for that is due to lower transmission power levels from the lateral element, and strong power levels from some areas of the ceiling. These negative levels indicate that there is sound produced by the tapping machine that is arriving to the lateral element by airborne transmission, inside the room, instead of out coming by structure borne transmission. However, the negative values, were evaluated in the Intensity charts as

positive values, to average the sub-areas sound power levels, as referred in Andrade et al. (2004).



Figure 5.2 – Partial view of DIENCA laboratory element ceiling (floating floor) and at the bottom, the lateral element

5.3.2 *In situ*, “Magisterio”

The expressions for SRI for the separating element and for the flanking contribution by the intensity method are given by equations 2.47 and 2.48:

$$R'_I = \left[L_{p1} - 6 + 10 \log \left(\frac{S}{S_0} \right) \right] - \left[\bar{L}_{in} + 10 \log \left(\frac{S_M}{S_0} \right) \right]$$

$$R'_{I_{Fj}} = \left[L_{p1} - 6 + 10 \log \left(\frac{S}{S_0} \right) \right] - \left[\bar{L}_{in,j} + 10 \log \left(\frac{S_{M_j}}{S_0} \right) \right]$$

The excitation and the measurements for source room (1) and the separating element are the same explained in the section 5.2.

The measurement surfaces S_M and S_{M_i} were divided in nine or twelve sub-areas, depending on the surface dimension. Figure 5.3 shows a partial view of the separating element, observed from the receiving room point of view and showing the sub-areas division.



Figure 5.3 – *In situ*, “Magisterio” receiving room measurement surface separating element, divided on twelve sub-areas

Table 5.2 – “Magisterio” receiving room elements and sub-areas dimensions

	Element dimension [m]	Sub-areas	Sub-area dimension [m]
Separating element	4,18 x 3,02	12	1,04 x 1
Lateral element with door	3,47 x 3,02	9	1,15 x 1*
Lateral element without door	3,47 x 3,02	9	1,15 x 1
Ceiling	4,18 x 3,47	12	1,04 x 1,15
Floor	4,18 x 3,47	12	1,04 x 1,15
Bottom element	4,18 x 3,02	12	1,04 x 1

The receiving room (2) elements and the corresponding number of sub-areas and dimensions are expressed on the Table 5.2. There is an exception to the lateral element with door. It has three sub-areas with different dimensions: (i) sub-area between door and separating element; (ii) sub-area above the door and (iii) door area it self. These three different sub areas are visible on the left side of the previous Figure 5.3.

All the measurements were carried out in one-third octave bands, between 50 and 5.000 [Hz], and the measurement conditions were in accordance with the requirements of ISO 15186-2 (2003).

Measurement scans were of two minute each (one minute in each direction), which corresponds to an average velocity of approximately 0,15 [m/s].

The source room (1) is significantly large, 181 [m³], improving room diffusion and the accuracy of the intensity sound reduction index in the low frequencies, Machimbarrena (1999).

The validation verification for this measurements surfaces, shown in chapter 6, were compared to the dynamic capability and the average surface pressure-intensity indicator (F_{pIn}).

The residual pressure-intensity index δ_{pI_0} or L_{k_0} , is obtained during the calibration process. This procedure is usually performed before each new measurement, and the scan intensity measurements were performed for all receiving room elements with the same calibration reference data. In the Figure 5.4 is shown the surface pressure-intensity indicator F_{pIn} , averaged for all contributing elements of the receiving room, compared to the residual pressure-intensity index δ_{pI_0} or L_{k_0} .

As it can be seen from Figure 5.4, using a spacer of 12 [mm] the reliability of the data, acquired below the 125 [Hz] is somewhat doubtful, because the surface pressure-intensity indicator F_{pIn} , at that frequency, exceeds the residual pressure-intensity index.

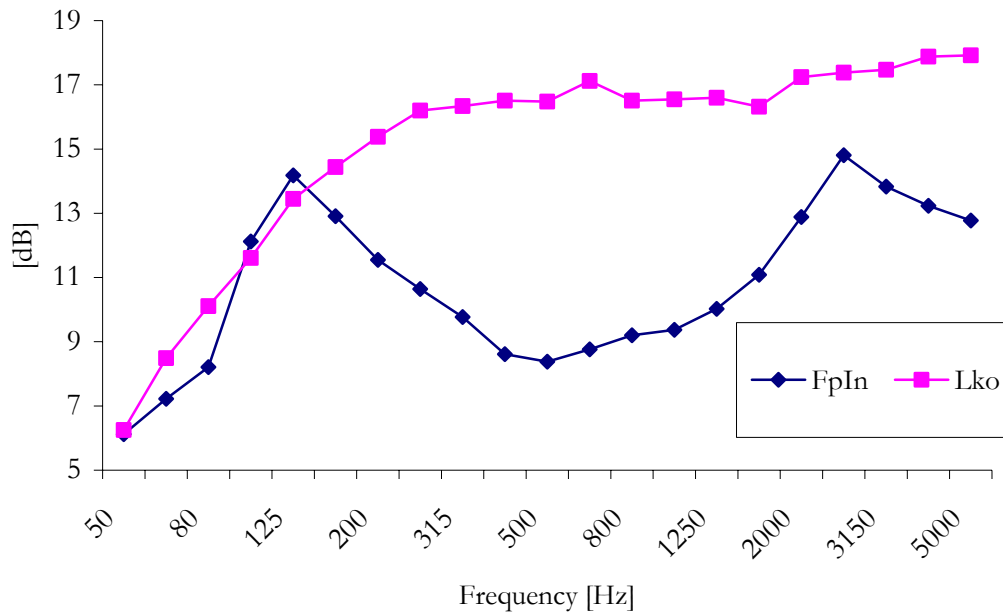


Figure 5.4 - Pressure-residual intensity index (L_{ko}) associated with a measurement and compared with the average surface pressure-intensity indicator (F_{pIn}), in “Magisterio”

5.4 Vibration velocity measurement layout

Over the last twenty years, vibration measurement equipments have emerged, and are widely used, from research laboratories to industries with vibration control requirements. The use of this kind of instrumentation nowadays is simple and with relative low cost implementation. This measurement method applied to structure borne sound transmission, as previously referred in chapter 2, is not standardized and can be of great interest when compared to the sound Intensity method.

Using the vibration velocity method, it is also possible to compare sound power levels emitted by the elements of a receiving room, and consequently evaluate the sound contribution of those elements.

The current heading is a description of the vibration velocity measurements, experiments and calculus procedures carried along this thesis. As previously explained in chapter 4, this research work started with experiments using sound intensity method

applied *in situ* conditions. Later the effort evolved to developments under laboratory conditions and eventually again *in situ* conditions.

The description here is summarized for two different situations. First the vibration velocity method used in laboratory conditions is described and then the *in situ* conditions. The conditions of the measurement procedures made in laboratory and *in situ* are exactly the same for the vibrations velocity method and sound intensity method.

The vibration velocity method measurements for laboratory, were performed in accordance with some aspects of the EN ISO 10848-1 (2006) to collect only the velocity values.

The measurement procedure to evaluate the determination of the vibration reduction index K_{ij} (not measured) in laboratory conditions can be achieved according to the procedures explained in prEN ISO 10848-1 (1999), prEN ISO 10848-1 (2004), or more recently EN ISO 10848-1 (2006).

For *in situ* conditions, the use of the tapping machine as a structure borne excitation, or to produce a sound field, is usually applied to the evaluation of impact noise of floors, according to EN ISO 140-7 (1998). This type of excitation was nevertheless used at the DIENCA laboratory. For *in situ*, in the source room, the sound was generated by a dodecahedral loudspeaker, connected to an amplifier and a white noise signal generator. The criterion used to determine the number of measurement positions was the same used in DIENCA measurements and is shown in Table 5.3.

EN ISO 10848-1 (2006) includes the algorithm to chose the minimum number of transducer positions required on each tested element.

Table 5.3 – Minimum number of velocity measurement positions n function of the number of modes in the one-third octave band N_i

n	N_i
12	≤ 3
8	$3 < N_i \leq 12$
6	$12 <$

The number of positions is calculated, using the equation (5.1):

$$N = \frac{0,23 \cdot \pi}{c_0^2} \cdot S \cdot f_c \cdot f_m \quad (5.1)$$

Where $c_0 = 340$ [m/s], S is the surface area of the test element in [m²], f_c is the tested element critical frequency in [Hz] and f_m is the centre octave band frequency in [Hz].

The element critical frequency is calculated according to the material characteristics of each element from equation (5.2) in prEN ISO 10848-1 (1999), being at present time EN ISO 10848-1 (2006):

$$f_c = \frac{c_0^2}{2\pi} \sqrt{\frac{\rho_m h}{B}} \quad [Hz] \quad (5.2)$$

Where $c_0 = 340$ [m/s], ρ_m is the surface density material in [kg.m²], h is the thickness in [m] and B is the bending stiffness in [N.m].

The bending stiffness B is:

$$B = \frac{Eh^3}{12(1-\nu^2)} \quad [N \cdot m] \quad (5.3)$$

Where E is the Young modulus in [N.m⁻²], h is the thickness [m] and ν is the Poisson ratio of the material element.

5.4.1 In laboratory, DIENCA

Before each set of measurements, the acceleration transducers were calibrated with an amplification of 3,16 [V/m.s⁻¹] corresponding to a power level of 40 [dB] and a velocity of 10 [mm/s]. The reference velocity during the measurements was of 5x10⁻⁸ [m/s] and the amplification level was of 100 [V/m.s⁻¹] corresponding to a power level of 30 [dB].

All the measurements were carried out in one-third octave bands, between 50 and 8.000 [Hz] for the ceiling, and between 50 and 5.000 [Hz] for the lateral element. On the

total, fourteen measurement positions were chosen arbitrarily distributed over the entire tested element surfaces: (i) lateral element and (ii) ceiling element. The measurement time for each position was a minimum of 30,5 [s] and a maximum of 80,5 [s], as it can be seen in Table 5.4. All the experiments were taken for steady-state conditions.

Table 5.4 – Measurement times for transducer positions in DIENCA

Transducer in	Time [s]	Transducer in	Time [s]
G	79,845	F	80,475
A	79,845	O	67,895
L	30,585	M	67,895
I	30,585	N	60,635
P	51,385	D	60,635
E	51,385	H	57,975
L	80,475	B	57,975



Figure 5.5 – Transducer support glued on the surface element of DIENCA laboratory



Figure 5.6 – Acceleration transducer screwed on the support glued at the floating floor element of DIENCA laboratory

5.4.2 *In situ*, “Magisterio”

The acceleration transducers were calibrated before each measurement and using a reference acceleration of 10^{-6} [m/s²].

The acceleration calibration value corresponds to 140 [dB]. This value is then inserted in the real time frequency analyser (B&K 2144) to ensure the relative measurement of the signal obtained by two charge accelerometers (B&K 4384).

The measurement procedure for this vibration velocity method, make use of some criterion suggested in the prEN ISO 10848-1 (2004) being at present time the EN ISO 10848-1 (2006). All data was acquired in acceleration levels $a_{r.m.s.}$ [m/s²] with the real-time frequency analyser (B&K 2144) and then post-processed to vibration velocities $v_{r.m.s.}$ [m/s], computed with a reference velocity of 5×10^{-8} [m/s] making use of a Microsoft ExcelTM sheet.

The frequency range measured was chosen according to the specific acceleration transducers and to the measurement range specified in the EN ISO 10848-1 (2006). Therefore, the measurement frequency range was between 50 [Hz] and 5.000 [Hz]. As a

result, the number “N” is a number less than $N=3$ and, according to Table 5.3, the “n”, the number of measured velocity positions, of EN ISO 10848-1 (2006) is $n=12$.

The twelve velocity measurement positions were randomly distributed over the entire elements under test, as can be seen in Figure 5.3, where some measurement position points are represented, in a partial view of the separating element under test. However, there are some requests to respect according to EN ISO 10848-1 (2006), such as: (i) the distance to junctions must be at least 25 [cm]; (ii) between measurement positions a minimum distance of 50 [cm]; (iii) 3,5 [m] maximum distance, away from the joint under test. Also similar distances used in Craik et al. (1995) were applied.

The joint under test is considered the one that connects the source room with the receiving room, for that flanking element. Another measurement demand is the time required for each measurement position; usually this time must obey to a pre-excitation stage to ensure steady state conditions and then a time quantity that can express a sufficient weighted measurement. Therefore for each measurement position was chosen one minute, value also used in the sound Intensity method for each measured sub-area scan pattern.

The acceleration transducers are connected to the elements under test with bee wax. This material is suitable for this type of applications. A major interest in this type of experiments is ensuring that the element surfaces are not scratched or get dirty and if this is the case, they can be easily clean. The following Figure 5.7 shows one acceleration transducer connected with bee wax to a test element surface.

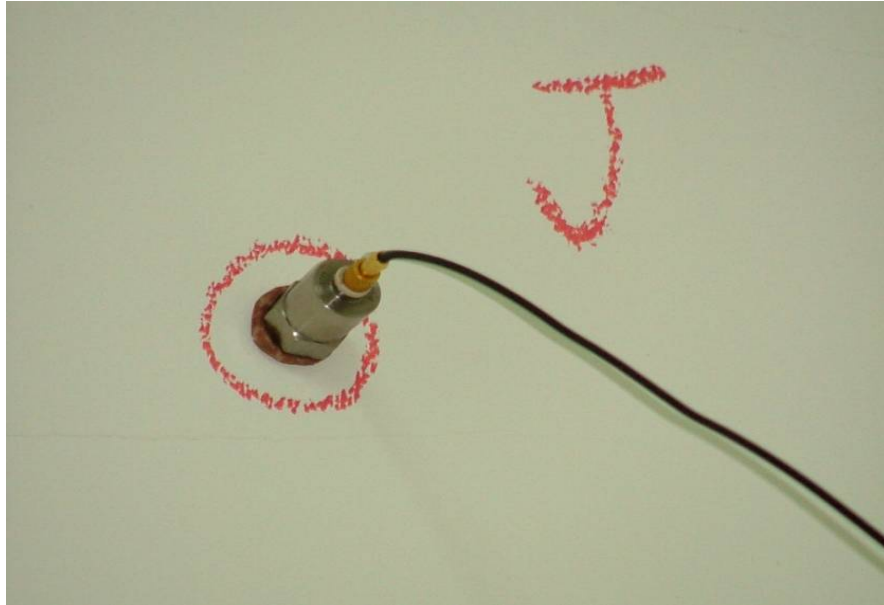


Figure 5.7 – Acceleration transducer connected with bee wax to a test element surface of “Magisterio”

Chapter 6, includes a set of figures with vibration interpolated surface images. These figures present the results, for the inner area between the measurement points, for each contributing element in the receiving room. The bottom element is not included because it was not computed on the final calculations of the contributing elements neither for vibration nor for intensity results.

The following tables describe the position of acceleration transducers in Cartesian coordinates, for each element under test of the “Magisterio” receiving room. The origin is always set on the lower left corner of the surface, considering the viewer positioned inside the room, except for the ceiling and floor elements where the origin is located on the lower left corner of the element with door when observed from above.

Table 5.5 – Transducer positions for separating element in [m]

Transducer position	x [m]	y [m]
A	0,55	2,30
B	1,28	2,60
C	2,30	2,20
D	4,40	2,80
E	0,8	1,73
F	1,60	1,51
G	3,40	1,30
H	4,25	1,70
I	0,80	0,50
J	1,70	0,78
K	2,30	0,35
L	4,30	0,97

Table 5.6 – Transducer positions for ceiling element in [m]

Transducer position	x [m]	y [m]
A	4,25	2,70
B	3,45	2,65
C	1,55	4,30
D	1,05	4,05
E	0,55	1,75
F	1,28	1,55
G	3,10	1,20
H	4,30	1,47
I	4,25	1,00
J	2,20	0,64
K	1,55	0,64
L	0,64	0,64

Table 5.7 – Transducer positions for lateral element with door in [m]

Transducer position	x [m]	y [m]
A	0,43	2,50
B	1,10	2,20
C	1,85	2,53
D	2,75	2,50
E	0,30	1,78
F	1,10	1,42
G	1,80	1,75
H	3,33	1,99
I (on door)	2,70	1,55
J	3,30	1,06
K	0,35	0,75
L	1,68	0,90

Table 5.8 – Transducer positions for lateral element without door in [m]

Transducer position	x [m]	y [m]
A	0,60	2,60
B	1,00	2,20
C	2,78	2,20
D	2,11	2,85
E	0,90	1,43
F	1,53	1,39
G	2,83	1,67
H	0,35	0,72
I	1,53	0,69
J	2,28	1,27
K	2,63	0,56
L	0,33	1,90

Table 5.9 – Transducer position for bottom element in [m]

Transducer position	x [m]	y [m]
A	0,5	2,60
B	1,40	2,85
C	0,35	1,75
D	0,72	1,17
E	0,50	0,62
F	1,62	2,10
G	1,82	1,25
H	2,57	1,59
I	2,57	0,50
J	3,50	2,55
K	3,50	1,50
L	3,78	0,74

Table 5.10 – Transducer position for floor element in [m]

Transducer position	x [m]	y [m]
A	0,85	2,80
B	0,52	2,15
C	2,92	2,98
D	2,00	2,72
E	1,15	1,15
F	0,64	0,64
G	2,13	0,62
H	1,60	1,80
I	2,31	2,95
J	1,63	2,40
K	3,70	2,20
L	3,45	0,85

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Chapter 6

6 Results of the comparison between vibration velocity, sound intensity and sound prediction methods

6 Resumen de comparación de resultados entre el método de velocidad de vibración, el método de intensidad sonora y los métodos de predicción acústica

En la actualidad de la acústica de edificación, es posible lograr muy buenos resultados gracias a la consideración de la medida de la contribución de los elementos de flanco a través del método de medida mediante intensidad sonora (apartado 2.5). A pesar de ello, se revela una tendencia de no hacer uso de este tipo de procedimiento de medida para condiciones en *in situ*, debido al tiempo utilizado en cada medida y a la necesidad de tener técnicos con capacidad y calificación suficiente, Fausti and Secchi (2002). La transmisión sonora por flancos, así como la transmisión estructural asociada con él, no presenta fuertes niveles de potencia y presentará aún menos con la tendencia actual de las mejoras del aislamiento acústico.

La reciente normativa EN ISO 10848-1 (2006) ha introducido, para condiciones de laboratorio, el método de velocidad de vibración (apartado 2.6) y revela la posibilidad de aplicarlo también a las condiciones de *in situ* y, consecuentemente, obtener una evaluación y contribución del sonido transmitido por flanco.

El procedimiento de cálculo requiere una estimación de la eficiencia de radiación, ecuación (2.21), según diferentes enfoques de diversos autores como; Sewell (1970); Rindel (1993) y, más reciente Davy (2004), descritos en esta tesis en el apartado (2.3.3).

Siendo así, este capítulo presenta los resultados organizados por medidas realizadas en condiciones de laboratorio, hasta el apartado 6.2.2, y en condiciones *in situ* desde ahí en adelante.

En ellos se explica el trabajo conseguido en este campo para mejorar la estimación de los resultados, utilizando el método de velocidad de vibración, cuando se aplica a la estimación de las medidas de transmisión del sonido por flanco en condiciones *in situ* (apartado 2.6), y por comparación con el método de intensimetría acústica. También se comparan los resultados, para el índice de reducción sonora aparente R' , siguiendo el método de medida mediante presión sonora frente a los modelos de estimación de la transmisión sonora propuestos por la EN 12354-1 (2000) y conocidos como modelo sencillo y detallado.

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6.1 Introduction

The most recent technology in building acoustics can achieve very good sound insulation measurement results. This is possible when the contribution of the flanking elements into a receiving room is taken into account, as it is when using the sound intensity method (section 2.5). However, the time spent in each measurement and the need of qualified and skilled technicians, reveal a tendency to not make use of this type of procedure for measurements *in situ* conditions, Fausti and Secchi (2002). In fact, the flanking sound and the associated structure borne sound transmission do not present a strong power level, and even less with increasing tendency of better buildings sound insulation.

