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AN SEA-LIKE MODEL FOR DOUBLE WALLS FILLED WITH ABSORBING MATERIALS

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Abstract

Modelling absorbing materials with statistical energy analysis (SEA) is an open issue. They are neither reverberant subsystems nor conservative couplings. The absorbing material layers located inside the cavities of double walls should be treated as non-conservative couplings between the wall leaves. However, the standard SEA formulation cannot take into account non-conservative couplings.

In this work, an equivalent circuit analogy is used to deduce how to introduce these couplings in an SEA-like system. Besides, a technique for obtaining the SEA-like factors associated to a double wall filled with absorbing material is presented. These factors are computed from numerical simulations of the vibroacoustic leaf-absorbing material-leaf system and applied for solving larger problems with SEA.

Keywords: absorbing materials, double walls, statistical energy analysis, computational vibroacoustics.

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1 Introduction

Modelling layers of absorbing materials with statistical energy analysis (SEA) is an open issue. These materials cannot be treated as reverberant subsystems, nor as conservative couplings. However, they are increasingly used in building design, as filling of double walls, and due to this, it is necessary to have models that can predict their acoustic behaviour.

Double walls can be approached either with statistical energy analysis or with deterministic models. In the deterministic approaches the vibroacoustic problem is modelled with partial differential equations and they are solved with the help of numerical techniques [1,2]. The wall leaves are usually modelled with the thin plate equation, and for the absorbing material different models can be used.

One big group of models are the equivalent fluid models. They treat the absorbing material as a fluid (and model it with Helmholtz equation) with complex, frequency-dependent values of its wavenumber and density, related to the material microstructure through empirical or semi-phenomenologic expressions. Different models exist, depending on the number of parameters required for the expression, such as the one suggested by Delany and Bazley [3] and later improved by Miki [4], which only depends on the flow resistivity, or the Johnson-Champoux-Allard model [5], which considers 5 different parameters.

Another group of models for absorbing materials are the poroelastic models. They consider both the elastic behaviour of the solid part and the fluid propagation through the pores. The theoretical basis for the mechanical behaviour of poroelastic materials was established by Biot [6] and the adaptation to acoustic propagation was done by Allard [7].

In general, the deterministic approach can be used for modelling any type of structure, by means of choosing the appropriate equations and numerical techniques. However, it has an unaffordable computational cost when dealing with real life problems for the highest frequencies required by regulations.

Statistical energy analysis [8] is widely used in building acoustics due to its low computational cost and simplicity, but its application is restricted to domains that can be divided into reverberant subsystems and conservative couplings [9]. The effect of absorbing materials is considered with SEA as if they were located at the boundary of a room, providing a loss factor to it. However, modelling a layer of absorbing material is still a challenge for the classical SEA formulation.

When trying to incorporate the absorbing material located at the cavity of double walls to SEA, different problems arise. First of all, absorbing materials should not be treated as SEA subsystems because their behaviour is not reverberant and the energy density is not the same all over the material [10]. This leaves the only option of considering the absorbing layer as a connection. However, SEA is not prepared for dealing with non-conservative joints [11]. Some efforts have been done in considering non-conservative connections with SEA by Beshara and Keane [12] and Sheng et al. [13]. They reach a SEA-like formulation that takes into account dissipative effects in the couplings. However, they are restricted to a mechanical approach, and do not apply this approach to any vibroacoustic problem, nor to modelling absorbing materials.

In this work an SEA-like model for non-conservative couplings is proposed and applied to the case of a double wall filled with a layer of absorbing material. Moreover, a systematic technique for obtaining the SEA-like parameters required by this approach is presented.

2 Non-conservative couplings with SEA

The SEA framework divides the problem domain into two types of elements: subsystems and connections. An SEA subsystem is a part of the domain such that the energy associated to each of its modes is ideally the same. Every subsystem has its own modal density and an internal loss factor that characterises the fraction of energy dissipated in it.

SEA connections are those elements connecting the subsystems. They have a conservative behaviour, transmitting energy from one subsystem to the other without dissipating any energy. They are characterised by a coupling loss factor that relates the power across the connection with the energies of the subsystems connected by it.

