Evaluation of Dynamic Characteristic of Structural Panels with Statistical Energy Analysis

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Abstract: - An implementation in a typical L joined plate system has been proposed to investigate the effects of damping and coupling on vibration energy transmission through plates junction. A combined statistical energy analysis (SEA) and finite element method (FEM) approach characterizing the dynamic behavior of the panels has been considered. Within the procedure, the wave approach has been used to obtain the coupling loss factor (CLF) and the apparent coupling loss factor (ACLF) obtained by experimental statistical energy analysis (ESEA) together with FEM. The influence of the frequency spectrum, excitation, damping, and panel edge boundary conditions on the coupling parameters has been observed. It is demonstrated in the ESEA/FEM procedure that the boundary conditions influence the coupling factors more significantly at low frequencies, and for the higher values of damping used the results approximate those of the wave approach, which in general tends to occur at high frequencies. Variations in the energy transmission is observed in agreement with the coupling changes.

Keywords: - Vibro-Acoustics, Coupling factors, Damping, Statistical energy analysis, Panel structures, Finite element method.

1. INTRODUCTION

Human beings are often subjected to various noise and vibration stimuli resulting from a wide set of sources, such as electrical power stations or vehicles, which can be detrimental to both comfort and health conditions. The two mentioned sources have in common a constructive structure very often found in a large number of applications, that is, panel structures. These structures, if well designed and assembled, provide a suitable combination of structural efficiency, lightweight, and reasonable production costs. However, these systems also transmit vibro-acoustic energy, a fact that requires careful consideration by designers [1].

Considering the variety of complex geometries in which panels may be combined, the application of prediction tools emerges as an essential step for the proper analysis of these structures. In general, engineers use two main techniques to study vibration transmission in built-up structures, statistical energy analysis (SEA) and finite element method (FEM). It is possible to say that SEA is more suited to cope with the higher range of the frequency spectrum and FEM with the lower range of the frequency spectrum [2]. These approaches are described as statistical and deterministic, respectively, and both methods have been successfully applied to various tasks.

SEA arose during the 1960s in the aerospace industry to predict the vibrational behavior while designing spacecrafts [3]. It is developed from the equations of the oscillator, which is excited by a set of random forces and coupling effects. Losses and hence energy flow may be conveniently evaluated through the damping and the coupling factors. Obtaining these factors is also one of the most important tasks of the engineering application of SEA [4].

In general, damping is a parameter difficult to estimate best obtained via experimental procedures, however, it is possible to estimate the influence of its amplitude on energy transmission from procedures similar to the one being analyzed. For a SEA structural model, the coupling loss factor (CLF) is often derived from averaged transmission coefficients of plane waves that are transmitted through an infinite junction between semi-infinite plates [5]. This analytical method is known as the wave approach and is widely applied.

Through the wave approach, Johansson and Comnell [6] have implemented and validated a SEA software using the calculation procedures proposed by [5]. Based on this analytical method, Bosmans and Vermeir [7] have derived coupling loss factors for the vibrational response of point-connected plates. Although computationally intense, the procedure demonstrates the influence of the distance between the point connections on the structure-borne sound transmission. Shastry and Swamy [8] have computed SEA parameters for an L-shaped configuration using the classical wave approach. Analysis was carried out using three different composite materials for an L-shaped configuration. Using experimental and analytical procedures, Yin [9] focused on vibrational energy transmission in an L-junction of plates where one or both plates were a periodic ribbed plate.

However, many problems of practical importance cannot be analyzed with this analytical method [10]. The applicability of the wave approach in predicting the flow of energy in an individual engineering structure can be limited, especially at low frequency, as the assumptions on which it is based break down [11]. Alternatively, the CLF values can be estimated by experiments or numerically [12]. Through these approaches, the CLF is estimated from an individual case and it is referred to as the apparent coupling loss factor (ACLF) or energy flow coefficient (EFC) in the literature, to distinguish it from ensemble-based estimates.

Lyon and Dejong [13] suggested the use of FEM in predicting systems coupling factors during the early development of SEA. The process is essentially a numerical analogue of the power injection method (PIM), which is often used to develop an experimental SEA (ESEA) model of a structure [14]. ESEA using numerical models is a highly useful tool for quantifying vibration transmission between plates that are connected at complicated junctions [15].