The recent standard EN ISO 10848-1 (2006) introduces a measurement procedure of vibration velocity measures for laboratory conditions (see section 2.6), and it reveals the possibility of also applying this method to *in situ* measurement conditions and, consequently, for evaluation and contribution of the flanking sound transmission.

The calculation procedure requires a radiation efficiency estimation by equation (2.21), according to different mathematical approaches of several authors; Sewell (1970); Rindel (1993) and more recently Davy (2004), as described in this thesis (section 2.3.3).

This chapter presents the results organized according to where the measurements took place: Laboratory results are shown until section 6.2.2 and *in situ* conditions are shown from that point till the end of the chapter.

In fact the purpose of the chapter is to expose what has been done in order to improve the estimated results by using the vibration velocity method to measure the apparent flanking sound transmission *in situ* conditions (section 2.6). These results are compared to the sound intensity method results including flanking transmission.. Besides, the apparent sound reduction index R' obtained using vibration, intensity, and pressure methods as well as the sound transmission prediction models proposed in EN 12354-1 (2000) (simplified and detailed) are compared.

6.2 Laboratory comparison between intensity and vibration velocity methods

The results presented here report the measurements made in the laboratory facilities described in section 4.2.1 and the calculus procedure applied to obtain these results is described in section 2.5.2 (sound intensity method) and 2.6 (vibration velocity method).

In both methods an impact machine was used as sound source excitation, as mentioned in section 2.7. The methods are the impact sound intensity method and impact vibration velocity method. The response has been measured for the ceiling (source room floating floor) and a lateral element of the receiving room.

6.2.1 Floating floor and lateral element vibration velocity measurements

Figure 6.1 shows the spatial-time average vibration velocity values \bar{v} [m/s], for the floating floor and a lateral element in one-third octave bands, according to the measurement layout described in section 5.4.1.

Figure 6.2 shows the same information (same elements), but in this case the spatial-time average vibration velocity levels are shown, expressed by $L_{\bar{v}}$ [dB re (5×10^{-8}) (m/s)] by equation 2.9.

In general, the frequency range of interest is set starting in 100 [Hz] till 3.150 [Hz], or enlarged to 50 and 5.000 [Hz]. However, for this case, measurements were made up to 8.000 [Hz] to show an atypical behaviour of the laboratory facility above the 3.150 [Hz]. The prediction methods were calculated maintaining the frequency range from 50 to 5.000 [Hz].

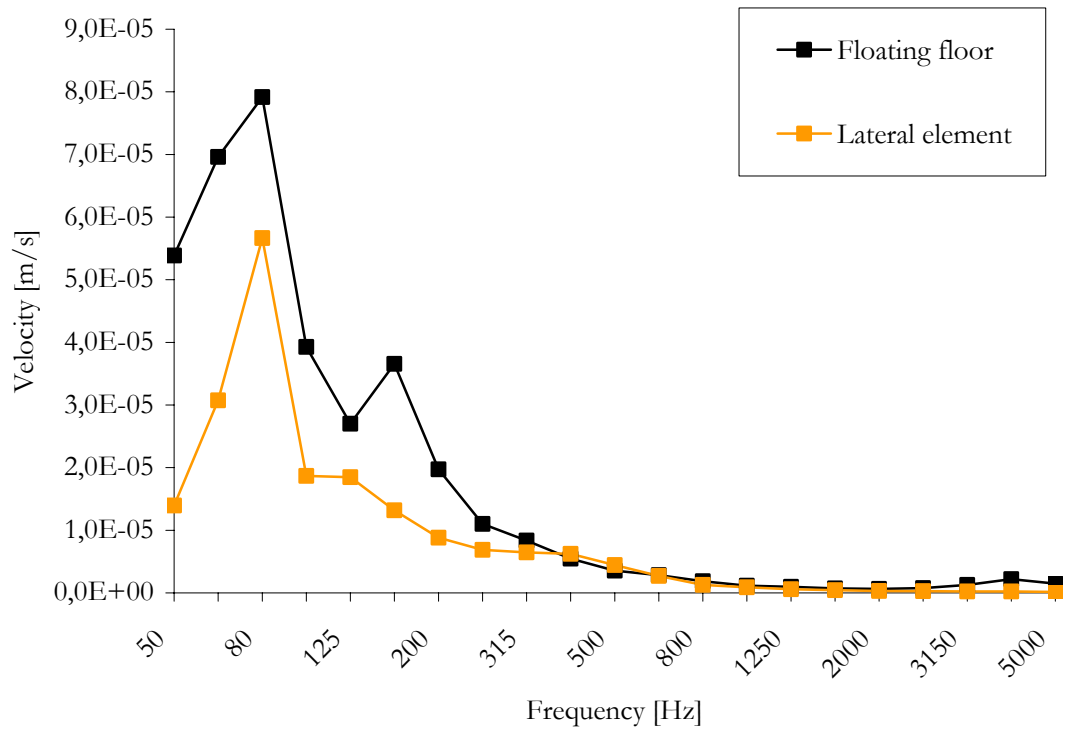


Figure 6.1 - Spatial-time average vibration velocity \bar{v} for floating floor and lateral element tested in laboratory

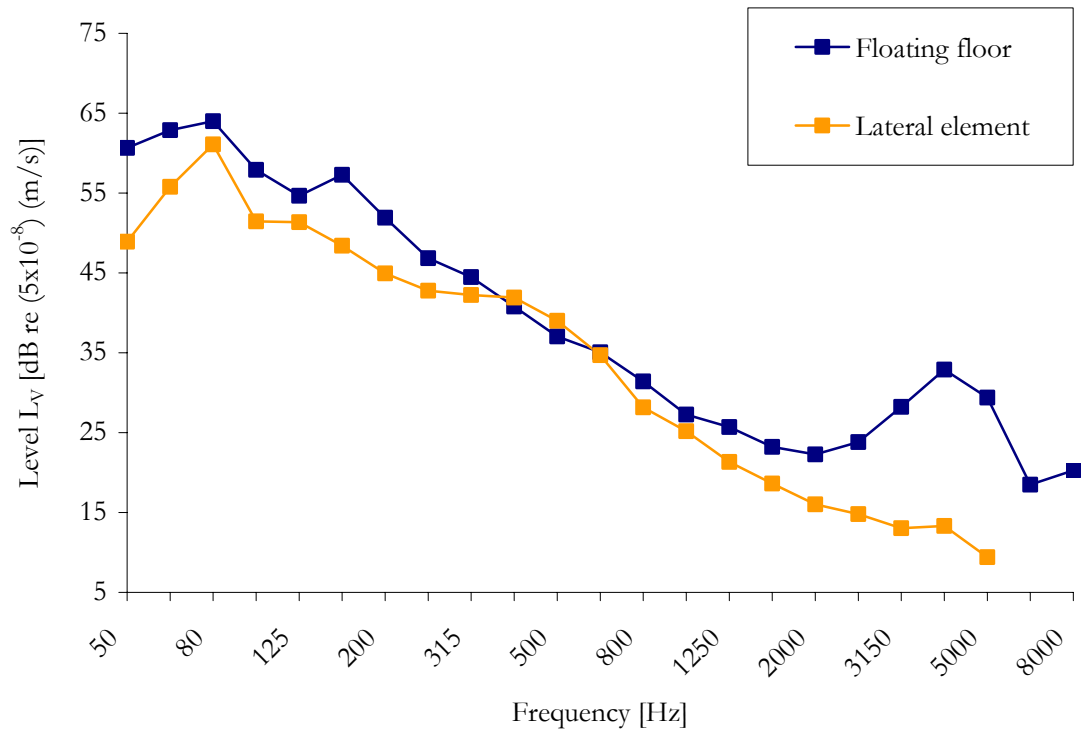


Figure 6.2 - Spatial-time average vibration velocity levels $L_{\bar{v}}$ for floating floor and lateral element tested in laboratory

Observing the previous Figures 6.1 and Figure 6.2 it is noticed that the velocities measured on the elements, present lower velocity values above the 1.000 [Hz]. This fact could be on the origin of some uncertainty. It is noticeable in Figure 6.2, above the 1.000 [Hz], a smoothness outline trend towards lower velocity levels in the separating element curve in comparison with the floating floor curve.

6.2.2 Floating floor and lateral element sound power

estimations: intensity vs. vibration

Starting from the velocity measurements, the sound power level radiated using surface average velocity vibration values $L_{w,v}$ in [dB re 10^{-12} W] equation (2.21) is calculated by different estimations according to the inference equations (2.48) of the radiation efficiency, as mentioned in section 2.3.3.

The calculations are executed according to four different equations, corresponding to four different radiation efficiencies. The radiation efficiency is estimated according to equation (2.22) by Sewell (1970), equation (2.23) obtained by Josse (1972), equation (2.24) by Rindel (1993) and with equation (2.26) obtained by Davy (2004).

The values are obtained in a receiving room due to the radiating area of the flanking elements: floating floor Figure 6.3 and lateral element Figure 6.4. These $L_{w,v}$ will be compared with the measured sound power level by ISO 9614-2 (1996) for the floating floor $L_{w2,l}$ in [dB re 10^{-12} W].

As it can be seen, the five curves in Figure 6.3 present a similar behaviour at almost all the one-third-octave octave bands, but it is observed that, in the central bands (between the 200 [Hz] and the 2.500 [Hz]), the estimation by vibration velocity method yields lower levels (3 to 4 [dB]) than the sound intensity method. This implies worse insulation levels. On the other hand the vibration velocity estimations are little higher than the intensity estimations in the lower bands (below the 200 [Hz]) and almost equal between the 3.150 [Hz] and 5.000 [Hz] bands. The higher levels observed, in general, of the sound intensity method could be explained by the strong and located noise produced by the tapping machine, which during the scan passage of the sound intensity

probe, increased the intensity levels measured by it. It must be said that the ISO 9614-2 (1996) was not created for impact sound measurements.

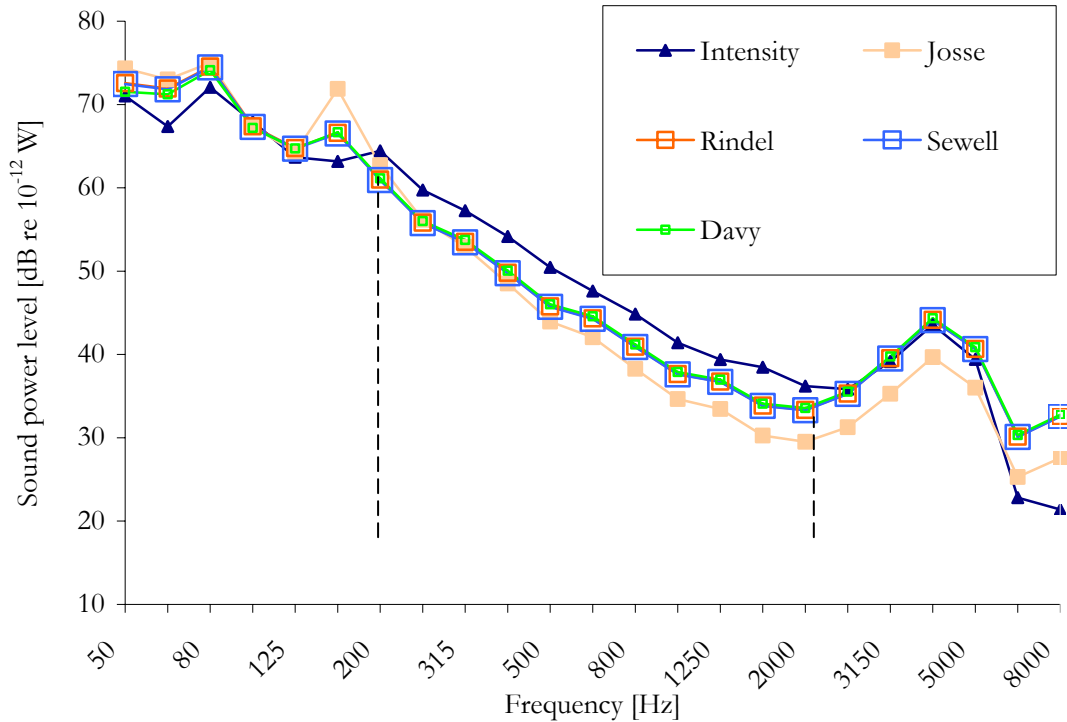


Figure 6.3 - Comparison between estimated sound power level in the receiving room by vibration velocity method and sound intensity method for floating floor element in laboratory conditions

The five curves in Figure 6.4 illustrate a similar outline between them, however in this case the differences in the central frequency bands previously observed in Figure 6.3, can not be seen. So, for the lateral element the curves are (to a large extent) matching and the differences between $L_{w,V}$ and $L_{w2,I}$ remain below to 4 [dB] in the 1.250 [Hz] to 2.500 [Hz] range. These differences for Josse's estimation are extended between 630 [Hz] and 5.000 [Hz] compared with the other curves tendency, with more identical results than those obtained for the floating floor.

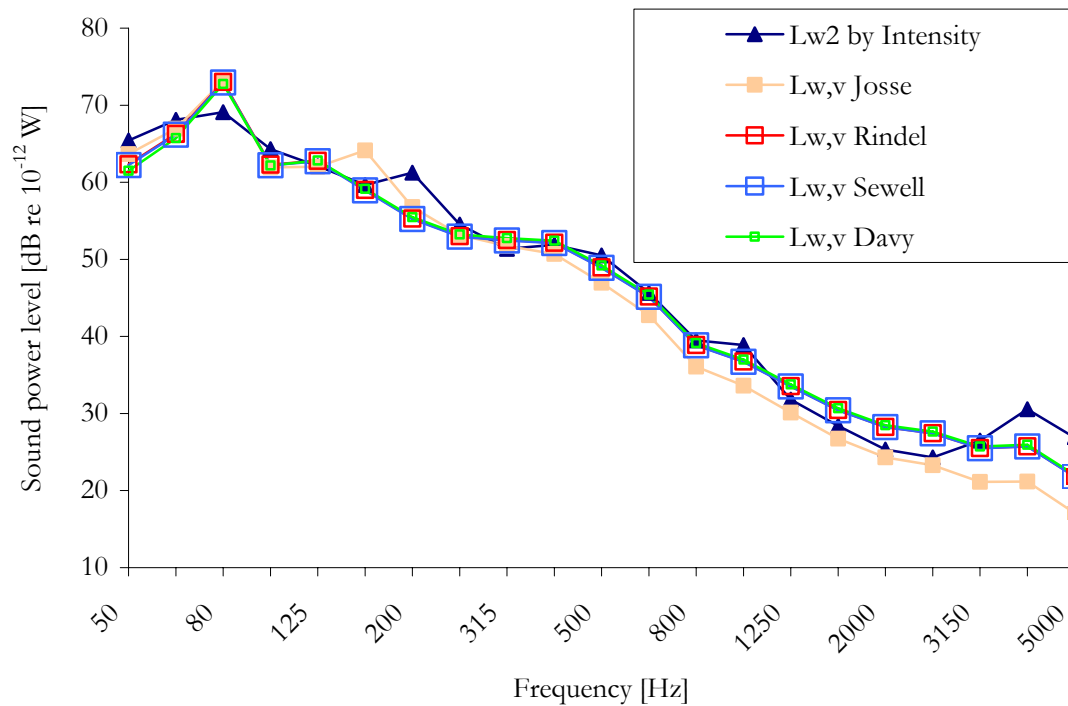


Figure 6.4 - Comparison between estimated sound power level in the receiving room by vibration velocity method and sound intensity method for the lateral element in laboratory conditions

6.3 *In situ* comparison between measurements and prediction methods

This section and the following refer to the results obtained for *in situ* conditions or field conditions, described in section 4.2.2. First for the separating element (section 6.3.1) and further for flanking elements (section 6.3.2): ceiling and the two lateral elements, one with door and the other without door. Previously on section 5.4.2 the corresponding measurement layout was described.

6.3.1 *In situ* separating element

In this section the results of the measurements performed by vibration velocity method, sound intensity method and prediction models for the separating element are shown.

6.3.1.1 *In situ* separating element vibration velocity

measurements

As previously described for the vibration velocity method in laboratory conditions, the vibration *in situ* measurements were time and spatial averaged in one minute on twelve positions using two accelerometers. Figure 6.5 shows the spatial-time averaging vibration velocity in [m/s], that provides the values measured with the acceleration transducers. The pink curve represents the background noise values and the blue curve represents the vibration velocity values for separating element. The background noise levels were obtained on the separating element for the same measurement points as for the white noise excitation measurements, but obviously, with the sound source off.

The same results are shown in Figure 6.6, but changed to spatial-time average vibration velocity levels in [dB re (5×10^{-8}) (m/s)]. In each figure it is also represented the background noise level (comparing both curves) for each tested element. The signal to noise ratio is high enough to guarantee that background noise level does not affect the measurements. The curve representing the background noise level provides relevant information concerning measurement precision. EN ISO 140-4 (1998) establishes as a rule to improve measurements, that it should present measured data with at least 10 [dB] above the background noise level in each third octave band. For the results this requirement fails at 125 [Hz] and below, as it can be seen in Figure 6.6.

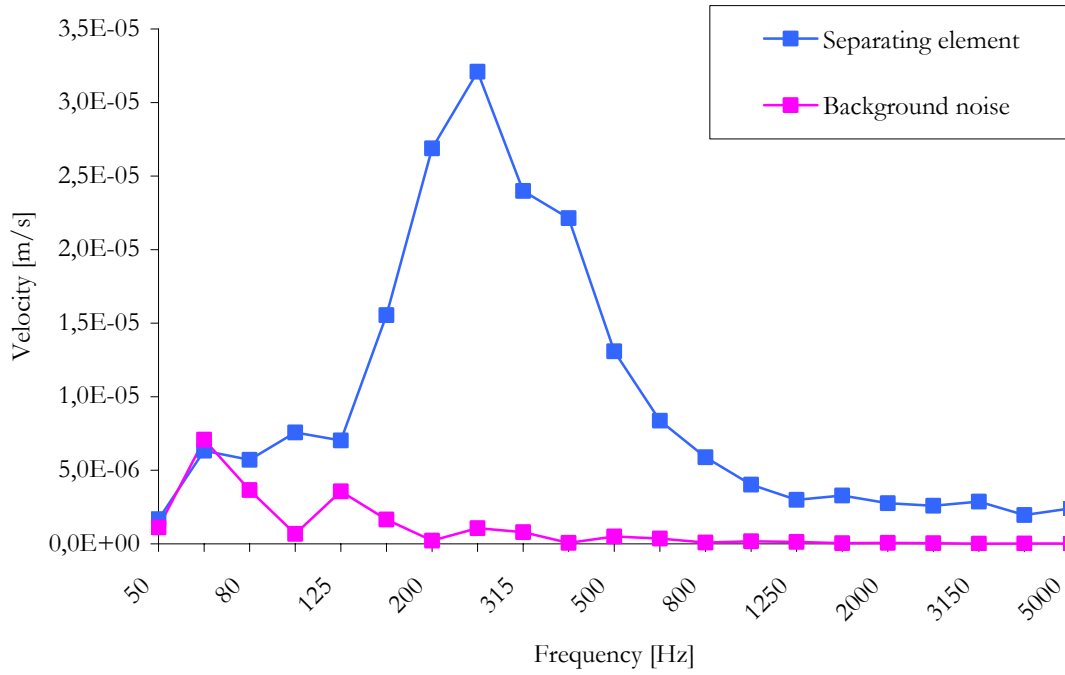


Figure 6.5 – Spatial-time averaging vibration velocity \bar{v} for the separating element tested *in situ*

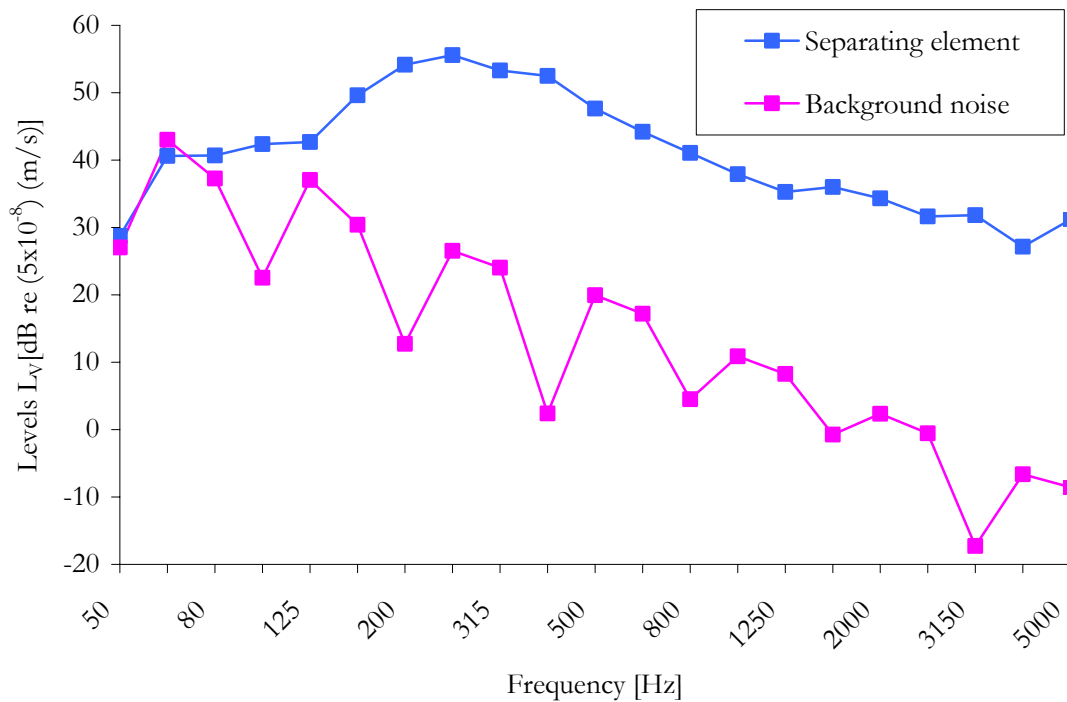


Figure 6.6 - Spatial-time average vibration velocity levels $L_{\bar{v}}$ for the separating element tested *in situ*

6.3.1.2 *In situ* separating element sound power estimations: intensity vs. vibration

Concerning the intensity measurements, in a first stage it was very difficult to perform sound intensity measurements and comply with the required environment conditions as stated in equation 2.54 ($F_{pIn} < \delta_{p10}^{-7}$).

