24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

BUILDING COMPONENTS AND MATERIALS FOR LOW FREQUENCY AIRBORNE AND STRUCTURE-BORNE SOUND INSULATION

Alessandro Schiavi and Andrea Prato

INRIM – National Institute of Metrological Research, Turin, ITALY
email: a.schiavi@inrim.it

Jean-Christophe Vallée

Ecole Normale Supérieure Paris-Saclay, Cachan, FRANCE

During the last years it has been observed a growing interest in the characterization of the acoustical performances of building elements at low frequencies. The proposal to extend measurements and ratings, in the frequency range from 50 Hz to 100 Hz (in small rooms) involves considerable experimental difficulties, and many papers have been published by various research groups, focused on this topic. In any case, experimental results show high uncertainties and the acoustical performances of the tested partitions are often unclear. Furthermore, many typologies of insulating systems (for both structure-borne and air-borne sound insulation) commonly used in dwellings, have structural resonances at that frequency range, allowing experimental data to be more inaccurate. It follows that, as a first observation, the actual acoustic insulation properties of such systems are not effective enough under the structural resonance. Except some special applications, in which peculiar insulation systems are adopted (such as *box-in-a-box* systems for listening or recording rooms or seismic systems), the common partitions significantly insulate the medium or high frequencies, but are inefficient at very low frequencies. A general review of the recent literature (and also of the commercial proposals) clearly shows this lack. In this work, in very general and qualitative terms, the technical issue of achieving efficient insulation system at low frequencies, both for air-borne sound insulation and for structure-borne sound insulation is addressed. Acoustical performances are analysed on the basis of traditional calculation models and experimental evidences.
Keywords: Low frequencies, airborne sound, structure-borne sound, insulation

1. Introduction

Low-frequency structure borne and airborne sound insulation is nowadays of particular importance because of the increase of low frequency noise sources, e.g. service equipment and audio set, impact sound sources such as footsteps and the building’s operating technical equipment, and transportation systems from outdoor. For this reason, the characterization of the acoustical performance of building elements at low frequencies, in terms of insulation or sound proofing, has recently become of interest. As consequence, different measurement procedures have been proposed, evaluated and tested for frequencies below 100 Hz, each one with its own metrological problems and practical difficulties. Even supposing the accuracy of such procedures, there is a lack of specific low frequency sound insulation systems on the market and few products are addressed to this purpose. Difficulties are mainly due to the physical behavior of the sound transmission at low frequencies since it is related to many parameters such as mass, resonance of the partition, damping and the stiffness of the building element and materials involved, and the modal behavior of rooms which cannot be completely under control.

Some proposals of new building technology, involving ancient traditional materials (such bricks or wood) seem able to achieve interesting acoustical performances, at low frequencies. It seems very suggestive also stone masonry buildings technology, for this purpose, but evidences are still not available. Moreover, a new interesting perspective is given by acoustic metamaterials whose insulation properties are attributed to the negative effective elastic constants during the vibration, thus realizing the total reflection of low-frequency sound and breaking the mass law.

2. Measuring low frequency noise in enclosures

Over last years several experimental methods were presented for the measurement of sound insulation of building elements (walls, floors and façade elements) at low frequency [1], in particular between 50 Hz and 100 Hz [2-6]. However, from the experimental point of view, an accurate measurement of the acoustical performance of building elements at low frequency, is not easy to be achieved and the results are often affected by relevant uncertainties, from 6 dB up to 10 dB [7-10]. The main source of uncertainty is due to the modal acoustic field of standing wave generated in small volumes (of about 50 m^3). As a matter of facts, below the Schroeder frequency, the acoustic pressure is not uniformly spread, but it is space-time-dependent [11-13]. Moreover, a further relevant source of uncertainty, is due to the structural resonance of the investigated partitions. Many typologies of insulating systems, commonly used in dwellings, have resonant frequency below 100 Hz, depending on the elastic and inertial properties. Both airborne and structure-borne sound insulation curves show relevant variations around the structural resonance "dip", as shown in Figure 1. The resonant behavior of the partitions significantly increases the uncertainty of the measured sound pressure level. In general terms, very low insulation or no insulation occurs, below resonance frequency.

