ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

SOUND INSULATION OF LAYERED PANELS: COMPARISION OF EXPERIMENTAL AND THEORETICAL RESULTS

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Abstract

In this work, the authors compare experimental and theoretical results for the airborne sound insulation of lightweight layered walls. For this purpose a number of specimens have been tested in the laboratory. The tested specimens consisted of a single plasterboard wall, a double plasterboard wall with an empty air-gap, and double plasterboard walls with a layer of absorbing material inside their air-gap. In the last case, the air-gap was either partially or fully filled with rockwool, or partially filled with expanded cork agglomerate panels. All lab results are obtained according to ISO 140-3:1995.
The theoretical calculations are performed using analytical solutions that allow the assessment of airborne sound insulation provided by multi-layer systems. The model uses fundamental solutions obtained in the frequency domain for the case of general multi layer structures, built as a sequence of fluid and solid layers. It extends the expressions derived previously by the authors for the prediction of airborne sound insulation of single and double panels, excited by 1D, 2D or 3D sources. The interaction between the solid and the fluid layers is fully taken into account, and internal loss factors are considered.

INTRODUCTION

In recent years, the increasing weight of labor in construction costs has led the industry to search for solutions which minimize labor needs. In the last few decades, therefore, the use of lightweight partition walls has increased significantly. This type of solution has become the rule in interior walls of office buildings, and even in residential buildings these partitions have become the solution of choice in many countries. Besides the experimental characterization of these systems, the development of mathematical models that allow the prediction of their acoustic performance has been studied by researchers. This topic is of great importance in the design stage of these partitions, allowing designers to have a clear idea about the behaviour expected of different solutions without needing to perform expensive and time-consuming laboratory tests.

Sound-transmission through walls is a complex phenomenon, involving the propagation of both body and guided waves. Many researchers have already developed simplified numerical and analytical models to predict the behavior of various types of walls. The simplest approach to this problem comes from the so-called theoretical mass-law [1]. This technique assumes the element behaves as a group of infinite juxtaposed masses moving independently, with null damping forces.

If the wall is made of two different panels, separated by an air gap, it is then important to take into account the multiple resonances of sound waves within the air gap and the dynamic behavior of the wall-air-wall system. London [2] proposed a model to estimate the mass controlled sound transmission caused by the incidence of plane waves with frequencies below the critical frequency of the panels, for the case of a wall made of panels with the same mass. Beranek [3] modified this model to allow the mass-air-mass resonance effect to be taken into account. However, neither of these models caters for additional materials within the air gap. Recently, Mechel [4] published a useful compilation of methods to analyze the insertion loss provided by different types of walls. Some of these assume a thin plate behavior of the wall panels, thus making the mathematical formulation simpler.

More recently, work by the authors analyzed the acoustic insulation provided by single [5] and double panel [6] homogeneous walls, struck by plane and harmonic line pressure loads. This paper extends these earlier works so that the model can be used for a layered structure with any number of fluid and solid layers, with different thicknesses and material properties. This model takes into account the full coupling between all the layers of the partition wall and between the wall and the host fluid medium (air). Unlike models based on the Kirchoff and Mindlin theories, it does not impose any limitations on the thickness of the layers involved. Using this model, the insertion loss of any given layered structure excited by incident plane, cylindrical or spherical waves may be computed.

In the work described here, the authors present an extension of the above model [5,6] for a general system made of solid and fluid layers, and compare the theoretical results it provides with experimental curves obtained for a number of lightweight standalone partitions. All the tested solutions are made of one or two plasterboard panels, and, in some cases, an additional layer of an absorbing material is inserted between the two panels. Two different absorbing materials are tested: rockwool and cork. All the laboratory tests were conducted in compliance with the ISO 140-3:1995 standard.

The paper is organized as follows: first, a brief description of the analytical model and its mathematical formulation is presented; this is followed by an explanation of the experimental procedures followed; the experimental results obtained for a number of configurations are then presented and compared with those predicted by the analytical model and by the mass law.