2.1 Modelling a double wall with SEA

Double walls consist of two leaves separated by a cavity (see Figure 1). This cavity may, or not, be filled with an absorbing material.

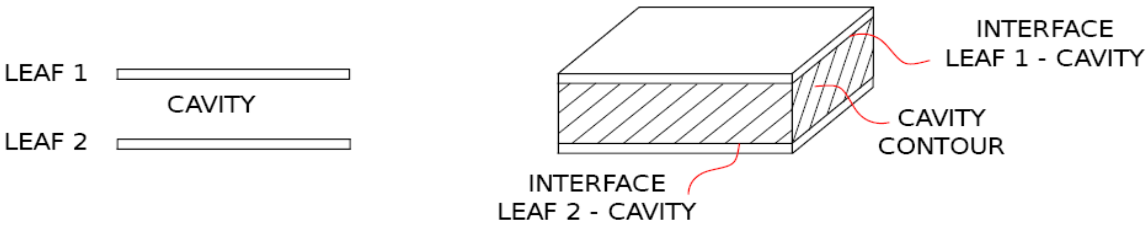

Figure 1: Parts of a double wall.

If the cavity between the leaves is only full of air, different authors do not agree on whether it should be treated as a subsystem or as a connection. An study on this particular is done in [14]. The main conclusion is that the air cavity can be considered just as a connection between the two subsystems (leaves), if the value of the coupling loss factor associated to it is estimated at each frequency band from the energies of the leaves. These energies are computed solving the vibroacoustic problem numerically. In this way, all the transmission phenomena are taken into account.

If the air cavity is considered as a conservative connection between the two leaves of the double wall, the physical approach is the same as if the cavity is considered as a spring with a frequency-dependent stiffness. The only difference is that the value of the equivalent stiffness has to be estimated from numerical simulations, in order to capture both the air stiffness and the coincidence phenomena in the cavity.

2.2 The absorbing material as an SEA connection

If the cavity between the leaves is filled with an absorbing material, it is neither a reverberant subsystem nor a conservative connection. The classical SEA approach is not prepared to consider this type of elements in a straightforward way. Therefore, an alternative SEA-like approach is suggested to deal with this problem.

Following with the spring analogy commented in Section 2.1, if the cavity is filled with absorbing material it cannot be assimilated to a spring anymore. The dissipation of energy that takes place at the absorbing material is more typical of a dashpot. However, the absorbing material also provides some stiffness to the connection. A combined connection, consisting of a spring and a dashpot in parallel (Figure 2) is a more suitable model for the absorbing material. An SEA-like approach to the effect of this new connection between the two leaves is presented. This approach will be extended to deal with absorbing materials in Section 3.

The effect of the connection in an SEA system is studied with the equivalent circuit approach. This technique is used by Hopkins [15] to compute the coupling loss factor caused by a spring connecting two leaves. For any connecting device between the two leaves of a double wall, the global system may be represented as a circuit like that of Figure 3, where Y_1 and Y_2 are the point mobilities of the two leaves (leaf 1 and leaf 2 respectively) forming the double wall and Y_c is the mobility of the connection.

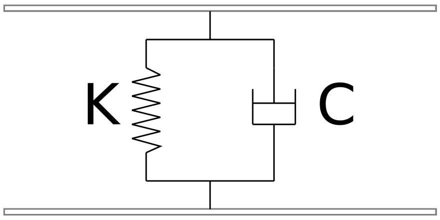

Figure 2: Connection consisting of a spring and a dashpot.

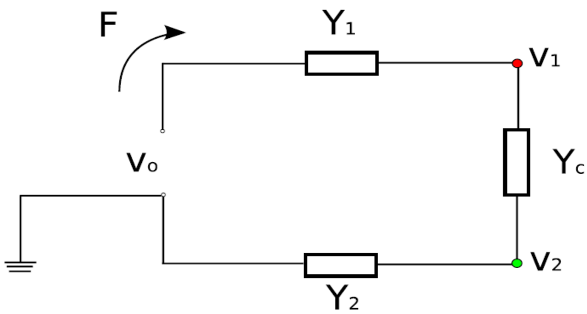

Figure 3: Circuit equivalent to a double wall.