In numerical methods, the behavior of the SEA model with changes in inputs (geometry, materials) can be easily evaluated and is less time consuming as compared to experimenting with the real structure. As a result, FEM associated with SEA has been successfully used for a variety of applications.

Simmons [10] used FEM to calculate the vibrational energy of plates forming L- and H-structures at discrete frequencies between 10 and 2000 Hz, where one plate was excited by a point force and the power was transmitted through the junction to the other plates. This strategy served as a starting point to the analysis of the junction in terms of the coupling factor. With the aim to catalog the coupling for a variety of junctions, Winter et al. [16] applied SEA-averaging techniques in the postprocessing of FEM calculations. The application of this method combined with a classical SEA calculation and laboratory measurements were also presented.

Pankaj et al. [12] has employed the same procedure to investigate the coupling factors in an L-shaped plate. In the analysis, the FEM model was excited by a point force. This excitation strategy was also applied by Wang et al. [17] in a similar analysis, although in the latter work the matrix approach to combine FEM and SEA was replaced by a direct application of a single equation. Using FEM to construct SEA models, Kuroda [18] has evaluated parameters to a simple flat plate and an L-shaped plate, in which a base excitation method was applied. Fasulo et al. [19] have focused on the characterization of the dynamic behavior of aeronautical panels reinforced with stringers. In his work SEA, FEM, and a hybrid approach were applied.

In the present paper, the focus is on examining the dynamic characteristics of two plates joined in an ‘L’ junction configuration using FEM and ESEA. The aim is to allow statistical information from a number of deterministic analyses to be used in the SEA framework, and hence, calculate the expected range of response for the coupled plates.

In practical applications, uncertainty in the material properties and dimensions means that a single deterministic analysis will rarely predict the large fluctuations in the same frequency bands as in the measured response. This is the reason why response statistics are also desirable in this analysis procedure.

In order to effectively estimate the system response, variables are considered in the analyses, namely: excitation, boundary conditions, and damping loss factor. The obtained results are in terms of the energy difference level between the plates and the coupling factors. The wave approach is also applied as a comparison to the obtained results.

As a contribution, this paper aims to present a way to investigate the suitability of SEA to analyze individual structures and also aspects that can be useful in using FEM data in SEA models.

2. STATISTICAL ENERGY ANALYSIS

In SEA, parts of the system having similar mode groups are described as subsystems. In a SEA model, mechanisms for energy dissipation, excitation by external sources, and energy transmission are assigned to the subsystems [13].

Figure 1 shows a generalized model composed of two subsystems, where the energy provided by the external sources (Π_i, Π_j) establishes an energy flow through the system.

The balance of energy can be expressed as:

$$\Pi_i + \Pi_{ji} = \Pi_{ij} + \Pi_{id} \quad (1)$$

$$\Pi_j + \Pi_{ij} = \Pi_{ji} + \Pi_{jd} \quad (2)$$

where Π_{ij} and Π_{ij} express the energy flow from one subsystem to the other, evaluated as follows:

$$\Pi_{ij} = \omega\eta_{ij}E_i \quad (3)$$

$$\Pi_{ji} = \omega\eta_{ji}E_j \quad (4)$$

where η_{ij} and η_{ji} are the CLF and represent the rate of energy exchange between subsystems, E_i represents the energy of subsystem i, and ω the angular frequency.

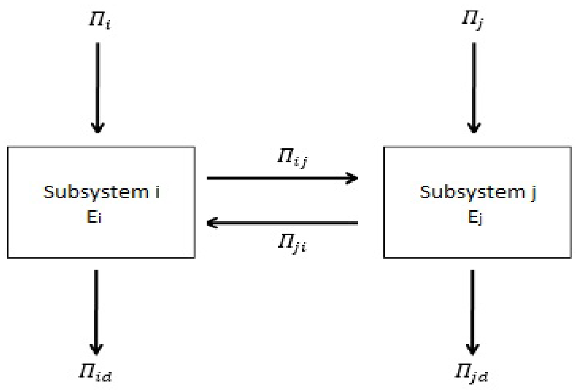

Figure 1. SEA model of two subsystems

Equations (1) and (2) indicate the power dissipation represented by Π_{id} and Π_{jd}, respectively. This energy does not return to the system and is dissipated mainly due to friction and viscosity. It is given by:

$$\Pi_{id} = \omega\eta_{id}E_i \quad (5)$$

$$\Pi_{jd} = \omega\eta_{jd}E_j \quad (6)$$

where η_{id} and η_{jd} represent the damping loss factors (DLF). When combining equations (1) - (6), the power balance equation for two subsystems can be expressed in the matrix form shown in equation (7) [6].