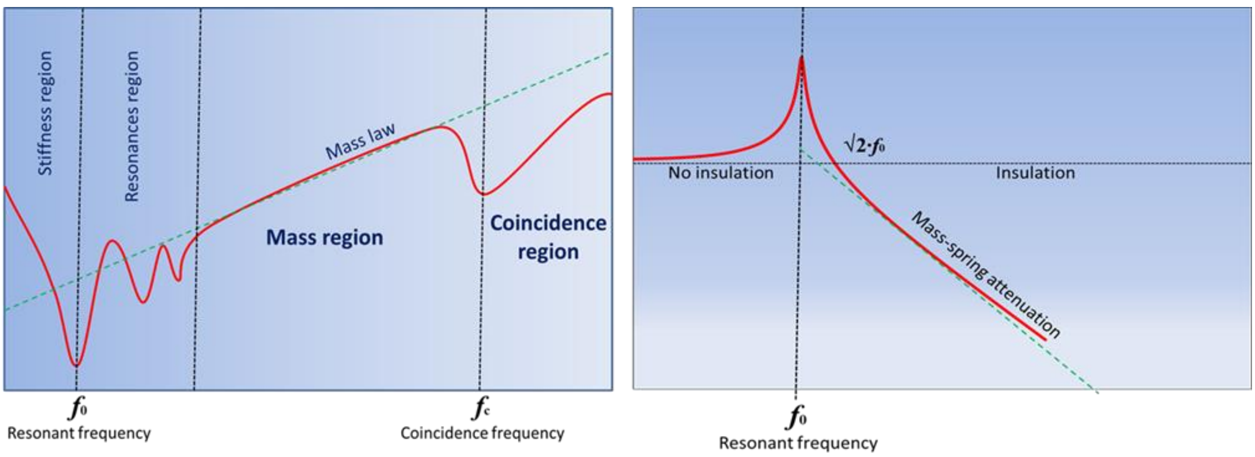

Figure 1: Typical graphs of air-borne sound insulation and structure-borne sound insulation behavior, as a function of frequency.

As a consequence, the actual quantification of the acoustical behavior, around the resonance frequency or below (in particular if the analysis is carried out in one-third octave bands), can provide inaccurate results. It follows that the systems currently used in building (except for some specific cases, such as *box in a box* systems for listening or recording studios, multiplex or seismic systems), do not significantly attenuate the sound pressure levels, in terms of sound insulation at low frequencies. By varying the properties of the used materials, increasing the mass, reducing the stiffness of additional layers or by introducing double walls, it is possible to improve the sound insulation, however, such constructive solutions are not always easily achievable.

2.1 Airborne sound insulation

The sound proofing efficiency of a partition, in particular in the low frequency region, depends on the mechanical properties of the materials used, i.e. elasticity (bending stiffness *B*), damping (in terms of loss factor η) and inertia (the mass *m*). In the graph of Figure 2 an example of experimental laboratory measurement of airborne sound insulation is reported. As it is possible to notice, the acoustical behavior of this system is relevant, R_w=63 dB. Obviously this is a peculiar partition, composed by heavy bricks (thickness 230 mm) finished on both surface by concrete (10 mm each layer) and an additional lying (55 mm), with a total mass per unit area of 414 kg/m^2.

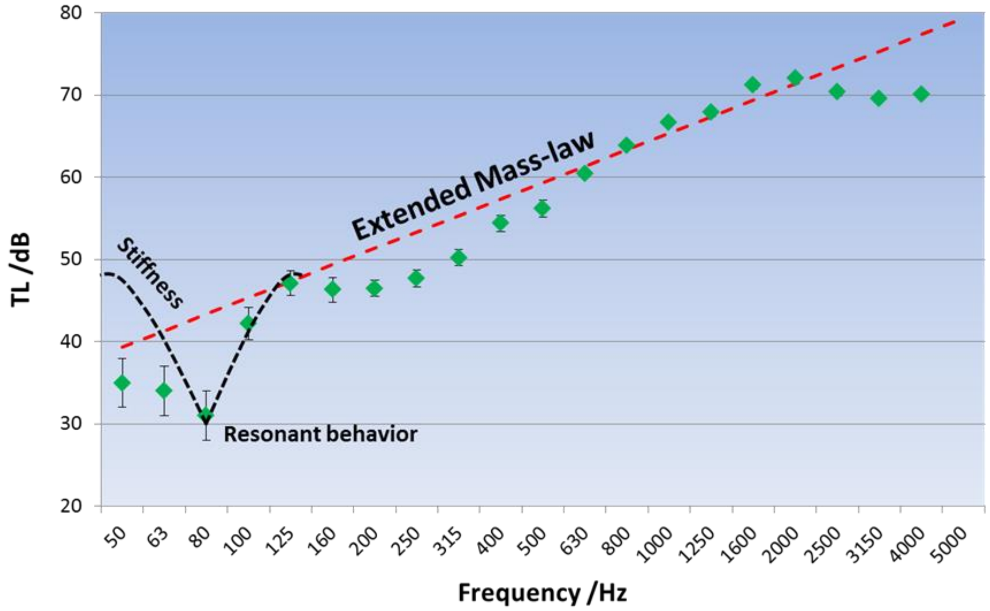

Figure 2: Typical graphs of experimental transmission loss (air-borne sound insulation, green marker) and stiffness, resonant and mass behavior (dotted lines), of a heavy brick wall.