The mechanical–electrical analogy is described in Table 1 and the assumptions of the analysis are:

- Leaf 1 has an external excitation and leaf 2 has none.
- v_0 is the velocity at the point where the excitation acts. It is not affected by the (weak) connection.
- Any point of the unexcited leaf that is far enough from the connection point has a negligible velocity compared to v_0.
- v_1 and v_2 are the velocities at the connecting point of leaves 1 and 2 respectively.

Applying electric criteria, the excitation force can be expressed in terms of the velocities and point mobilities as

$$F=\frac{v_0}{Y_1+Y_2+Y_c} \tag{1}$$

and the velocities of the leaves at the connecting point can be expressed as $v_1 = (Y_2 + Y_c)\,F$ and $v_2 = Y_2\,F$.

Table 1: Mechanical-electrical analogy.

Mechanics	Electrics
Force *F*	Intensity *I*
Velocity *v*	Potential *V*
Admittance (point mobility *Y*)	Impedance *Z*

The power entering the connection (on the side of the connection closest to leaf 1) is [15]

$$W_{12}^{(1)}=\frac{1}{2}\Re\left\{Fv_1^*\right\}=\frac{1}{2}\frac{\Re\left\{Y_2+Y_c\right\}|v_0|^2}{|Y_1+Y_2+Y_c|^2} \tag{2}$$

and the power leaving the connection (on side closest to leaf 2) is

$$W_{12}^{(2)}=\frac{1}{2}\Re\left\{Fv_2^*\right\}=\frac{1}{2}\frac{\Re\left\{Y_2\right\}|v_0|^2}{|Y_1+Y_2+Y_c|^2}\,. \tag{3}$$

If the connector is a spring, the value of the mobility is Y_c = iω/K where K is the spring stiffness, $\omega=2\pi f$, and f is the vibration frequency. In that case, $\Re\left\{Y_2+Y_c\right\}=\Re\left\{Y_2\right\}$ and, therefore $W_{12}^{(1)}=W_{12}^{(2)}$, verifying that there is no dissipation at the connection: the power entering the connection is the same as the power leaving it. However, if the connector consists of a spring and a dashpot, its mobility is

$$Y_c=\frac{1}{C+K/\mathrm{i}\,\omega}\,, \tag{4}$$

and therefore $\Re\left\{Y_2+Y_c\right\}\neq\Re\left\{Y_2\right\}$. The connector dissipates power.

For the SEA-like analysis of two leaves connected with the connection of Figure 2, two parameters are defined. On the one side, the factor governing the amount of power leaving the excited leaf:

$$\beta_{ij}=\frac{\Re\left\{Y_j+Y_c\right\}}{\omega \mathrm{M}_i|Y_i+Y_j+Y_c|^2}\,,\ i\neq j \tag{5}$$

and, on the other hand, the factor governing the amount of power reaching the unexcited leaf

$$\eta_{ij}=\frac{\Re\left\{Y_j\right\}}{\omega \mathrm{M}_i|Y_i+Y_j+Y_c|^2}\,,\ i\neq j \tag{6}$$

where M_i is the mass of leaf i. The power balances of the two leaves are $P_1^{\mathrm{in}}=P_1^{\mathrm{diss}}+W_{12}^{(1)}$ for the excited leaf and $P_2^{\mathrm{diss}}=W_{12}^{(2)}$ for the unexcited one respectively, where P_1^{in} is the power incoming to leaf 1, $P_i^{\mathrm{diss}}=\omega\,\eta_{ii}\langle E_i\rangle$ is the power dissipated at leaf i and η_{ii} is the internal loss factor of leaf i. Assuming that $\langle E_1\rangle=M_1|v_0|^2/2$ and $W_{12}^{(1)}=\omega\eta_{12}\langle E_1\rangle$, these balances can be rewritten in terms of η_{ij} and β_{ij} as

$$P_1^{\mathrm{in}}/\,\omega=\eta_{11}\langle E_1\rangle+\beta_{12}\langle E_1\rangle \tag{7}$$