After several measurements trials performed in the receiving room and considering the advices in the ISO 15186-2 (2003), to improve the intensity measurement results, the measurements were, in spite of everything, performed. In the next table it is shown, as an example, the criteria of the equation 2.54 for each measured sub-areas 1 to 4. These four sub-areas compile the section area of the separating element near the floor junction. Between, the lower left corner (sub-area 1) and the lower right corner (sub-area 4) of the separating element. The “Ok” label indicates that the criterion is verified. When it is not verified, the figures express the value of $F_{pIn} - (\delta_{p10}^{-7})$. High values indicate higher deviation from compliance with criterion. Lower values indicate better compliance, although with no compliance with criterion.

The representation of the same criterion including the contribution of all the twelve measured sections of the separating element is represented in the previous section in Figure 5.4.

It can be observed that in the section 1 (first column) there is not one-third-octave that complies with the criterion. This section is next to the door; therefore the measurements are influenced by the strong flanking transmission of sound with origin in the door. The influence and presence of strong flanking sound is one of the main reasons of the bad measurement intensity performance for our *in situ* conditions. The resolution of this problem would be possible by means of shielding the flanking elements, but this type of resource was out of our considerations and possibilities.

The sound power level radiated by the separating element using surface average velocity vibration values $L_{w,v}$ in [dB re 10^{-12} W] is estimated using equation 2.21. There will again be three $L_{w,v}$ estimations corresponding the three different radiation efficiency models, as mentioned in section 2.3.3. The values are obtained in a receiving room due to the radiating area of the separating element. These $L_{w,v}$ levels will be compared with

the estimated sound power levels by intensity method for the receiving room L_{w2} equation (2.48) in [dB re 10^{-12} W].

Table 6.1 shows the sound power levels radiated for the separating element using surface average velocity vibration values $L_{w,v}$ in [dB re 10^{-12} W] obtained using the three different equations.

Table 6.1 – Sound power level radiated by the separating element $L_{w,v}$ in [dB re 10^{-12} W] by vibration velocity

Frequency [Hz]	$L_{w,v}$ Rindel [dB]	$L_{w,v}$ Davy [dB]	$L_{w,v}$ Sewell [dB]
50	27,1	26,2	27,0
63	39,7	39,0	39,6
80	40,3	40,0	40,3
100	53,5	53,3	53,4
125	55,2	55,2	55,1
160	61,5	61,6	61,5
200	66,4	66,6	66,3
250	67,7	67,9	67,7
315	65,5	65,7	65,4
400	64,6	64,9	64,6
500	59,4	59,6	59,3
630	55,8	56,0	55,7
800	52,7	53,0	52,7
1000	49,9	50,1	49,8
1250	47,3	47,6	47,3
1600	48,4	48,6	48,4
2000	46,7	46,9	46,7
2500	44,2	44,4	44,2
3150	44,3	44,5	44,3
4000	31,7	31,9	31,7
5000	35,9	36,1	35,9

Figure 6.7, compares the $L_{w,v}$ sound power levels for the three estimated curves against L_{w2} by sound intensity method *in situ* conditions. It is noticeable that the four curves present the same shape and also the same maximum value at 250 [Hz]. The intensity curve presents, in general lower values except below 80 [Hz]. In order to enhance the differences, Table 6.2 shows, in the second column, L_{w2} levels, obtained by sound intensity method and in the following columns the differences between $L_{w,v}$ and L_{w2} for each of the three estimations. At low frequencies (50-80 [Hz]) the values for the

intensity method are greater than the vibration velocity estimations. Between 100 [Hz] and 800 [Hz], it can be seen that for the three estimations, vibration velocity estimation is about 2 to 6 [dB] above the sound intensity estimation, with exception to the 125 [Hz] one 1/3 octave band where the difference is considerably lower (1,3 [dB]). Above 800 [Hz] the agreement is acceptable and differences remain below 1,8 [dB], except at 4.000 [Hz] (3,5 [dB]). Sewell's estimation is slightly closer to the values obtained by sound intensity method than Rindel's or Davy's.

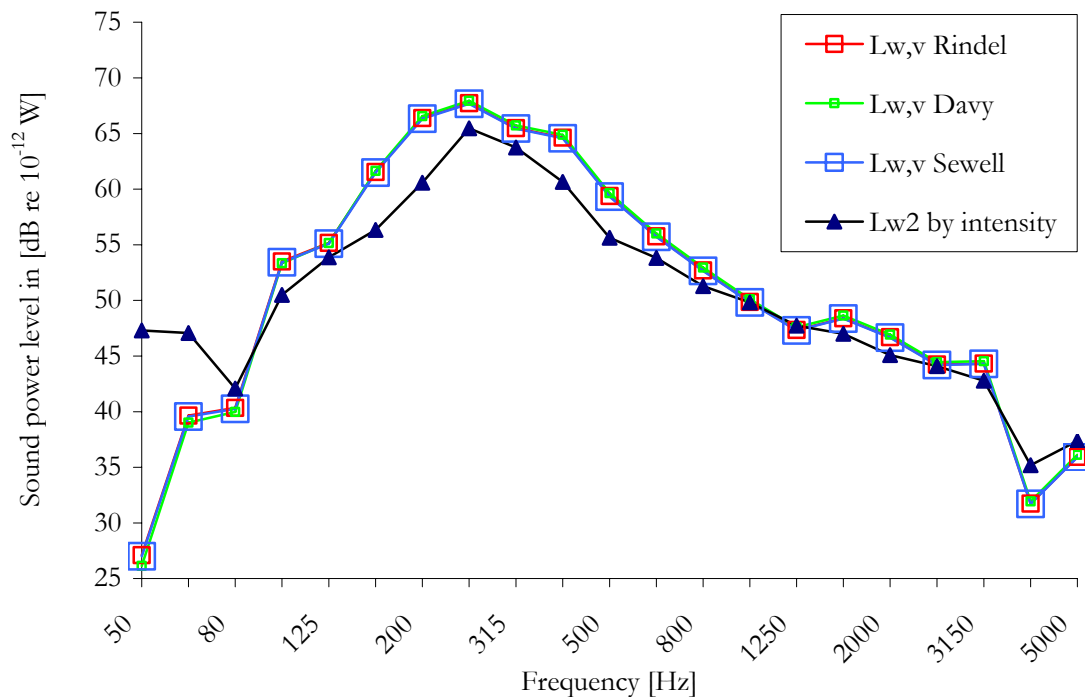


Figure 6.7 - Comparison between estimated sound power level in the receiving room by vibration velocity method and sound intensity method for separating element *in situ* conditions

In the following Table 6.2 it can be observe the three $L_{w,v}$ estimations presents very good similarity between them, with differences below 0,3 [dB]. It is observed once again, that there is a fairly good agreement between intensity R'_1 and vibration velocity results R'_v for frequencies above 800 [Hz], where the differences are less than 2 [dB] or even almost equal.

Table 6.2 - Differences between L_{w2} by sound intensity and $L_{w,v}$ for the three estimations by vibration velocity

Frequency [Hz]	L_{w2} by intensity [dB]	$L_{w,v}-L_{w2}$ Davy [dB]	$L_{w,v}-L_{w2}$ Rindel [dB]	$L_{w,v}-L_{w2}$ Sewell [dB]
50	47,3	-20,2	-21,2	-20,3
63	47,1	-7,4	-8,1	-7,5
80	42,1	-1,7	-2,1	-1,8
100	50,5	3,0	2,9	2,9
125	53,9	1,3	1,3	1,2
160	56,3	5,2	5,3	5,1
200	60,6	5,8	6,0	5,8
250	65,5	2,3	2,5	2,2
315	63,7	1,8	2,0	1,7
400	60,7	4,0	4,2	3,9
500	55,6	3,7	4,0	3,7
630	53,8	1,9	2,2	1,9
800	51,3	1,4	1,7	1,4
1000	49,8	0,0	0,3	0,0
1250	47,7	-0,4	-0,1	-0,4
1600	47,0	1,4	1,6	1,4
2000	45,1	1,6	1,8	1,6
2500	44,1	0,1	0,4	0,1
3150	42,8	1,5	1,7	1,5
4000	35,2	-3,5	-3,2	-3,5
5000	37,2	-1,4	-1,2	-1,5

6.3.1.3 *In situ* separating element: comparison between measurements and predicted R'

Using the $L_{w,v}$ estimated levels two apparent sound reduction indexes can be calculated (section 2.6): one corresponds only to the separating element (equation 2.54) and the other involves the contribution of all flanking elements (equation 2.56). The results of the first situation will be seen in this section and the results for the second will be seen in section 6.3.3.

According to equation 2.55:

$$R'_v = \left[L_{p1} - 6 + 10 \log \left(\frac{S}{S_0} \right) \right] - L_{w,v}$$

The estimated apparent sound reduction index, R'_v of the separating element has been estimated using the vibration velocity method, with vibration measurements data and using the same three mathematical approaches for the radiation efficiency.

Table 6.3 – Criterion of satisfactory environment for intensity measurements by $F_{pIn} < \delta_{p10} - 7$

Frequency [Hz]	Sector 1 [dB]	Sector 2 [dB]	Sector 3 [dB]	Sector 4 [dB]
100	5,91	5,32	7,87	7,51
125	11,80	2,26	7,68	5,48
160	4,79	12,04	10,19	5,85
200	4,80	1,34	2,53	1,67
250	0,77	0,12	1,76	1,68
315	2,02	Ok	0,54	2,32
400	2,55	Ok	Ok	Ok
500	1,33	Ok	Ok	Ok
630	1,41	Ok	Ok	Ok
800	0,75	Ok	Ok	Ok
1000	1,59	Ok	Ok	Ok
1250	3,48	0,13	Ok	Ok
1600	6,39	1,05	0,50	Ok
2000	11,90	1,48	1,21	Ok
2500	3,07	4,99	4,09	1,02
3150	1,96	6,36	4,72	2,14

The following Figure 6.8 shows a comparison of the apparent sound reduction index. The comparison is between: R'_v vibration velocity method, estimated by the three radiation efficiency equations, the $R'_{12354Det}$ prediction model by means of the detailed model, equation (3.26), and the R'_I sound intensity method, equation (2.49), by ISO 15186-2 (2003).

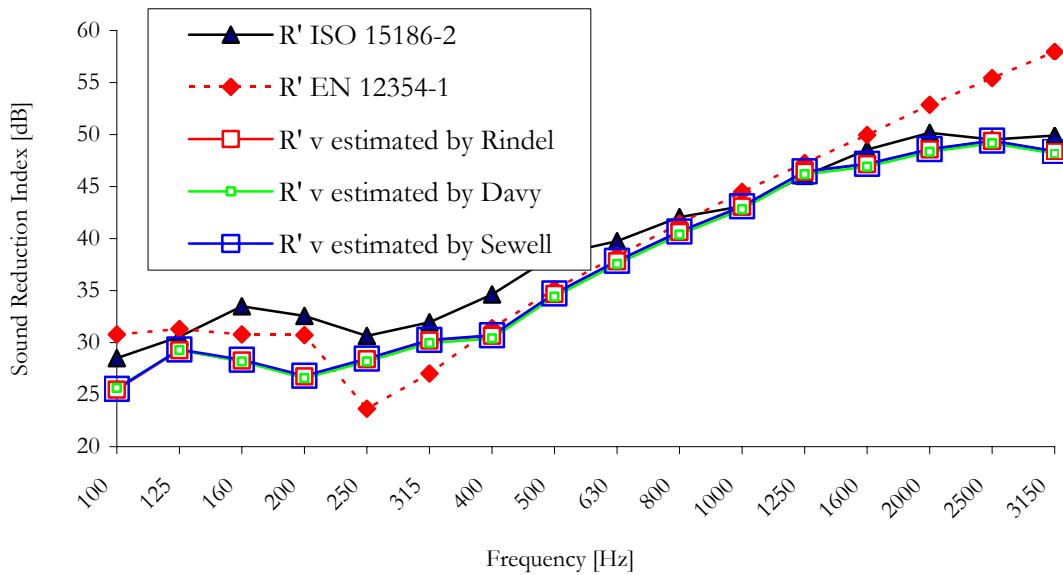


Figure 6.8 - Comparison of predicted and estimated R' for separating element

As it can be seen in Figure 6.8, the comparison is made in a smaller frequency bandwidth (100 to 3.150 [Hz]). This was changed in order to be compatible to the prediction model based on the acoustic data for the building elements, as mentioned in section 4.1 of the EN 12354-1 (2000).

When compared to the R'_i , the similarity continues for frequencies higher than 800 [Hz], where the differences are less than 2 [dB] or even almost equal.

The prediction model in EN 12354-1 (2000), $R'_{12354Det}$ also presents similar values than the other experimental methods R'_v and R'_i , for the frequency range of 400-1250 [Hz]. The critical frequency was mathematically estimated, based on local measurements, in 175 [Hz] and introduced in the detailed prediction model $R'_{12354Det}$ calculation algorithm for the separating element. The noticeable drop of curve $R'_{12354Det}$ at 250 [Hz], in Figure 6.8, reveal a difference value of 75 [Hz] against the mathematically estimated. The three R'_v curves present a gentle fall at 200 [Hz]. The most significant differences (2 to 4 [dB]) occur between 160 and 500 [Hz] for the R'_i and the three R'_v . Below 250 [Hz] there is a significant disagreement between all the curves. The R'_i curve also presents a decrease at the 250 [Hz] one-third-octave frequency band, but more smoothness.

Table 6.4 shows a comparison for the separating element, of the weighted apparent sound reduction index R'_w according to EN ISO 717-1 (1996) for the different methods under study: EN 12354-1 (2000) simplified and detailed models; ISO 15186-2 (2003);

and vibration velocity levels estimated by Sewell (1970), Rindel (1993) and Davy (2004). The single number quantity R'_w is expressed together with the spectrum adaptation terms C (A-weighted pink noise) and C_{tr} (A-weighted urban traffic noise). For the simplified method, only one adaptation term of -1 [dB] according to EN 12354-1 (2000). The results expressed show that sound intensity method yields higher single values compared to the detailed prediction model $R'_{w,l}$ 42 (-1,-4)/ $R'_{w,12354Det}$ 39 (-1;-4) [dB], for *in situ* conditions and considering only the separating element. It can then be concluded, for this case, that the prediction model predicts worse results than those physically obtained by the sound intensity method, meaning a 3 [dB] of insurance for the acoustic project of the separating element between rooms. However, the results obtained by the vibration velocity method indicate lower values of $R'_{w,v}$: two of 40 [dB] and one of 39 [dB].

Table 6.4 - Comparison of R'_w for separating element by EN 717-1

Method	R'_w EN 717-1
EN 12354-1 simplified model	42,7 ¹ (-1)
EN 12354-1 detailed model	39 (-1;-4)
Sound intensity by ISO 15186-2	42 (-1;-4)
Vibration velocity by Sewell	40 (-2;-5)
Vibration velocity by Rindel	40 (-2;-5)
Vibration velocity by Davy	39 (-1;-4)

6.3.2 *In situ* flanking sound measurements and comparison results

This section shows the results of the field measurements performed over the flanking elements with the vibration velocity method. The separating element values shown in

¹ Value obtained according based on the mass law equation 3.18.

the previous section are obviously higher compared to all the flanking elements measured levels.

6.3.2.1 *In situ* flanking elements vibration velocity measurements

For each element shown in section 4.2.2 (lateral element without door, lateral element with door, ceiling and floor) two sets of figures are shown: one in m/s and the other one in dB re (5×10^{-8}) m/s. The Figure 6.9, Figure 6.11, Figure 6.13 and Figure 6.15, show velocities values in [m/s], that provide the values measured with the acceleration transducers. These figures do not point up the acceleration values, therefore the same results are shown in Figure 6.10, Figure 6.12, Figure 6.14 and Figure 6.16, but transformed into sound levels in [dB re (5×10^{-8}) m/s]. The comparison of the different figures for the same element allows better visualizing the aspect of the curves and values of the measurements and corresponding one-third octave bands. As an example of good signal to noise ratio is for the lateral element with door (Figure 6.10 and

Figure 6.11 the more reliable values can be easily observe in the bandwidth between 100 [Hz] and 2.000 [Hz]. Between this two one-third octave bands the difference involving background noise values (pink curve) and the measured values (blue curve) for white noise excitation is perceptible. The traced vertical lines in Figure 6.11 draw up the boundaries of this bandwidth for this element with door.

