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Improvement of the prediction of transmission loss of double partitions with cavity absorption by minimization techniques

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Abstract

In this paper, a method based on the minimization of a quadratic error function is used as a tool to improve the predictions of noise transmission loss, and it is applied to the case of a double partition filled with an absorbent material. When experimental results are available, the method can be used to determine the value of the parameters of the materials composing the structure.

1. Introduction

The prediction of the transmission loss of air noise through a multi-layer partition is an important subject, with important applications in the field of building acoustics. At present, there are several theories developed for the prediction of the transmission loss of different multi-layer configurations. In the seminal paper [1] the case of normal incidence on a multiple-layer configuration was modelled. Later, London [2] introduced the diffuse field approximation in these studies, generalizing to the case of oblique incidence, and Mullholland et al. [3] proposed a limit angle condition for the applicability of the diffuse field approximation.

In practice, the modelling of the transmission loss of a given configuration is only possible once the mechanical and acoustical parameters of each element in the structure are known. In Refs. [4–7] the prediction of transmission losses was performed considering different characteristics of the layers in diffuse field approximation. The numerical values of the parameters characterizing the acoustic behaviour of the impervious layer and the absorbent material can be taken from a number of tables, obtained from experimental measurements [8–11]. However, in most of the

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cases only average values of the parameters are available. For a closer agreement between the theoretical models and the experimental results, in particular those referring to the prediction of the transmission loss, it is desirable to deal with material parameters with values closer to their real ones. This is actually one of the main causes of disagreement between the theoretical predictions and the measurements of the transmission loss. Then, in order to improve the predicted results, the parameters characterizing the different materials forming the structure must be accurately evaluated.

In this paper, a minimization method is proposed for the determination of material parameters, which subsequently provides an improvement of the prediction loss of a layered configuration. The starting point of this analysis is the theoretical model proposed by Trochidis and Kalaroutis [12]. Using this model, together with experimental measurements, a quadratic error function is defined in order to find the parameters that minimize the error. The results obtained with this method are compared with others presented in Refs. [6,12], showing the efficiency of the proposed method.

2. Theoretical model

2.1. Model of Trochidis and Kalaroutis

The system considered in Ref. [12] is shown in Fig. 1. It consists of two infinite and uncoupled thin, elastic layers, whose inner space is filled with an absorbent material. Similar configurations have been considered in Refs. [13,14].

The structure is excited with a plane sound wave, with pressure $p_{in}(x,z)$, which impinges on the first layer at an angle θ. It is assumed that the time dependence is harmonic, with an angle frequency ω. The theoretical model for this system was derived in Ref. [12]. In this section the main results are reviewed.

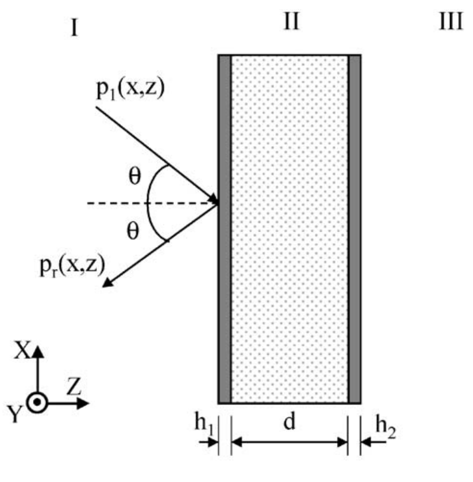

Fig. 1. Configuration studied by Trochidis and Kalaroutis [12].