MATHEMATICAL FORMULATION

Consider a partition wall of infinite extent built from a series of fluid and solid layers with different thicknesses and properties, bounded by a homogenous fluid medium and excited by a spatially sinusoidal harmonic pressure load located in the host fluid at (x_0, y_0), as represented in Figure 1.

The incident field generated by this source can be defined by

$$\sigma^{full} = -\frac{\mathrm{i}}{2}\mathrm{H}_0^{(2)}\left[k_{\alpha f_{\sup}}\sqrt{(x-x_0)^2+(y-y_0)^2}\right] \text{ with } \mathrm{Im}\,k_{\alpha f_{\sup}} \le 0 \qquad (1)$$

with $\mathrm{H}_0^{(2)}(...)$ being second Hankel functions of order 0, $k_{\alpha f_{\sup}} = \sqrt{{k_{f_{\sup}}}^2 - {k_z}^2}$, $k_{f_{\sup}} = \omega / \alpha^{f_{\sup}}$, $\alpha^{f_{\sup}}$ being the acoustic wave velocity of the host fluid medium, ω the excitation frequency, $\mathrm{i} = \sqrt{-1}$ and k_z being the wavenumber in the z direction. In the presence of a partition wall, the total pressure field in the host medium can be expressed as the sum of the incident field with the surface terms needed to satisfy the continuity of normal displacements and stresses, and null tangential stress conditions at all fluid-solid interfaces, and the continuity of stresses and displacements along the solid-solid interfaces.

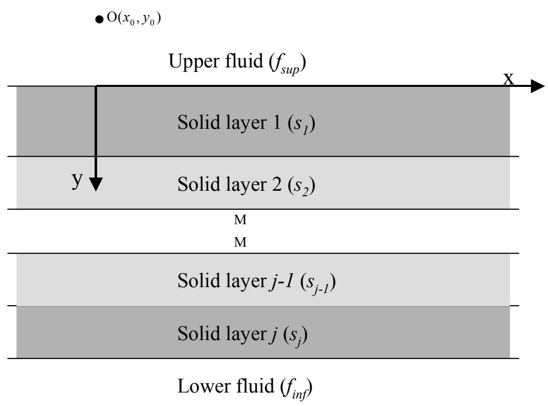

Figure 1 - Geometry of the problem.

For this purpose, σ^{full} may be expressed as a superposition of plane waves, following the methodology presented in earlier work [9], as

$$\sigma^{full} = -\frac{\mathrm{i}}{L_x}\sum_{n=-N}^{n=+N}\left[\frac{E_f}{\nu_n^{f_{\sup}}}\right]E_d\,, \qquad (2)$$

where $E_d = e^{-\mathrm{i}k_n(x-x_0)}$, $k_n = \frac{2\pi}{L_x}n$, $E_f = e^{-i\nu_n^{f_{\sup}}|y-y_0|}$, and $\nu_n^{f_{\sup}} = \sqrt{{k_{f_{\sup}}}^2 - {k_z}^2 - {k_n}^2}$ with $\mathrm{Im}\left(\nu_n^{f_{\sup}}\right) \le 0$. Note that this summation corresponds to discretizing a continuous integral, assuming the existence of an infinite number of virtual sources placed along the x direction at equal intervals, L_x [10]. The distance L_x must be large enough to prevent the virtual loads from contaminating the response.

Similarly, the pressure field in the fluid media outside the wall structure, due to a spatially sinusoidal harmonic pressure load applied in the top fluid, can be expressed as a superposition of plane waves using the expressions

$$\sigma^{f_{\sup}} = \sigma^{full} - \frac{\mathrm{i}}{L_x}\sum_{n=-N}^{n=+N}\left[\frac{E_f^{f_{\sup}}}{\nu_n^{f_{\sup}}} A_n^{f_{\sup}}\right] E_d \quad (\text{when } y < 0)$$

$$\sigma^{f_{\inf}} = -\frac{\mathrm{i}}{L_x}\sum_{n=-N}^{n=+N}\left[\frac{E_f^{f_{\inf}}}{\nu_n^{f_{\inf}}} A_n^{f_{\inf}}\right] E_d \quad (\text{when } y > h) \tag{3}$$