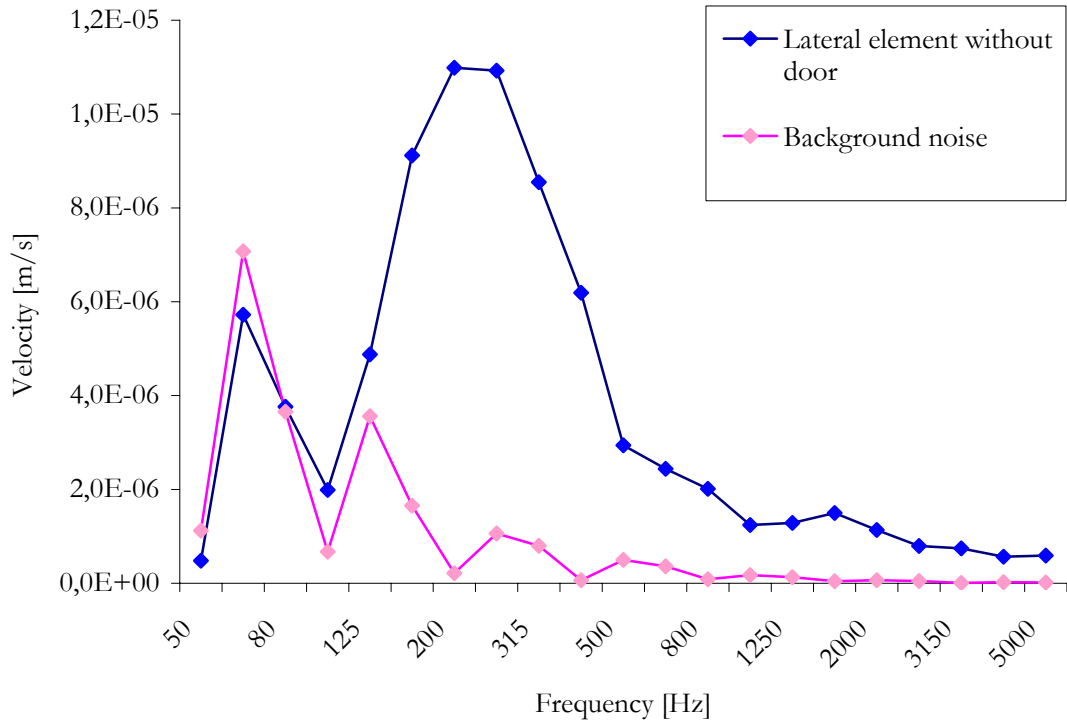


Figure 6.9 – Spatial-time average vibration velocity \bar{v} for lateral element without door

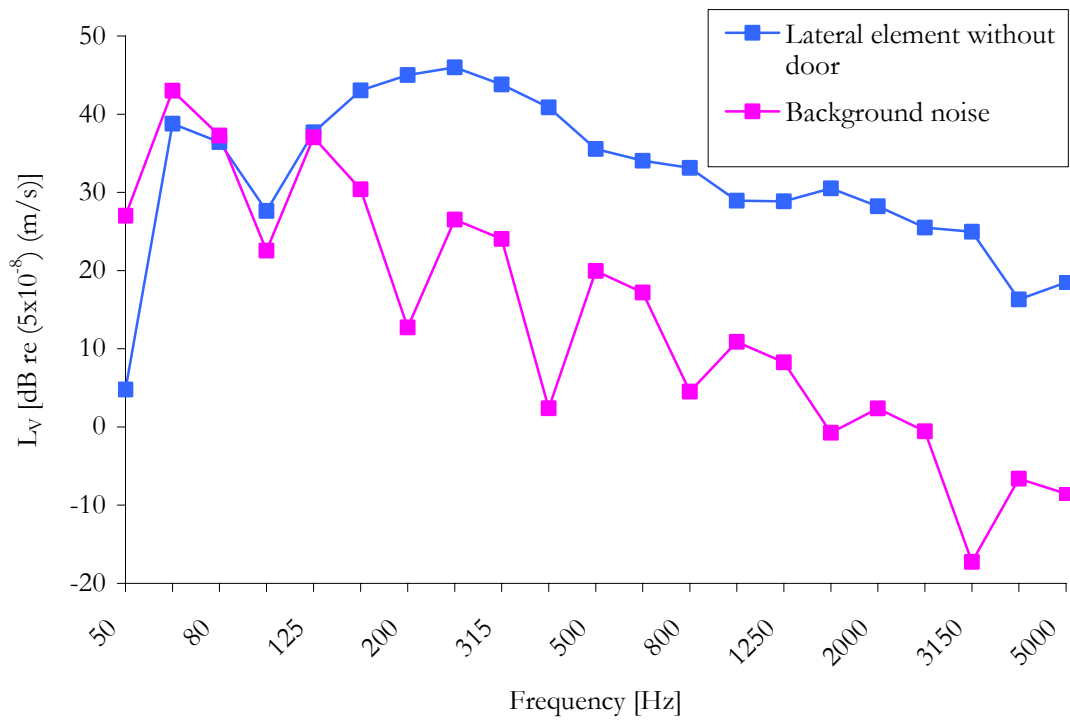


Figure 6.10 - Spatial-time average $L_{\bar{v}}$ for the lateral element without door

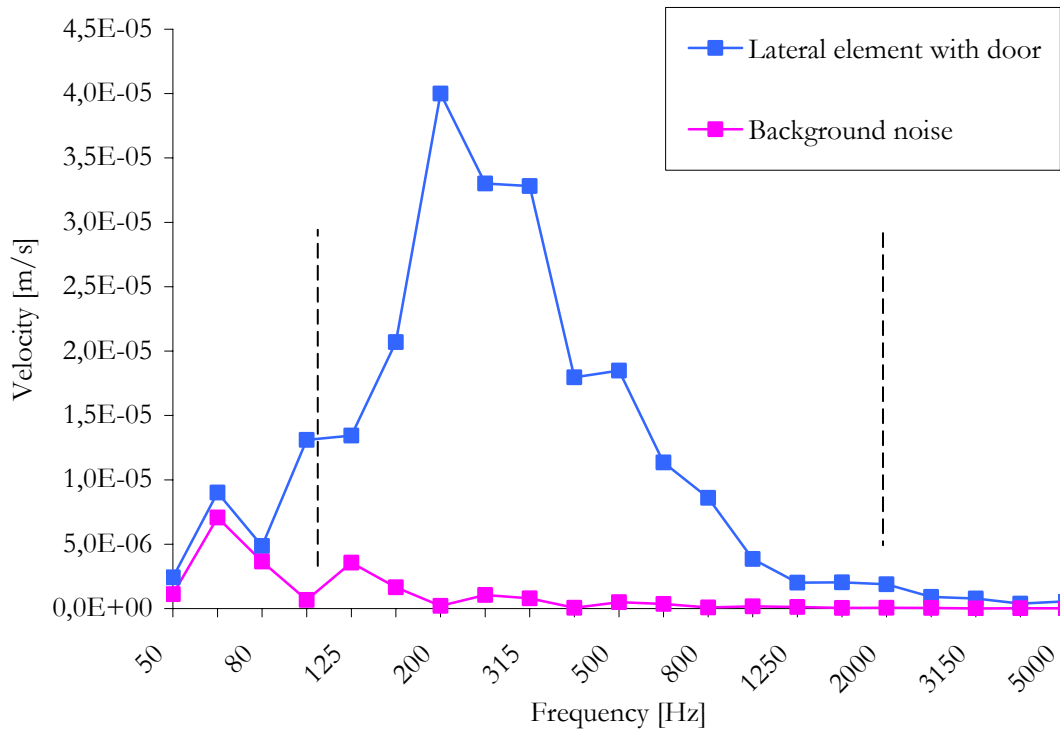


Figure 6.11 - Spatial-time average vibration velocity \bar{v} for lateral element with door

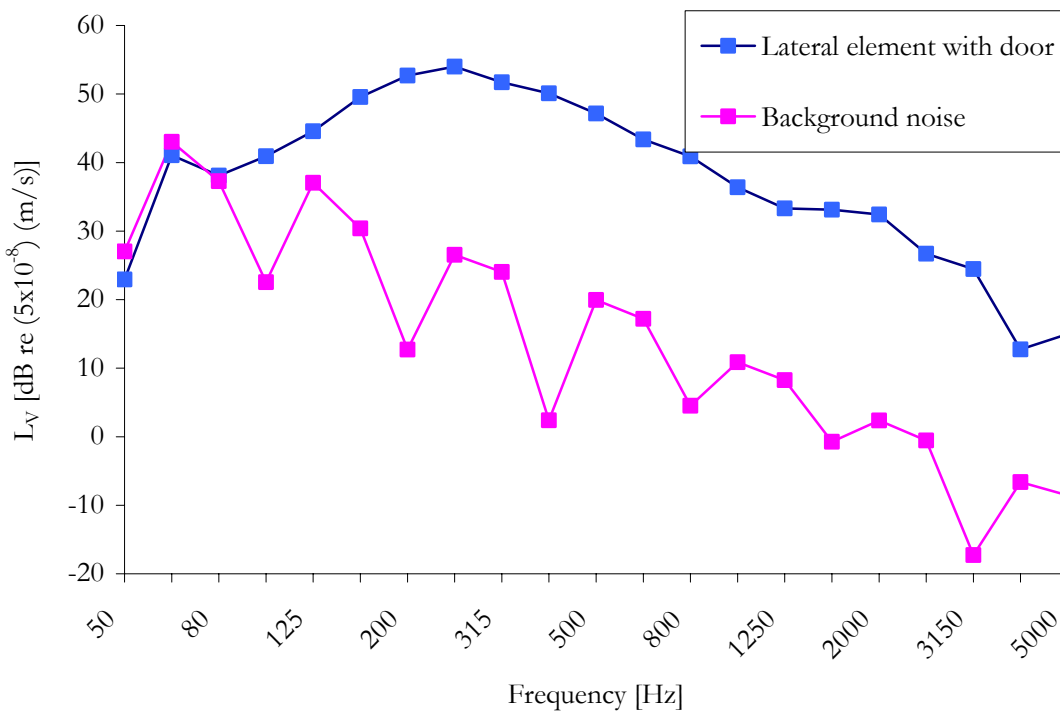
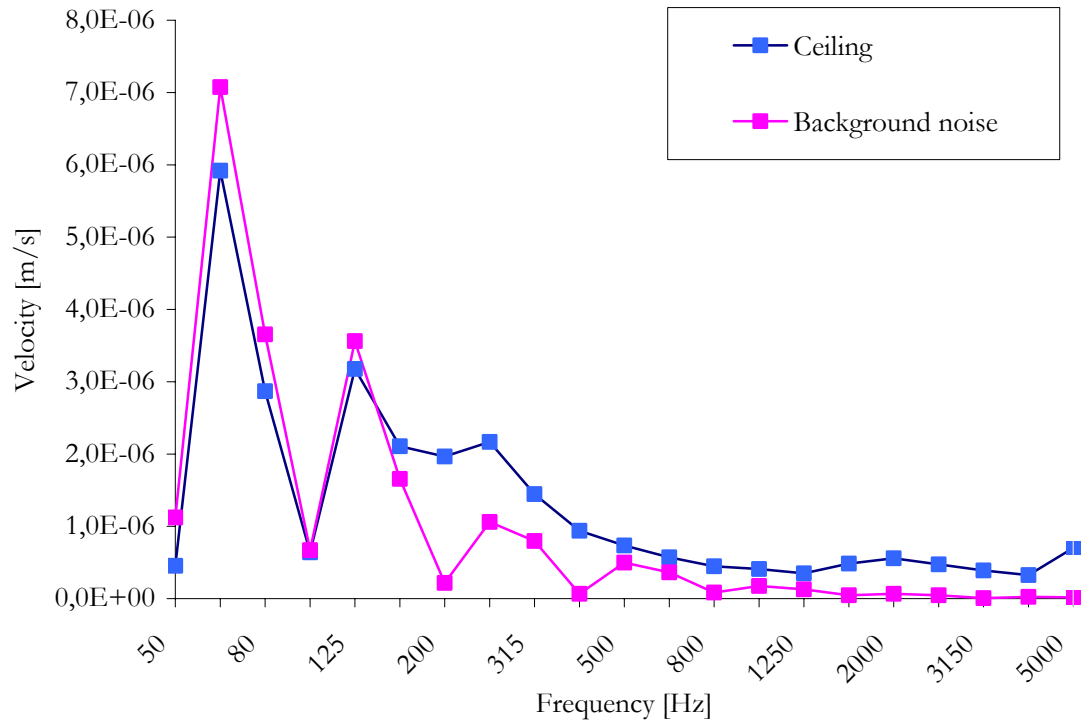
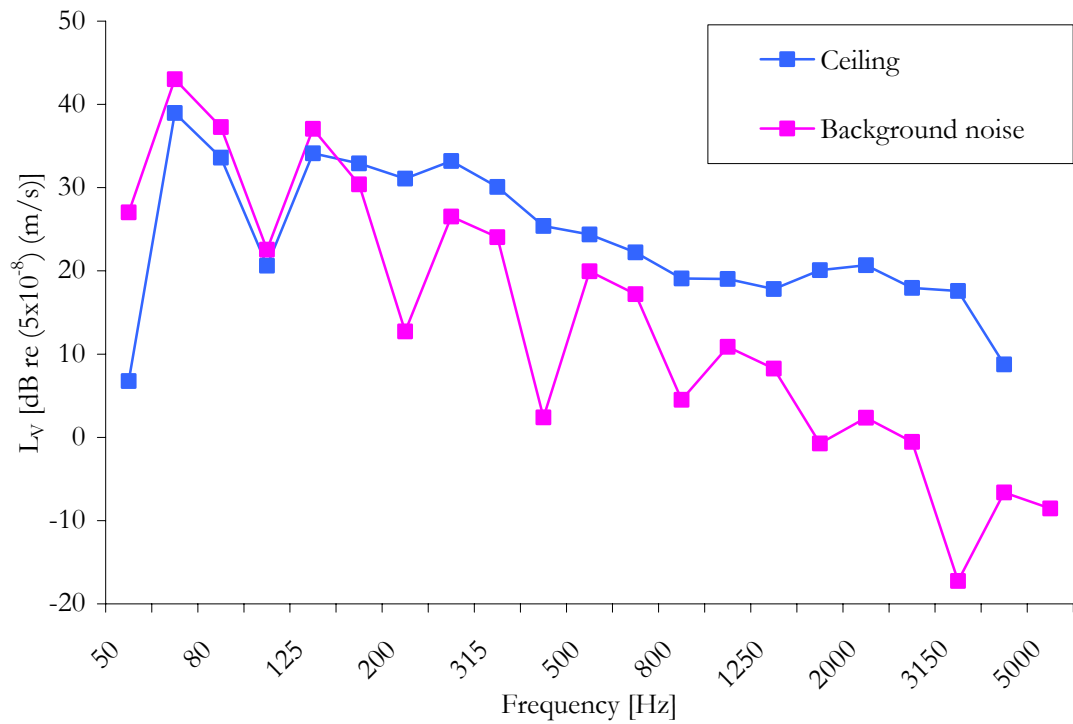


Figure 6.12 – Spatial-time average $L_{\bar{v}}$ for the lateral element with door

Figure 6.13 - Spatial-time average vibration velocity \bar{v} for the ceilingFigure 6.14 - Spatial-time average $L_{\bar{v}}$ for the ceiling

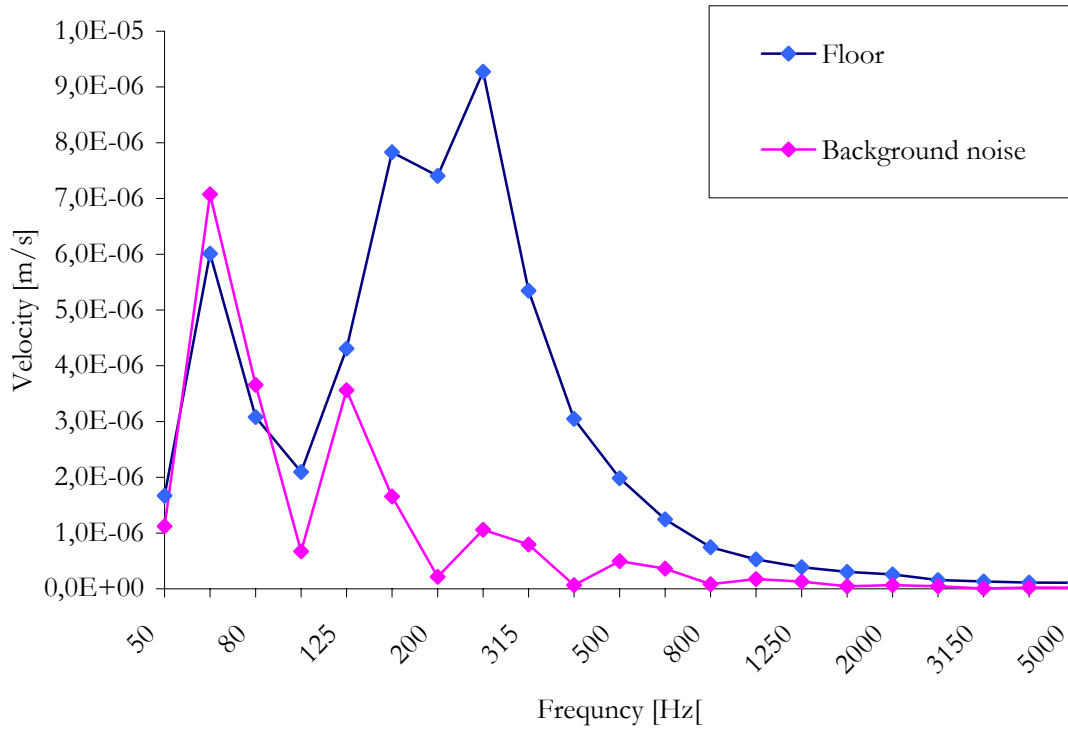


Figure 6.15 - Spatial-time average vibration velocity \bar{v} for the floor

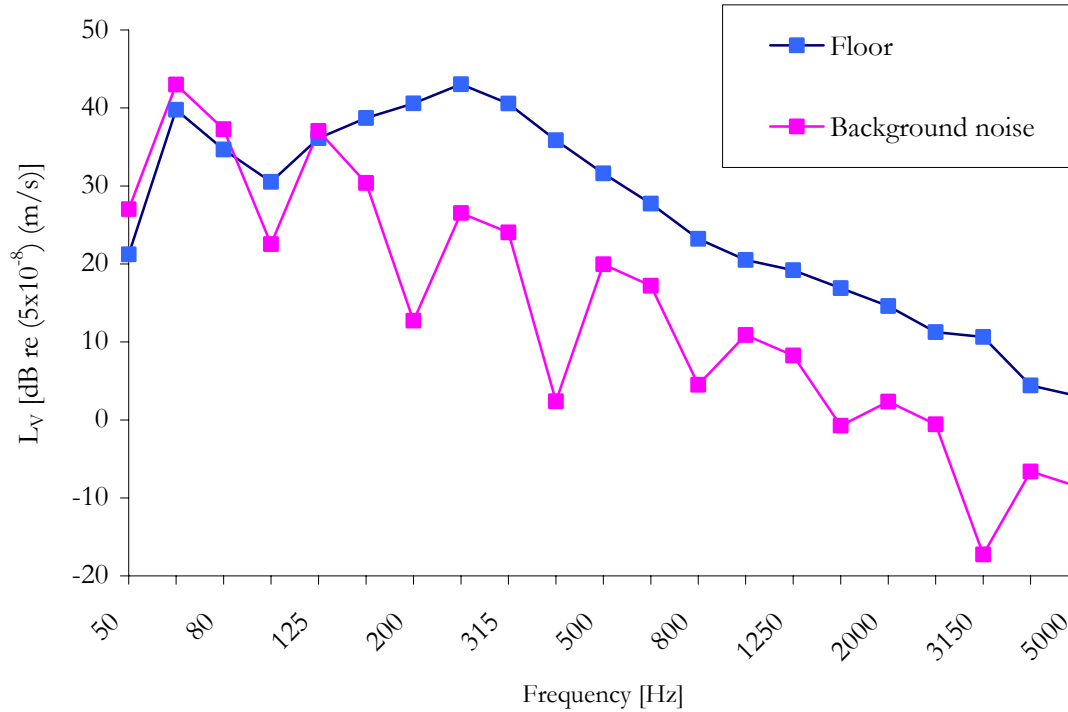


Figure 6.16 - Spatial-time average $L_{\bar{v}}$ for the floor

In the measured flanking elements the requirement of 10 [dB] differences between the flanking element and the background noise level is more difficult to achieve, especially in the elements with higher density, the ceiling and the floor. This can be observed in the Figure 6.14 for flanking element ceiling and in Figure 6.16 for flanking element floor. The ceiling presents lower velocity values which means lower flanking transmission results compared to the floor; this also means that this element is the one contributing the least to the apparent sound reduction index, R' .

6.3.2.2 Comparison of interpolated surface velocity levels between separating and flanking elements

For each surface instrumented with acceleration transducers, an interpolation surface was evaluated between the twelve measured points with all levels in [dB re (5×10^{-8}) (m/s)]. With this feature images it is possible to map the velocity levels between the measured points and to visualize the worst or best insulation areas of each element.

The x and y values represent the real element dimensions in meters between the measured points. The origin is always located on the bottom left side of the image. The interpolation was possible with the MatLab[®] software and by means of a short program (see annex C for separating element) using a Delaunay cubic interpolation, capable of producing smooth RGB[®] surface images. These images are only interpolated for the inner area of the measured points; the outer area was not interpolated, consequently the images produced are variable according to the random distribution of the twelve measured points.