The system can be divided in three regions I–III, separated by the layers. The propagation of the sound field in each region is described by the scalar Helmholtz equation

$$(\nabla^2 + k_0^2)p_{\mathrm{I}}(x,z) = 0, \quad z<0, \tag{1}$$

$$(\nabla^2 + k_b^2)p_{\mathrm{II}}(x,z) = 0, \quad h_1<z<d+h_1, \tag{2}$$

$$(\nabla^2 + k_0^2)p_{\mathrm{III}}(x,z) = 0, \quad z>d+h_1+h_2, \tag{3}$$

where $k_0 = \omega/c_0$ is the acoustic wavenumber, and k_b is a complex wavenumber describing the propagation in the absorbing material, with complex density ρ_b. This complex wavenumber is defined as $\mathrm{j}k_b = \Gamma = \alpha + \mathrm{j}\beta$, where Γ is the material propagation constant. Several authors work on the characterization of absorbing materials, and empirical formulas for the evaluation of k_b have been proposed by, e.g., Delany and Bazley [10], Miki [15], Allard and Champoux [16] or Voronina [11]. Thus, the propagation constant can be obtained from any of these models. The total pressure in zone I is given by $p_{\mathrm{I}}(x,z) = p_{in}(x,z) + p_r(x,z)$.

Together with Eqs. (1)–(3), the equation of movement of the layers must be considered, given by

$$(D_1\nabla^4 - \rho_1 h_1\omega^2)w_1(x) = p_{\mathrm{I}}(x,0) - p_{\mathrm{II}}(x,h_1), \tag{4}$$

$$(D_2\nabla^4 - \rho_2 h_2\omega^2)w_2(x) = -p_{\mathrm{III}}(x,d+h_1+h_2) + p_{\mathrm{II}}(x,d+h_1), \tag{5}$$

where $w_n(x)$ is the displacement of the layer on its normal direction ($n = 1,2$), ρ_n is the density of the layer material, h_n is the layer thickness, D_n is the bending stiffness of the layer and $p_{\mathrm{II}}\ (x,z)$ is the pressure in the acoustic absorbent material. The loss factor η is introduced through the complex Young's module, defined as $E'_n = E_n(1 + \mathrm{j}\eta_n)$. Since D_n is proportional to E_n, then the layers can be characterized by a complex bending stiffness $D'_n = D_n(1 + \mathrm{j}\eta_n)$. In the following the primes are omitted, and it is assumed that D_n is a complex quantity.

Considering that the absorbent material is in perfect contact with both layers, the boundary conditions are, at the first layer,

$$\left|\frac{\partial p_{\mathrm{I}}}{\partial z}\right|_{z=0} = \rho_0\omega^2 w_1(x), \quad \left|\frac{\partial p_{\mathrm{II}}}{\partial z}\right|_{z=h_1} = \rho_b\omega^2 w_1(x) \tag{6}$$

and at the second layer

$$\left|\frac{\partial p_{\mathrm{II}}}{\partial z}\right|_{z=d+h_1} = \rho_b\omega^2 w_2(x), \quad \left|\frac{\partial p_{\mathrm{III}}}{\partial z}\right|_{z=d+h_1+h_2} = \rho_0\omega^2 w_2(x). \tag{7}$$

The complex density appearing in Eqs. (6) and (7) relates to the complex wavenumber through the expression

$$\frac{k_b^2}{k_0^2} = \frac{\gamma\sigma\rho_b}{\rho_0}, \tag{8}$$

where γ is the specific heats ratio, σ is the porosity and ρ_0 the air density.

The system of differential equations obtained allows one to find the value of the transmitted pressure, and from it, the transmission loss of the configuration. The solution can be found numerically after a Fourier transform in the propagation variable x is performed [12]. Consider the following transformations:

$$w_n(x) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} w_n(s)\mathrm{e}^{-\,\mathrm{j}sx}\,\mathrm{d}s, \quad n = 1, 2, \tag{9}$$

$$P_{\mathrm{I}}(x,z) = P_{in}(x,z) + P_r(x,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} [\mathrm{P}_{in}(s)\mathrm{e}^{az} + \mathrm{P}_r(s)\mathrm{e}^{-az}]\mathrm{e}^{-\,\mathrm{j}sx}\,\mathrm{d}s, \tag{10}$$

$$P_{\mathrm{II}}(x,z) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} (A(s)\cos bz + B(s)\sin bz)\mathrm{e}^{-\,\mathrm{j}sx}\,\mathrm{d}s, \tag{11}$$

$$p_{\mathrm{III}}(x,z) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} p_t(s)\mathrm{e}^{az}\,\mathrm{e}^{-\,\mathrm{j}sx}\,\mathrm{d}s, \tag{12}$$

where the transformation variables are defined as $a = \sqrt{s^2 - k_0^2}$ and $b = \sqrt{k_b^2 - s^2}$.

