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Sound insulation of building elements at low frequency: a modal approach

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Abstract

In typical laboratory volumes (50-80 m^3) and at low frequencies (50-100 Hz), the acoustic field is non-diffuse due to the presence of source and receiving room modes. Under such conditions, standard sound insulation measurements and descriptors are not adequate to correctly characterize the insulating property of partitions or flooring systems. The «modal approach» allows to evaluate the airborne sound insulation by the determination of modal transmission loss, or modal sound insulation, of a single mode passing through the partition. Proper normalization terms and an extension method to one-third octave bands are also introduced. The same approach is applied to impact sound insulation measurement.

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Keywords: Airborne sound insulation; Building acoustics; Low frequency; Impact sound insulation; Laboratory measurements.

1. Introduction

In recent years an increasing interest in building acoustics measurements at low frequencies (i.e. below 100 Hz, and typically from 50 Hz) has been observed. The consideration of low frequency noise has become more and more important because of the increasing occurrence of sound sources with low frequency content, like technical equipment inside and outside buildings, increased traffic volume and improved video and audio equipment in dwellings, and renewable energy sources [1,2]. Simultaneously, newer multilayer building elements, developed to be cheaper and lighter and possibly to have a better thermal insulation, use to have resonant frequencies below 100 Hz, which become more and more disturbing under such circumstances. Nevertheless, at present time, effective protection systems against low frequency noise are still an open challenge both for researchers and components

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manufacturers. In building acoustics, noise below 100 Hz has been generally neglected up to now, because the actual sound insulation measurement methods require diffuse sound fields. Standard measurements are performed in the frequency range between 100 Hz and 5000 Hz in one-third-octave bands and are not suitable and accurate enough in order to achieve repeatable and reproducible measurements in the low-frequency range (50-100 Hz). Standardized airborne and impact sound insulation laboratories, in which volumes range between 50 m^3 and 80 m^3, are characterized by a non-diffuse field (i.e. wavelengths equal or wider than room dimensions) below the Schroeder frequency, usually around 350 Hz. In any case, for practical reasons, a condition of diffuse field from 100 Hz on is conventionally accepted. Below 100 Hz, acoustic room modes lead to a high spatial spread of sound pressure levels and a high dependence on boundary conditions (modal damping, room volumes, room dimensions). On the basis of this, measurement solutions are needed in order to extend standard sound insulation measurements down to 50 Hz.

2. The modal approach for airborne sound insulation

The standard descriptor of sound insulation, i.e. the sound reduction R, is related to the transmission coefficient τ that is defined as the ratio of the sound power transmitted by the test element to the sound power incident on the test element. Assuming diffuse field, sound reduction is expressed as the difference between average sound pressure levels in source and receiving rooms plus a term depending on equivalent absorption area A. Application of such approach to non-diffuse field condition entails low reproducibility values of sound insulation [3,4] and it is not representative for the correct physical phenomena involved (low modal density, not uniform acoustic field in space and frequency domains). Currently it is not possible to correctly define the incident and transmitted sound power in such modal acoustic field according to the standard approach. Besides, a new sound intensity measurement procedure has been recently proposed in order to achieve low frequencies airborne sound insulation in laboratory [6]. Nevertheless sound intensity approach is subjected to several practical complication, such as the presence of a totally sound absorbing surface on the opposite wall, in receiving room and, at this time, the lack of a standardized calibration procedure of the sound intensity probes. Theoretical background and fundamental equations for calculations are provided by Morse and Jo's works [7,8].

2.1. The modal sound insulation

As described in [9], the evidence of transmission of source room modes into the receiving room through the partition allows to introduce the modal approach in the evaluation of sound insulation based on a description of modal sound transmission loss, i.e. the attenuation of source room modes passing through the partition into the receiving room. Such evaluation allows to shift from a statistical point of view in terms of average sound pressure levels, typical of diffuse field condition, to a discrete one, focused, in frequency domain, on source room modes and, in space, on the points of highest modal sound pressure levels (corners of rectangular rooms). Such descriptor of sound transmission loss in non-diffuse field can be represented by the modal sound insulation, $D_{modal}(f_n)$ which is defined as difference between the highest sound pressure levels of natural and transmitted source room modes, f_n, evaluated in the corner positions, $\boldsymbol{x}_{\boldsymbol{corner}}$, of source (*chamber 1*) and receiving (*chamber 2*) rooms (Eq. 1).

$$D_{modal}(f_n) = 10\ \log_{10}\left(\frac{p^2_{1,\max}(\mathbf{x}_{\mathbf{corner}}, f_n)}{p^2_{2,\max}(\mathbf{x}_{\mathbf{corner}}, f_n)}\right) = L_{1,\max}(f_n) - L_{2,\max}(f_n) \tag{1}$$

It is a discrete index as it refers just to source room resonant frequencies and provides an indication of sound transmission loss of a single mode passing through the partition from the source to the receiving room. In addition, resonant frequencies provide information about the resonant half bandwidth Δf_{-3dB} related to modal absorption [10] and are stable in time.