where h is the total thickness of the wall structure, $E_f^{f_{\sup}} = e^{-\mathrm{i}\nu_n^{f_{\sup}}|y|}$, $E_f^{f_{\inf}} = e^{-\mathrm{i}\nu_n^{f_{\inf}}|y-h|}$, $\nu_n^{f_{\inf}} = \sqrt{k_{f_{\inf}}{}^2 - k_z{}^2 - k_n{}^2}$ with $\mathrm{Im}\left(\nu_n^{f_{\inf}}\right) \le 0$, $k_{f_{\inf}} = \omega / \alpha^{f_{\inf}}$, $\alpha^{f_{\inf}}$ is the acoustic wave velocity allowed in the bottom fluid medium. $A_n^{f_{\sup}}$ and $A_n^{f_{\inf}}$ are (so far) unknown potential coefficients. To compute their values the required boundary conditions must be imposed. For this, potentials for each material interface must be used, as explained in [6], yielding a system of n equations, with $n = 2 + 2n_f + 6n_s$ (where n_s and n_f are the number of solid and fluid layers in the wall structure, respectively).

It is possible to take into account the internal material losses by introducing a complex Young's modulus and complex Lamé constants. This complex Young's modulus is calculated as $E = E_r(1 + \mathrm{i}\eta)$, with E_r corresponding to the classic modulus and η being the material loss factor. In a fluid medium, these losses may be introduced by using a similar procedure to calculate a complex Lamé constant.

To account for the sound absorption provided by some materials used inside the air-gap of double walls, such as rockwool or mineral wool, the model proposed by Fahy [7] can be adopted. This model proposes a complex density for the layer of absorbing material, given by $\rho' = s\rho\vartheta - \mathrm{i}\sigma/\omega$, where ρ is the density of the fluid filling the air-gap, s is a factor that accounts for the internal structure of the material, ϑ is the porosity and σ the flow resistivity.

Using the above formulation, the airborne sound insulation provided by a general layered wall may be computed by the following procedure: the sound pressure level is first computed in two sets of receivers, placed on each side of the wall; then, the airborne sound insulation at each frequency is calculated as the difference between the average sound pressure levels in the emitter medium and the receiver medium.

EXPERIMENTAL PROCEDURES

All laboratory tests were conducted in the Department of Civil Engineering of the University of Coimbra, in two contiguous acoustic chambers with volumes of 110 m^3 (receiving chamber) and 100 m^3 (emitting chamber). The airborne sound insulation curve was determined following the procedures indicated in the ISO 140-3:1995 and ISO 354:2003 standards, while the airborne sound insulation rating, R_w, was determined using ISO 717-1. In all cases presented in this paper, the frequency domain is divided into 1/3 octave bands, ranging from 100 Hz to 4000 Hz.

AIRBORNE SOUND INSULATION RESULTS

To validate the analytical model proposed, lightweight partition solutions have been experimentally tested in the laboratory. The tested partitions correspond to constructive solutions that are currently used in building construction. All of these involve plasterboard, and in some cases an additional layer of absorbing material has been used.

Five different standalone partitions have been analyzed theoretically and tested in the laboratory, using test specimens with an area of 10 m^2. These partitions consisted of:

A. A single plasterboard panel 15 mm thick, with a density of 800 kg/m^3, attached to a structure of metal studs;
B. A double wall made of two plasterboard panels 15 mm thick, and with a density of 800 kg/m^3, both attached to a structure of metal studs, which separated them by 70mm.
C. A double wall, as in (B), with 40 mm of rockwool, with a density of 40 kg/m^3 partially filling its air gap;
D. A double wall, as in (B), with 70mm of rockwool, with a density of 40 kg/m^3 completely filling its air gap;
E. A double wall, as in (B), with 30mm of expanded cork agglomerate, with a density of 120 kg/m^3, partially filling its air gap.

