inter noise
2013 | INNSBRUCK | AUSTRIA
15.-18. SEPTEMBER 2013
NOISE CONTROL FOR QUALITY OF LIFE

Pushing SEA beyond its limits: a model for real building structures

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ABSTRACT

The main challenge for models of building acoustics is being able to consider all the geometrical and physical details of real structures with a reasonable computational cost for high frequencies. The SEA (Statistical Energy Analysis) framework is suitable for these frequencies, but presents some difficulties for dealing with complex structural configurations. For instance, modelling absorbing materials with SEA is an open issue, since they are neither reverberant subsystems nor conservative couplings.

In this work, a model to account for absorbing materials with a SEA-like approach is performed. It is obtained by analogy with an electrical circuit. This approach is combined with numerical simulations in order to solve vibroacoustic problems in real structural configurations (including complex geometries or dissipative connections) throughout the entire frequency range required by regulations. The proposed technique is applied to modelling the sound insulation of double walls. These walls consist of two leaves of plasterboard connected through metallic studs and filled with a layer of absorbing material. The combination of numerical simulations and SEA arises as a good technique for modelling the acoustic behaviour of real life structures with an affordable computational cost.

Keywords: Statistical Energy Analysis, vibroacoustics, absorbing materials

1. INTRODUCTION

Problems in the field of building acoustics can be modelled in two main ways. On the one hand, they can be addressed in a deterministic way using numerical methods, like the Finite Element Method [1], to solve the differential equations governing the problem. On the other hand, statistical methods such as SEA (Statistical Energy Analysis) [2] can be used.

Deterministic approaches, complemented with numerical methods, provide detailed information about vibroacoustic systems. They are useful for modelling complex elements, since they can take into account complicated geometries or heterogeneities. The main drawback of these approaches is the high computational cost required for the calculation at high frequencies, especially when working in large domains.

The statistical energy analysis is suitable for high frequencies, and has a very low computational cost. It deals directly with averaged energies but requires specific parameters of power transmission, like internal loss factors and coupling loss factors, whose values cannot be calculated analytically for complex geometries. It is also restricted to systems consisting of reverberant subsystems and

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conservative couplings, and therefore shows problems when dealing with thin layers of absorbing materials, or any other type of non-conservative couplings [3].

In this work two main ideas are presented. On the one hand, an SEA-like model for non-conservative couplings is proposed. On the other hand, numerical simulations and SEA are coupled so that real-life problems can be modelled for the whole frequency range required by regulations with a reasonable computational cost.

2. AN SEA-LIKE MODEL FOR NON-CONSERVATIVE COUPLINGS

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 losses. They are characterised by a coupling loss factor that relates the power across the connection with the energies of the subsystems connected by it.

The effect of a point connection between two SEA subsystems may be studied with the equivalent circuit approach [4]. This technique is used by Hopkins [5] to compute the coupling loss factor of a spring connecting two leaves. In general, for any point device connecting two subsystems, the global system may be represented as a circuit like that of Figure 1 where Y_1 and Y_2 are the point mobilities of subsystems 1 and 2 (excited and unexcited leaf respectively) and Y_C is the mobility of the connection.

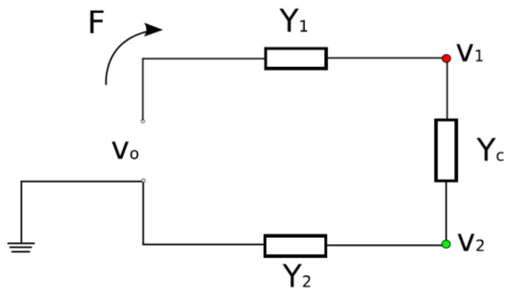

Figure 1 – Circuit equivalent to a double wall

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.

Table 1 – Mechanical-electrical analogy

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

By analogy with the electrical circuit, 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 $v_2 = Y_2 F$.

