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A variational formulation for vibro-acoustic analysis of a panel backed by an irregularly-bounded cavity

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ABSTRACT

A weak form variational based method is developed to study the vibro-acoustic responses of coupled structural-acoustic system consisting of an irregular acoustic cavity with general wall impedance and a flexible panel subjected to arbitrary edge-supporting conditions. The structural and acoustical models of the coupled system are formulated on the basis of a modified variational method combined with multi-segment partitioning strategy. Meanwhile, the continuity constraints on the sub-segment interfaces are further incorporated into the system stiffness matrix by means of least-squares weighted residual method. Orthogonal polynomials, such as Chebyshev polynomials of the first kind, are employed as the wholly admissible unknown displacement and sound pressure field variables functions for separate components without meshing, and hence mapping the irregular physical domain into a square spectral domain is necessary. The effects of weighted parameter together with the number of truncated polynomial terms and divided partitions on the accuracy of present theoretical solutions are investigated. It is observed that applying this methodology, accurate and efficient predictions can be obtained for various types of coupled panel-cavity problems; and in weak or strong coupling cases for a panel surrounded by a light or heavy fluid, the inherent principle of velocity continuity on the panel-cavity contacting interface can all be handled satisfactorily. Key parametric studies concerning the influences of the geometrical properties as well as impedance boundary are performed. Finally, by performing the vibro-acoustic analyses of 3D car-like coupled miniature, we demonstrate that the present method seems to be an excellent way to obtain accurate mid-frequency solution with an acceptable CPU time.

1. Introduction

Over the past years, the steadily growing requirements for acoustic performance of products as well as comfortable working and living conditions, has made the interior acoustic behavior an important criterion in many acoustic-related industries, for instance, automobiles, underwater vehicles, aircraft, aerospace and office partitions etc. In this framework, the vibro-acoustic coupling phenomenon is significant and will become even more important over the next decades with increasing restrictive legal regulations regarding noise emission levels. Therefore, the study on coherent vibro-acoustic

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coupling has become increasingly interesting for both scientific research and practical applications. Coupled vibro-acoustic systems are often decomposed into two interacting components, i.e. the elastic structure and acoustic fluid domain. Typically, a three-dimensional (3D) bounded cavity enclosed by a flexible vibrating panel is a valuable representation of numerous engineering backgrounds and has been extensively studied [1–11]. In general, most of the previous investigations on acoustic-structural coupling were based on the models having simple geometries of cavities and perfectly rigid walls. Actually, sound field behavior inside a cavity obviously depends upon its shape, which either effects the sound pressure distribution in an acoustic system or impacts the interaction between the enclosure and surrounding flexible wall in a vibro-acoustic system [11]. Thus the modeling of the complex built-up coupled system is important for acoustic design or the quality of inside cabins (cars, airplane, room, etc.) with the objective to control noise. Moreover, an accurate characterization of a coupled system with arbitrary acoustic impedance walls is further essential for real life situations, such as the use of porous materials in room optimization design or car interior acoustic treatments. Hence, it is of crucial importance to develop the analytical and numerical techniques that can precisely predict the vibro-acoustic response of a large, complex system of various geometries. Finite element method (FEM) [11–14], boundary element method (BEM) [14,15] and statistical energy analysis (SEA) [16,17] are often used to predict the vibrations of the elastic structure and interior sound pressure. However, the element based methods such as FEM and BEM are restricted to a lower frequency range, whereas the SEA is only applicable in a higher frequency range. In order to overcome this limitation, Langley and Cordioli [18] proposed a hybrid deterministic (e.g., FEM)-statistical (i.e., SEA) analysis method for the complex structural-acoustic system. It is shown this the method yields very good results from low to high frequency excitations. Using the Green theorem, Succi [19] calculated the interior acoustic field in an automobile cabin and the effects of arbitrary shape and surface impedance were studied. Bouillard et al. [20] proposed a wave-oriented meshless formulation for 2D vibro-acoustical coupled problems and demonstrated that such a scheme was available to the medium frequency. Li and Cheng [21,22] used the combined integro-modal (CIM) approach to characterize the structural and acoustic coupling of a flexible panel backed by a rectangular-like cavity with a slight geometrical distortion. David and Menelle [23] used a specific algorithm called the "Onera-MF method" to study the medium-frequency response behaviors of strong coupling between a plate and a cavity filled with water and the validity was confirmed by comparing the experiment, numerical and analytical results. Lately, Zhang and Cheng [24] presented a wavelet-Galerkin formulation to explore the general problem of internal sound field prediction and the optimization of the boundary shape. It is worth noting that Desmet et al. [25,26] proposed the wave based method (WBM) which is based on an indirect Trefftz approach to the analysis of both bounded and unbounded acoustic problems. This novel technique expands the dynamic response variables in terms of wave functions which are exact solutions of the governing differential equations, and it is, thus suitable for the mid-frequency range. However, the high computational efficiency just exists only for systems of moderate geometrical complexity and hence, the use of the WBM is limited [27]. To this end, attempts to improve the adaptation of solutions resulting from WBM for problems of complex geometry are required. Recently, a hybrid FE/BE-WBM, which is the combination of the advantages of the both finite element/boundary element and wave based techniques was proposed and has drawn considerable attention [27–29]. A combined WBM-SEA framework has been developed by Vergote et al [30]. By successfully coupling a WBM model for an acoustic cavity to a set of SEA subsystems for statistical structure an efficient and meaningful mid-frequency dynamic model is obtained. In addition, Deckers et al. [31] presented the use of B-splines for the efficient description of curved edges within the WBM to alleviate the geometrical restrictions. From the literature review, it appears that even though a variety of analytical and numerical methods are successfully applied to the coupled vibro-acoustic problems, the development of efficient and alternative prediction approaches for this classical coupling interaction is of great significance and strongly needed. Furthermore, in order to incorporate the vibro-acoustic coupling effects, the structural and acoustic analyses should be done solved simultaneously, thereby resulting in large and asymmetric matrices [25]. Since the Chebyshev orthogonal polynomials possess some prominent characteristics including linearly independent, complete, and highly smooth properties [32], they are accordingly adopted as the entire or at least large partial (sub-domain) basis function to drastically reduce the model sizes without meshing process like FEM/BEM does. Certainly, if the considered problem domain is even more complicated in geometry, then dividing this complex domain into some relatively regular regions is needed.

On the other hand, most of the published investigations focused on the simple structural boundary conditions such as the simply-supported and clamped ones. In practice, in addition to all the classical boundary conditions, there are many cases of realistic interest to the engineer in which there are many different combinations of non-classical (elastic) edge restraints [33]. As a result, there is an imperative for unified formulations that provide simple implementation in handling the various boundary conditions which are often encountered in engineering applications.

The aim of the present work is to develop a unified method for modeling and predicting the vibro-acoustic features of 3D coupled structural-acoustic systems consisting of irregular acoustic enclosure with general wall impedances and an elastic plate subjected to arbitrary restrained boundaries. A modified variational method in conjunction with a multi-segment partitioning technique is employed to formulate the structural and interior acoustical models. The least-squares weighted residual method is utilized to ensure a numerically stable scheme and furnish a uniform formulation that can deal with non-classical structural boundary conditions. According to the principle of compatibility and consistency, the displacement components of the thin plate and the sound pressure inside the acoustic domain are approximated in terms of the 2D and 3D Chebyshev orthogonal polynomials, respectively. This enables handling vibro-acoustic problems without requiring any modal information a priori which is widely needed in conventional modal coupling approaches [3–5]. Consequently, it is more convenient to provide the necessary insight in the physical phenomena which dominates the coupled vibro-acoustic