Figure 6.17 shows the separating element projected surface in the pair of axis x-y, showing the measured points in black. All the interpolated surfaces go through the measured data points. This type of display was chosen, because it illustrates, in a better way, the different measured levels for each surface. All the surfaces images are comparable for the same colours scale. The colour bar represented at the right of the image, shows levels in [dB re (5×10^{-8}) (m/s)] and the scale is set between 37 and 74 [dB].

Figure 6.17 shows the separating element interpolated surface image where very similar levels can be seen, except for slow increasing levels as one move towards the ceiling junction. This image shows that the T junction with the ceiling is the one in the separating element side, responsible for the flanking transmission. It can also be seen on the right side of the separating element that the colour transition is maintained in direction to the floor, due to the influence of the lateral element without door junction.

Figure 6.18 shows the lateral element with door in a three dimension surface interpolation and corresponding projected surface in the pair of axis x-y, showing in the upper image the measured points in black. All the interpolated surfaces go through the measured data points. The other test elements surface images, produced by this interpolation, are further presented only in the 2D appearance with the pair of axis x-y. This type of display was chosen, because it illustrates in a better way, the different measured levels for each surface. All the surfaces images are comparable for the same colours scale. Figure 6.19 shows the $L_{\bar{v}}$ lateral element with door interpolated surface. It is noticeable that the higher levels (represented in red) correspond to the door location and the verified $L_{\bar{v}}$ spatial-time average vibration velocity level transmitted through it, and also shows in the y axis the height in [m] and in the x axis the length in [m]. The colour bar, represented at the right of the image, shows levels in [dB re (5×10^{-8}) (m/s)] and the scale is set between 37 and 74 [dB].

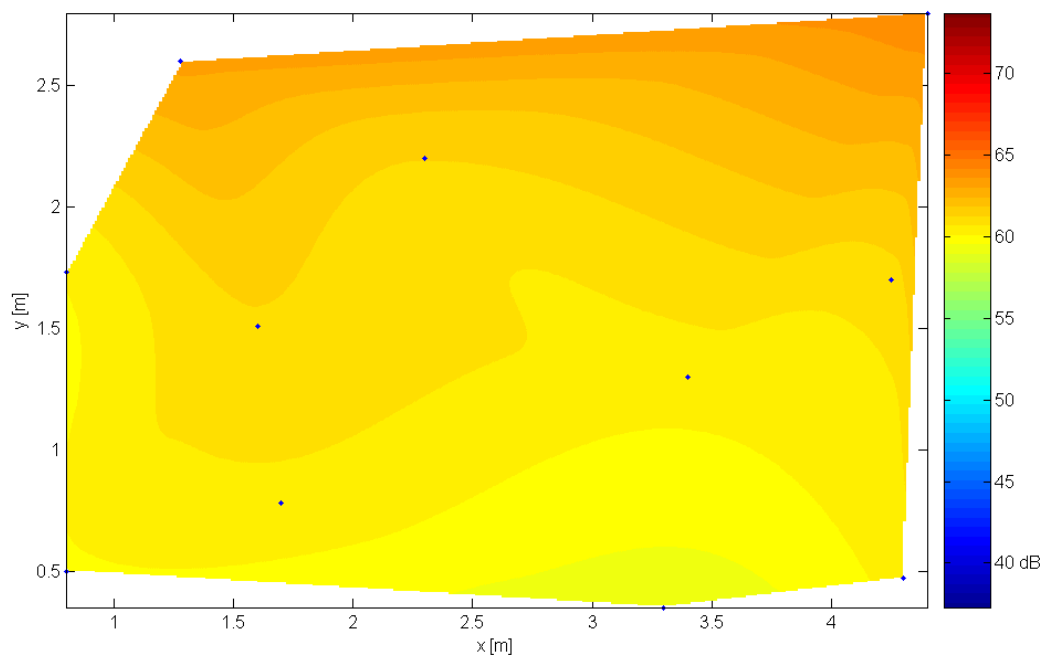


Figure 6.17 - Separating element interpolated projected 2D image of $L_{\bar{v}}$ in [dB re (5×10^{-8}) (m/s)]

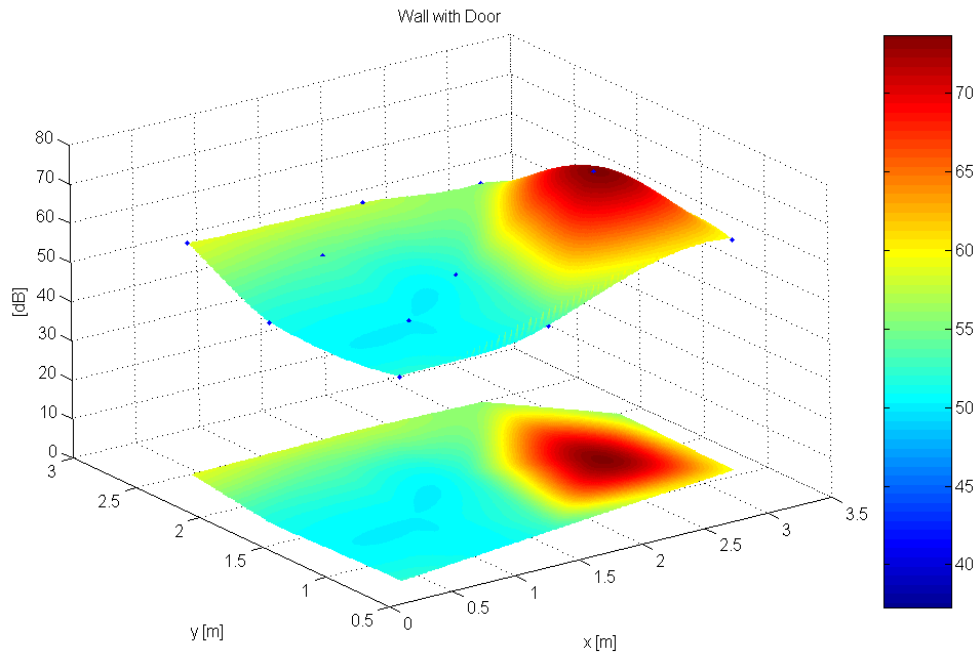


Figure 6.18 - Lateral element with door surface interpolation, in 3D representation of $L_{\bar{v}}$ in [dB re (5×10^{-8}) (m/s)]

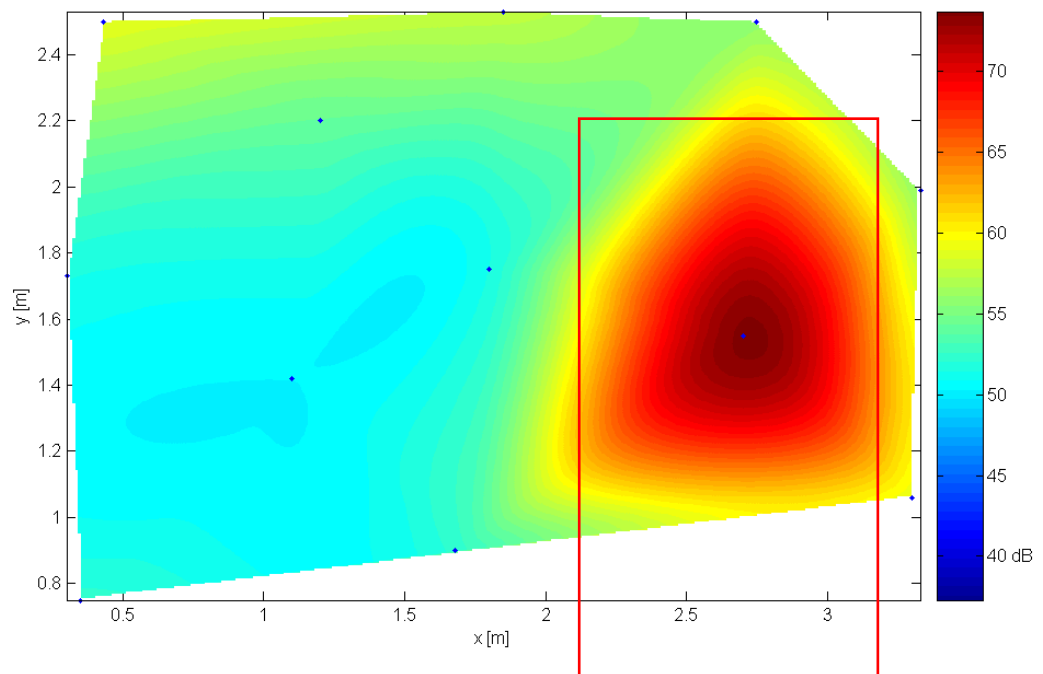


Figure 6.19 - Lateral element with door (rectangle) interpolated projected 2D image of $L_{\bar{v}}$ in [dB re (5×10^{-8}) (m/s)]

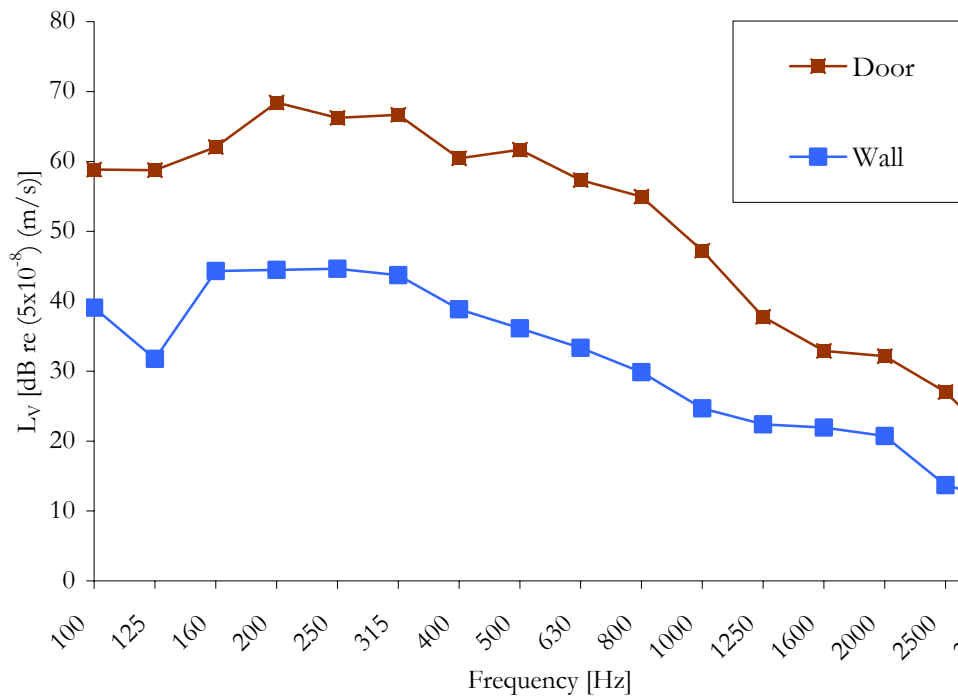


Figure 6.20 - Spatial-time average L_v for the door compared with a point in the wall

Complementary information to this element with door can be seen in Figure 6.20, where the velocity levels measured by the acceleration transducer on one point on the door and on the wall surface, are shown.

It is clear from the analysis of the curves in the previous figure that the vibration velocity levels, for all bandwidth, are much higher for the door (position I²) in comparison to a point in the wall at similar high (position G³). Therefore, it illustrates in one-third octave bands, the higher levels reported in the door illustrated by Figure 6.19 and representing the strong presence of flanking sound transmission travelling across the door.

Figure 6.21 shows the lateral element without door interpolated surface image, where cyan colours are more present, representing comparable lower [dB] levels than yellow colour. The yellow colour appears bordering the $x=1$ [m], because in the outer side, there is an ending junction wall, as previously referred in section 4.2.2.

When the first set of *in situ* measurements took place at “Magisterio”, the discontinuity of the outer wall was not detected. This was observed/confirmed while

² I=(2,7 ; 1,55) in [m]

³ G=(1,8 ; 1,75) in [m]

performing the *in situ* measurements, (sound intensity levels and vibration velocity levels) around that position. On the top right side it can be observed also slightly higher levels, but it is difficult to come to a definitive conclusion about its origin.

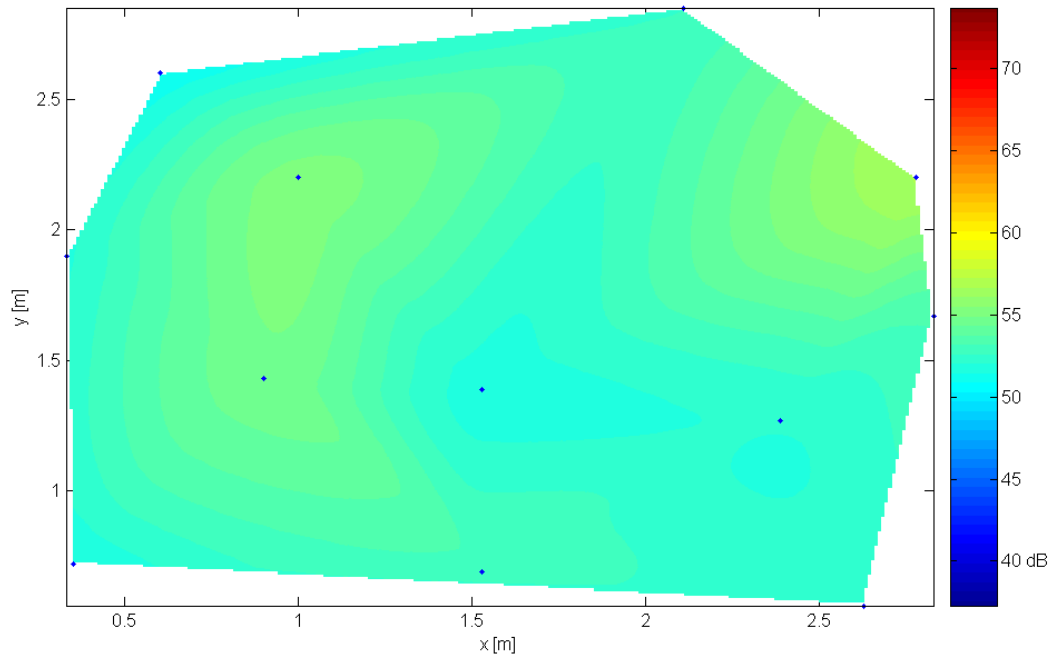


Figure 6.21 - Lateral element interpolated projected 2D image $L_{\bar{v}}$ in [dB re (5×10^{-8}) (m/s)]

Figure 6.22 shows the floor interpolated projected surface image. As it can be seen, there are more blue colours which correspond to lower [dB] levels, on the ground of our receiving room. Cyan and yellow colours represent higher levels in areas close to the door and to the main separating element junction. The influence of these relatively higher levels transmitted by the door is noticeable but the overall levels represented are lower than those observed in the other flanking elements, which means a lower contribution of this flanking element.

Figure 6.23 shows the ceiling and corresponding interpolated surface image, where the presence of blue colours it is highly noticeable, showing the lowest [dB] levels among all the flanking elements and therefore the lower influence of the element ceiling on the flanking contribution.

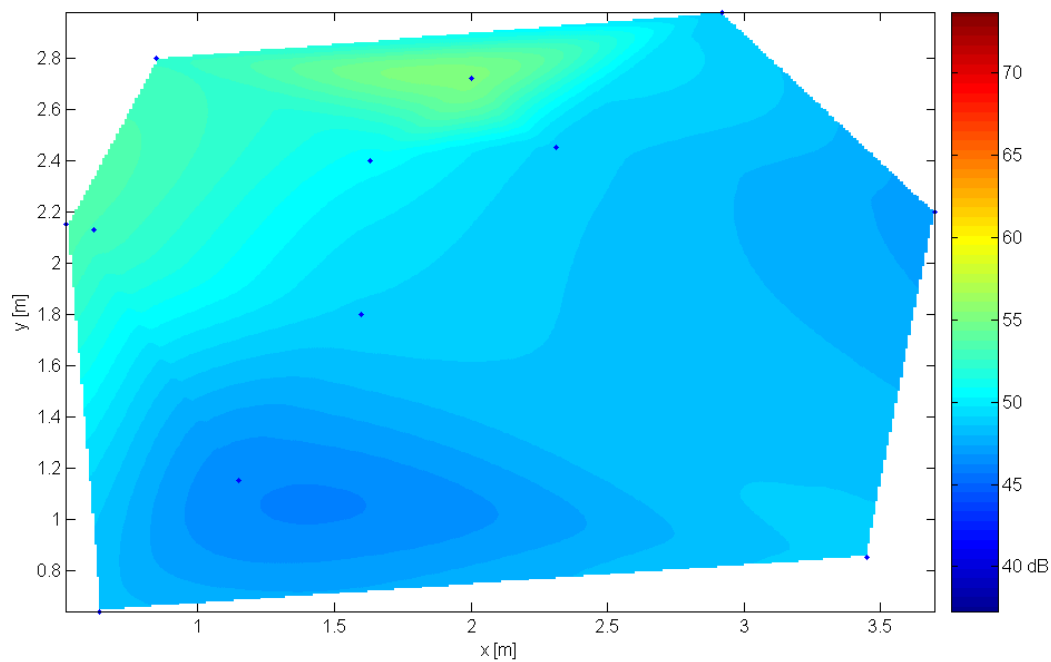


Figure 6.22 - Floor interpolated projected 2D image of $L_{\bar{v}}$ in [dB re (5×10^{-8}) (m/s)]

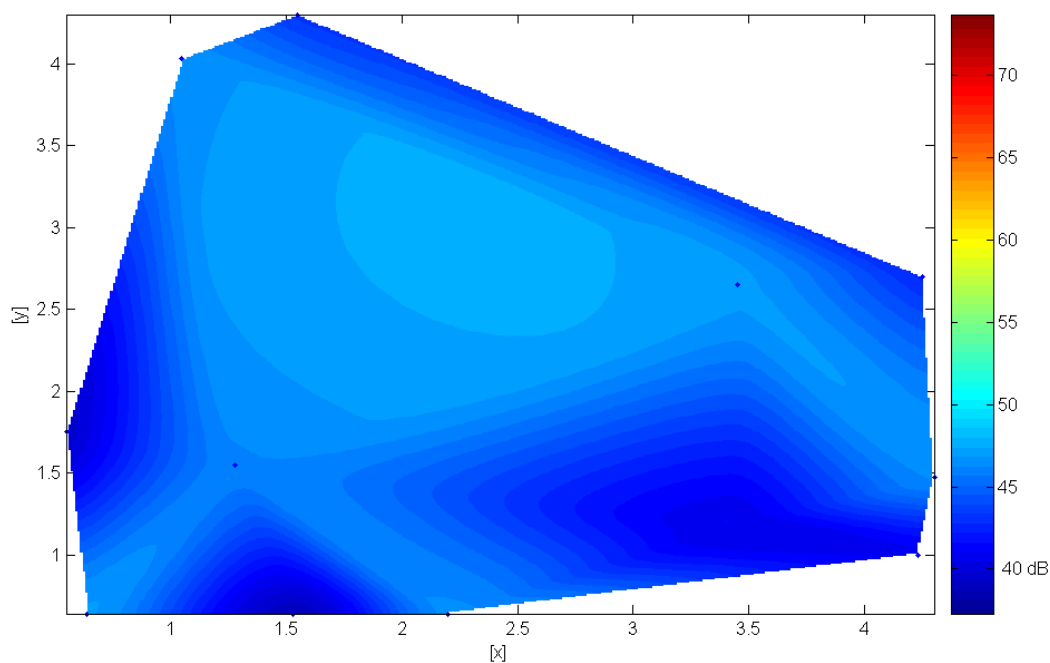


Figure 6.23 - Ceiling interpolated projected 2D image of $L_{\bar{v}}$ in [dB re (5×10^{-8}) (m/s)]

6.3.3 *In situ* comparison (measured and predicted) of R' including flanking contribution

The apparent airborne sound reduction index R'_v , using the vibration velocity method, including the flanking contribution of all elements, is calculated with the equation (2.56). The radiation ratio is obtained using the equation (2.24) developed by Rindel (1993) and equation (2.26) developed by Davy (2004). The results obtained by Sewell (1970) can be considered equal to those obtained by Rindel (1993) as previously verified in the sub-section 6.3.1.

