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A hybrid patch transfer-Green functions method to solve transmission loss problems of flat single and double walls with attached sound packages

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ABSTRACT

This paper presents and studies the performance of a sub-structuring method that employs a patch transfer approach (PTF) to couple the standard finite element schemes of the structures and cavities with an analytical model of the sound package. First, the approach is presented followed by a convergence study to define a patch mesh criterion. Then, the accuracy of the proposed methodology is assessed for single and double wall transmission problems with two different attached noise control treatments. The obtained results are systematically compared to three models, namely full finite element/boundary element strategies (FEM/BEM), and to two sub-structuring approaches based on the modeling of the sound package by (i) a locally reacting model and (ii) FEM. It is observed that the proposed method predict accurately and efficiently the dynamic behavior of flat trimmed vibroacoustic systems.

1. Introduction

Passive noise control treatments (NCT), also called sound package [1], are widely used in different industries to dissipate energy of sound and vibration waves. Such acoustic components are usually multilayered and made up of several layers of highly dissipative materials, inserted between the structure and the acoustic domains. They are efficient at high frequencies, but perform poorly in the low frequency range (i.e. long wavelength). Therefore, it is highly demanded to enhance their vibroacoustical performance. Classical optimization processes, at low frequencies, use finite element/boundary element (FEM/BEM) strategies [2]; they are however computationally expensive. Indeed, each layer of the sound package, for each tested configuration, must be carefully meshed at a preprocessing phase. Also, to correctly capture the behavior of the coupled trimmed vibroacoustic system, the NCT necessitate a refined mesh (up to 12 elements/wavelength for linear elements), because of their highly dissipative and soft nature. Moreover, in the standard FEM strategies the global system must be remeshed and solved each time a sub-system is modified.

To overcome these limitations, several authors have proposed hybrid approaches wherein a simplified analytical model of the acoustic treatment is included in a finite element framework. Such strategies are inspired by the fact that a detailed description of the master systems (e.g. main structures and cavities), characterized by geometrical complexity and longer wavelengths, is always necessary for low/mid-frequency analysis. Therefore, this class of methods model the elastic and acoustic domains

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by classical FEM, while the subdomains with much shorter wavelengths (i.e. acoustic treatment) are modeled by using the Transfer Matrix method (TMM) [1] and thus avoids the time consuming meshing phase. The TMM relies on several assumptions, namely, the soft multilayer is assumed to be flat, homogeneous and laterally unbounded. Under these circumstances, two main classes arise among the proposed hybrid strategies. First, the local impedance model [3,4] where the acoustic treatment is taken into account by its wall impedances calculated by means of the TMM or characterized experimentally. Such approaches can achieve a drastic reduction of the computational cost, but lacks accuracy, especially, if practical acoustic treatments involving complex layups, such as foams or fibers with heavy layers, are considered. Second, an impedance model based on an integral formulation (i.e., Green functions) has been proposed in order to capture the non-local behavior of the NCT [5–9]. For instance, Shorter and Mueller [6] coupled the FEM of a structure with a transfer matrix model of the sound package radiating into an unbounded fluid medium by considering a formulation in terms of self and mutual piston impedances. On the other hand, a hybrid FEM-TMM hybrid method was proposed recently by Alimonti et al. [7–9]. This hybrid methodology also employs an integral formulation to account for the dynamic response of the acoustic treatment, the latter is replaced by surface impedances added to the finite element domains of the structure and the cavity. These impedances are expressed in terms of convolution integrals between external stresses and Green functions which are judiciously estimated by the TMM. The model neglects the reflected field contribution, since the sound package is assumed to be laterally unbounded in TMM. The effect of the latter assumption was analyzed in Ref. [9]. It was shown that direct field model, which neglects the reverberant field contribution emanating from the rigid lateral boundaries of the acoustic treatment may sometimes underestimate the radiated acoustic power and overestimate the absorption at low frequencies. In order to enhance the accuracy of the Green functions (GF) based model, the image source method was proposed by Alimonti and Atalla [10] to account for the reflected field. The latter was approximated only by the first and second reflections on the lateral boundaries of the NCT. Such approximation is justified by the large dissipation nature of the acoustic treatment of a sufficiently large surface. Also, the impact of two different formulations based on baffling conditions of the acoustic treatment were assessed. It was observed that the two formulations give similar results. A systematic comparison with the finite element method was also used to demonstrate the validity, precision and numerical efficiency of the proposed methodology in different configurations involving a plate-cavity problem. In addition to the gain in computation time and the perfect matching with FEM solution a substantial simplification of the modeling of the problem is also performed.

On the other hand, to avoid the classical point to point coupling between subdomains used in the FEM-TMM hybrid method, the patch transfer function (PTF) approach can be employed to speed up the solution of the coupled problem. The latter method was developed by Maxit et al. [11] on the basis of the work of Cacciolati et al. [12] on acoustic mobilities. The PTF approach has been studied by several researchers. For instance, Ouisse et al. [13] used the PTF procedure to couple linear acoustic problems and proved its efficiency through a convergence study. Pavic et al. [14] used the PTF technique for noise source identification. Aucejo et al. [15] studied and accelerated the convergence of the approach in the case of heavy fluid-structure interaction by using the modal synthesis model with residual shapes to estimate the mobility and impedance (PTFs) relations of subsystems, Maxit et al. [16] proposed an improvement of the efficiency of the approach by structuring the structure-cavity system outside the near-field zone of the structure and by using a non-standard modal decomposition. Guyader et al. [17] and Chazot et al. [18,19] used the PTF approach to solve a transmission loss problem for double wall configurations. The radiation impedance into an unbounded fluid domain was computed by means of Rayleigh's integral. Finally, Veronesi et al. [20] used the PTF technique for a plate-cavity system with attached acoustic foam, the PTFs relations of the foam were determined experimentally. In this context, the PTF method can be very useful because the mechanical and acoustical properties of the acoustic treatment can be modified during the assembly process, as well as, the boundary conditions which may be unknown. To improve the efficiency of the method, a reduced experimental method was proposed by Albert et al. [21], where PTFs of a spring-mass treatment are deduced from single-patch tests. However, in practice this class of methodology remains limited by the size of the patches, which controls the convergence of the approach. Also, non-local effects can be difficult to measure due to the dissipative nature of the acoustic treatment, which limits the accuracy of the experimental PTF approach.

In this paper, a hybrid approach based on the PTF method combining the FEM for the master systems and the GF model for the sound package is presented and used to solve transmission loss problems involving flat single and double wall configurations. The needed theoretical background of the GF methodology and the PTF is provided in section 2. Next, the principle of the PTF procedure and the used coupling schemes are presented for the considered cases. In section 3, the convergence of PTF schemes is assessed numerically and a criterion is proposed. Finally, the accuracy of the proposed methodology is assessed on various transmission problems for two acoustic treatment configurations (light foam and a foam with a heavy layer) by a systematic comparison with FEM. It is shown that the introduction of the GF model in the sub-structuring method allows a perfect matching with FEM/BEM solutions and a substantial simplification of the modeling of the problem. In addition, the presented examples corroborate the limitations of the widely used locally reacting impedance models. The case of a double wall with empty cavity is also presented to show the limit of employing the classical TMM to represent the cavity.

2. Theory

The sub-structuring Patch transfer functions procedure is used to couple subsystems. First, the impedance and mobility surface relations are estimated using the classical FEM for the master systems (structure and the acoustic cavity) while the impedance matrix of the acoustic treatments backed by a rigid wall is characterized by three models: FEM, a locally reacting model and a Green Function based model. These three models will be presented and compared in this paper. Once each sub-