2.2. Experimental test

Once localized highest modal excitation points, i.e. corners of rectangular laboratory rooms, sound pressure level measurements are performed (closed-box loudspeaker emitting equalized pink noise at a corner of source room, microphones at 7 corners of source room and at 8 corners of receiving room). Spectrum analysis is realized through FFT (frequency resolution of 0.25 Hz, temporal linear average of 60 s), in order to identify all modes. Different partitions were evaluated, but, for simplicity, only results related to a specific one are reported in order to focus only on the measurement procedure. The layered partition is composed as follows: plasterboard (12.5 mm), plaster layer (15 mm), perforated brick (8x24x24 cm^3), plaster layer (15 mm), expanded clay concrete blocks (25x20x25 cm^3), plaster layer (15 mm), perforated brick (8x24x24 cm^3), plaster layer (15 mm), plasterboard (12.5 mm). For each microphone position, a FFT spectrum is obtained. According to the modal sound insulation definition, the highest sound pressure levels are selected for each frequency band in order to get 2 spectra, for source and receiving rooms respectively (Fig. 1). Both spectra are characterized by a large number of modes.

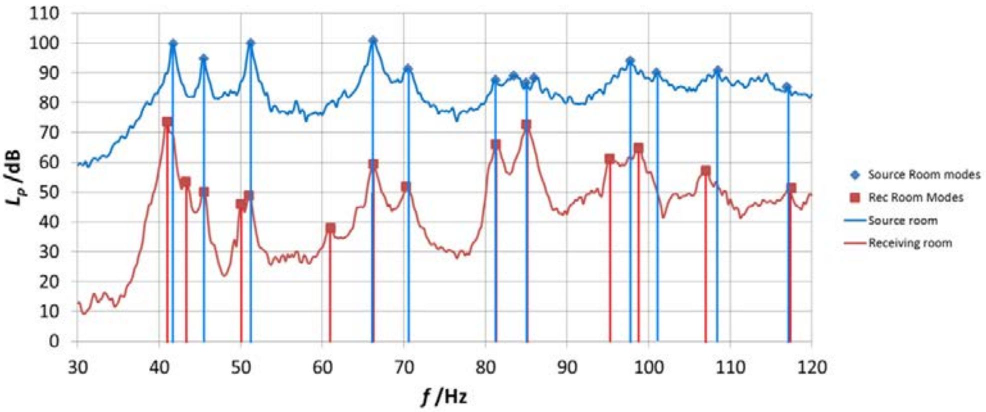

Fig. 1. Source and receiving room spectra.

Difference between source room modes in source and receiving room spectra, along blue vertical lines, represents the modal sound insulation (red curve in Fig. 2). Since some source and receiving room natural modes (blue and red vertical lines in Fig. 1) are close or completely matching due to comparable laboratory dimensions, the overlap entails an increases of modal sound pressure level and an underestimation of modal sound insulation at such frequencies (e.g. 41 Hz, 66.25 Hz, 81.25 Hz, 85 Hz, 98.75 Hz, 107 Hz and 117.5 Hz). Only three source room transmitted modes can be distinguished from receiving room natural ones (e.g. 45.5 Hz, 51.25 Hz, 70.5 Hz). In particular the curve (Fig. 2) presents a minimum at 85 Hz, which corresponds to the resonant frequency of the partition. Such comparison makes modal sound insulation measurement a significant sound transmission loss descriptor. Although the possibility to get a denser curve instead of considering only source room modes, operations with non-resonant frequencies are not reliable sound transmission loss descriptors because of their variable and unpredictable behavior. For this reason, the focus on source room modes can be considered the best choice to possibly get a reliable description of modal sound transmission loss. Now, another step occurs: combining equations from Jo's theory and making some mathematical assumptions, not reported here, modal sound insulation in different laboratories results to be dependent only on receiving room volume V_2. Fixing a standard value for receiving room volume $V_{2,0}$=50 m^3, normalized modal sound insulation becomes (Eq. 2) and the curve (blue) is depicted in Fig. 2.

$$D_{modal,nV}(f_n) = L_{1,\max}(f_n) - L_{2,\max}(f_n) - 20\log_{10}\left(\frac{V_2}{V_{2,0}}\right) \tag{2}$$