The power entering the connection (on the closest side to leaf 1) is [5]

$$\Pi_{12}^{(1)} = \frac{\Re\{F v_1^*\}}{2} = \frac{\Re\{Y_2 + Y_C\}|v_0|^2}{2|Y_1 + Y_2 + Y_C|^2} \tag{2}$$

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

$$\Pi_{12}^{(2)} = \frac{\Re\{F v_2^*\}}{2} = \frac{\Re\{Y_2\}|v_0|^2}{2|Y_1 + Y_2 + Y_C|^2}. \tag{3}$$

Therefore, the power dissipated at the connection is

$$\Pi_{12}^{diss} = \Pi_{12}^{(1)} - \Pi_{12}^{(2)} = \frac{\Re\{Y_C\}|v_0|^2}{2|Y_1 + Y_2 + Y_C|^2}. \tag{4}$$

If the connection is conservative, the power leaving subsystem 1 enters subsystem 2 without losses. This means that $\Pi_{12}^{\mathrm{diss}}=0$: the connection mobility Y_C is purely imaginary. That is the case of a connection consisting of a spring. In that case, $Y_C = \mathrm{i}\omega/K$ (purely imaginary), where K is the spring stiffness, i is the imaginary unit, $\omega = 2\pi f$ and f is the vibration frequency.

If the coupling, on the contrary, has a dissipative behaviour, part of the power leaving subsystem 1 is transmitted to subsystem 2 and the rest is dissipated at the connection. The mobility Y_C in this case has a non-zero real part. For instance, in the particular case of the set of spring and dashpot shown in Figure 2, $Y_C = 1/(C+K/\mathrm{i}\omega)$ and therefore the real part of Y_C is different from zero. Some power is dissipated at the connection.

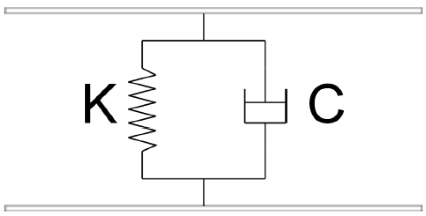

Figure 2 – Connection consisting of a spring and a dashpot.

The power balances of the two leaves are

$$\begin{aligned} \Pi_1^{in} &= \Pi_1^{diss} + \Pi_{12}^{(1)} \\ \Pi_2^{diss} &= \Pi_{12}^{(2)} \end{aligned} \tag{5}$$

for the excited and the unexcited one respectively, where Π_1^{in} is the power injected to leaf 1, $\Pi_i^{\mathrm{diss}} = \eta_{ii}\omega E_i$ is the power dissipated, η_{ii} the internal loss factor and E_i the averaged energy of leaf i.

Assuming that $E_1 = M_1 v_{\mathrm{rms}}^2$, where M_1 is the mass of leaf 1 and $v_{\mathrm{rms}}^2 = v_0^2/2$, the power dissipated at the connection can be expressed as

$$\Pi_{12}^{diss} = \omega \gamma_{12} E_1 \tag{6}$$

and the power transmitted to subsystem 2 as

$$\Pi_{12}^{(2)} = \omega \eta_{12} E_1. \tag{7}$$

Therefore, the power entering the connection from subsystem 1 is

$$\Pi_{12}^{(1)} = \omega(\eta_{12} + \gamma_{12}) E_1. \tag{8}$$

In Equations (6) and (7), two new parameters have been introduced. On the one hand, a factor governing the amount of power dissipated at the connection: the Non-conservative Coupling Loss

Factor (NCLF)

$$\gamma_{ij} = \frac{\Re\{Y_C\}}{M_i\omega \left|Y_i + Y_j + Y_C\right|^2}, \qquad i \neq j. \tag{9}$$

On the other hand, a factor governing the amount of power reaching the unexcited leaf: the Conservative Coupling Loss Factor (CCLF)

$$\eta_{ij} = \frac{\Re\{Y_j\}}{M_i\omega \left|Y_i + Y_j + Y_C\right|^2}, \qquad i \neq j. \tag{10}$$

The power balances of Equation (5) can be rewritten in terms of the averaged energies for the non-conservative coupling as

$$\begin{gathered} \Pi_1^{in} / \omega = \eta_{11}E_1 + (\eta_{12} + \gamma_{12})E_1 \\ \eta_{22}E_2 = \eta_{12}E_1. \end{gathered} \tag{11}$$

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

$$\begin{gathered} \Pi_1^{in} / \omega = \eta_{11}E_1 + (\eta_{12} + \gamma_{12})E_1 - \eta_{21}E_2 \\ \Pi_2^{in} / \omega = \eta_{22}E_2 + (\eta_{21} + \gamma_{21})E_2 - \eta_{12}E_1. \end{gathered} \tag{12}$$

The effect of the non-conservative connection leads to an SEA-like system with two new factors: the non-conservative coupling loss factors γ_{12} and γ_{21}. If these factors are equal to zero, the conservative case is recovered. However, if the coupling dissipates energy, they are different from zero and factors η_{12} and η_{21} change with respect to the conservative case.