$$\begin{bmatrix}\Pi_i\\ \Pi_j\end{bmatrix} = \omega\begin{bmatrix}(\eta_{id}+\eta_{ij}) & -\eta_{ji}\\ -\eta_{ij} & (\eta_{jd}+\eta_{ji})\end{bmatrix}\begin{bmatrix}E_i\\ E_j\end{bmatrix} \quad (7)$$

SEA is more reliable when dealing with the so-called weak coupling, occurring when the losses due to damping predominate ($\eta_{ij} << \eta_{id}$).

2.1. Wave approach

The wave transmission across plate junction, as illustrated in Figure 2, can be characterized by the transmission coefficient [5]. In SEA, the transmission coefficient may also be used to determine the CLF, as expressed in equation (8).

$$\eta_{12} = \frac{c_g L}{\omega\pi S}\bar{\tau}_{12} \quad (8)$$

where c_g is the group speed, L is the length of the junction, S is the plate area, and $\bar{\tau}_{12}$ is the angular-average transmission coefficient. Assuming diffuse incidence, the latter can be obtained by:

$$\bar{\tau}_{12} = \int_0^{\pi/2} \tau_{12}(\theta)\cos\theta\, d\theta \quad (9)$$

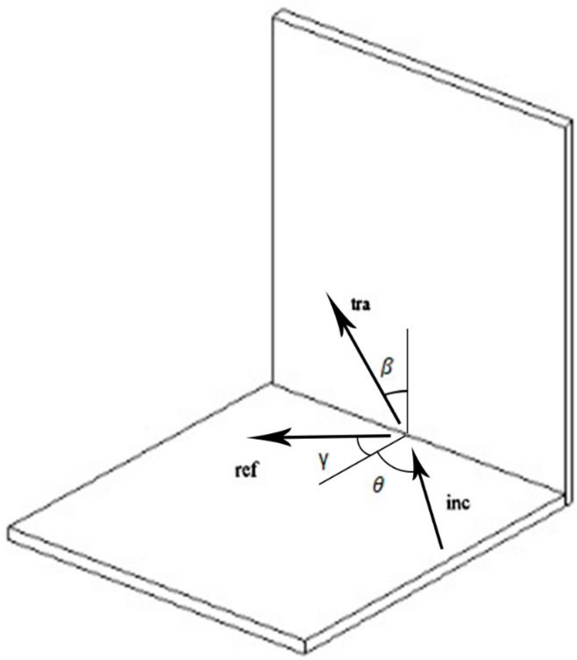

Figure 2. Wave transmission and reflection at the junction between two plates joined in 'L' configuration

Considering an L-shaped junction with the boundary condition simply supported between two isotropic and homogeneous plates, the transmission coefficient can be obtained using the parameters χ and Ψ, given by [20]:

$$\chi = \sqrt[4]{\frac{\rho_2 h_2 B_1}{\rho_1 h_1 B_2}} \quad (10)$$

$$\Psi = \sqrt{\frac{\rho_2 h_2 B_2}{\rho_1 h_1 B_1}} \quad (11)$$

This boundary condition implies that only bending waves are transmitted between the plates.

If $\chi > \sin\theta$, then the transmission coefficient according to the angle of the incident wave is obtained by:

$$\tau_{12}(\theta) = \frac{2\Psi\, cos\, cos\, \theta\, \sqrt{\chi^2 - sin^2\theta}}{\Psi^2 + \chi^2 + \Psi\left(\sqrt{1 + sin^2\theta}\sqrt{\chi^2 + sin^2\theta}\sqrt{1 - sin^2\theta}\sqrt{\chi^2 - sin^2\theta}\right)} \tag{12}$$

In case of $\chi < sin\,\theta$,

$$\tau_{12}(\theta) = 0 \tag{13}$$

3. EXPERIMENTAL STATISTICAL ENERGY ANALYSIS

Experimental statistical energy analysis is a useful tool to obtain the coupling factor, particularly for the more complex subsystems and coupling junctions [9]. In this method, the data can be obtained either by means of laboratory experiments or by numerical simulation. Finite element analysis is usually the preferred method, as a larger number of tests may be quickly carried out reducing costs and time demanded in laboratory testing [17].