and

$$\eta_{22}\langle E_2\rangle=\eta_{12}\langle E_1\rangle. \tag{8}$$

Following the same procedure in a more general case, with excitations on both subsystems, the global system yields

$$\begin{aligned} P_1^{\text{in}}/\omega &= \eta_{11}\langle E_1\rangle + \beta_{12}\langle E_1\rangle - \eta_{21}\langle E_2\rangle \\ P_2^{\text{in}}/\omega &= \eta_{22}\langle E_2\rangle + \beta_{21}\langle E_2\rangle - \eta_{12}\langle E_1\rangle \end{aligned}, \tag{9}$$

which has the same shape as the system shown by Sheng et al. [13]. Eq. (9) can be written in matrix form as

$$\omega \begin{bmatrix} \eta_{11}+\beta_{12} & -\eta_{12} \\ -\eta_{21} & \eta_{22}+\beta_{21} \end{bmatrix} \begin{Bmatrix} \langle E_1\rangle \\ \langle E_2\rangle \end{Bmatrix} = \begin{Bmatrix} P_1^{\text{in}} \\ P_2^{\text{in}} \end{Bmatrix} \tag{10}$$

or, equivalently, as

$$\omega \begin{bmatrix} \eta_{11}+\eta_{12}+\alpha_{12} & -\eta_{12} \\ -\eta_{21} & \eta_{22}+\eta_{21}+\alpha_{21} \end{bmatrix} \begin{Bmatrix} \langle E_1\rangle \\ \langle E_2\rangle \end{Bmatrix} = \begin{Bmatrix} P_1^{\text{in}} \\ P_2^{\text{in}} \end{Bmatrix}, \tag{11}$$

where the parameter α_{ij} is defined as a coefficient that governs the amount of power dissipated at the connection

$$\alpha_{ij} = \beta_{ij} - \eta_{ij} = \frac{\Re\{Y_c\}}{\omega \mathrm{M}_i |Y_i + Y_j + Y_c|^2}. \tag{12}$$

The effect of the non-conservative joint leads to a SEA-like system with two new factors in the diagonal. If an analogy to the classical SEA is done, they would play the role of extra internal loss factors of the subsystems connected by the joint. However, since the value of η_{ij} also depends on the properties of the absorbing material, this analogy is only referred to the shape of the system but not to the values of the parameters involved. These values should be estimated from experiments or simulations.

3 Estimation of SEA parameters with numerical simulations

3.1 Estimation of the parameters

The values of η_{ij} and α_{ij} defined in Eqs. (6) and (12) respectively cannot be computed with analytical expressions for a generic absorbing material. Therefore, the best option to model a vibroacoustic problem consisting of double walls and other building elements like, for instance, rooms, is to compute these parameters from the numerical simulation of smaller parts of the problem, as done in [14]. The difference here is that, besides the computation of the coupling loss factors, extra parameters are required by the new SEA-like model for characterising double walls.

The obtention of parameters η_{ij} and α_{ij} associated to a double wall filled with absorbing material is performed computing them from the results of a numerical simulation of the double wall with an excitation on one of the subsystems. Assuming that η_{ii} is known for every subsystem and that, for a given excitation, both the input power P_1^{in} and the averaged energies of the leaves $\langle E_i \rangle$ can be computed solving the vibroacoustic problem numerically, the rest of the SEA parameters can be isolated from the SEA system (11).

If the leaves of the double wall have different properties (which is the most common configuration, used in building design in order to avoid resonances), the structure is not symmetric and there are four parameters to compute: η_{12}, η_{21}, α_{12} and α_{21}. To obtain them all, four equations are required.