Figure 6.24, Figure 6.25 and Figure 6.26 represent the apparent airborne sound reduction index estimation using the intensity R'_i , R'_v Rindel (1993) and R'_v Davy (2004) for separating element alone and including the flanking contribution. Table 6.5, Table 6.6 and Table 6.7 show the values for the curves represented in Figure 6.24, Figure 6.25 and Figure 6.26 and the corresponding differences. Figure 6.27 represents all the curves in the same chart.

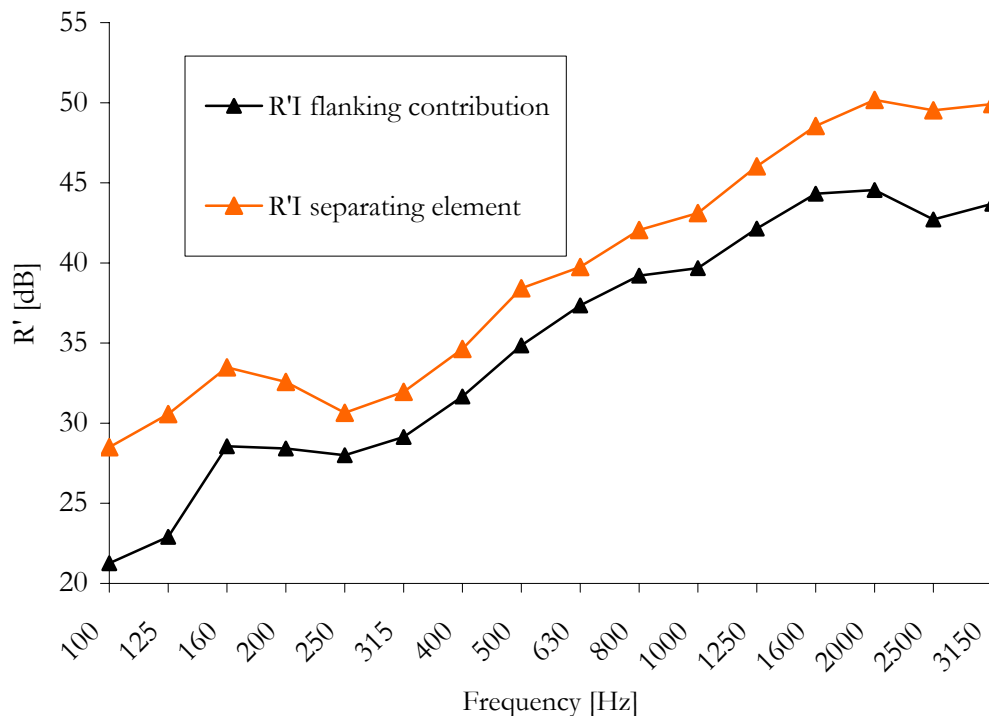


Figure 6.24 - R'_i including flanking contribution, compared with separating element by sound intensity method

Table 6.5 – R'_1 including flanking contribution, compared with separating element by sound intensity method and respective difference

Frequency [Hz]	R'_1 separating element [dB]	R'_1 including flanking [dB]	Difference [dB]
100	28,5	21,3	7,2
125	30,6	22,9	7,7
160	33,5	28,6	4,9
200	32,6	28,4	4,2
250	30,7	28,0	2,7
315	32,0	29,1	2,8
400	34,6	31,7	3,0
500	38,4	34,8	3,6
630	39,8	37,4	2,4
800	42,1	39,2	2,9
1000	43,1	39,7	3,4
1250	46,0	42,1	3,9
1600	48,5	44,3	4,2
2000	50,2	44,5	5,6
2500	49,5	42,7	6,8
3150	49,9	43,7	6,2

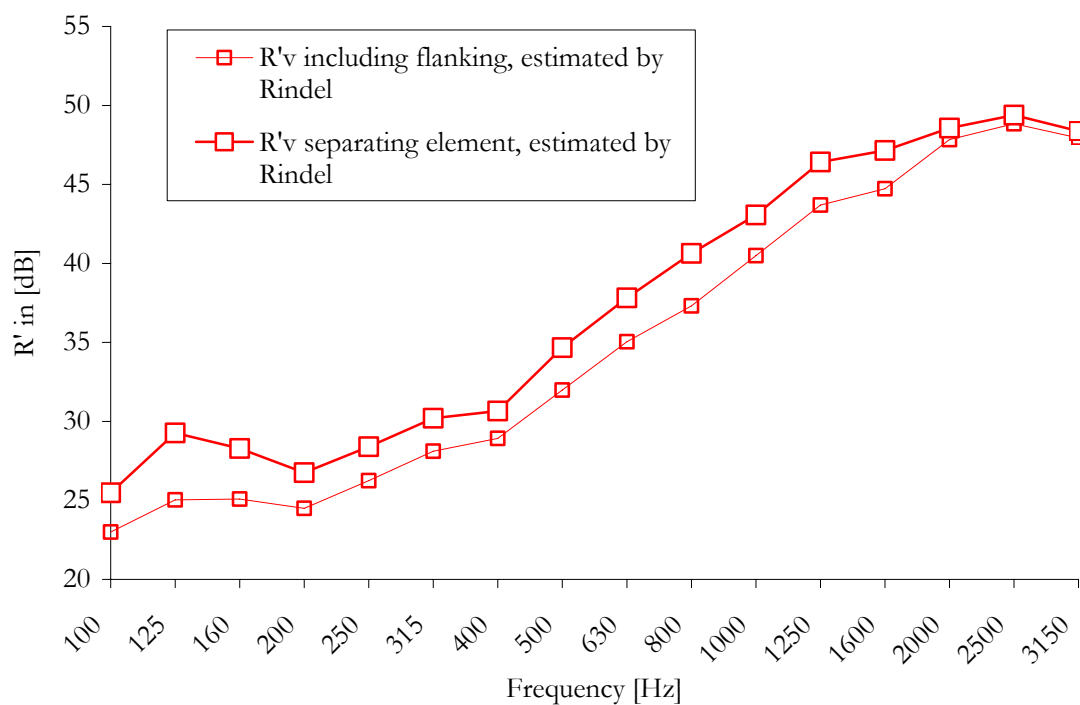

 Figure 6.25 - R'_v including flanking contribution, compared with separating element by Rindel

Table 6.6 – R'_v including flanking contribution, compared with separating element by Rindel and respective difference

Frequency [Hz]	R'_v separating element Rindel [dB]	R'_v including flanking Rindel [dB]	Difference [dB]
100	25,5	23,0	2,5
125	29,3	25,0	4,2
160	28,3	25,1	3,2
200	26,8	24,5	2,3
250	28,4	26,3	2,1
315	30,2	28,1	2,1
400	30,7	28,9	1,7
500	34,7	32,0	2,7
630	37,8	35,0	2,8
800	40,6	37,3	3,3
1000	43,1	40,5	2,6
1250	46,4	43,7	2,7
1600	47,1	44,7	2,4
2000	48,6	47,8	0,7
2500	49,4	48,8	0,5
3150	48,4	47,9	0,4

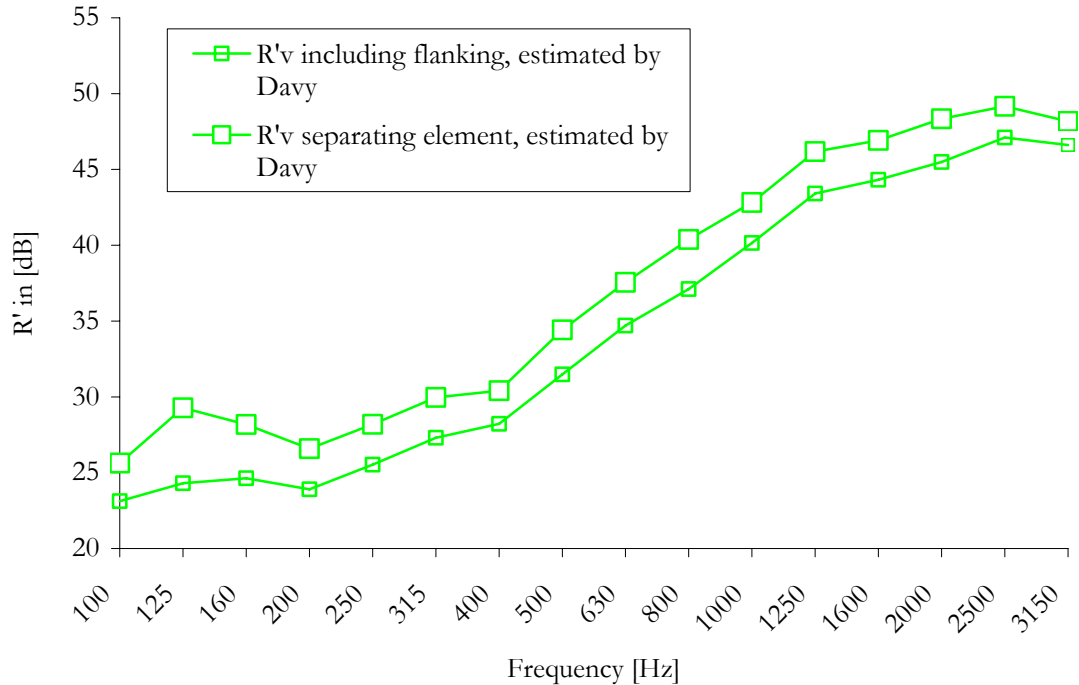
Figure 6.26 - Comparison of estimated R'_v including flanking contribution compared with separating element by Davy

Table 6.7 - R'_v including flanking contribution, compared with separating element by Davy and respective difference

Frequency [Hz]	R'_v separating element Davy [dB]	R'_v including flanking Davy [dB]	Difference [dB]
100	25,6	23,1	2,5
125	29,3	24,3	5,0
160	28,2	24,6	3,5
200	26,6	23,9	2,7
250	28,2	25,5	2,7
315	30,0	27,3	2,7
400	30,4	28,2	2,2
500	34,4	31,5	2,9
630	37,6	34,7	2,9
800	40,4	37,1	3,3
1000	42,8	40,2	2,7
1250	46,2	43,4	2,8
1600	46,9	44,3	2,6
2000	48,3	45,5	2,9
2500	49,2	47,1	2,1
3150	48,2	46,6	1,6

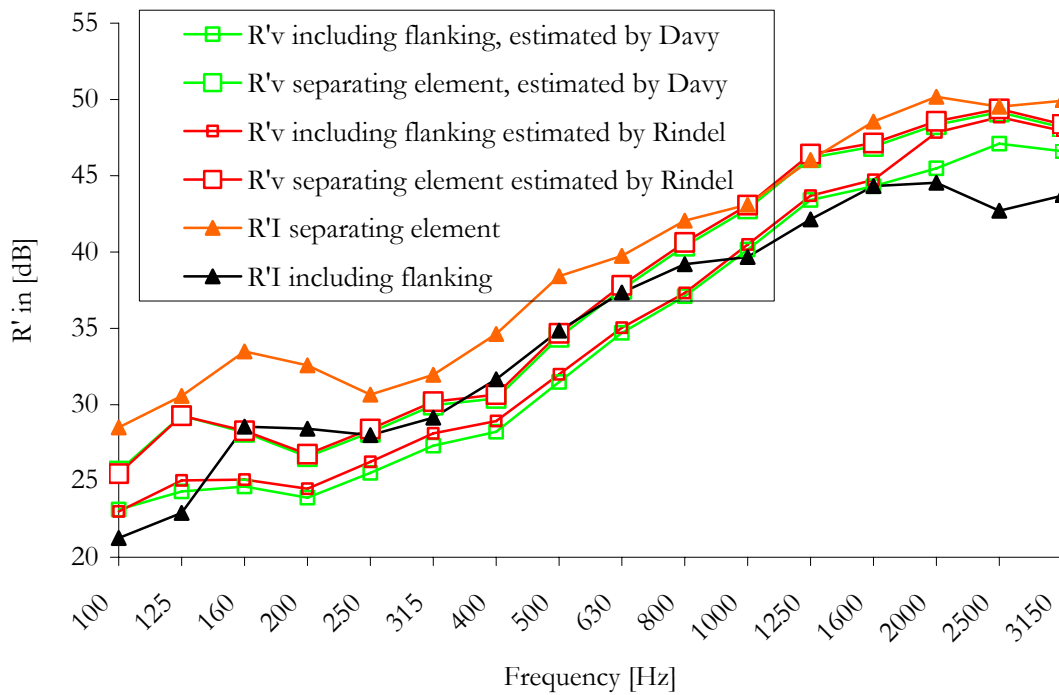
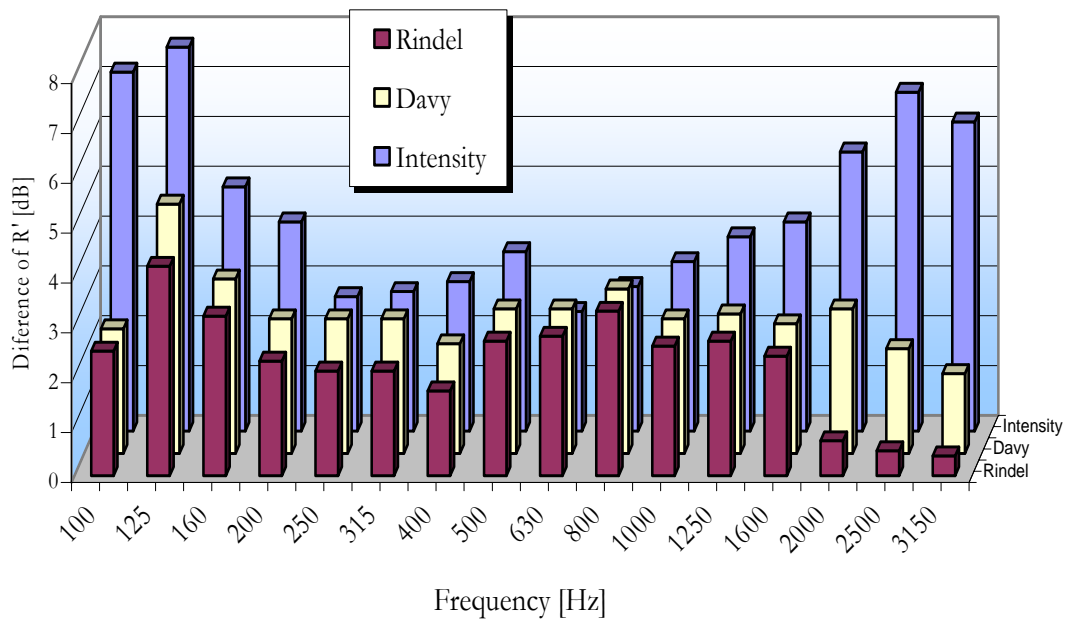


Figure 6.27 - Comparison of estimated R' for separating element and including flanking contribution between intensity and vibration velocity method

Table 6.8 – Differences between the R' of separating element and the R' including flanking

Frequency [Hz]	Intensity method difference [dB]	Rindel difference [dB]	Davy difference [dB]
100	7,2	2,5	2,5
125	7,7	4,2	5,0
160	4,9	3,2	3,5
200	4,2	2,3	2,7
250	2,7	2,1	2,7
315	2,8	2,1	2,7
400	3,0	1,7	2,2
500	3,6	2,7	2,9
630	2,4	2,8	2,9
800	2,9	3,3	3,3
1000	3,4	2,6	2,7
1250	3,9	2,7	2,8
1600	4,2	2,4	2,6
2000	5,6	0,7	2,9
2500	6,8	0,5	2,1
3150	6,2	0,4	1,6

Figure 6.28 - Differences between the R' of separating element and the R' including flanking

The comparison of the differences between the R' for the separating element and the corresponding R' with the flanking contribution, shown in the previous Figure 6.28, allows visualizing where the major differences are located for each one third octave

band. It is noticeable that the sound intensity method shows the major differences, below 200 [Hz] and above 1.000 [Hz]. The major difference reaches 8 [dB] for 125 [Hz] and almost the same value for 2.500 [Hz]. The differences verified for the lower frequency bands are probably due to an inappropriate sound intensity probe spacer, as previously referred. For higher frequencies the differences are very important and reveal that sound intensity method yields comparably lower R'_I when including the flanking contribution. Therefore, these differences reveal, that sound intensity method, gives relatively more importance to the flanking component.

The two vibration velocity estimations present fewer differences over all the considered bandwidth. Rindel's estimation is the one presenting even smaller differences for all the bandwidth, but more noticeable above the 2.000 [Hz].

Figure 6.29 compares all the apparent sound reduction indexes R' estimated and predicted including flanking contribution: R'_p (sound pressure method) using EN ISO 140-4 (1998) equation (2.41); R'_I (sound intensity method) using ISO 15186-2 (2003) equation (2.50) and R'_I with Waterhouse correction factor; $R'_{12354Det}$ (detailed prediction model) proposed in EN 12354-1 (2000) equation (3.21) and R'_v (vibration velocity method) using Rindel and Davy estimations with equation (2.56).

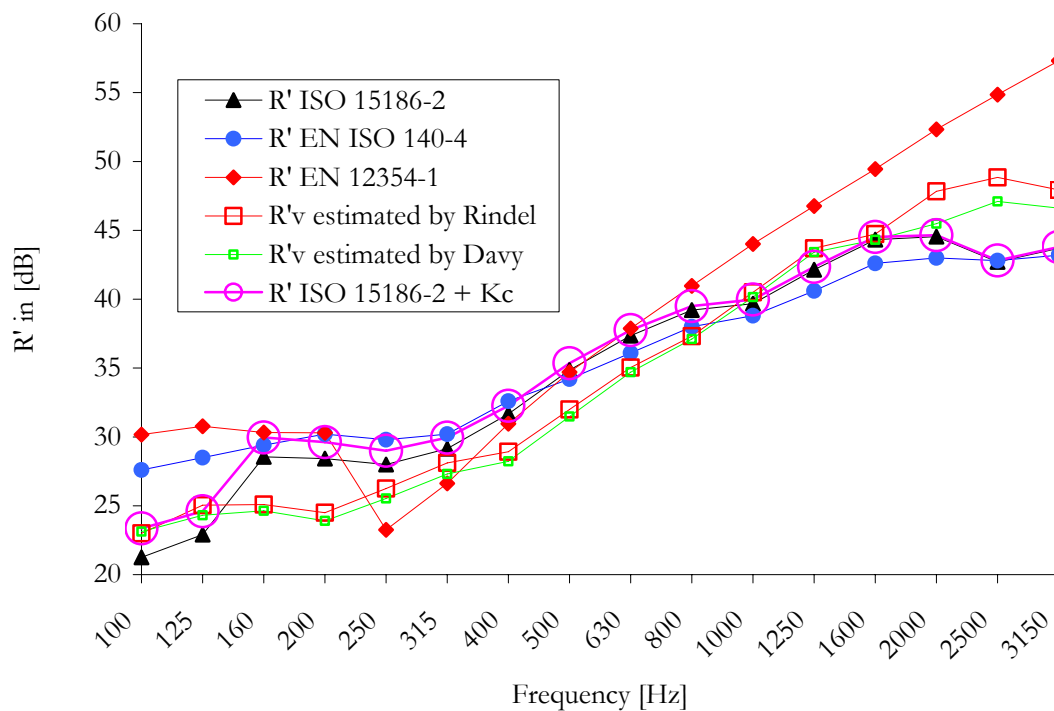


Figure 6.29 - Comparison of estimated and predicted R' including flanking contribution

The $R'_{12354Det}$ presents a significant fall at 250 [Hz], because it is at this frequency that the critical frequency is expressed, with a deviation of 75 [Hz] from the calculated value. This can be due to the fact that the standard uses different calculus algorithms for frequencies above and below the critical frequency and the valley lies within this “algorithm matching lap”.