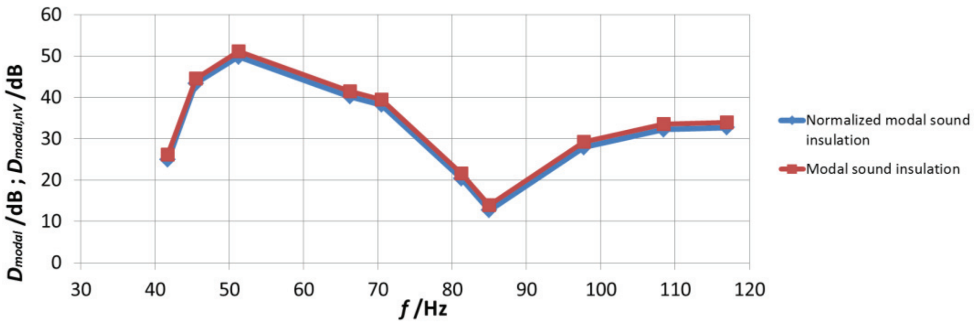

Fig. 2. The modal sound insulation curve.

2.3. Extension to the whole low frequency range

Because of the discrete nature of modal sound insulation, a new method is also introduced in order to extend it to the whole low frequency range in one-third octave bands. Considering a laboratory room with different volume and dimensions, it is possible to assume that resonant frequencies can shift in frequency and move along the envelope of source and receiving room spectra, i.e. along the curve that connects resonance peaks [11]. In this way, modal sound insulation (both for D_{modal} and $D_{modal,nV}$) is extendible to the whole 44-112 Hz range and one-third octave band representation is possible (Fig. 3).

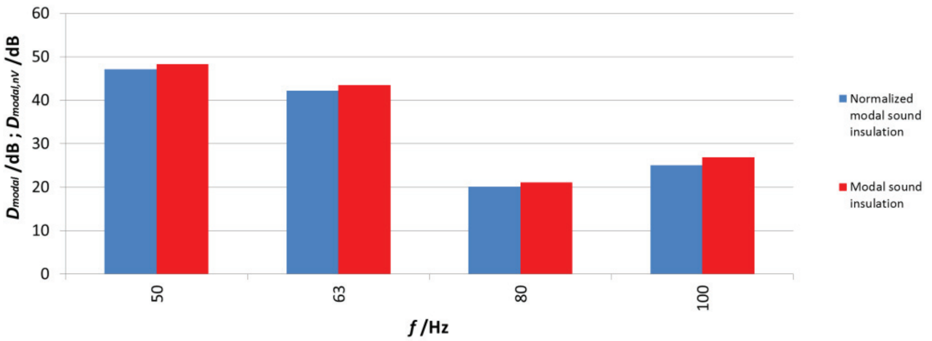

Fig. 3. The modal sound insulation in one-third octave bands.

3. The modal approach for impact sound insulation

3.1. The modal impact sound pressure level and the improvement of modal impact sound insulation

As for airborne sound insulation, also existing impact sound insulation indexes described in ISO 10140-3:2010 need to be reviewed and adapted in order to best describe the physical phenomenon in connection with the actual auditory perception of noise due to modal field and to ensure repeatable and reproducible laboratory values. Different authors have modelled the effect of the impact sound transmission by using low frequency modal analysis and provided a good prediction of the acoustic field generated in a rectangular room with a punctual sound source [12]. Based on these results and on the modal approach introduced for airborne sound insulation, it is proposed to move from a statistical approach typical of diffuse field to a discrete one, focused on the points of highest noise and annoyance, i.e. the highest sound pressure levels in the space (corners) and frequency (resonance modes). For this purpose, two descriptors are introduced: the modal impact sound pressure level, $L_{modal}\,(f_n) = L_{p,max}\,(f_n)$, defined as the highest sound pressure level measured at corners of receiving room for each resonance frequency, f_n, and the improvement of modal impact sound insulation, ΔL_{modal} (f_n), defined as the difference between the highest sound pressure levels measured with the bare floor and the covered floor:

$$\Delta L_{modal}(f_n) = L_{modal,0}(f_n) - L_{modal}(f_n) \tag{3}$$

where $L_{modal,0}$ (f_n) is the highest modal sound pressure level measured with the bare slab and L_{modal} (f_n) is the highest modal sound pressure level measured in receiving room corners with the covered floor. Such descriptor provides an indication of modal sound pressure level reduction due to the floating floor. For mass-spring systems (a rigid covering and the resilient layer), transmissibility curve has a peak around the resonant frequency of the system, f_0. Around the resonant frequency, the transmissibility is greater than 1 and higher sound pressure levels with the floating floor are obtained rather than with the bare slab. For lower frequencies, transmissibility is close to 1, and sound insulation is close to 0 [13].

3.2. Experimental tests

On the base of this, experimental measurements of modal impact sound pressure levels and improvement of modal impact sound insulation are performed with different mass-spring systems. Three floating floor samples, assuming locally reactive approximation, according to their different structural characteristics (mass and resonant frequency measured with dynamic stiffness method, ISO 9052-1:1993) are tested and described in Table 1.