The airborne sound insulation of the partition can be empirically estimated, e.g. on the basis of well-known relationships from Beranek and Fahy [14-15], in the stiffness controlled region ($f << f_0$), at the resonance ($f = f_0$) and in the mass controlled region ($f >> f_0$), as shown in Figure 2. Over the years the calculation models have been improved significantly (as a function of many different boundary conditions, involved materials and elements composition), nevertheless a first roughly estimation can be achieved on the basis of extended mass-law only:

$$R_m = 20\log m + 20\log f - 47 . \qquad (1)$$

where *m* is mass per unit area (kg/m^2) and *f* is frequency (Hz).

By using only relation (1) an overestimation of the airborne sound insulation of a partition is expected, in particular at low frequencies and around the resonance, but it is enough to clearly show that increasing sound insulation, below 100 Hz, is a difficult challenge in buildings. In order to achieve values of about 50 dB of sound reduction, between 50 Hz and 100 Hz, it is necessary to build a hypothetical partition with a mass per unit area of about 1200 kg/m^2. This value can be obtained by using a 50 cm thick monolithic concrete partition (ρ=2400 kg/m^3), or 70 cm thick monolithic brick partition (ρ=1700 kg/m^3); 70 cm thick monolithic concrete partition (ρ=2400 kg/m^3), or 100 cm thick monolithic brick partition (ρ=1700 kg/m^3), which allow improving sound insulation of about 3 dB.

As a matter of fact, taking into account the actual mechanical properties of concrete (i.e. E=20 GPa, B=1.04 GPa, ν=0.15, η=0.01) and brick (i.e. E=5 GPa, B=60 MPa, ν=0.2, η=0.01), the sound insulation, below 100 Hz of both hypothetical partitions, is of about 30 dB. Expected acoustical behavior, of such hypothetical partitions, is calculated on the basis of Fahy models (implemented by Matlab® software). In the graphs of Figure 3 the airborne sound insulations of the concrete partition (50 cm and 70 cm) and of the brick partition (70 cm and 100 cm) are shown.

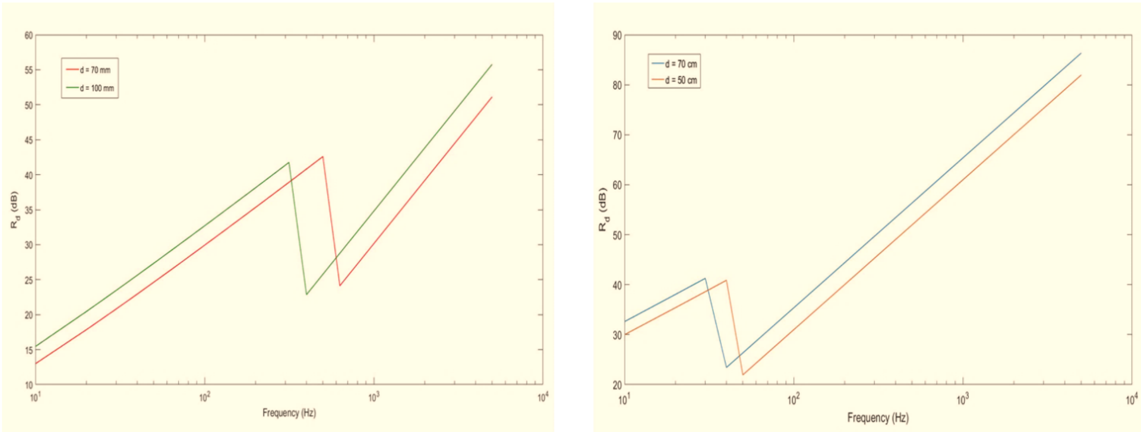

Figure 3: Simulation of heavy monolithic brick and concrete vertical partitions insulation.

2.2 Structure-borne sound insulation

The structure-borne sound insulation (impact noise), also depends on the mechanical properties of the materials involved in the partition, in particular on the mass and stiffness. One the most effective insulating systems for horizontal partition is the floating floor. This system acts as a mass-spring system and the insulation can be achieved in terms of force transmissibility. As a consequence it is possible to empirically evaluate the acoustical behavior of the floating floor, from the mechanical properties of the materials. In the graph of Figure 4, an example of laboratory measurement of the improvement of impact noise sound insulation, is shown.