The $R'_{12354Det}$ diverges from the other methods significantly above 800 [Hz]. It can also be observed that “standard” curves and “non standard” curves have different slopes, but with similar curves. The crossing point is between 800 and 1.000 [Hz]. Below the 630 [Hz], $R'_{12354Det}$, R'_v and R'_I present similar curves. For the middle range one-third octave bands, the R'_v and R'_I show the same curve which is different from the curve of R'_p .

The sound intensity method and vibration velocity method show the same shape for the middle range one-third octave bands in opposition to the curve of sound pressure method.

The curve obtained by the sound pressure method and the curve obtained from the EN 12354-1 prediction detailed model present similar values below the 630 [Hz].

Furthermore, it can be observed different slopes between the standard curves and the non-standard curves, with the crossing point between 800 and 1.000 [Hz]. A similar tendency was verified by Machimbarrena (1999) in the *in situ* sound intensity method measurements.

The R'_w according to EN ISO 717-1 (1996) for *in situ* measurements are shown in the following Table 6.9.

- (i) In fact, lower values mean worse insulation performance of the rooms, showing that vibration velocity method is probably representing a worse acoustical performance, compared to other measurement methods, but those results are not corroborated by either of the standardized methods. The three standardized methods present the same weighted quantity $R'_{w,I}$, $R'_{w,p}$, $R'_{w,12354Det}=39$ [dB]. By this, the conclusion is that the algorithm of calculus and the element data used by it, on the detailed prediction model of the EN 12354-1 (2000), can be applied to the Spanish constructions buildings analysed in this thesis. In opposition, the simplified prediction model

presents a result indicating a possible better weighted $R'_{w,12354Sim}$ of 41 [dB], pointing out to the project engineer a potential mistake in the prediction acoustical behaviour of the building. Important notice is that these results are consistent with the standard deviation of 2 [dB] for the simplified model, referred on section 5, of the EN 12354-1 (2000). Finally, the $R'_{w,vRindel}$ $R'_{w,vDavy}$ have presented a weighted level of 37 [dB]. This weighted level, means a worse acoustical performance in comparison with the standardized measurements, but from the acoustical project engineer point of view it makes it to be on the safer side.

Table 6.9 - Comparison of weighted R'_w , including flanking transmission of receiving room by EN 717-1

	R'_w EN ISO 717-1
EN 12354-1 simplified model - $R'_{w,12354Sim}$,	41 (-1)
EN 12354-1 detailed model - $R'_{w,12354Det}$.	39 (-2;-5)
Sound pressure method - $R'_{w,p}$	39 (-1;-3)
Sound intensity method - $R'_{w,I}$	39 (-2;-5)
Vibration velocity for Rindel - $R'_{w,vRindel}$	37 (-1;-4)
Vibration velocity for Davy - $R'_{w,vDavy}$	37 (-2;-5)

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Capítulo 7

7 Conclusiones

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7.1 Conclusiones

En este capítulo se presenta un resumen de las conclusiones más relevantes encontradas en el presente trabajo.

Al final se plantean posibles líneas futuras de trabajo relacionadas con la temática expuesta.

7.1.1 Medidas de transmisiones indirectas en laboratorio

Para poder implementar la técnica de medida de niveles de velocidad *in situ*, se consideró preciso efectuar medidas preliminares en laboratorios con facilidades para evaluación de transmisiones indirectas. Con ello se valida la metodología propuesta en un entorno controlado ya que en un laboratorio de transmisiones indirectas es posible conectar-desconectar las uniones entre los diversos elementos con el fin de evaluar cada flanco por separado.

Las primeras medidas en laboratorio de transmisiones indirectas se realizaron en DIENCA. Allí se midió la vibración de un suelo flotante conectado a una pared, usando una máquina de impactos como fuente sonora. Estas condiciones de laboratorio son bastante parecidas a las que uno puede encontrar *in situ*. Los resultados obtenidos en esta tanda de medidas no son excesivamente relevantes “per se”, dado que la metodología utilizada en laboratorio se encuentra ya estandarizada. Lo más interesante surge al comparar estos resultados con los que se obtienen efectuando medidas intensimétricas y con la estimación de potencia radiada por los diversos elementos a partir de la eficiencia de radiación dada por diversas funciones matemáticas.

La determinación de la potencia sonora por velocidad $L_{w,v}$, se efectuó usando cuatro modelos distintos para la eficiencia de radiación: El modelo de Sewell (1970), de Josse (1972), de Rindel (1993) y el de Davy (2004). Al comparar estas estimaciones con las obtenidas por intensidad se puede decir que:

- (i) Las curvas que se obtienen para el suelo flotante presentan el mismo comportamiento en todos los tercios de octava. Se observa que en las

frecuencias medias (entre 200 [Hz] y 2.500 [Hz]), la estimación de la potencia sonora por velocidad $L_{w,v}$ resulta del orden de 3 a 4 [dB] menor que la estimación por intensidad para los cuatro modelos de eficiencia de radiación utilizados. A bajas frecuencias $L_{w,v}$ es sobreestimado y entre 3.150 [Hz] y 5.000 [Hz] las estimaciones coinciden prácticamente con los resultados obtenidos por intensidad.

- (ii) En general, el hecho de que los niveles sean algo mayores al efectuar la estimación de potencia sonora por intensidad, podría ser debido a que la máquina de impactos genera un ruido fuerte y muy localizado. Al escanear con la sonda justo frente a la máquina de impactos, los niveles aumentan significativamente. En todo caso conviene señalar que el método de intensidad no está pensado para ser usado con máquina de impactos como fuente, sino para excitación mediante una fuente de ruido aéreo.
- (iii) Por lo que respecta a la pared lateral, todas las curvas presentan una misma tendencia salvo en las frecuencias comprendidas entre 1.250 [Hz] y 2.500 [Hz] donde se observa que la estimación de potencia por velocidad ($L_{w,v}$) queda ligeramente subestimada, aunque menos de 3 [dB]. Estas diferencias se observan para la estimación por Josse en un rango más amplio de frecuencias, entre 630 [Hz] y 5.000 [Hz]. Sin embargo, estas curvas presentan resultados más parecidos que los verificados para el suelo flotante.

Cuando el elemento es directamente excitado por la máquina de impactos, la estimación de potencia por velocidad de vibración $L_{w,v}$ se comporta mejor que la estimación de potencia por intensidad L_{wI} . Así mismo se observa que al utilizar la formulación de Josse (1972) para la estimación de la eficiencia de radiación, el valor de la potencia sonora queda ligeramente subestimada por comparación con los resultados obtenidos con las restantes formulaciones utilizadas. Se puede por tanto concluir que el método de vibración es más adecuado para estimar el aislamiento a ruido de impacto que el método intensimétrico, puesto que no es adecuado efectuar medidas de intensidad sobre un elemento excitado por una máquina de impactos. Esta idea se confirma al observar los valores tan bajos de aislamiento que se obtienen para el suelo flotante por comparación con los obtenidos para la pared conectada.

7.1.2 Medidas *in situ*

Por lo que respecta a las medidas efectuadas en las instalaciones de la antigua Escuela de Magisterio de la Universidad de Valladolid (España), se han extraído diversas conclusiones basadas en la comparación de distintas técnicas de medidas experimentales y predicciones teóricas. Inicialmente se han comparado los valores de potencia sonora obtenidos y así como el aislamiento del elemento separador. En una segunda etapa se han comparado los valores experimentales y estimados, incluyendo el posible efecto de las transmisiones indirectas. Por último se ha comparado el valor global R'_w *in situ* que se obtiene según los distintos métodos utilizados.

7.1.2.1 Comparación de los resultados experimentales

obtenidos usando los métodos de intensidad y vibración así como los modelos de predicción, sobre el elemento separador

Inicialmente se han comparado por un lado los valores de potencia sonora por velocidad $L_{w,v}$ y por intensidad $L_{w2,i}$ y en una segunda etapa se ha calculado el aislamiento a partir de los valores de potencia sonora así como el aislamiento según el método general descrito en la EN 12354-1 (2000) $R'_{12354Det}$:

- (i) Al comparar los valores de $L_{w,v}$ y $L_{w2,i}$, se observa que presentan curvas similares en el rango de frecuencias comprendido entre 100-3.150 [Hz]. Las diferencias más visibles son para el rango de 100-800 [Hz], donde $L_{w,v}$ presenta una curva con valores más altos.
- (ii) Las tres estimaciones de $L_{w,v}$ presentan una gran semejanza entre ellas, con diferencias por debajo de 0,3 [dB];
- (iii) Comparando todos los R'_v con R'_I las semejanzas continúan para frecuencias por encima de los 800 [Hz] y en todo caso las diferencias son aproximadamente iguales o menores que 2 [dB];

El modelo de predicción detallado de EN 12354-1 (2000), $R'_{12354Det}$ también presenta valores similares a los otros métodos experimentales R'_v y R'_I para el rango de frecuencias entre 400-1.250 [Hz]. La curva de R'_I presenta una caída en la frecuencia de 250 [Hz]. La frecuencia crítica fue calculada matemáticamente en 175 [Hz], a partir de los datos físicos del cerramiento, y después fue introducido en el algoritmo de cálculo del modelo detallado $R'_{12354Det}$ para la pared separadora. Las tres curvas de R'_v presentan este comportamiento a 200 [Hz], pero de una forma más suave. Las diferencias más significativas (de 2 a 4 [dB]) se observan entre los 160 y los 500 [Hz] para R'_I y R'_v . por debajo de 250 [Hz] hay diferencias significativas entre todas las curvas.

A la vista de estos resultados, se puede concluir que el método de predicción detallado en la EN 12354-1 (2000) produce estimaciones de aislamiento comprendidas entre los valores R'_I y R'_v , a bajas frecuencias, análogas a frecuencias medias, y mayores que R'_I y R'_v , a altas frecuencias.

El aislamiento por intensidad R'_I resulta mayor que cualquiera de los otros resultados en todo el rango de frecuencia.

7.1.2.2 Comparación de resultados experimentales y modelos de predicción, incluyendo transmisiones indirectas

El aislamiento $R'_{12354Det}$ cae significativamente a 250 [Hz], con un desvío de 75 [Hz] respecto a la frecuencia crítica calculada. El algoritmo de cálculo que utiliza este modelo es distinto por encima de la frecuencia crítica y por debajo de la misma, y es precisamente a esta frecuencia donde se observa el valle.

Por otra parte, el $R'_{12354Det}$ diverge considerablemente de las demás curvas por encima de 800 [Hz]. También se observa que las curvas “standardizadas” y “no-standardizadas” presentan diferentes mínimos aunque las curvas son semejantes. El punto de cruce se encuentra entre los 800 y 1.000 [Hz]. Por debajo de los 630 [Hz] $R'_{12354Det}$, R'_v y R'_I presentan curvas similares mientras que para el rango de frecuencias central sólo R'_v y R'_I presentan la misma curva, distinta de la curva obtenida por el método de presión R'_p .

Los $R'_{v,Rindel}$, $R'_{v,Davy}$ y $R'_{v,Sewell}$ presentan curvas similares, con diferencias muy pequeñas entre ellas. El mínimo en los tres casos se observa a 200 [Hz]. Esta caída es próxima de la frecuencia crítica estimada, 175 [Hz]. Por otra parte la curva de R'_I tiene su valor mínimo a 250 [Hz] al igual que la curva de $R'_{12354Det}$. Si se comparan los valores de aislamiento por intensidad y todos los R'_v se observan ligeras diferencias: Por debajo de los 1.000 [Hz] R'_v es algo menor que R'_I ; por encima de este rango y hasta los 1.600 [Hz] la concordancia es razonable y por encima de los 1.600 [Hz] las diferencias llegan a 5 [dB] con respecto a la curva de Rindel y 3 [dB] respecto a la curva de Davy.

Para las frecuencias bajas (por debajo de los 315 [Hz]) los valores de R'_I quizás no sean del todo fiables pues se ha medido con espaciador de 12mm. Sería interesante repetir las medidas con un espaciador más largo, por ejemplo de 50 [mm] y verificar si los resultados concuerdan mejor. De hecho en los resultados obtenidos la concordancia entre R'_I y R'_p es mejor por encima de esta frecuencia.

Un comportamiento semejante fue verificado por Machimbarrena (1999) para medidas *in situ* por el método de intensidad.

7.1.2.3 Comparativa *in situ* del índice ponderado de reducción sonora aparente para todos los métodos

Se ha realizado la comparación del índice ponderado de reducción sonora aparente R'_w obtenido según la norma EN ISO 717-1 (1996) tanto para los dos métodos experimentales estandarizados como para los dos modelos de predicción propuestos por EN 12354-1 (2000). Esta comparativa se ha realizado solamente para las condiciones *in situ*. Los resultados se presentan divididos por dos grupos: los resultados obtenidos para el elemento pared separadora y los resultados obtenidos incluyendo la contribución de la transmisión por flancos:

- (i) En la evaluación de la pared separadora, solamente se pueden utilizar los métodos experimentales de intensidad y velocidad de vibración. El método de intensidad revela $R'_{w,I}=42$ [dB]. Los resultados $R'_{w,vRindel}$ y $R'_{w,vSewell}$ presentan el mismo valor ponderado de 40 [dB], mientras que $R'_{w,vDavy}=39$ [dB] coincide con el modelo detallado $R'_{w,12354Det}=39$ [dB]. El modelo

simplificado presenta un $R'_{w,12354Sim.} = 42,7$ [dB]. A la vista de todos estos resultados se verifica que $R'_{w,12354Det.}$ es capaz de obtener un valor ponderado muy similar a los obtenidos por los otros métodos;

- (ii) Para la situación en la que se incluye la contribución por flancos, los tres métodos estandarizados presentan el mismo valor de aislamiento ponderado $R'_{w,I}$, $R'_{w,p}$, $R'_{w,12354Det.} = 39$ [dB]. Esto nos lleva a concluir que el algoritmo de cálculo del modelo detallado descrito en la normativa EN 12354-1 (2000) así como los datos de las tablas incluidos en ella, se pueden aplicar para el caso de los edificios españoles y tipos constructivos analizados en esta tesis. Por el contrario, el modelo sencillo de predicción presenta resultados algo mejores del índice ponderado $R'_{w,12354Sim.}$ of 41 [dB], lo cual podría llevar a un posible error al ingeniero proyectista por lo que respecta a la predicción del comportamiento acústico del edificio. Un aspecto importante es que este resultado es consistente con la desviación estándar de 2 [dB] prevista en la sección 5 de la normativa EN 12354-1 (2000) para el método simplificado de predicción. Por último, los valores de aislamiento ponderado $R'_{w,vRindel}$ y $R'_{w,vDavy}$ resultan idénticos entre sí e igual a 37 [dB]. Este resultado implica un peor rendimiento acústico por comparación con los métodos estandarizados basados en medidas experimentales.

A partir de la comparación de los valores de aislamiento ponderado es posible concluir que los métodos estandarizados producen un mismo valor final de aislamiento, lo cual demuestra que el proyecto acústico del edificio según el modelo detallado en la EN 12354-1 (2000) es consistente. Por lo que respecta al aislamiento acústico ponderado obtenido mediante las estimaciones por velocidad, $R'_{w,v}$, el mejor resultado se obtiene con la ecuación de Davy, aunque los resultados son bastante parecidos a los obtenidos con la ecuación de Rindel.

7.1.3 Conclusiones relacionadas con la implementación del método de velocidad de vibración

La comparativa entre R'_1 y R'_v sin considerar la contribución de flanco, nos muestra valores más altos de R'_1 . Puesto que el valor de aislamiento por intensidad es el de referencia, esto significa que el $R'_{w,v}$ para la pared separadora es peor que su valor real (dado por R'_1). El nivel de referencia ponderado viene dado por $R'_{w,l}$.

Al comparar R'_1 sin considerar las transmisiones por flanco y R'_1 considerando las transmisiones por flanco, se observa que las diferencias son incluso mayores que al comparar R'_v sin flancos y con flancos. Esto implica que R'_1 da más importancia a las transmisiones por flancos que el método de velocidad de vibración R'_v . Por lo tanto, R'_v presenta menores niveles significando que la pared separadora tiene peor aislamiento de lo que en realidad tiene.

La implementación del método de medidas de vibraciones para las condiciones *in situ* se efectuó adaptándose a los requisitos de EN ISO 10848-1 (2006) para la medida de la velocidad de vibración sobre los elementos constructivos de la sala estudiada.

Para validar y confirmar el método de medidas de velocidad de vibraciones, se han comparado los resultados con los obtenidos por intensidad. Con el método de medida de velocidad se pretende evaluar la transmisión directa así como la contribución de la transmisión a ruido aéreo por flancos. Para ello, como ya se ha comentado, se han utilizado distintos modelos matemáticos para la estimación de la eficiencia de radiación.

Usando los resultados obtenidos por el método de velocidad de vibración, ha sido posible generar imágenes espaciales capaces de reproducir la distribución espacial de la velocidad sobre cada elemento. Con estas imágenes es más sencillo localizar las diferencias de velocidad. Se observa que los elementos ligeros tienen niveles de velocidad más altos, lo cual podría suponer una mayor radiación sonora, sobre todo cerca de las uniones entre elementos. Por el contrario, en el caso de elementos más pesados, los niveles de velocidad más altos se encuentran en el centro y no cerca de las uniones.

En comparación con el método de intensidad, el método de velocidad de vibración resulta ser un método de medida más conveniente por diversas razones. Por lo que respecta al proceso de medida en sí, cabe señalar que instalar la instrumentación

adecuada sobre la superficie de medida es relativamente sencillo y rápido pues el adherir los acelerómetros a las superficies no presenta problemas a temperaturas normales (no excesivamente frías) y, usando cera de abeja limpia, en la mayor parte de los casos no se deja ninguna mancha en la pared. Por otra parte, los resultados no dependen de si el campo sonoro es reverberante ó no y el procedimiento de calibración es más sencillo y rápido. Así mismo es importante tener en cuenta que el coste de implementación es relativamente bajo, dependiendo del mínimo de acelerómetros..

Por lo que respecta al método de intensidad una de las desventajas importantes es que requiere técnicos con alta preparación y experiencia para poder ejecutar las medidas con éxito. Además hay que efectuar al menos dos barridos sobre cada superficie, lo cual puede resultar muy lento y tedioso a la hora de evaluar la contribución de los elementos de flanco. En el lado positivo de la intensimetría está su precisión y el hecho de que en ningún caso se deteriora/modifica la superficie de medida.

Si el método de intensidad se compara con el de presión, sin embargo, tiene a su favor que resulta más económico que éste a la hora de evaluar las transmisiones por flancos, pues el apantallamiento propuesto por el método de presión es bastante costoso.. Además, no modifica el campo sonoro de la sala receptora y, a pesar de lo mencionado anteriormente (barridos en todas las superficies), resulta más rápido que el método de presión.

Los resultados muestran que, en general, el método de velocidad de vibración puede ser utilizado como método de medida, dado que subestima ligeramente el aislamiento acústico del elemento, y por tanto el resultado aumentará el margen de seguridad y por tanto favorecerá al usuario final.

Por último cabe señalar que para poner a punto del método y que pueda ser utilizado de forma sistemática, es necesario elaborar una nueva normativa orientada a la aplicación en condiciones *in situ*. Los resultados presentados en esta tesis no son suficientes para confirmar que este procedimiento de medida aplicado *in situ* a través de la EN ISO 10848-1 (2006) sea el correcto pero, sí permite concluir que la metodología es apropiada. Es evidente que son necesarios más estudios y una gran recopilación de datos *in situ* para poder alcanzar resultados más precisos y desarrollar dicha normativa.

7.2 Trabajo futuro

Como futuras líneas de desarrollo se presentan algunas ideas. El método de intensidad y el método de velocidad de vibración son capaces de estimar el índice de aislamiento sonoro entre dos salas con la cuantificación de la transmisión de flanco. Para el futuro próximo, la valoración del índice de aislamiento sonoro debe poder efectuarse sin tanto esfuerzo personal y de forma más rápida por lo que al procedimiento de medida respecta. Por esto, los más recientes desarrollos en vibrometría láser y holografía TV son adecuados para la acústica de edificación. Estos son capaces de proporcionar datos temporales usando por obtención remota en un punto de la superficie, tal y como refieren Halliwell and Petzing (2004).