The system formed by Eqs. (3) and (6), together with the boundary conditions (6) and (7) can be now expressed as algebraic relations, in the form

$$(D_1 s^4 - \rho_1 h_1 \omega^2)w_1 = p_{in} + p_r - A\cos(bh_1) - B\sin(bh_1), \tag{13}$$

$$(D_2 s^4 - \rho_2 h_2 \omega^2)w_2 = A\cos(b(h_1 + d)) + B\sin(b(h_1 + d)) - p_t\mathrm{e}^{a(h_1+h_2+d)}, \tag{14}$$

$$a(p_{in} - p_r) = \rho_0\omega^2 w_1, \tag{15}$$

$$b[-A\sin(bh_1) + B\cos(bh_1)] = \rho_b\omega^2 w_1, \tag{16}$$

$$b[-A\sin(b(h_1 + d)) + B\cos(b(h_1 + d))] = \rho_b\omega^2 w_2, \tag{17}$$

$$ap_t\mathrm{e}^{a(h_1+h_2+d)} = \rho_0\omega^2 w_2. \tag{18}$$

Eqs. (13)–(18) constitute the model from which the transmitted pressure can be obtained. However, for the numerical analysis it is convenient to write system (13)–(18) in the matrix form $\mathbf{MX} = \mathbf{B}$, where $\mathbf{X} = (p_r, w_1, A, B, w_2, p_t)^{\mathrm{T}}$, $\mathbf{B} = (ap_{in}, p_{in}, 0, 0, 0, 0)^{\mathrm{T}}$ and the matrix $\mathbf{M}$ defined as

$$\mathbf{M} = \begin{pmatrix} a & \rho_0\omega^2 & 0 & 0 & 0 & 0 \\ -1 & D_1 s^4 - \rho_1 h_1\omega^2 & \cos bh_1 & \sin bh_1 & 0 & 0 \\ 0 & -\rho_b\omega^2 & -b\sin bh_1 & b\cos bh_1 & 0 & 0 \\ 0 & 0 & -b\sin(b(h_1+d)) & b\cos(b(h_1+d)) & -\rho_b\omega^2 & 0 \\ 0 & 0 & -\cos(b(h_1+d)) & -\sin(b(h_1+d)) & D_2 s^4 - \rho_2 h_2\omega^2 & \mathrm{e}^{a(h_1+h_2+d)} \\ 0 & 0 & 0 & 0 & \rho_0\omega^2 & -a\mathrm{e}^{a(h_1+h_2+d)} \end{pmatrix} \tag{19}$$

whose unknowns are the reflected pressure, p_r, the layer displacements, w_1 and w_2, the pressure wave generated in the chamber and modelled by A and B as defined in Eq. (11), and the transmitted pressure p_t. The number of unknowns of the system could be reduced to w_1, w_2, A and B by using Eqs. (15) and (18), which relate p_t and p_r with w_2 and w_1, respectively. However, since the matrix **M** is sparse, the added computational cost is not high. Hence the number of unknowns in X is maintained.

Once the transmitted pressure is found, the transmission coefficient for a wave incident at an angle θ can be obtained from the relation

$$\tau(\theta) = \left|\frac{p_t}{p_{in}}\right|^2. \tag{20}$$

Note that, for the plane wave considered, the angle of incidence θ relates to the variables s and a of the spatial Fourier transform as $s = k_0 \sin\theta$, and $a = \mathrm{j}k_0 \cos\theta$.

