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ASSESSING THE QUALITY OF CORRECTED NEGATIVE SEA LOSS FACTORS USING TLF CRITERION

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ABSTRACT

Statistical Energy Analysis (SEA) is a numerical method designed to predict vibroacoustic energy flow in complex systems. Loss factors are the main parameters describing the SEA model. Loss factors are positive real numbers and can be predicted theoretically or measured. Unfortunately, experimentally determined loss factors may be negative due to the inversion of the error-sensitive matrix. One recently proposed method utilizes Monte Carlo Filtering (MCF) to correct negative loss factors. In this paper, we introduce and validate a simple quality-control tool that allows checking if performed negative loss factor correction delivered physically meaningful results. To achieve this, we propose to utilize the Total Loss Factor criterion. This approach requires additional calculations in which only a single subsystem is considered, and all junctions are ignored. Experiments were performed on nine systems comprising junctions commonly used in the industry. MCF was then used to correct negative loss factors in some frequency bands. We have shown that a poorly generated Monte Carlo sample can lead to results that do not fulfill the required criterion, even though negative loss factors were no longer present. Narrowing the search area during sample generation was crucial to obtain quality results that met the TLF criterion.

Keywords: *Statistical Energy Analysis, Coupling Loss Factor, Monte Carlo Filtering, Power Injection Method*

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1. INTRODUCTION

The SEA method has been widely used to perform vibroacoustic energy flow simulations in complex systems [1]. In order to perform SEA calculations, one needs to identify coupling and damping loss factors. Loss factors can be determined by using on of the E-SEA (Experimental SEA) methods like the PIM (Power Injection Method) [2]. However, numerical errors can cause loss factors to be negative [3]. In this paper, we investigate one of the recently proposed methods of correcting negative loss factors, namely the Monte Carlo Filtering (MCF) method [4]. In MCF, a statistical ensemble of energy matrices is generated based on the mean value and variance of the experimental data. The population is then filtered in order to remove all matrices that will produce negative LFs. The final step is to compute the mean value of the obtained LFs. The MCF proved to be successful in correcting negative loss factors [5], but strong dependence of loss factors value on the so-called search area has been pointed out [6]. This observation raises the question of whether the quality of obtained results is acceptable and physically meaningful. Even though some methods of minimizing MCF errors were proposed in the previous paper [6], the appropriate criterion of loss factors quality is still missing.

In this paper, we will show how to utilize total loss factor (TLF) properties to derive the criterion in question. The new method is simple to implement and takes advantage of the principal dependencies between the exact and approximate value of the total loss factor. Experiments performed on nine simple systems proved the usefulness of the proposed approach.

In MCF, one can control the search area by increasing the γ parameter (expansion of the search area) or decreasing the γ parameter (narrowing the search area). The search area determines the range of values used in energy matrices during Monte Carlo sample generation. If the TLF criterion is unmet, one can state that the permissible value of γ has been exceeded. Nevertheless, the CLF quality deterioration caused by other factors (like lack of compliance with the SEA assumptions) will not be detected by the TLF criterion and must be dealt with separately.

2. TLF CRITERION DERIVATION

In the classical approach, the total loss factor η_{TOT} is determined using the method of structural reverberation time (according to relevant standards). The reverberation time measured in this way takes into account all mechanisms in which energy is dissipated, including losses associated with energy flow to neighboring subsystems. Such a situation can also be reproduced during PIM measurements if one ignores all connections to the other subsystems (treats the selected subsystem as a complete system consisting of only one subsystem i). Then the determined damping loss factor of the selected subsystem i will correspond to the total losses making it equal to $\eta_{TOT,i}$. Thus, the following equation applies

$$\eta_{TOT,i} = \frac{P_i}{\omega E_i}. \tag{1}$$

On the other hand, the formula for $\eta_{TOT,i}$ can be determined using the complete energy balance, where the other subsystems are not omitted. If, for the purpose of the example, we assume for now a system consisting of only two subsystems and choose $i = 1$, then the $\eta_{TOT,1}$ of subsystem „1" connected to subsystem „2" can be derived using SEA energy balance equation

$$\omega\eta_{11}E_1 + \omega\eta_{12}E_1 - \omega\eta_{21}E_2 = P_1. \tag{2}$$

From the formula 2, a relationship for the average energy of the subsystem „1" can be derived:

$$E_1 = \frac{P_1 + \omega\eta_{21}E_2}{\omega(\eta_{11} + \eta_{12})}. \tag{3}$$