The four equations are obtained from the SEA formulation of two mutually independent problems. They correspond to the sound transmission through the double wall with two different excitations: one on leaf 1 and the other on leaf 2. For each different excitation, the vibration of the leaves is computed numerically, as well as their averaged energies. These energies are replaced in the SEA-like formulation of each problem (11) and, with the information of the two problems, a 4×4 linear system can be solved to obtain the four parameters desired

$$\begin{bmatrix} \langle E_1 \rangle & -\langle E_2 \rangle & \langle E_1 \rangle & 0 \\ \langle \hat{E}_1 \rangle & -\langle \hat{E}_2 \rangle & \langle \hat{E}_1 \rangle & 0 \\ -\langle E_1 \rangle & \langle E_2 \rangle & 0 & \langle E_2 \rangle \\ -\langle \hat{E}_1 \rangle & \langle \hat{E}_2 \rangle & 0 & \langle \hat{E}_2 \rangle \end{bmatrix} \begin{Bmatrix} \eta_{12} \\ \eta_{21} \\ \alpha_{12} \\ \alpha_{21} \end{Bmatrix} = \begin{Bmatrix} P_1^{\text{in}}/\omega - \eta_{11}\langle E_1 \rangle \\ -\eta_{11}\langle \hat{E}_1 \rangle \\ -\eta_{22}\langle E_2 \rangle \\ P_2^{\text{in}}/\omega - \eta_{22}\langle \hat{E}_2 \rangle \end{Bmatrix}. \tag{13}$$

In Eq. (13), those values of the energies without the hat correspond to the results of a simulation with the excitation applied to leaf 1, and those marked with a hat correspond to the simulation where the excitation is applied to leaf 2. If the two leaves are identical, the problem is symmetric and $\eta_{12}=\eta_{21}$, $\alpha_{12}=\alpha_{21}$. Therefore, only one simulation is required and the first and third equations of Eq. (13) are enough for computing the parameters.

3.2 Numerical simulations

In this work, the SEA-like parameters associated to a double wall filled with absorbing material are obtained. The values of the powers and energies required in Eq. (13) are computed numerically. The deterministic analysis is based on modelling the wall leaves as thin plates

$$D\nabla^4 u(x,y) - \omega^2 \rho_s u(x,y) = q(x,y) \tag{14}$$

and the absorbing material as an equivalent fluid. In Eq. (14), $D = Eh^3/12(1-\nu^2)$ is the bending stiffness of the leaf (with h, E and ν the thickness, Young's modulus and Poisson's ratio of the leaf respectively), ρ_s its mass per unit surface and $u(x,y)$ the displacement of the leaf. The equivalent fluid is modelled with Helmholtz equation

$$\nabla^2 p(\mathbf{x}) + k^2 p(\mathbf{x}) = 0, \tag{15}$$

and the complex values of the wavenumber and density suggested by Miki [4]. In Eq. (15), $p(\mathbf{x})$ is the pressure field and k is the wavenumber in the absorbing material.

The vibration field in the plates is expressed with modal analysis and the pressure field inside the absorbing material is discretised with the finite layer method, as described in [16]. The equilibrium and continuity at the leaf-absorbing material interface are imposed weakly.

Once the displacement field $u(x,y)$ in the plates is known, their velocity is obtained as $v(x,y) = \mathrm{i}\omega u(x,y)$, where $\mathrm{i} = \sqrt{-1}$. Then, the averaged energy of each plate is computed as [15]

$$\langle E\rangle = M\langle v_{\mathrm{RMS}}^2\rangle , \tag{16}$$

where M is the mass of the leaf and $\langle v_{\mathrm{RMS}}^2\rangle$ is the spatial mean square value of its velocity.

The excitation of the system is a pressure wave impinging on one of the plates, modelled as

$$p(\mathbf{x}) = p_0 e^{-\mathrm{i}(k_x x + k_y y + k_z z)}, \tag{17}$$

where $k_x = k\sin\varphi\cos\theta$, $k_y = k\sin\varphi\sin\theta$, and $k_z = k\cos\varphi$.

This wave may have several orientations, defined by angles θ and φ as shown in Figure 4. Four different values of θ , equispaced between $\theta = 0$ and $\theta = 45^{\circ}$ due to the symmetry of the problem, are considered. Also ten different values of φ have been considered, equispaced between $\varphi = 0$ and $\varphi = 90^{\circ}$. The final values of the energies are averaged throughout all these angles.