Finally, if the incident pressure field verifies the diffuse field condition [3], typical for most realistic situations, the total transmittivity can be obtained from the integral formula

$$\tau_d = \frac{\int_0^{\theta_{\lim}} \tau(\theta)\cos\theta \sin\theta \, \mathrm{d}\theta}{\int_0^{\theta_{\lim}} \cos\theta \sin\theta \, \mathrm{d}\theta}, \tag{21}$$

where $\theta_{\lim}$ represents the limit angle past which the contribution of the sound field is considered negligible [12]. From Eq. (21), the transmission loss can be obtained from

$$TL = -10 \log \tau_d. \tag{22}$$

2.2. Error function and minimization procedure

When the values of the parameters characterizing the layers and the absorbent material are known, the previous model can be used to predict the transmission loss of the partition. Alternatively, when experimental values of the transmission loss are available, the model can be used to obtain the system parameters which give the best agreement between the theory and the experimental results.

These optimal parameters can be obtained by introducing a quadratic error function, ε, defined as [17]

$$\varepsilon = \sum_{i=1}^{N} (\tau_i - \hat{\tau}_i)^2, \tag{23}$$

where τ_i represents the value of the transmission coefficient obtained from the experimental measurements at the ith frequency and $\hat{\tau}_i$ is the theoretical value which follows from the equation obtained for the transmission coefficient in the diffuse field approximation. The minimization of the error function requires the evaluation of partial derivatives with respect to the parameters to optimize and to equate them to zero [18,19]. Such parameters, appearing in Eq. (19), are the following:

(a) Volumetric density ρ_j and thickness h_j of the layers. These values are often precisely known from measurements, and can be considered as constants in the minimization procedure.

(b) Bending stiffness D_j and loss factor η_j of the layers. These parameters, although they can be found in different tables, usually have different values in the bibliography [6,9,12]. Thus, there exists an uncertainty in the results obtained from the model based on concrete values of material parameters from previous studies. In this case, it is claimed that the optimal values of these parameters (those giving predictions closer to the experimental measurements) can be obtained from the theoretical model, as those satisfying the following conditions:

$$\frac{\partial \varepsilon}{\partial D_j} = 2\sum_{i=1}^{N} (\tau_i - \hat{\tau}_i)\frac{\partial \hat{\tau}_i}{\partial D_j} = 0, \tag{24}$$

$$\frac{\partial \varepsilon}{\partial \eta_j} = 2\sum_{i=1}^{N} (\tau_i - \hat{\tau}_i)\frac{\partial \hat{\tau}_i}{\partial \eta_j} = 0. \tag{25}$$

Note also that different authors assign different values for the loss factors, depending on the boundary conditions [20].

(c) The absorbent material in the inner part of the partition can be described by means of the complex wavenumber k_b or, alternatively, by means of the complex density ρ_b, both frequency-dependent and related through Eq. (8). In the case in which the absorbent is a fibrous material (as is commonly considered in most of the practical applications), several authors have proposed formulas relating the complex wavenumber with the flow resistance of the material R, and the frequency f of the incident sound, both being real valued. These formulas are valid only in a finite frequency range. In the following discussion the absorbent material as described by its flow resistance R is considered, making use of different models in order to compare the obtained results. In particular, the following three absorption models are considered:

(a) Delany and Bazley [10] derived the following formula from the adjustment to experimental measurements:

$$k_b = \frac{2\pi f}{c_0}\left[1 + 0.0978\left(\frac{\rho_0 f}{R}\right)^{-0.754} - \mathrm{j}0.189\left(\frac{\rho_0 f}{R}\right)^{-0.595}\right] \tag{26}$$

whose applicability is limited to frequencies in the range [16]

$$0.04 \leqslant \frac{f}{R} \leqslant 1. \tag{27}$$

(b) Following a similar technique, Miki [15] proposed the relation

$$k_b = \frac{2\pi f}{c_0}\left[1 + 0.109\left(\frac{\rho_0 f}{R}\right)^{-0.618} - \mathrm{j}0.160\left(\frac{\rho_0 f}{R}\right)^{-0.618}\right] \tag{28}$$

applicable in the same frequency range as Eq. (26).