The ESEA matrix can be expressed by equation (14), which is developed from the energy balance equations of SEA.

$$\begin{bmatrix} \sum_{n=1}^{N}\eta_{1n} & -\eta_{21} & \cdots & -\eta_{N1} \\ -\eta_{12} & \sum_{n=1}^{N}\eta_{2n} & & \vdots \\ \vdots & & \ddots & \\ -\eta_{1n} & \cdots & & \sum\eta_{Nn} \end{bmatrix} \begin{bmatrix} E_{11} & E_{12} & \cdots & E_{1N} \\ E_{21} & E_{22} & & \vdots \\ \vdots & & \ddots & \\ E_{N1} & \cdots & & E_{NN} \end{bmatrix} = \begin{bmatrix} \Pi_{in,1}/\omega & 0 & \cdots & 0 \\ 0 & \Pi_{in,2}/\omega & & 0 \\ \vdots & & \ddots & \\ 0 & 0 & & \Pi_{in,N}/\omega \end{bmatrix} \tag{14}$$

This approach involves excitation of each subsystem at a time obtaining the displacement responses of the elements in FEM, which are used to determine the vibration energy of the structure as follows [21]:

$$E = \frac{1}{2}\omega^2 \sum_{n=1}^{N} m_n {\eta_n}^2 \tag{15}$$

In equation (15), η_n is the out-of-plane displacement of the element and m_n is the mass of the element. The input of energy generated by the force application on the nodes can be expressed as [9]:

$$\Pi_{in} = \frac{\omega}{2}\sum_{n=1}^{N}\left(Im\{F_n\} * Re\{\xi_n\} - Re\{F_n\} * Im\{\xi_n\}\right)_n \tag{16}$$

where F_n is the force applied and ξ_n is the resulting displacement at the node.

Using the generated results as input in equation (14), the coupling factors can be obtained.

3.1. Finite element method

The finite element method is used in a variety of applications, presenting facilities such as defining loads and boundary conditions, studying dynamic effects, and modeling structures [22].

In FEM application to obtain the ACLF, it is important to highlight that the way in which the force is applied to establish the energy flow in the model is an important aspect. As this procedure is used in connection with SEA, it is vital to ensure that the following basic SEA assumptions are met, namely: the input system is composed by uncorrelated forces having a wide spectral range, and diffuse field assumptions hold true.

The usual strategy to achieve these conditions is by means of the so-called “rain-on-the-roof” (ROTR) excitation, where a series of random excitations are imposed on the nodes of the model. The use of more than one set of ROTR excitation is recommended in order to ensure that the previously mentioned assumptions are met. Other less common means of excitation are available, such as the one presented by Kuroda [18].

Figure 3 illustrates the FEM model developed in the Ansys software for the numerical experiments, exposed in the next section.

4. NUMERICAL EXPERIMENTS

In order to exemplify the procedure, a classical assembly consisting of L joined aluminum plates is analyzed. The plates dimensions are 1,0 x 0,9 x 0,002 meters, which have been chosen as being typical for many applications.

The junction is continuous (line) with boundary conditions simply supported, which allows only bending waves to be transmitted. An element size less than 1/6 of the shortest wavelength of the analysis is employed.

Within the analysis, variations in the results are evaluated by changing the boundary conditions for the plates edges to free or simply supported (except the junction, which is always simply supported), and by changing the DLF values (0.02, 0.04, 0.08, 0.16). The damping is included in the FEM model considering the relation $\eta_d = 2\zeta$, where ζ is the damping ratio.

In the procedure, the excitation is performed with a classical ROTR excitation, the data are obtained in 10 Hz intervals and averaged values are calculated for third-octave bands (100-3150) Hz. The mesh adequacy was verified through the comparison between the input and output of power, as expressed in equation (17):

$$e_{mesh} = \frac{|\Pi_{out} - \Pi_{in}|}{\Pi_{in}} x100\% \quad (17)$$

where $\Pi_{out} = \omega\eta_d E$.

The highest mesh error found in the analysis was about 9% which is less than the 40% recommended by [15], representing that the mesh was adequate.