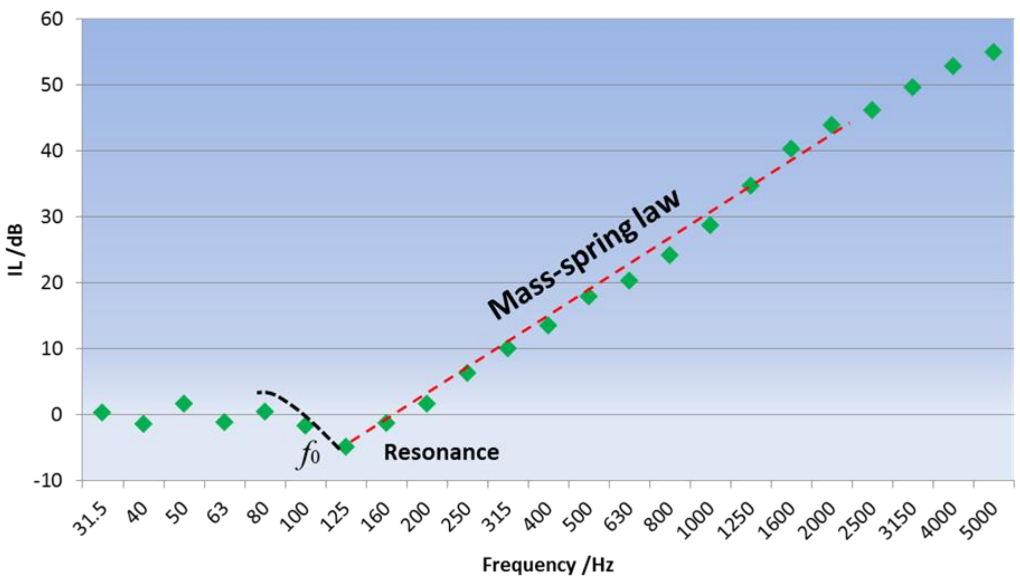

Figure 4: Impact noise insulation of a floating floor, as a function of frequency, and the sound pressure amplification near the resonance.

The laboratory measurement on the standard heavyweight base floor (ISO), with the floating slab mass (in concrete) of 109 kg/m^2 and the resilient layer (polyurethane foam 5 mm thick) of 115 MN/m^3 dynamic stiffness, entailed an improvement of impact sound insulation of ΔL=21 dB.

Impact noise sound reduction of a floating floor can be estimated on the basis of the following simple relation, according to Cremer [16]:

$$\Delta L = 30 \log \frac{f}{f_0} . \tag{2}$$

Where the resonance frequency f_0 of the floating floor only depends on the mass per unit area m' (kg/m^2) of the floating slab and on the dynamic stiffness s' (MN/m^3) of the resilient material used as an interlayer:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{s'}{m'}} . \tag{3}$$

As an example, in floating floors with highly performing elastic interlayers (dynamic stiffness between 15 and 50 MN/m^3 and floating mass of 100 kg/m^2), with low internal damping, the resonance of the system is between 50 Hz and 100 Hz. This implies that, below the resonance of the system, the whole input energy is transmitted and no sound insulation occurs.

In impact noise insulation is therefore difficult, from a technical point of view, to achieve a relevant sound insulation in the frequency range between 50 Hz and 100 Hz. Assuming to use a floating floor, in order to obtain a noise reduction value of about 50 dB, between 50 Hz and 100 Hz with a floating floor system, it is necessary to have a floating mass of about 1500 kg/m^2 united with a resilient material of about 0.1 MN/m^3 of stiffness. These values are only achievable with seismic systems, by using real springs. In the graph of Figure 5, it is shown the simulated comparison between the structure-borne sound insulations of the hypothetical above-mentioned floating floor (green line) and the actual floating floor insulation (red line). Black markers are experimental data.

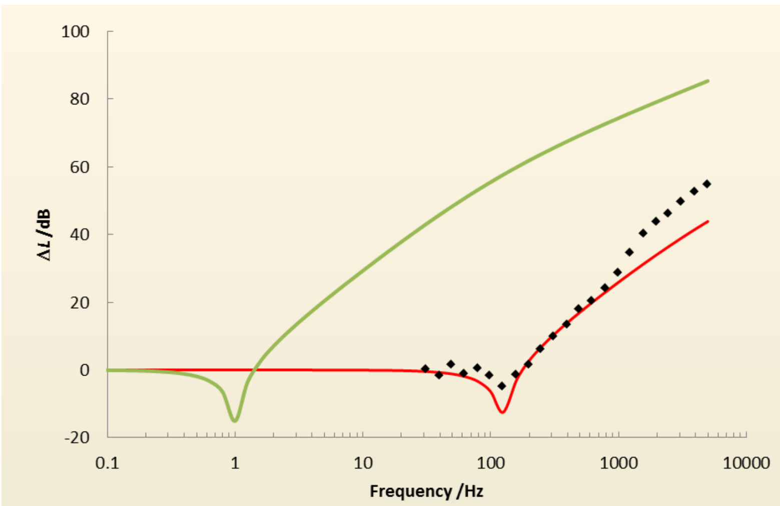

Figure 5: Simulation of floating floors insulation.