(c) Finally, Allard and Champoux [16] derived an expression for the material parameters, in terms of the physical quantities ρ and K, corresponding to the dynamic density and the effective compressibility modulus, corresponding to

$$k_b = 2\pi f\sqrt{\frac{\rho}{K}}, \tag{29}$$

where the values ρ and K are given by

$$\rho = 1.2 + \sqrt{-0.0364\left(\frac{\rho_0 f}{R}\right)^{-2} - \mathrm{j}0.1144\left(\frac{\rho_0 f}{R}\right)^{-1}}, \tag{30}$$

$$K = 101320\,\frac{29.64j + \sqrt{2.82\left(\frac{\rho_0 f}{R}\right)^{-2} + \mathrm{j}24.9\left(\frac{\rho_0 f}{R}\right)^{-1}}}{21.17j + \sqrt{2.82\left(\frac{\rho_0 f}{R}\right)^{-2} + \mathrm{j}24.9\left(\frac{\rho_0 f}{R}\right)^{-1}}}. \tag{31}$$

This model is applicable whenever the frequencies are in the range

$$\frac{f}{R} \leqslant 1, \tag{32}$$

i.e., there is no restriction at low frequencies in this case.

The flow resistance R can be obtained by solving the following differential equation:

$$\frac{\partial \varepsilon}{\partial R} = 2\sum_{i=1}^{N} (\tau_i - \hat{\tau}_i)\frac{\partial \hat{\tau}_i}{\partial R} = 0 \tag{33}$$

which, together with Eqs. (24) and (25), is evaluated for the three different models described above, thus obtaining different predictions in the function of the particular model used.

Eqs. (24), (25) and (33) constitute a system of non-linear equations whose resolution allows one to obtain, therefore, the bending stiffness values D_1 and D_2, the loss factors η_1 and η_2 of the layers and the flow resistance R of the absorbent material that minimize the error function. The complexity of the system suggests the application of an iterative method of resolution of non-linear systems. In the case of a symmetrical configuration, that is, when both layers are identical, the system can be simplified to only three equations.

3. Numerical results

Several iterative methods have been used to obtain the optimal parameters which minimize the error function. For this purpose, a Matlab program was used [18]. Among the gradient-based methods considered, the method of Broyden [18,19] was the one which offered the highest convergence velocity towards satisfactory solutions. Furthermore, this method has as the advantage to avoid to evaluate the Jacobian, thus reducing the computation time. Other methods based on the gradient, such as the Newton method, also converge to the same solutions, but on the contrary, the evaluation of the Jacobian slows down calculations. A more extensive discussion regarding the convergence and the stability of these methods can be found in Ref. [19].

In the studied cases, all the methods converged faster when the input (initial) data were closer to the searched solution, the convergence times of the methods being similar. Care must be taken with the choice of the initial values, since due to the non-linear character of the equations, the iterative algorithm employed for the resolution can converge to wrong solutions. To avoid this problem the initial values for the iteration were chosen close enough to the expected solution. These values can be inferred from the literature, such us in the case of the bending stiffness parameter (varying in a broad range depending on the material) or the loss parameter, whose value was taken as $\eta = 0.015$ [20]. In the case of the flow resistance, the results are not sensible to the value chosen (being it positive).

The implemented methods show convergence problems only when the value of the flow resistance is very high (of the order of 10^6 Rayls/m), or when the loss factor is larger than unity, owing to the bad conditioning of the matrices that appear in the recursive calculation. These problems were absent since the initial data were much smaller than these values. In those cases, however, the Simplex method [18,19] gives satisfactory results.

Next, the results obtained after the numerical solving of the model for a double-leaf partition containing different absorbent materials are presented: a gypsum board (Fig. 2), a steel board (Fig. 3) and a plywood panel (Fig. 4). In the figures, the results obtained for the transmission loss at different frequencies are shown together with the experimental data taken from Ref. [12] (in the case of Fig. 2) and [6] (in the case of Figs. 3 and 4). In every case, the transmission loss was evaluated with the use of the three different models for absorbent materials in terms of the flow resistance R, and in the figures are represented by symbols.