Then by substituting 3 into 1, the following expression is obtained

$$\eta_{TOT,1} = (\eta_{11} + \eta_{12})\frac{P_1}{P_1 + \omega\eta_{21}E_2}. \tag{4}$$

From the equation 4, it can be seen that when the term $\omega\eta_{21}E_2$ of the sum $P_1 + \omega\eta_{21}E_2$ is negligible, the following approximation can be used

$$\eta_{T\hat{O}T,1} = \eta_{11} + \eta_{12}. \tag{5}$$

The term $\omega\eta_{21}E_2$ does not affect the value of the expression 4 when the receiving system is heavily damped (the energy E_2 is very small). Analyzing the form of the formula 4, it can be seen that the approximation 5 determines the upper limit of the exact value, $\eta_{TOT,1}$

$$\eta_{TOT,1} \leq \eta_{T\hat{O}T,1} \tag{6}$$

or after simple rearrangement

$$\frac{\eta_{T\hat{O}T,1}}{\eta_{TOT,1}} \geq 1. \tag{7}$$

The formula 5 can be generalized to the case where M receiving subsystems are connected to any i-th subsystem. The exact formula for the TLF of a subsystem i then has the form

$$\eta_{TOT,i} = \left(\eta_{ii} + \sum_{k=1,k\neq i}^{M} \eta_{ik}\right) \frac{P_i}{P_i + \omega \sum_{k=1,k\neq i}^{M} \eta_{ki}E_k}. \tag{8}$$

As in equation 4, when the energies of all receiving subsystems are negligible, the generalized approximation can be used

$$\eta_{T\hat{O}T,i} = \eta_{11} + \eta_{12} + ... + \eta_{1M}. \tag{9}$$

Having the values determined from equations 9 and 1 for all subsystems ($i = 1, 2, ..., N$), the TLF ratio inequality can be stated independently for each „i":

$$\frac{\eta_{T\hat{O}T,i}}{\eta_{TOT,i}} \geq 1. \tag{10}$$

The value of $\eta_{T\hat{O}T}$ is much easier to determine at the simulation stage, and it should be taken into account that it represents the upper limit of the exact value of η_{TOT}, which is, in turn, easier to determine experimentally (e.g., the total loss factor measurements of a partition in a reverberation chamber during sound insulation measurements). Note that the inequality 10 can be used as a simple criterion to check the accuracy of the MCF method for systems with the number of subsystems $N > 1$ (for $N = 1$ we have $\eta_{11} = \eta_{TOT} = \eta_{T\hat{O}T}$ and the criterion is always satisfied). Suppose the negative loss factor has been successfully corrected in a given band, but the inequality 10 is not satisfied. In that case, the result associated with that band is subject to error, and such a band can be marked as a „poor-quality" band.

Table 1. The geometrical and material properties of the plates

Geometrical parameters	
Thickness	2 mm
Length	490 mm
Width	490 mm
Material parameters	
Material	Steel
Density	7827 $\mathrm{kg/m^3}$
Young's modulus	205 GPa
Poisson number	0.3

The usefulness of the proposed criterion (inequality 10) will be demonstrated in the next section, where we show that it is necessary to apply (in some cases) a narrowing of the search area during MCF (setting $\gamma < 1$) to minimize the number of corrected bands that initially failed to meet the TLF criterion.

3. EXPERIMENTS

PIM measurements were performed on nine subsystems in order to validate the proposed approach. Each system consisted of two steel plates connected by different technical junctions at right angles. Each plate was treated as a single bending wave subsystem. Therefore, responses were measured only along the „z" axis (direction normal to the plate surface). The geometrical and mechanical properties of the plates are shown in Tab. 1. Technical junctions used to connect plates are shown in Fig. 1. Some systems consisted of the same junction but differed in the damping level. The systems discussed in this paper are the same ones that were measured in the previous study [5]. The reader is referred to this previous article in order to find a detailed description of the measurement process.

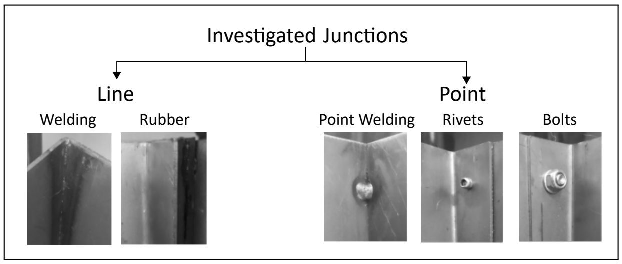

Figure 1. Investigated junctions

Postprocessing of the results was done in 2 stages. In the first stage, full PIM analysis (2x2 matrix inversion) was performed in order to determine all CLFs and DLFs. This allowed to determine $\eta_{T\hat{O}T}$ by simply summing up DLF and CLFs. At the second stage, one of the plates was treated *as if* it was an isolated system disconnected from the second plate. This allowed us to determine η_{TOT}, which was equal to DLF, as explained in the previous section. At both stages, MCF was utilized. Finally, it was possible to implement inequality 10 and evaluate the quality of all measured loss factors. Described postprocessing procedure was performed separately for $\gamma = 1$ and $\gamma < 1$ cases.