3. A brief review on sound insulation systems for low frequencies

In this section a brief literature survey is collected, for both airborne [17-21] and structure-borne [22-28] sound insulation at low frequency. In particular only recent experimental works are taken into account, at this stage. It is known that the availability of scientific papers regarding air-borne and structure-borne sound insulation is very huge, throughout the last 5 decades, nevertheless papers regarding actual material properties suitable for sound insulation at low frequency are less widespread. New building technology, involving traditional materials, such as brick, wood and stone, show interesting performances, in terms of climate comfort and thermal and acoustic insulation. It has to be said that brick and wood building components and materials, do not behave as monolithic partition, as a consequence computational models need to be improved, on the basis of new experimental evidences [29 - 32].

Some interesting result, also based on subjective evaluation, regards wood systems. For both airborne and structure-borne sound insulation, wood-based structures seem to guarantee a certain acoustical comfort, also at low frequencies. In Sweden, wood vertical partition with proper insulation systems, are considered good solutions. In South Korea several wood-based floor, united with very soft resilient materials, improve sound insulation also at low frequency. In Figure 6, examples of new wood technology in buildings are shown.

Figure 6: New wood building technology: on the left the awarded project by Cynthia Hsu, Justin Oh, Nicolas Kemper, Yale, School of Architecture, Course: Building Technology; on right the FMO (Finnforest Modular Office) Tapiola Building, Espoo, Finland.

Also heavy and hollow bricks, used as walls and base floor in dwellings in Mediterranean area and British Isles, have shown good acoustical performances at low frequency, with respect to monolithic and homogeneous systems. As a matter of facts, acoustical performances of inhomogeneous and anisotropic partitions, with systematic structural discontinuity (brick-concrete), allow to guarantee a certain comfort at low frequencies. Recent building technology, involving stones, shows promising features regarding thermal comfort [33], but no evidences of acoustical behavior are achieved. In Figure 7, two examples of recent building, involving ancient traditional materials, such bricks and stone, are shown.

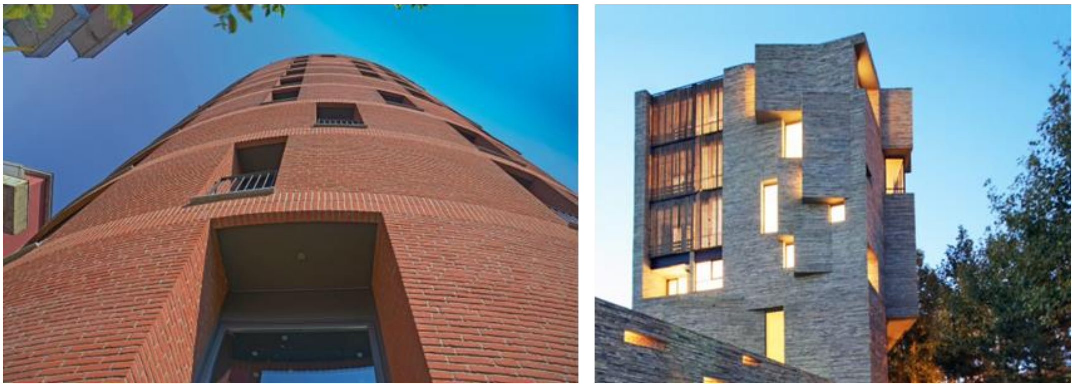

Figure 5: New brick and stone building technology: on the left Residential tower in Milano, by Barbieri & Negri; on right Recycled Stone in Mahallat, Iran.

Noise mitigation by using metamaterials [34 – 36] on large scale or sonic crystals [37], is nowadays a possible new frontier for sound insulation, but, at present day, this kind of technologies are not applied in building. Some attempt, by means of calculation models or small scale experiments (in impedance tube) suggest interesting perspective, but it is a research field not completely explored yet. Insulation properties of metamaterials and sonic crystals are attributed to the negative effective elastic constants during the mechanical vibration, thus realizing the total reflection of low-frequency sound and breaking the mass law.

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