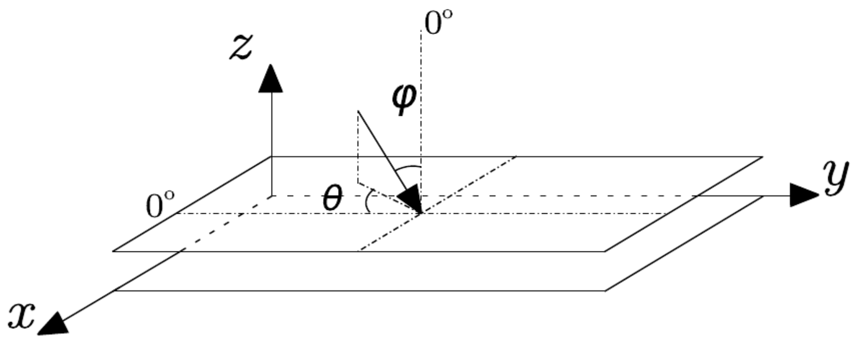

Figure 4: Incidence angles.

4 Application examples

4.1 Effect of the flow resistivity on α_{12}

The technique described in Section 3.1. has been used for studying the influence of the flow resistivity of the absorbing material on the parameter α_{12} between two leaves of plasterboard. Since this parameter brings the information of the amount of energy dissipated by the absorbing material, it is expected to be intimately related to the value of the flow resistivity. The vibroacoustic problem is solved numerically for a double wall with plasterboard leaves of $2.4\,\mathrm{m}\times 2.4\,\mathrm{m}$ and a thickness of 13 mm. The absorbing layer is 70 mm thick and four values of the flow resistivity have been simulated: $\sigma = 1000$, 4000, 8000, and $10\,000$ N s m^{-4}.

In Figure 5 the value of α_{12} for the different flow resistivities is depicted. The behaviour is the expected one: the larger the value of σ, the larger the value of α_{12}. The differences between the value of α_{12} for $\sigma = 8000$ and $\sigma = 10\,000$ N s m^{-4} are almost negligible. This behaviour coincides with the conclusions reached by Royar [17] regarding the lack of improvement in the sound insulation of lightweight structures with absorbing materials with a flow resistivity larger than 5000 N s m^{-4}.

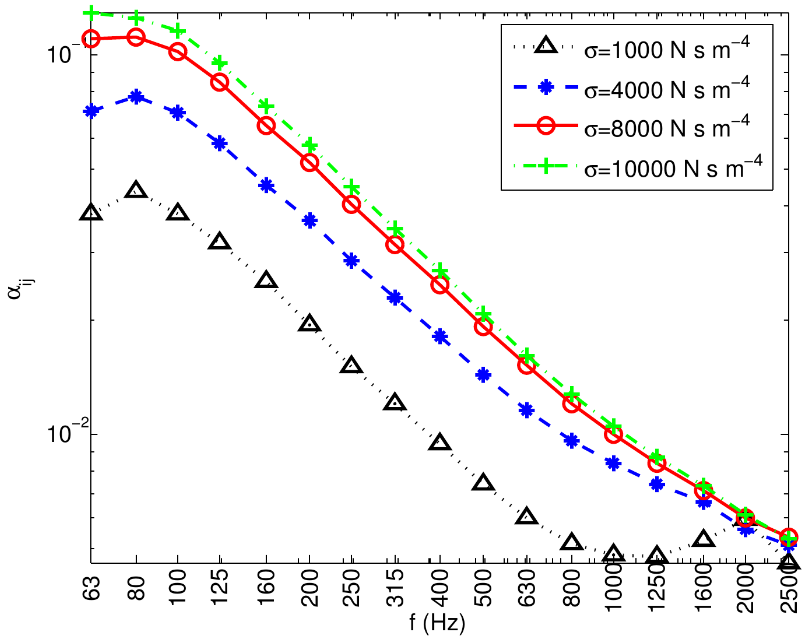

Figure 5: Effect of the flow resistivity on α_{ij}

4.2 Effect of the flow resistivity on the sound reduction index

In order to study the influence of the flow resistivity on a real-life problem, the SEA-like approach suggested in this work is used to simulate the sound reduction index between two rooms separated by a double wall filled of absorbing material. The four double walls studied in Section 4.1 are compared with one without absorbing material inside. The rooms have dimensions $2\ \text{m} \times 3\,\text{m} \times 5\ \text{m}$.