Figure 3. FEM model

5. RESULTS AND DISCUSSION

5.1. Implementation of the wave approach and excitation of the FEM model

Initially, the routines based on the wave approach developed by the authors were verified by comparing the obtained results with the software SEALab. The results are shown in Figure 4, which expresses the adequacy of the implementation.

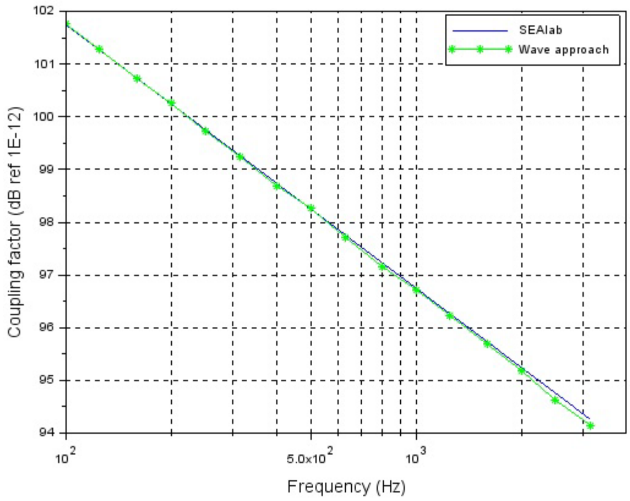

Figure 4. Coupling factors obtained using different procedures

After that, the FEM model was defined and an excitation was applied to this model using the ROTR excitation, which corresponds to complex forces acting on all nodes (except those at the edges of the plate) having unit magnitude and different from each other by the phase values.

Figure 5 shows ACLF results for 5 different sets of ROTR applied to the model. From this figure, it is possible to observe the influence of the excitation on the ACLF and the need for applying more than one set of ROTR to obtain more reliable results. It is therefore important to use average values, as also shown in Figure 5, which better represent the system.

For this reason, this same procedure for averaging is adopted in the following analyses, using the same 5 sets of ROTR excitation.

5.2. Boundary conditions

The influence of the boundary conditions can be analyzed by changing the displacement constraints of the plate edges prior to the FEM/ESEA procedure. The average ACLF values for the models with edges free and with edges simply supported are presented with 95% confidence intervals in Figure 6, as well as values obtained by the wave approach.

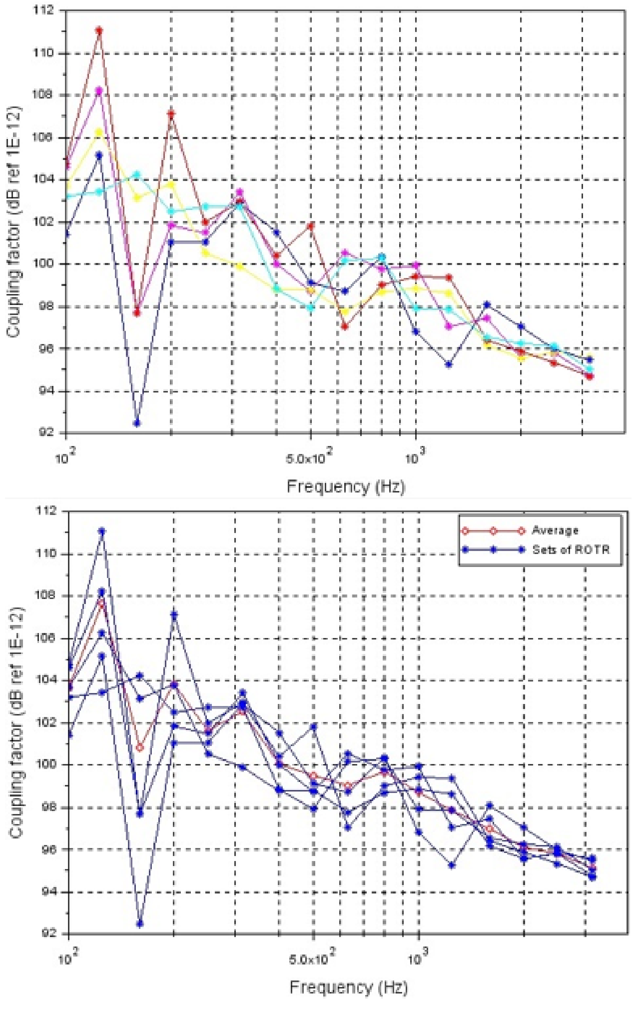

Figure 5. ACLF for 5 Sets of ROTR (Simply supported edges, DLF=0.04)