Corresponding to these figures, the Tables 1–3 show the numerical values of the material parameters which minimize the error, together with the average error value and the frequency ranges in which the models for absorbent materials are applicable, also for the three different models of absorption.

In a symmetric configuration, the error function corresponds to a three-dimensional surface. Fixing one of the parameters, it is possible to represent graphically the error as a function of the other two parameters. This is shown in Fig. 5 for fixed flow resistance R (Fig. 5a) and for fixed bending stiffness D (Fig. 5b), where the minimum value is appreciated. The plots were obtained for the case of the double-leaf gypsum board partition, using the Trochidis and Kalaroutis theory

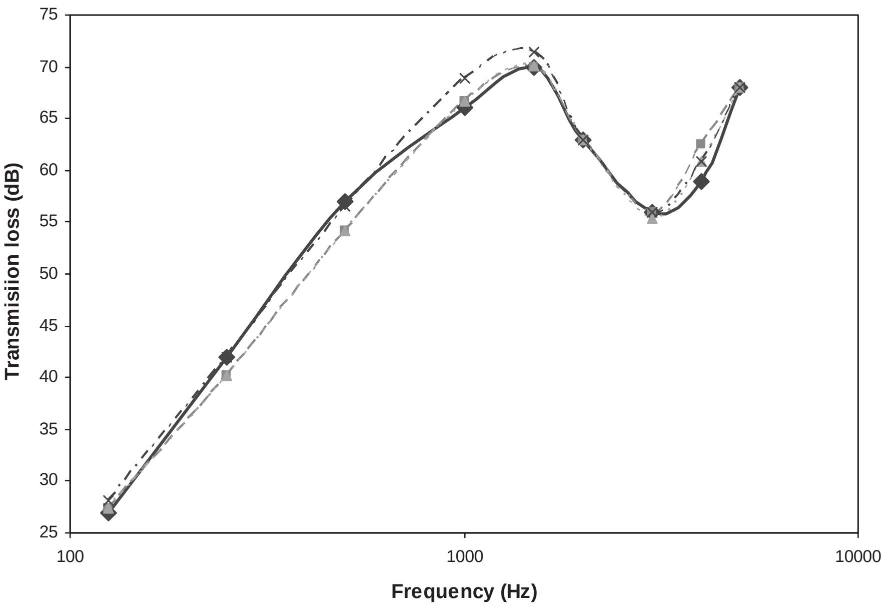

Fig. 2. Transmission loss for a double-leaf gypsum board partition, as a function of the frequency, obtained from the minimization method. Theoretical results obtained with three different models of absorbent materials are shown and compared with the measured values. —♦—, measured; —■—, Delany and Bazley; - - ▲ - - , Miki; - - × —, Allard and Champoux.