Equation (12) provides similar relations between the connection losses and the energies of the subsystems as Sheng et al. [6] do. However, the information included in the coefficients is different. Sheng et al. define a new equivalent internal loss factor instead of adding an extra term in the diagonal (defined here as NCLF). The advantage of defining the NCLF is that several non-conservative couplings of the same type can be concatenated easily without having to recompute any parameter. The equivalent internal loss factor defined in [6] needs to be recomputed when the subsystem is in contact with more than one non-conservative coupling.

Another remarkable difference with Sheng et al. is the nomenclature used for the loss factors. In their formulation, they incorporate the value of γ_{ij} within the equivalent internal loss factor. Therefore, they only have one coupling loss factor, which they call non-conservative coupling loss factor. In this work, however, a formulation with two coupling loss factors has been developed. They have been called CCLF and NCLF because, if the dissipative component of the coupling is removed, the NCLF becomes zero and the CCLF becomes the classical coupling loss factor. Therefore, the name *non-conservative coupling loss factor* is used with a different meaning in the two works.

3. ESTIMATION OF COUPLING LOSS FACTORS

Both in classical SEA problems and in SEA-like systems like those defined in Section 2, the power distribution throughout the domain is defined by the internal and coupling loss factors. In typical building applications, the subsystems are walls and rooms and their associated internal loss factors are usually known. However, the connections between these subsystems are not always simple devices, and sometimes have complex geometries or even absorbing characteristics, that need to be taken into account in the coupling loss factor.

The main idea presented here is that numerical simulations of two coupled systems can be used to estimate the coupling los factors (both conservative and non-conservative) between them. These factors can then be applied to solve larger problems with a SEA (or SEA-like) formulation.

3.1 Conservative case

The classical SEA formulation for a system consisting of two subsystems when only the first one is excited is

$$\omega \begin{bmatrix} \eta_{11}+\eta_{12} & -\eta_{21} \\ -\eta_{12} & \eta_{22}+\eta_{21} \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \end{Bmatrix} = \begin{Bmatrix} \Pi_1^{in} \\ 0 \end{Bmatrix}. \tag{13}$$

The coupling loss factors satisfy the consistency relation $\eta_{12}\, n_1 = \eta_{21}\, n_2$, where n_i is the modal density of subsystem i.

The general procedure is to use SEA to compute the averaged energies of the subsystems. The input powers are usually known for a given excitation and, for most subsystems used in building acoustics, the internal loss factors can be computed with analytical expressions, available in the literature [7]. However, the analytical expression for the coupling loss factor is only available for simple connections.

In this work, the SEA formulation for a system consisting of two subsystems is used to estimate the coupling loss factors. The averaged energies of the subsystems are obtained from the numerical simulation of the same vibroacoustic problem and the SEA power balances are used to compute η_{ij}. Since the energy values are frequency dependent, the CLF obtained will also depend on the frequency, and therefore the result of the computation will not be a single value but a CLF law in terms of the frequency.

Using Equation (13) and the consistency relation, the CLF can be isolated from the power balance of subsystem 1 (first SEA equation) as

$$\eta_{12} = \frac{\Pi_1^{in} / \omega - \eta_{11} E_1}{E_1 - \frac{n_1}{n_2} E_2} \tag{14}$$

or from the power balance of subsystem 2 (second SEA equation) as

$$\eta_{12} = \frac{\eta_{22} E_2}{E_1 - \frac{n_1}{n_2} E_2}. \tag{15}$$

Also computing the power transmitted through the connection and using that

$$\Pi_{12} = \omega \left(\eta_{12} E_1 - \eta_{21} E_2 \right), \tag{16}$$

the CLF can be obtained as

$$\eta_{12} = \frac{\Pi_{12}}{\omega \left(E_1 - \frac{n_1}{n_2} E_2 \right)}. \tag{17}$$

Since the values of the energies are computed numerically, they may have a certain error. Operating with them may lead to higher errors for the CLF estimation if not done carefully. An analysis in this sense was performed in [8], leading to the conclusion that Equation (14) is not trustable for computing the CLF, because it implies the subtraction of two very similar quantities. Indeed, the subtraction of two similar quantities is prone to amplify any errors in the numerical estimation of the energies and powers, leading to unreliable results for the CLF. Equations (15) and (17) are both trustable, since the relative error of the CLF is of the same order of magnitude as that of the energies and powers used in the computation. Equation (17) requires some extra postprocessing effort to obtain the power at the connection and therefore the recommended expression is Equation (15).