For the simulation, the system is divided into four SEA subsystems: sending room, leaf 1, leaf 2 and receiving room. The absorbing material is considered as a non-conservative connection between subsystems 2 and 3. Therefore, the SEA-like system to be solved is

$$\omega\begin{bmatrix} \eta_{11}+\eta_{12} & -\eta_{21} & 0 & 0 \\ -\eta_{12} & \eta_{21}+\eta_{22}+\eta_{23}+\alpha_{23} & -\eta_{32} & 0 \\ 0 & -\eta_{23} & \eta_{32}+\eta_{33}+\eta_{34}+\alpha_{32} & -\eta_{43} \\ 0 & 0 & -\eta_{34} & \eta_{43}+\eta_{44} \end{bmatrix}\begin{Bmatrix} \langle E_1\rangle \\ \langle E_2\rangle \\ \langle E_3\rangle \\ \langle E_4\rangle \end{Bmatrix}=\begin{Bmatrix} P_1^{\text{in}} \\ 0 \\ 0 \\ 0 \end{Bmatrix}. \tag{18}$$

The internal loss factors of subsystems 2 and 3 are the loss factors of the leaves ($\eta_{ii} = \eta = 0.03$) and the internal loss factors of subsystems 1 and 4 are computed as

$$\eta_{ii} = \frac{c\, S_{\mathrm{cav}}\, \alpha}{8\pi f V_{\mathrm{cav}}}, \tag{19}$$

where S_{cav} is the surface of the room boundary, α is the absorption coefficient at that boundary and V_{cav} is the volume of the room. The excitation is a sound source in one of the rooms (subsystem 1).

To obtain all the parameters η_{ij} and α_{ij} required by the SEA-like approach, three small deterministic problems have been solved. On the one hand, the double wall itself has been simulated, in order to obtain the values of η_{ij} and α_{ij} between the two leaves as described in Section 3. On the other hand, the coupling loss factors between each leaf and its adjacent room have been computed from the numerical simulation of a system consisting of a room in contact with a leaf (see Figure 6).