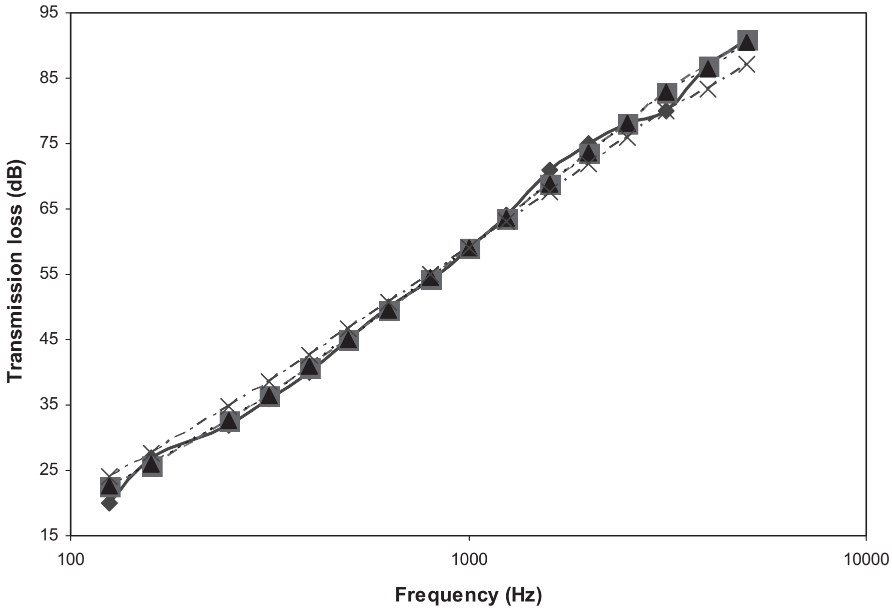

Fig. 3. As in Fig. 2, for a double-leaf steel board partition. —♦—, measured; —■—, Delany and Bazley; - - ▲ - - , Miki; - - × —, Allard and Champoux.

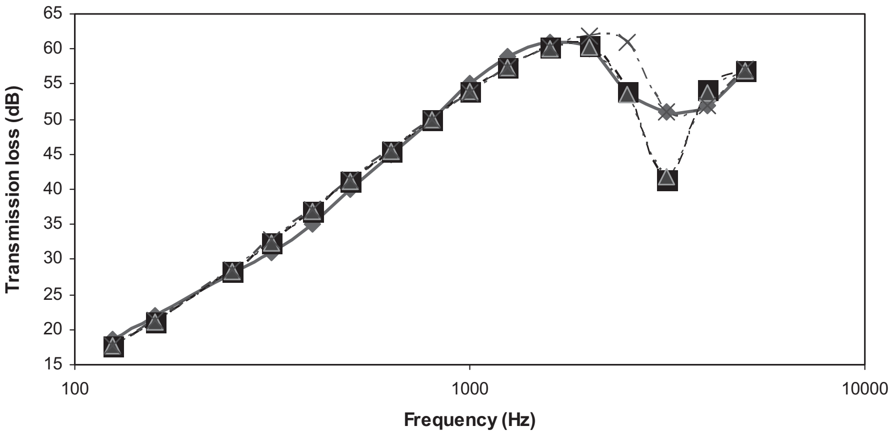

Fig. 4. As in Fig. 2, for a double-leaf plywood panel partition. —♦—, measured; —■—, Delany and Bazley; - - ▲ - - , Miki; - - × —, Allard and Champoux.

[12] to modelize the partition, and the Miki's formula [15] to modelize the absorbent material. The results correspond to those shown in Table 1.

4. Conclusions

From the results obtained, some conclusions can be extracted. First, the predictions of transmission loss obtained with the proposed minimization method show a better agreement with

Table 1
Numerical results from the minimization method, for a double-leaf gypsum board partition

Model	*D* (Nm)	*η*	*R* (Rayls/m)	Average error (dB)	Frequency lower limit (Hz)	Frequency higher limit (Hz)
Delany and Bazley	791.33	0.046	20188	0.98	808	20188
Miki	791.02	0.045	20812	0.93	832	20812
Allard and Champoux	810.85	0.046	23098	0.86		23098

Optimal values of the bending stiffness and the flow resistance are given, as obtained with the three different models of absorbent material, together with the average error and the frequency limits in which the models are applicable.

Table 2
As in Table 1, for a partition containing a steel board

Model	*D* (Nm)	*η*	*R* (Rayls/m)	Average error (dB)	Frequency lower limit (Hz)	Frequency higher limit (Hz)
Delany and Bazley	0.922	0.0037	2943.2	0.85	116	2943
Miki	0.939	0.0038	2787.8	0.9	112	2788
Allard and Champoux	0.933	0.0004	2959.8	2		2960

Table 3
As in Table 1, for a partition containing a plywood panel

Model	*D* (Nm)	*η*	*R* (Rayls/m)	Average error (dB)	Frequency lower limit (Hz)	Frequency higher limit (Hz)
Delany and Bazley	209	0.0868	26526	1.4	1061	26526
Miki	210	0.0889	26796	1.37	1072	26796
Allard and Champoux	142.3	0.125	29886	1.25		29886