3.2 Non-conservative case

Parameters η_{ij} and γ_{ij} of a non-conservative coupling between two subsystems can be obtained from numerical simulations of the energy transmission between the two subsystems. These simulations should include the dissipative behaviour of the coupling. For a given excitation, both the input powers Π_i^{in} and the averaged energies of the leaves E_i can be computed solving the vibroacoustic problem numerically. Assuming that η_{ii} is known for every subsystem, the rest of the SEA parameters can be isolated from the power balances of the system.

If the two subsystems have different properties (which is the most common case), the structure is not symmetric and there are four parameters to compute: η_{12}, η_{21}, γ_{12} and γ_{21}.

To obtain them all, the SEA formulation of two mutually independent problems is required. These two problems correspond to the system behaviour for two different excitations: one on subsystem 1 and the other on subsystem 2. For each different excitation, the averaged energies of the subsystems are computed numerically. If these energies are replaced in the SEA-like formulation of each problem (12), a 4x4 linear system can be solved to obtain the four parameters desired

$$\begin{bmatrix} E_1 & -E_2 & E_1 & 0 \\ \hat{E}_1 & -\hat{E}_2 & \hat{E}_1 & 0 \\ -E_1 & E_2 & 0 & E_2 \\ -\hat{E}_1 & \hat{E}_2 & 0 & \hat{E}_2 \end{bmatrix} \begin{Bmatrix} \eta_{12} \\ \eta_{21} \\ \gamma_{12} \\ \gamma_{21} \end{Bmatrix} = \begin{Bmatrix} \Pi_1^{in}/\omega - \eta_{11}E_1 \\ -\eta_{11}\hat{E}_1 \\ -\eta_{22}E_2 \\ \Pi_2^{in}/\omega - \eta_{22}\hat{E}_2 \end{Bmatrix}. \tag{18}$$

In system (18), E_i and $\hat{E}_i$ are the averaged energies of subsystem i for excitations applied to subsystems 1 and 2 respectively.

System (18) is a robust way for computing the conservative coupling loss factor η_{12} but it is unreliable for computing γ_{12} if $\gamma_{12} << \eta_{11}$. This unreliability is caused by the implicit subtraction of two similar numbers in the computation of γ_{12} with system (18). The equations leading to this conclusion are shown in detail in [9].

Due to the unreliability of Equation (18) for $\gamma_{12} << \eta_{11}$, an alternative formulation is proposed. If the power exchanged between the subsystems and the connection is computed on both sides of the connection, it can be expressed in terms of the energies of the subsystems for the two types of excitations as

$$\begin{aligned} \Pi_{12}^{(1)}/\omega &= (\eta_{12}+\gamma_{12})E_1 - \eta_{21}E_2 \\ \Pi_{12}^{(2)}/\omega &= \eta_{12}E_1 - (\eta_{21}+\gamma_{21})E_2 \end{aligned} \tag{19}$$

and

$$\begin{aligned} \hat{\Pi}_{12}^{(2)}/\omega &= (\eta_{21}+\gamma_{21})\hat{E}_2 - \eta_{12}\hat{E}_1 \\ \hat{\Pi}_{12}^{(1)}/\omega &= \eta_{21}\hat{E}_2 - (\eta_{12}+\gamma_{12})\hat{E}_1. \end{aligned} \tag{20}$$

Subtracting the two equations of each system and rearranging them, the following system results:

$$\begin{bmatrix} E_1 & E_2 \\ \hat{E}_1 & \hat{E}_2 \end{bmatrix} \begin{Bmatrix} \gamma_{12} \\ \gamma_{21} \end{Bmatrix} = \frac{1}{\omega} \begin{Bmatrix} \Pi_{12}^{(1)} - \Pi_{12}^{(2)} \\ \hat{\Pi}_{12}^{(1)} - \hat{\Pi}_{12}^{(2)} \end{Bmatrix}. \tag{21}$$

As shown in [9], Equation (21) is only unreliable if the coupling transmission is much higher than the dissipation ($\Pi_{12}^{(2)} >> \Pi_{12}^{(1)} - \Pi_{12}^{(2)}$). However, in that case the connection may be considered conservative and the classical SEA formulation should be used, assuming $\gamma_{12}=0$. Therefore, Equation (21) is more robust than Equation (18) for computing the NCLF because its reliability does not depend on the properties of the subsystems.