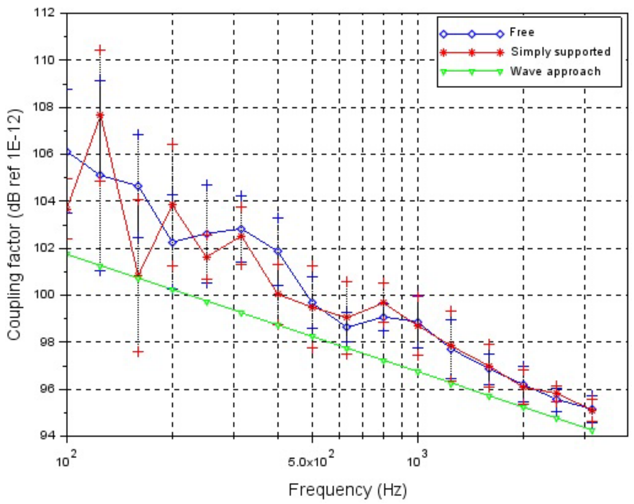

Figure 6. Comparison between ESEA (simply supported and free edges, DLF=0.04) and the wave approach

From the results of Figure 6, it is possible to observe that the influence of the boundary conditions tends to be more pronounced in the lower frequency ranges, where the differences between the curves for the edges conditions simply supported and free are larger. Increasing the frequency has the effect of reducing these differences and therefore indicating less influence of the boundary conditions in the higher frequency ranges. It is also possible to observe that the solutions obtained from the wave approach improve with this increase in frequency.

At lower frequencies, the structure response tends to be governed by global modes which are modified by the boundary conditions. This behavior may be the reason for the greater influence of the boundary in the frequency range observed in Figure 6. On the other hand, increasing the frequency the structure response tends to be governed by local modes, which may be associated with the decrease of the influence of the boundary conditions.

The coupling behavior observed in Figure 6, naturally modifies the energy level difference between the plates. By using the results of the previous analysis this difference is presented in Figure 7, which expresses the energy difference between the two subsystems. The two conditions, energy and coupling, are obviously related, each result being more useful depending on the needs for a specific practical use.

Consequently, as far as the transmitted energy is concerned, greater differences between the boundary conditions are observed in the low-frequency range, reaching a difference close to 3 dB in the 160 Hz band. As expected from the previous results, frequency increase is accompanied by a decrease of boundary condition influence and a solution similar to that obtained via statistical energy analysis using the wave approach.

5.3. Damping loss factor

In the wave approach, the DLF is not directly treated in obtaining the coupling factor, whereas in ESEA, it can be accounted for from the moment when the model is defined in FEM.

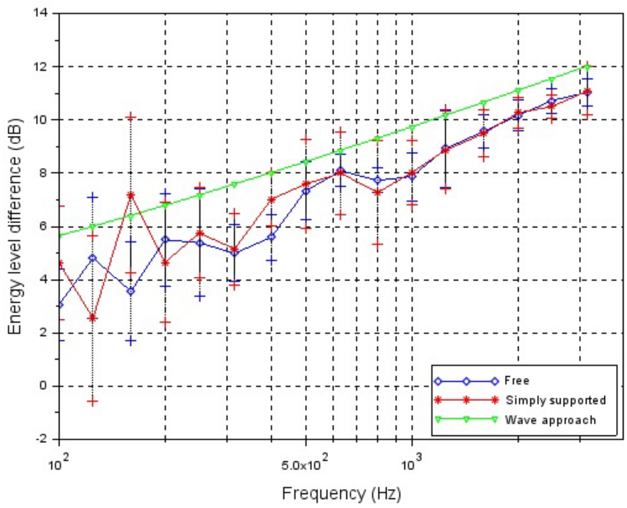

Figure 7. Energy level difference between the plates using SEA and FEM (simply supported and free edges, DLF=0.04)

In order to compare the effect of this aspect, the results by using both methods are shown in Figure 8. In this figure, the confidence intervals are not represented because they could compromise the graphical visualization, anyway, these confidence intervals are also larger at lower frequencies and smaller at higher frequencies.