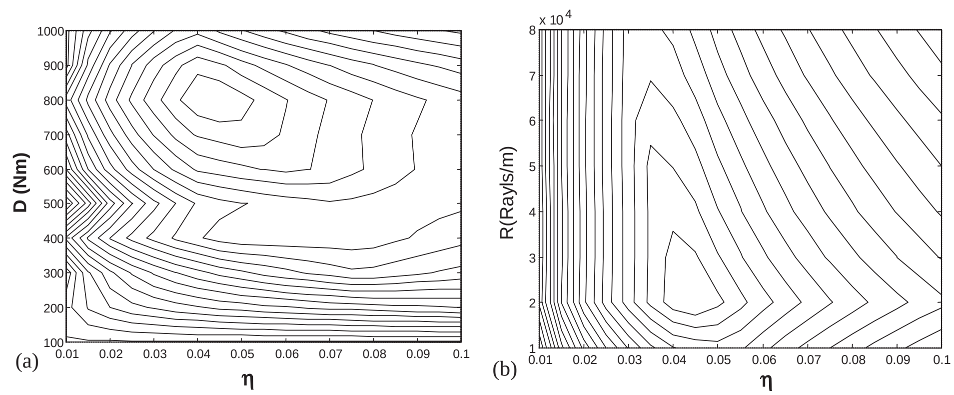

Fig. 5. Contour plot of the error function obtained for fixed flow resistance *R* (5a) and for fixed bending stiffness *D* (5b), as a function of the other parameters. The results correspond to a double-leaf gypsum board partition with the absorbent material modelled by the Miki's formula. The minimum values correspond to those in Table 1.

the experimental values than those published previously [6,12]. This improvement of the prediction was obtained with three different models of absorbent materials. These predictions are well adjusted to the experimental measurements, with errors below the typical values in similar studies. As shown in the tables, the error is of the order of 1 dB. This results in an error in the prediction of same order of magnitude as that of the error obtained from the measurement of the transmission loss. In recent papers [21,22] a deviation between predictions and measurements of the transmission loss between 1 and 2 dB is reported. Then, it seems reasonable to optimize the material parameters to that degree of resolution.

Second, a study has been performed considering three different models of absorbent material. The prediction of the transmission loss can also be refined with the choice of a concrete model, which is strictly applicable only in a given frequency band. It is observed that, however, in those cases where the measurements correspond to frequencies outside the range of validity of the models, the adjustment can still be considered as reasonable. This can be appreciated in Fig. 2, with the models of Delany and Bazley and Miki.

Finally, although the results obtained for the transmission loss in the case of a double-leaf plywood panel partition (Fig. 4) show a better agreement with the experimental values than those published previously [6,12], the predictions near the critical frequency of the partition (corresponding to the maximum excitation of bending waves in the layers) show some discrepancy with respect to the measurements. This fact can be related to several factors, such as a non-homogeneous behaviour of the plywood, which was not taken into account in this study. Furthermore, as it was shown in Ref. [6], the bending stiffness is not constant, but dependent on the frequency (for example, $D = 190$ Nm at 100 Hz and 390 Nm at 2000 Hz, having considered for the prediction the mean value 290 Nm). Moreover, the model assumes that the layers and the absorbent material have infinite dimensions whereas the measurements have been performed on samples of finite dimensions. The cutting of the samples may have changed the mechanical properties of the material, thus influencing the measuring results. The clamping of the partition can also have a considerable influence on the measurements. Then, assuming a bending stiffness with constant value it is difficult to improve the prediction near the critical frequency. However, the simplified model considered here, which assumes constant parameter values, allows improvement of the predictions in most of the frequency range. It is expected that the correct description of the transmission loss near the critical frequency requires the consideration of a frequency-dependent bending stiffness. The numerical study of the predictions of the model in such a case is in progress.

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