4. RESULTS

To illustrate the potential of the two techniques described in Section 3, an example with both conservative and non-conservative couplings is shown here. It reproduces the sound transmission between two rooms divided by a double wall filled with absorbing material. This problem is solved with a SEA-like approach, dividing the system in four subsystems: sending room, leaf 1, leaf 2 and receiving room (see Figure 3). The absorbing material is considered as a non-conservative connection between subsystems 2 and 3.

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

$$\eta_{ii} = \frac{cS_{cav}\alpha}{8\pi f V_{cav}}, \tag{22}$$

where S_{cav} is the surface of the room boundary, $\alpha = 0.1$ is the absorption coefficient at that boundary, c

is the sound speed in the air and V_{cav} is the volume of the room. The excitation is a sound source in one of the rooms (subsystem 1).

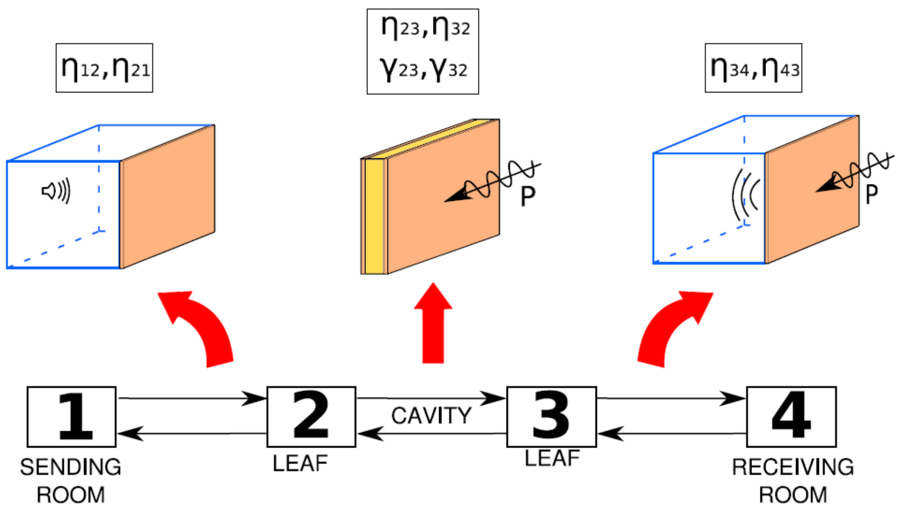

Figure 3 – Small problems solved numerically to obtain the CLFs.

To obtain all the coupling loss factors η_{ij} and γ_{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_{23}, η_{32}, γ_{23} and γ_{32} between the two leaves. The simulation has been performed with a combination of modal analysis for the leaves and the Finite Layer Method for the cavity, as described in [10]. This method combines a FEM-like disretisation in the direction perpendicular to the wall with trigonometric functions in the other two directions. The absorbing material is modelled as an equivalent fluid with the Delany-Bazley-Miki approach [11], and the excitation of the system is a pressure wave impinging on one of the leaves.

On the other hand, the coupling loss factors between each leaf and its adjacent room have been computed. To do so, two numerical simulations of systems consisting of a room in contact with a leaf are performed. One of them has a sound source on the room and is used to obtain η_{12} and η_{21}. The excitation of the other simulation is a pressure wave impinging on the leaf. That one is used to compute η_{34} and η_{43}. The importance of computing the CLF with the same excitation of the problem where it is going to be applied has been shown in [8]. In the two room-leaf simulations, the vibroacoustic problem has been solved with modal analysis.

Once all the coupling loss factors are obtained, the SEA-like system

$$\omega \begin{bmatrix} \eta_{11}+\eta_{12} & -\eta_{21} & 0 & 0 \\ -\eta_{12} & \eta_{22}+\eta_{21}+\eta_{23}+\gamma_{23} & -\eta_{32} & 0 \\ 0 & -\eta_{23} & \eta_{33}+\eta_{32}+\eta_{34}+\gamma_{32} & -\eta_{43} \\ 0 & 0 & -\eta_{34} & \eta_{44}+\eta_{43} \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{Bmatrix} = \begin{Bmatrix} \Pi_1^{in} \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{22}$$

is used to obtain the energies in all the subsystems. The energies of the sending and receiving room (E_1 and E_4 respectively) are used to obtain the sound reduction index of the double wall.

The described approach has been used to analyse the influence of the absorbing material filling the double wall in the sound insulation of the wall. In Figure 4 the effect of the flow resistivity of the material on the sound reduction index between the two rooms is analysed. 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. [12]. The explanation for this phenomenon is that increasing the resistivity causes an increment both on the density and the wavenumber of the equivalent fluid. An increment of the fluid density causes a better propagation of the waves through it. On the other hand, a larger wavenumber results in a lower transmission of the waves through the fluid.