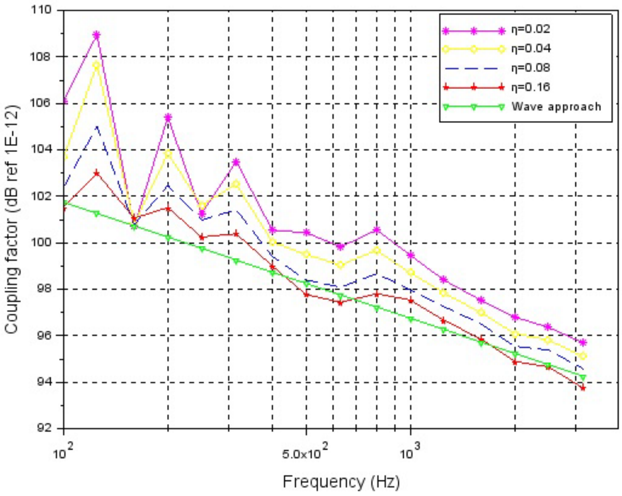

Figure 8. Comparison between ESEA (simply supported edges, different DLFs) and the wave approach

The ESEA results correspond to 4 distinct DLF values to the system, which curves present similar oscillation behaviors throughout the frequency range. It is also noticeable in the low-frequency region that these curves have a greater distance from the wave approach. This behavior is a well-known behavior, previously described by many authors such as Fredo [11], confirming the unsuitability of SEA for estimations in this region.

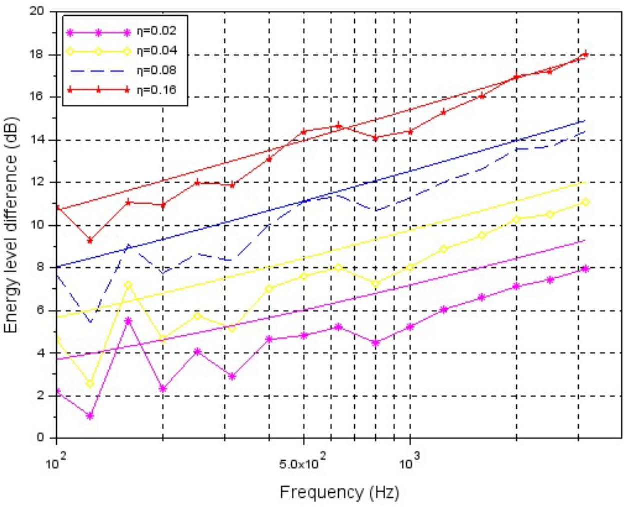

Figure 9. Energy level difference between the plates using SEA (solid lines) and FEM (lines with marks)

It is also possible to observe that as the damping factor increases, the wave approach also becomes closer to the ESEA solution, not only an expected result but one that is consistent with the previously coupling factor analysis.

The energy level difference between the plates for each case is shown in Figure 9, where higher damping values provide closer proximity between the methods. The energy level difference between the plates results from a combination of both the damping factor and the coupling factor.

Figure 9 illustrates how effective is a particular solution to determine the energy flow from one subsystem to the other, depending on the damping and frequency range under consideration.

6. CONCLUSION

The dynamic behavior of panels using a variety of SEA and FEM approaches has been considered. After obtaining the CLF by means of the wave approach and the ACLF using an ESEA and FEM approach applying a ROTR excitation, the results for a typical system consisting of two L joined aluminum plates could be analyzed.

Initially, it was possible to observe that it is important to use more than one set of ROTR excitation and average the results to reduce scattering in the ESEA/FEM procedure. With regards to the variability of solutions concerning the frequency range, it was possible to observe that the ACLF results at the higher range of the spectrum are very much similar to what is to be obtained as CLF using the wave approach. Also, as expected, higher damping losses provide better SEA results, whereas there is a noticeable reduction in quality when damping is reduced and the effects of the losses due to coupling effects become more pronounced. When the limit edge boundary conditions, that is free and clamped edges, are compared regarding their influence on the coupling factors, it has been possible to observe that at the lower frequency range of the spectrum it becomes very important to identify how the system is supported as the response is more dependent for this range. Also, for this condition, the wave approach solution is more similar for the higher frequency range. These results were also confirmed by means of the energy level difference between the two subsystems.

These analyzes signify the effects of the damping loss factor and boundary conditions on proper selection and usage of the proposed approaches. It also makes explicit the potential of the proposed approach to explore the adequacy of conventional SEA in predictions for the individual case and situations where the subsystems have strong coupling.

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