To model these partitions, a number of mechanical and physical properties for each material involved must be known. For the present study, the properties ascribed to each material were based both on information provided by the manufacturers and on the values proposed in [4]. For plasterboard and rockwool, these properties are as follows:

- Plasterboard:
  Shear modulus: μ=1276 MPa;
  Poisson modulus: ν=0.262;
  Density: ρ=800 kg/m^3.
- Rockwool:
  Density: ρ=40 kg/m^3;
  Flow resistivity: σ=1300 $kg.m^{-3}.s^{-1}$.

For the case of expanded cork agglomerate, the approximate elastic properties of the material can also be found in the specialized literature, with a proposed density of 120 kg/m^3, a null Poisson modulus and a shear modulus of 7.5 MPa. However, for this specific case, the behaviour of the material can be rather complex. In fact, as it is partially filling the air-gap between plasterboard panels, its surface properties make it act as an absorbing material inside an air-gap, while its density and stiffness allow a behaviour close to that of a solid layer. To account for these distinct behaviours, the authors propose that the 30 mm of expanded cork agglomerate is modelled as two different layers:

- one layer of elastic material 20 mm thick, with the density, and shear and Poisson modulus given before;
- one fluid layer 10 mm thick, with the density of air (1.22 kg/m^3) and with a flow resistivity of 600 kg.m^{-3}.s^{-1}.

The results computed for the above configurations are shown in Figure 2.

The results shown reveal that, for all cases, there is a good approximation between the solution provided by the proposed analytical model and the experimental results, obtained in the laboratory. The analytical model can reproduce the shape of the sound insulation curve quite closely, clearly identifying the presence of a dip in the insulation curve in the same frequency zone as for the experimental results. By contrast, for all cases the theoretical mass-law (R=20.Log(m.f)-47 dB) is clearly unable to provide a usable estimate for the sound insulation across the frequency domain.

For the case of partitions A and B (without any absorbing materials) the predicted curves have a similar evolution, with the sound insulation growing as the frequency increases, up to the so-called coincidence frequency. At this point, a dip is visible in these curves, after which the insulation starts increasing. For the case of partitions C and D, the computed curves reveal higher values of airborne sound insulation, demonstrating the absorbing effect of the rockwool placed inside the air-gap. This behaviour shows that the model correctly accounts for the presence of the rockwool, although the predicted insulation between 500 Hz and 2000 Hz seems to be slightly higher than the experimental values. Analyzing the results for partition E, one can conclude that the predicted curve is also closely following the experimental results up to the coincidence frequency. However, after this frequency, the sound insulation predicted by the analytical model increases very rapidly, a behavior which is not observed in the experimental curve.

It is also important to note that, although the coincidence effect is correctly predicted for all configurations, the amplitude of the corresponding insulation dip differs from the experimental observations. This can be explained by the difference between the support conditions of the test specimens in the laboratory and the analytical model. As explained before, these specimens were mounted on a structure of metal studs, spaced 0.6 m from each other, while the analytical model assumes the plasterboard panels to be infinite, allowing the full development of guided waves which propagate along the panel.

In current engineering practice, the quality of a partition in terms of airborne sound insulation is, in many cases, measured by the airborne sound insulation rating, R_W. This parameter has been estimated for the curves computed for the analytical model and for the experimental results. The results, shown in Table 1, confirm the proximity between the theoretical and the experimental results, indicating differences of no more than 2 dB between them.