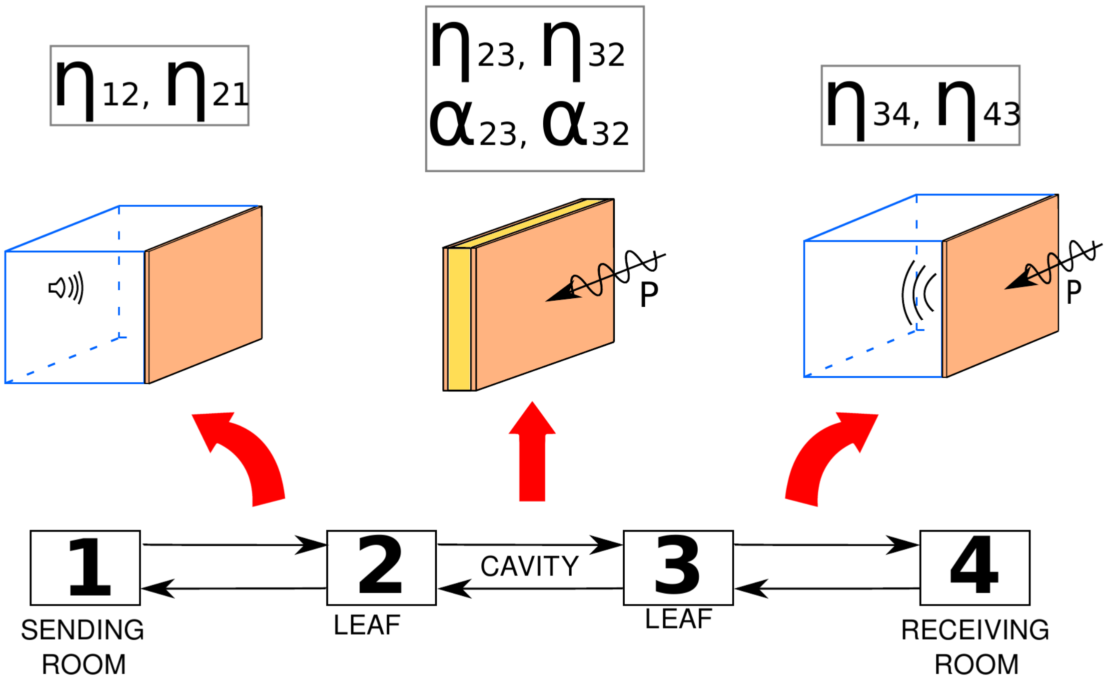

Figure 6: Small problems required for obtaining the SEA CLFs.

In Figure 7 the effect of the flow resistivity on the sound reduction index between the two rooms is analysed. Lower frequencies are not depicted because the coupling is too strong and therefore the SEA-like results are not reliable. The insulating effect of filling the cavity with an absorbing material is remarkable. However, different values of the flow resistivity only provide different values of the sound reduction index for high frequencies. This behaviour was also reported by Stani et al. in [18].

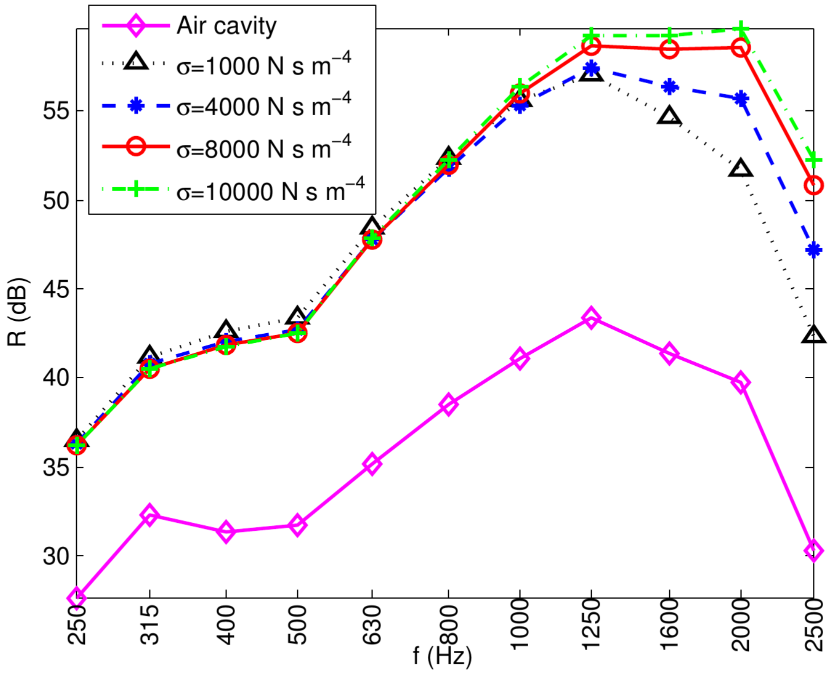

Figure 7: Effect of the flow resistivity on the sound reduction index

5 Conclusions

The main conclusions drawn from this work are the following:

- Modelling absorbing materials with an SEA-like analysis should be done treating them as non-conservative connections.
- Non-conservative connections can be taken into account in the SEA formulation adding extra terms in the diagonal. These terms play the role of extra internal loss factors of the subsystems connected by the absorbing material.
- Factors η_{ij} and α_{ij} required for modelling non-conservative couplings cannot be obtained with analytical expressions. Numerical simulations of a system consisting of 2 subsystems are a useful tool for estimating them. Once these factors are computed, they can be used to solve larger problems with SEA.
- An increment in the flow resistivity causes, as expected, an increment on the parameter governing the dissipation at the connection α_{ij}. However, beyond a certain value of σ (5000 N s m^{-4}), increasing it does not involve significant changes on the α_{ij} factor.
- Double walls filled with absorbing materials have a more insulating behaviour than those with an air cavity. However, the influence of the flow resistivity of the absorbing material filling a plasterboard double wall is only relevant for high frequencies .

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