Table 1. Description of test elements.

Name	*Covering material*	*Resilient layer*	*M* / kg m^{-2}	*A* / m^2	f_0 / Hz
M1	Carpet	LDPE	7.65	0.1830	511
M2	Concrete	LDPE	89.95	0.0756	149
M3	Steel	LDPE	200	0.04	38

The purpose of such measurement campaign is to verify the new measurement method for the evaluation of the impact sound insulation at low frequency and compare it with the sound transmission theory. In accordance with the definition of the new impact sound insulation descriptors, measurements of modal sound pressure level in the receiving room were performed. The source room floor was mechanically stressed by a heavy/soft ball and the sound field radiated by the floor was measured at the four corners of the receiving room. From the four spectra obtained for each corner, maximum levels for each narrow band were selected in order to obtain the discrete spectrum of $L_{modal}(f_n)$. Modal sound pressure level curves of the three test elements, with bare and covered floor, agree with transmissibility theory. Curves of improvement of modal impact sound insulation are depicted in Fig. 4. The analyzed mass-spring systems, with resonance frequencies between 38 Hz and 511 Hz, do not contribute to the sound insulation in the low frequency range (M1, the curve is, on average, around zero), but, on the contrary, can cause noise amplification (M2 and M3 curves decrease approaching their resonant frequencies).

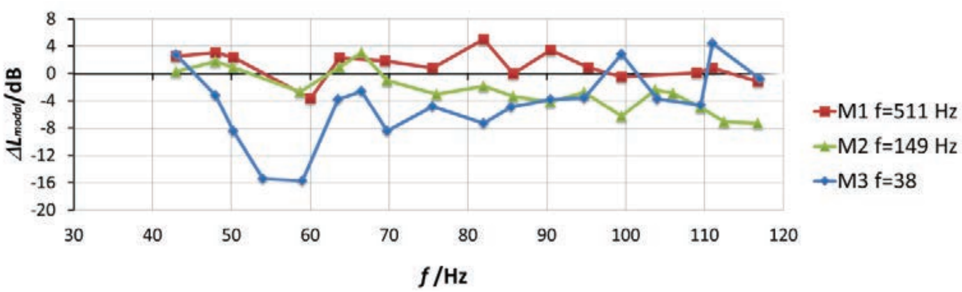

Fig. 4. Improvement of modal sound pressure level for the three mass-spring systems.

In M3 curve, the negative peak is reached at 55 Hz and 65 Hz, instead of 38 Hz. Below 55 Hz, improvement of modal impact sound insulation even increases until the first mode at 43 Hz. This is probably due to the airborne transmission of first modes from the source into the receiving room through the floor. For this reason, in the future it is necessary to evaluate the influence of airborne component in impact sound insulation measurements.

As for modal airborne sound insulation, the application of the envelope method allows a representation in one-third octave bands, as required by ISO Standard, of modal impact sound pressure levels, as well as for the improvement of modal impact sound insulation (Fig. 5).

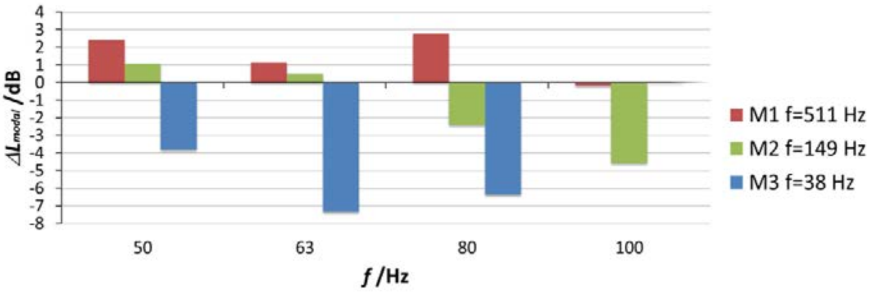

Fig. 5. Improvement of modal sound pressure level in one-third octave bands.

Improvement of modal impact sound insulation presents negative values around their resonant frequency. As most of the common covering floors are characterized by resonance frequencies above 50 Hz, the range of low frequencies presents, in most cases, a null sound insulation, even negative in some cases. Thus, for low frequencies and common flooring systems, it is more useful to control sound amplification rather than sound insulation.

4. Conclusions

The modal approach for the main laboratory measurements of building acoustics (airborne sound insulation and impact sound insulation) at low frequency (50-100 Hz) is introduced and new descriptors are investigated. The preliminary experimental measurements, in accordance with theory, confirm the significance of such indexes. This new approach represents a possible solution for the required extensions of building acoustics measurements down to 50 Hz. Nevertheless, further measurements are necessary in order to validate introduced normalization terms, measurement procedure and to evaluate a weighted procedure to overcome modal match.

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