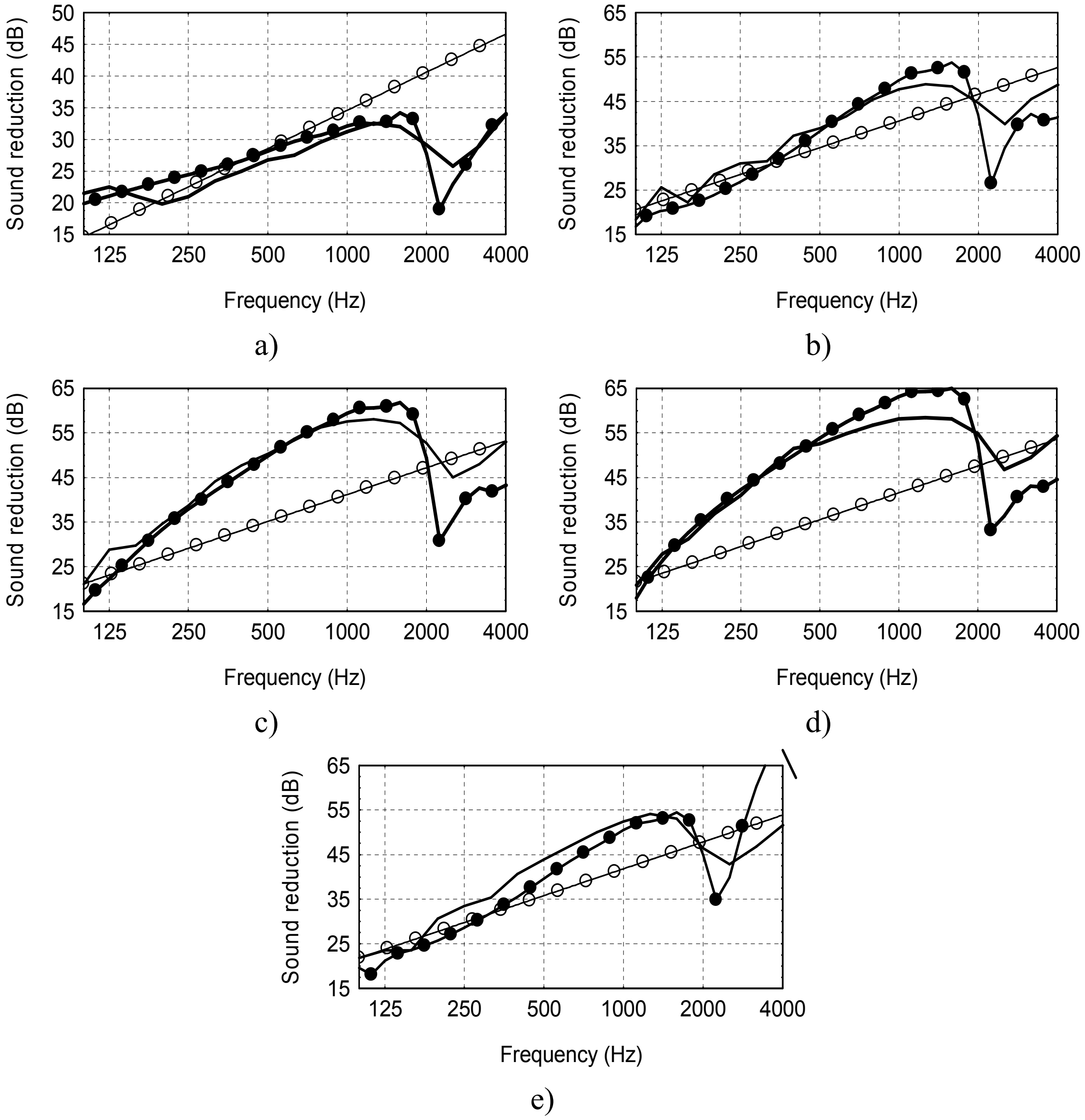

Figure 2 – Comparison between experimental results (——), analytical model (●–●) and the mass law (○–○): a) partition A; b) partition B; c) partition C; d) partition D, e) partition E.

Table 1 – Sound reduction index (Dn,w) for the tested partitions.

Partition	R_w (dB) (analytical model)	R_w (dB) (experimental)
A	30	29
B	38	40
C	40	41
D	43	45
E	45	47

CONCLUSIONS

A comparison between theoretical predictions and experimental results for a number of lightweight partitions has been presented.

An analytical model, based on wave propagation theory for layered media, has been described and used to model the acoustic behavior of the partitions. To validate this model, partitions consisting of plasterboard panels mounted on metal studs, with and without absorbing material in the air-gap, have been built and tested in the laboratory.

Comparing the theoretical and experimental results we find that the proposed model was able to predict the behavior of the different partitions correctly, and indicate that it may be a good option for estimating the airborne sound insulation provided by lightweight solutions.

ACKNOWLEDGEMENTS

The authors thank the Foundation for Science and Technology, Portugal, for the financial support granted through project POCI/ECM/55889/2004.

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