At low frequencies the increment of the wave number compensates the increment of the density and the sound insulation does not change with the resistivity. However, at high frequencies the effect of the wave number dominates that of the density and larger resistivities cause more insulating behaviours.

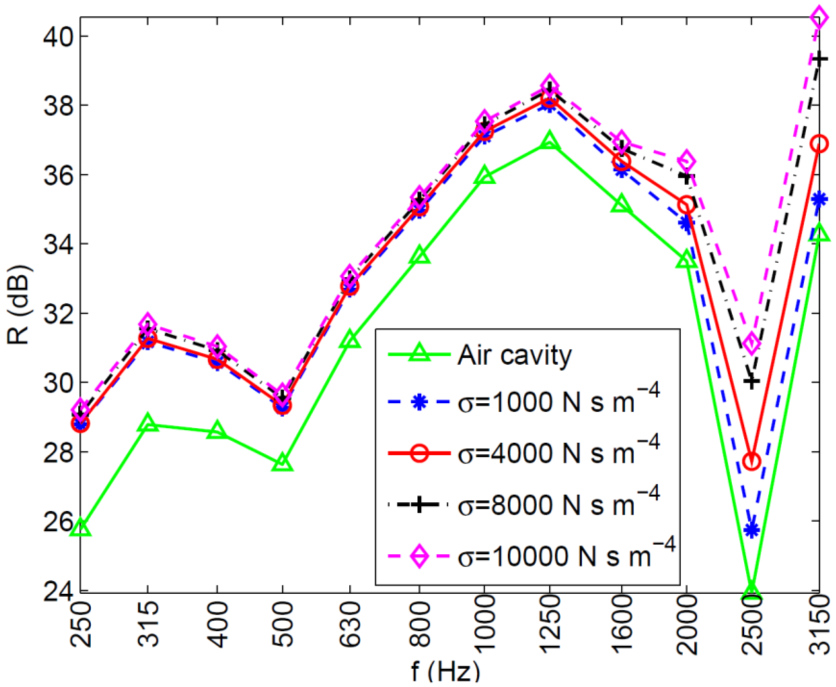

Figure 4 – Effect of the flow resistivity on the sound reduction index

5. CONCLUSIONS

- The combination of numerical and statistical methods is useful to solve realistic vibroacoustic problems. It allows reaching the whole frequency range required by regulations with a reasonable computational cost for large domains.
- Non-conservative connections can be taken into account in a SEA-like formulation with two types of coupling loss factors: the conservative η_{ij} and the non-conservative γ_{ij} coupling loss factors.
- Factors η_{ij} and γ_{ij} required for modelling couplings can be computed with numerical simulations of a system consisting of 2 subsystems. Attention must be paid to the error propagation in these computations. Once they are computed, these factors can be used to solve larger problems with SEA.
- The influence of the flow resistivity of the absorbing material filling a plasterboard double wall is only relevant for high frequencies. At low frequencies, the behaviour is different if the cavity is empty or filled with absorbing material, but the resistivity of the material does not affect the sound insulation.

6. FUTURE WORK

The estimation of (conservative or non-conservative) coupling loss factors requires the division of the domain into subsystems. These subsystems are usually defined as those sets of modes that have a similar response for any kind of excitation.

In many cases, especially in building acoustics, the subdivision is clear. However, complicated geometries or heterogeneous systems with alternation of acoustic and mechanical domains may be difficult to subdivide, and therefore difficult to analyse with statistical energy analysis.

Numerical simulations may be a helpful tool to solve this problem. Since the definition of subsystem is done in terms of modes, an eingenvalue analysis can provide insights of the modal behaviour of the domain. Then, the independence between the different regions of the domain can be studied, as well as the different types of relevant modes existing in each region.

The ongoing work is based on using modal analysis at low and medium frequencies to identify the different subsystems in a vibroacoustic domain. The final goal is to use numerical simulations to provide all the extra information required to deal with complex vibroacoustic problems with SEA.

First, the subsystem division would be performed with modal analysis. Then, numerical simulations of each pair of contiguous subsystems would be performed to estimate their coupling loss factors. Finally, the global problem would be solved with statistical energy analysis.

ACKNOWLEDGEMENTS

The financial support of the Ministerio de Educación y Ciencia (FPU scholarship program) is gratefully acknowledged.

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