4. RESULTS

Fig. 2 shows the $\eta_{T\hat{O}T}/\eta_{TOT}$ ratio for all tested systems. Each subplot in Fig. 2 applies to one system and contains two curves. One curve relates to the effective MCF correction using $\gamma = 1$, while the other relates to the effective MCF correction with $\gamma < 1$. It can be seen from the figure that the results obtained by the MCF method in the basic version ($\gamma = 1$) do not meet the TLF criterion in many frequency bands, despite the full correction of the negative loss factors in all cases. In contrast, narrowing the search area allowed the TLF criterion to be met in all analyzed bands. In order to narrow the search area γ was set to 0.25 in the considered cases.

Results show that during MCF, a proper γ must be chosen, and the TLF criterion can be helpful to confirm if γ is not too big. In the considered case, using $\gamma < 1$ can be considered as a reaction (intervention) to poor-quality results obtained for the $\gamma = 1$ case. Without utilizing the TLF criterion, bad-quality results could have been accepted as correct.

5. CONCLUSIONS

The TLF criterion proposed in this work can be considered a useful complement to the process of correcting negative loss factors with the MCF method. Evaluation of the TLF criterion makes it possible to determine whether changing the search area during Monte Carlo sample generation is necessary to obtain a result that makes sense from a physical point of view. The effectiveness of the technique has been demonstrated in measurements of 9 different SEA systems consisting of 2 subsystems. Tests on larger systems are also planned to validate the generalized inequality of the TLF criterion.

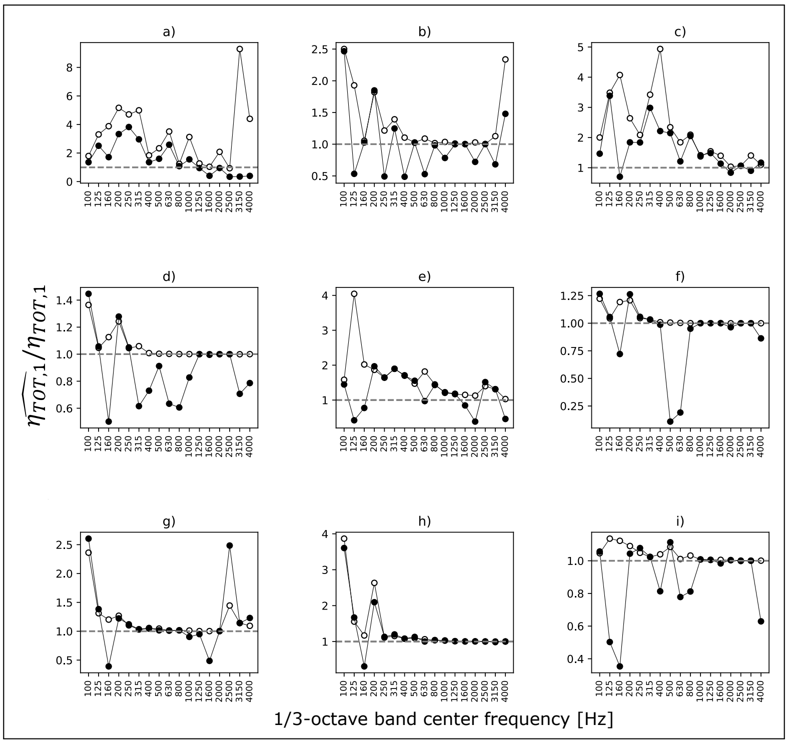

Figure 2. TLF criterion utilized in measured systems. Black marker corresponds to $\gamma = 1$ case, while white marker corresponds to $\gamma < 1$ case; a) Line welding, low damping; b) Rubber, low damping; c) Line welding, medium damping; d) Rubber, medium damping; e) Line welding, high damping; f) Rubber, high damping; g) Point welding, high damping; h) Bolt junction, high damping; i) Rivet junction, high damping

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