A través de la aplicación de estos métodos de medida será posible la ampliación del estudio de paredes dobles desde el punto de vista de las transmisiones indirectas tanto en el ámbito teórico como en el experimental. Se propone una revisión de la norma UNE EN ISO 10848-1. Medida en laboratorio de la transmisión por flancos del ruido aéreo y de impacto entre recintos adyacentes. Parte I: documento marco (2006) para que trate más ampliamente el caso de paredes dobles.

Sería también importante hacer un estudio exhaustivo de algún tipo de unión característico mediante medidas realizadas *in situ*. Evaluar la importancia que puedan tener en la medida de las transmisiones indirectas algunos elementos inherentes a la obra. Recopilación de casos prácticos que puedan dar las primeras pautas de medida tanto de las diferencias de nivel de velocidad como del tiempo de reverberación estructural en obra.

Con el fin de desarrollar nuevos modelos de transmisión de flanco sería interesante recopilar datos de factores de pérdida de las construcciones típicas utilizadas en España y también comparar con las bases de datos existentes de otros grupos Europeos.

Chapter 7

7 Conclusions

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7.1 Introduction

In this last chapter, a resume of the most significant conclusions obtained during this study is presented.

Finally, as future line of work, various possible research trends related to this thematic are presented.

7.1.1 Flanking laboratory measurements

To achieve the objective of implementing the vibration velocity method *in situ*, it was relevant to consider performing some initial measurements at a flanking laboratory, in order to validate the methodology in a “controlled” environment. In a laboratory with these characteristics, it is possible to connect-disconnect the junctions between elements and thus, to evaluate each transmission path separately.

The first measurements were then performed in the flanking laboratory called DIENCA, measuring the vibrations of a floating floor and a connected wall, having a tapping machine as sound source. This laboratory conditions are quite similar to the ones that can be found *in situ* conditions. These results, by themselves, do not provide important information since the methodology applied in laboratory is already standardized. But interesting results are presented from the comparison with the sound intensity method, when applied the radiation efficiency given from several mathematical functions, obtaining an estimation of the sound power level radiated by these elements.

The calculations of the sound power level velocity estimation, $L_{w,v}$, were implemented according to four different equations, corresponding to four different radiation efficiencies. The radiation efficiency is estimated according to Sewell (1970), Josse (1972), Rindel (1993) and Davy (2004). Comparing with the sound power intensity estimation, $L_{w2,l}$, is then possible to say:

- (i) The curves for the floating floor present a similar behaviour for almost all the one-third-octave octave bands. It can be verified that, in the middle bands (between the 200 [Hz] and the 2.500 [Hz]), the sound power level velocity

estimation, $L_{w,v}$, presents lower levels (3 to 4 [dB]) (by the four mathematical functions) comparing to the sound power by sound intensity. The sound power velocity estimation is higher in the lower bands (below the 200 [Hz]) and almost equal between the 3.150 [Hz] and 5.000 [Hz] bands.

- (ii) In general, the higher levels observed, when using the sound power intensity estimation, could be explained by the strong and located noise produced by the tapping machine. During the scan passage of the sound intensity probe at the exact position of the impact machine, the intensity levels measured by it increase. Nevertheless, it must be referred that the sound intensity method was not created for this type of excitation but for airborne sound excitation with a loudspeaker.
- (iii) For the lateral wall, the curves illustrate a similar shape between them. However, at the middle one-third octave bands, between the 1.250 [Hz] and 2.500 [Hz], the ($L_{w,v}$) is also slightly underestimated, but less than 3 [dB]. These differences are extended, between 630 [Hz] and 5.000 [Hz], for Josse's estimation compared to the other curves shape. However, the curves are closer than in for the floating floor case.

The sound power level velocity estimations, $L_{w,v}$, performs better than sound power intensity estimation, $L_{w,i}$, when the element is directly excited by the tapping machine. Also, it is possible to say that the radiation efficiency estimated by Josse (1972) equation is the one presenting the most different results, estimating less sound power, when compared with the others authors. Through this, it is possible to conclude that the vibration velocity method could be adequate to estimate impact sound insulation levels whereas the sound intensity method can not, since it is not adequate to perform measures directly over the excited element by a tapping machine. This is confirmed by higher sound power levels values obtained for the floating floor relatively to the sound power levels values presented for the lateral element.

7.1.2 *In situ* measurements

For *in situ* measurements performed in Spain at “Magisterio”, it is possible to present several conclusions based on the comparison of different sound experimental methods and prediction methods. First, the sound power levels and then the sound reduction indexes are compared only for the separating element. Further, the results from measurement and prediction methods including flanking transmission are compared. Finally, the comparison of the weighted R'_w *in situ* for all methods is presented.

7.1.2.1 Comparison of results from intensity, velocity and prediction methods for the separating wall

The conclusions are divided by sound power levels obtained from sound power velocity levels, $L_{w,v}$, and sound intensity method, $L_{w2,l}$, with the correspondent sound reduction indexes obtained with the additionally detailed prediction method of EN 12354-1 (2000)- $R'_{12354Det}$:

- (i) Comparing $L_{w,v}$ and $L_{w2,l}$, they present a similar curve for the 100-3.150 [Hz] bandwidth. The noticeable differences are for the bandwidth frequencies 100-800 [Hz], where $L_{w,v}$ presents a curve with higher values;
- (ii) The three $L_{w,v}$ estimations present very good similarity between them, with differences below 0,3 [dB];
- (iii) When comparing all the R'_v against the R'_l , the similarity continues and for frequencies higher than 800 [Hz] the differences are now less than 2 [dB] or even almost equal;
- (iv) The detailed prediction model by EN 12354-1 (2000), $R'_{12354Det}$, also presents similar values as the other experimental methods R'_v and R'_l , for the frequency range of 400-1.250 [Hz]. The R'_l curve presents a fall at the 250 [Hz] frequency band. The critical frequency was mathematically estimated, in 175 [Hz] based on the physical characterisation of the assembly, and introduced on the detailed model $R'_{12354Det}$ algorithm calculus for the

separating element. The three R'_v curves present a gentle fall at 200 [Hz]. The most significant differences (2 to 4 [dB]) occur between 160 and 500 [Hz] for R'_I and the three R'_v . Below the 250 [Hz], there is a significant disagreement between all the curves.

From these curves, it is possible to conclude that the prediction detailed method of EN 12354-1 (2000) presents, in comparison with intensity and velocity ones, a $R'_{12354Det}$ curve with values between these two estimations for low frequencies; the same values for middle range frequencies; and higher values than the other two estimations, for high frequencies.

The R'_I curve presents higher values than the other methods over all the frequency range.

7.1.2.2 Comparison of results from measurement and prediction methods including flanking transmission

The $R'_{12354Det}$ presents a significant fall at 250 [Hz], because it is at this frequency that the critical frequency is expressed, with a deviation of 75 [Hz] from the calculated value. This can be due to the fact that the standard uses different calculus algorithms for frequencies above and below the critical frequency and the valley lies within this “algorithm matching lap”.

The $R'_{12354Det}$ diverges from the other methods significantly above 800 [Hz]. It can also be observed that “standard” curves and “non standard” curves have different slopes, but with similar curves. The crossing point is between 800 and 1.000 [Hz]. Below the 630 [Hz], $R'_{12354Det}$, R'_v and R'_I present similar curves. For the middle range one-third octave bands, the R'_v and R'_I show the same curve which is different from the curve of R'_p

The $R'_{v,Rindel}$, $R'_{v,Davy}$ and $R'_{v,Sewell}$ present similar curves with very small differences between them. For these vibration velocity methods, the SRI takes a minimum value at 200 [Hz] band. In this case, the minimum is reached very close to the calculated critical frequency of 175 [Hz]. The R'_I and $R'_{12354Det}$ have their minimum values at 250 [Hz]. The

slopes trend between the R'_I and all the R'_V are slightly different, presenting the R'_V lower values below the 1.000 [Hz]. Above this frequency the agreement is reasonable until 1.600 [Hz]. Above this frequency the differences reach 5 [dB] for Rindel and 3 [dB] for Davy curve.

For the lower bands (below 315 [Hz]), it would be needed to use a 50 [mm] spacer in order to get reliable results. In fact, the best agreement between R'_I and R'_p is found above this frequency, which is consistent with the use of the 12 [mm] spacer.

A similar behaviour was also verified by Machimbarrena (1999) in the *in situ* sound intensity method measurements.

7.1.2.3 Comparison of *in situ* weighted SRI for all methods

Another important comparison is the apparent weighted sound reduction index R'_w obtained from the EN ISO 717-1 (1996) for the two standardized experimental methods and for the two prediction models proposed by the EN 12354-1 (2000). This comparison was performed for *in situ* conditions. The results have been divided in two cases; the one's obtained by separating element and the others obtained through including the flanking contribution:

- (i) For the evaluation of the separating element, the sound intensity method was used, and it yield a $R'_{w,I}=42$ [dB]. The simplified prediction model produced a similar result, with a $R'_{w,12354Sim}=42,7$ [dB]. The $R'_{w,vRindel}$ and $R'_{w,vSewell}$ present the same weighted value of 40 [dB], whereas $R'_{w,vDavy}=39$ [dB]. Finally the detailed model turned out $R'_{w,12354Det}=39$ [dB]. As it can be seen, $R'_{w,12354Det}$ is capable of predicting a weighted level similar to the one obtained by the other methods;
- (ii) When the flanking contribution was taken into account, the three standardized methods produced the same weighted quantity $R'_{w,I}$, $R'_{w,p}$, $R'_{w,12354Det}=39$ [dB]. It can then be concluded that the detailed prediction model included in EN 12354-1 (2000) can be applied to the Spanish building constructions analysed in this thesis. On the other hand the simplified prediction model yields higher weighted airborne sound insulations values

$R'_{w,12354Sim} = 41$ [dB], which could lead the project engineer to a potential mistake in the prediction of the acoustical behaviour of the building. It is important to notice that these results are consistent with the standard deviation of 2 [dB] for the simplified model that is referred in section 5 of the EN 12354-1 (2000). Finally, the $R'_{w,vRindel}$ $R'_{w,vDavy}$ have presented a weighted level of 37 [dB]. This weighted level, means a worse acoustical performance in comparison with the standardized measurements, but from the acoustical project engineer point of view it makes it to be on the safer side.

From the comparison of the weighted levels, it is possible to conclude that the standardized methods reach the same final insulation value, denoting that the acoustic project of the building according to the detailed model could be consistent. From the $R'_{w,v}$ estimation point of view the best result is obtained by Rindel's equation being however very similar to Davy's results.

7.1.3 Conclusions related to implementation of vibration

velocity method

The comparison between the R'_I and R'_v without the flanking contribution reveals that the R'_I against R'_v presents a curve with higher values. This means that if one considers the $R'_{w,v}$ weighted level, the separating wall presents a worse sound insulation than it really has, assuming that the reference weighted level is given by the $R'_{w,I}$.

If R'_I with and without flanking contributions are compared, the differences between both curves are even bigger than when R'_v with and without flanking are compared. This leads to suppose that the intensity method in fact is measuring “more flanking” energy than the vibration method.

Comparing without flanking, against R'_I with flanking, it is verified even a bigger difference than when comparing R'_v without flanking against R'_v with flanking. It means that the R'_I points out that the flanking contribution is so important and that the vibration velocity method considers flanking with less importance. By this, the R'_v

presents lower levels, meaning R'_v expresses that separating element has worse insulation than it really has.

The implementation of the vibration velocity method for field conditions was possible following EN ISO 10848-1 (2006) as close as possible, specially in all what concerns the measurement of the vibration velocities on the surfaces elements of a room.

To validate and to confirm the vibration velocity method, its results were compared with the sound intensity method results. Several different radiation efficiency models where used as it has previously been mentioned. The basic idea is to use the vibration velocity method, to evaluate the direct transmission and the flanking contribution of airborne sound transmission between adjoining rooms.

Using the results obtained by the vibration velocity method, it was possible to generate 2D spatial images of the velocity distribution over each element. With these images, it becomes easy to analyse where different velocity levels are located. It is noticed that, in general, the lightest elements present higher velocity levels which corresponds to higher sound radiation. In fact, for the light elements, the spatial distribution showed that the higher contributions are found near the elements junctions. On the other hand, the heaviest elements present higher velocity levels on the centre, than near the junctions.

There are a few reasons to declare that in fact the vibration velocity method is more convenient than the sound intensity method. From the practical point of view, it is very easy to place accelerometers on the surfaces and in most cases using clean bee wax guarantees no damage to the walls. Besides, the measurement results do not depend on whether the surrounding sound field is reverberant or not and the calibration task is also much simpler and faster. Last but not least, the implementation cost is relatively lower, depending on the number of accelerometers used.

On the other hand, there are some well known difficulties related to the sound intensity method. It is not unknown that it requires high technical knowledge and skills, from the technician carrying out the measurements and that at least two scans shall be performed over all the elements under study. This means that the evaluation of the contribution of all flanking elements can be very tedious and slow.

If the intensity method is compared to the pressure method when taking into account flanking transmissions, it is obvious that the costs are much lower, since

shielding all flanking paths can be extremely expensive. Besides, the intensity method does not modify the sound field in the receiving room and in spite of what was previously mentioned concerning scanning twice each surface; it is still faster than the pressure method.

The results show that the vibration velocity method can be used because, in general, it underestimates the acoustical performance of the element and this underestimation will in any case always benefit the final user.

Although this thesis has validated the use of the vibration velocity method in order to evaluate sound insulation including flanking transmission, it is still necessary to develop a corresponding standard for *in situ* conditions. The data presented in this thesis are not sufficient to confirm if this measurement procedure directly applied from EN ISO 10848-1 (2006) is correct for *in situ* application, even though it seems that the methodology is appropriate.

7.2 Future work

The sound intensity and the vibration velocity methods are capable to estimate the sound reduction between two rooms including the flanking contribution. This sound reduction index requires, in a near future, faster and less human intervention on the measurement process. This is why the recent improvements in laser vibrometry velocity measurements and TV holography are suited for building acoustics. They are capable of providing remote time-resolved vibrations data at a point on a surface, as referred by Halliwell and Petzing (2004).

Through the application of these accurate measurement techniques, the future line of work could be expanded to the study, on laboratory conditions, of the flanking transmission between rooms by airborne and structure borne excitation, regarding the improvement of the EN ISO 10848-1 (2006) for double layer-walls.

It would also be interesting to perform an exhaustive study for *in situ* conditions of one specific type of junction and to evaluate the significance of some elements regarding the flanking transmissions.

It is interesting to point out that within the research group that has been behind this PhD Thesis, there is another ongoing PhD research work trying to validate the EN 12354-1 (2000) expressions for the vibration reduction index K_{ij} for the specific construction types found in Spain.

In order to develop new flanking transmission models, it would be interesting to provide loss factor data for the typical constructive solutions frequently used in Spain, and also compare the results to the data base found in other European groups.

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ANNEX A

A Transforming the acceleration levels in velocity levels

$$L_a = 10 \log \frac{a_{\text{rms}}^2}{a_0^2} \Leftrightarrow a_{\text{rms}}^2 = a_0^2 10^{(L_a/10)}$$

$$\Leftrightarrow a_{\text{rms}}^2 = \omega^2 v_{\text{rms}}^2 = (2\pi f_m)^2 v_{\text{rms}}^2$$

$$v_{\text{rms}}^2 = \frac{a_{\text{rms}}^2}{4\pi^2 f_m^2} = \frac{a_0^2}{4\pi^2 f_m^2} 10^{(L_a/10)}$$

$$L_v = 10 \log \frac{\frac{a_0^2}{4\pi^2 f_m^2} 10^{(L_a/10)}}{v_0^2} = 10 \log \left[\frac{a_0^2}{4\pi^2 v_0^2} \right] + 10 \log \frac{1}{f_m^2} + L_a$$

$$L_v = 10 \log \left[\frac{a_0^2}{4\pi^2 v_0^2} \right] - 20 \log f_m + L_a$$

ANNEX B

B1 SRI or R' estimation calculus

```

Static Function Log10(X)
  Log10 = Log(X) / Log(10#)
End Function

```

```

Public Function calculo_R(f As Double, fc As Double, sigma As Double, ntot As
Double, m As Double, l1 As Double, l2 As Double, t As Double, cl As Double)

```

```

  ro0 = 1.01          'density of air
  c0 = 340            'velocity of sound in air
  Pi = 3.14159
  k0 = (2 * Pi * f) / c0  'wave number
  fp = cl / (5.5 * t)

```

```

  If f >= fc Then

```

```

    If f >= fp Then
      fcef = 2 * fc * (f / fp) ^ 3

```

```

    Else
      fcef = fc * ((4.05 * t * f / cl) + (Sqr(1 + (4.05 * t * f / cl))))

```

```

  End If

```

```

  Tf = (((2 * ro0 * c0) / (2 * Pi * f * m)) ^ 2) * ((Pi * fcef * sigma ^ 2) / (2 * f *
ntot))

```

```

  Else

```

```

    sigmaf = 0.5 * (Log(k0 * Sqr(l1 * l2)) - (-0.964 - ((0.5 + (l2 / Pi * l1)) * Log(l2 /
l1) + (5 * l2) / (2 * Pi * l1) - (1 / (4 * Pi * l1 * l2 * k0 ^ 2))))))

```

```

    Tf = (((2 * ro0 * c0) / (2 * Pi * f * m)) ^ 2) * (2 * sigmaf + ((l1 + l2) ^ 2 / (l1 ^ 2
+ l2 ^ 2)) * Sqr((fc / f) * sigma ^ 2 / ntot))

```

```

    If sigmaf > 2 Then

```

```

      sigmaf = 2

```

```

    End If

```

```

  End If

```

```

  R = -10 * Log10(Tf)

```

```

  calculo_R = R

```

```

End Function

```

B2 Radiation efficiency estimation calculus

Public Function calculo_sigma(f As Double, fc As Double, f11 As Double, sigma1 As Double, sigma2 As Double, sigma3 As Double, l1 As Double, l2 As Double)

```

sigma = 0
lambda = Sqr(f / fc)
c0 = 340
Pi = 3.14159

If f11 <= fc / 2 Then
  If f >= fc Then
    sigma = sigma1
  Else
    delta1 = ((1 - lambda ^ 2) * (Log(1 + lambda) / (1 - lambda)) + 2 * lambda) /
    ((4 * Pi ^ 2) * (1 - lambda ^ 2) ^ 1.5)

    If f > fc / 2 Then
      delta2 = 0
    Else
      delta2 = (8 * c0 ^ 2 * (1 - 2 * lambda ^ 2)) / (fc ^ 2 * Pi ^ 4 * l1 * l2 * lambda
* Sqr(1 - lambda ^ 2))

    End If
    sigma = (((2 * (l1 + l2) * c0) / (l1 * l2 * fc)) * delta1) + delta2

    If f < f11 And f11 < fc / 2 And sigma > sigma2 Then
      sigma = sigma2
    End If
    If sigma > 2 Then
      sigma = 2
    End If

  End If

Else
  If f < fc And sigma2 < sigma3 Then
    sigma = sigma2
  End If
  If f > fc And sigma1 < sigma3 Then
    sigma = sigma1
  End If
  If f = fc Then
    sigma = sigma3
  End If

End If

If sigma > 2 Then

```

```
sigma = 2  
End If
```

```
calculo_sigma = sigma
```

```
End Function
```

ANNEX C

```
load PSep.m
x=PSep(:, 1);
y=PSep(:, 2);
z=PSep(:, 3);

xi =min(x):0.01:max(x);
yi =linspace(min(y), max(y), length(xi));
[XI YI]=meshgrid(xi, yi);
ZI=griiddata(x, y, z, XI, YI, 'cubic');
pcolor(XI, YI, ZI);
caxis([37 74])
colorbar
shading interp
xlabel('x [m]')
ylabel('y [m]')
hold on
plot(x, y, '. ')

figure
surf(XI, YI, ZI)
shading interp
caxis([37 74])
hold on
plot3(x, y, z, '. ')
title 'Separating wall'
xlabel(' [x]')
ylabel(' [y]')
zlabel(' [dB]')
```

“If you obey all the rules you miss all the fun.”

Katherine Hepburn