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Modeling and vibro-acoustic analysis of elastically restrained panel backed by irregular sound space

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ABSTRACT

A general analytical method is developed for the natural features and vibro-acoustic response analysis of an arbitrarily restrained rectangular plate backed by an irregular cavity. The modeling of the structure and the sound space are developed by employing the variational theory based on the sub-structure method. The irregular enclosure is disassembled into sub-cavities and the coupling formulae are deduced. The continuity conditions of both sound pressure and particle velocity at the coupling interface are exactly satisfied. The variational expressions of elastic boundary conditions of the panel are presented and thus the classical boundary conditions can be easily obtained by assigning appropriate elastic coupling coefficients. The vibration and sound pressure solutions are obtained by performing the Rayleigh–Ritz procedure. The accuracy and efficiency of the present method are validated by checking the present results against the finite element method (FEM) results for systems separately with right-angled trapezoidal and concave curved trapezoidal sub-cavity. It is shown that the present method is suitable for a system with an irregular cavity and an elastically restrained plate by exhibiting satisfactory accuracy, fast convergence speed while requiring small computation effort.

1. Introduction

The vibro-acoustic coupling problem is one of the most exciting and challenging topics in the field of noise control. These problems often arise from the practical requirements of controlling the cabin noise in transportation vehicles. In general, practical vibro-acoustic systems, such as passenger compartments of cars, passenger cabins of boats and halls of architectures, often refer to an irregularly bounded single enclosure with its bounding walls and surrounding flexible structures or refer to a coupled system that is composed of several sub-systems with regular or complicated geometry. In previous decades, the acoustic-structural coupling model, which consists of a regular cavity with a vibrating panel, has been thoroughly investigated, and analytical solutions [1–5], that offer physical insights into structural–acoustic coupling interactions have been provided. For instance, Dowell et al. [1] proposed the general theory for acoustoelasticity, in which the interaction between an acoustic field and an elastic structure was derived by expanding the sound pressure into normal modes of a rigid cavity while adopting the *in vacuo* structural normal modes for the structure displacement. As an important measure of the acoustic quality of an enclosure, the decay behavior of a rectangular cavity-panel system was investigated by Pan and

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Bies [2] using the modal coupling analysis method. Employing the impedance and mobility method, Kim and Brennan [3] derived the representations of force-velocity and the pressure-source strength and their connections when various excitations were considered and obtained a compact matrix formula when the method was extended to a general structural-acoustic coupled system. Rajalingham et al. [4] investigated the natural frequencies of a rectangular cavity backed by a simply supported panelto characterize the interaction as the plate receptance and the cavity rejectance. The modal coupling method has its limitations because the modal solution of an acoustically rigid cavity is employed in the structural-acoustic coupling problem [5,6]. To solve this problem, Tanaka et al. [5] derived explicit eigenfunctions based on the obtained coupling orthogonality conditions, and Chen et al. [6] proposed a Chebyshev-Lagrangian method to model a rectangular cavity with one flexible panel.

As the analytical solution to sound enclosure with complicated shape is hardly to be obtained, this practical difficulty motivates researchers developing alternative methods for irregular cavities [7–10] or seeking the acoustic mechanisms from enclosures with simple irregularity [11–17]. Petyt et al. [7] investigated the acoustic characteristics of irregular sound cavity by using finite element method (FEM). Kang and Lee [9] proposed a point-matching method in which no interpolation functions between boundary nodes were used. Félix et al. [10] revealed the boundary irregularity caused localization and corresponding enhancement of damping of a 2D cavity by adopting the FEM method. Sum and Pan [11] studied the changes of modes with the inclination for a trapezoidal cavity and further investigations on the decay times of the trapezoidal cavity were carried out [12]. Jing and Xiang [13] proposed a modified diffusion model for two coupled rectangular rooms and subsequently systematic investigations on the effect of aperture size and the sound source and receiver positions on the sound propagation and sound energy decays were performed [14]. Meissner studied the influence of wall damping on the reverberation time [15] and further analyzed the energy distribution and sound intensity field of two coupled rectangular spaces with light damping [16] by using the modal expansion method.

The vibro-acoustic characteristics of a structural-acoustic system are closely related to the geometrical shape of the enclosure [18]. However, literature review mentioned above shows that neither the irregular enclosure nor the structural-acoustic system with complicated geometry has been theoretically solved. Therefore, the development of analytical techniques for the vibro-acoustic predictions of a system with a complex geometry of enclosure is important. In Ref. [1], the characteristics of a cavity that consists of several component cavities were also investigated by placing a flexible structural member between adjacent cavities. For the case with a pure opening between adjacent cavities, a structural member was assumed to have zero mass and stiffness. Lee and Lee [19] investigated the modal characteristics of a structural-acoustic system with cavities that are connected in series by necks. In their study, both the evanescent waves and the standing waves were selected as basis functions; this new basis function enriched the physical meaning of the neck's length. The vibro-acoustic characteristics of a flexible panel that is backed by a trapezoidal cavity were investigated by Li and Cheng [20] using the integro-modal method. In their model, the trapezoidal cavity was bounded by a rectangular enclosure, and the acoustic mode of the trapezoidal cavity was expanded as the normal mode of the rectangular enclosure. This method was previously applied by Missaoui and Cheng [21] to the acoustic predictions of a cavity with an irregular shape. Henry and Clark [22] investigated the acoustical characteristics of an airplane cabin by decomposing the aircraft fuselage into a series of curved panels and developing a coupling model of a curved panel and the interior cylindrical space. Xie et al. [23] applied the domain partitioning technique and the coordinate transformation to the structural-acoustic modeling, in which the irregular enclosure was divided into a right trapezoid and rectangle cavity segments. At the interfaces of both the structure part and the cavity part, the Lagrange multiplier approach was employed. Yu and Cheng [24] proposed a sub-structuring formula that was based on the patch transfer function approach to investigate the transmission loss of a rectangular silencer with a complex internal configuration. The structuralized treatment of the air aperture that connected the two acoustic domains was considered.

Despite these analytical methods, numerical approaches such as the finite element method (FEM), the boundary element method (BEM), and the Treffz method, seems to be more powerful for obtaining the solutions to vibro-acoustic systems with complex geometries [25–31]. A coupling approach based on the FEM and the BEM was proposed by Warszawski et al. [27] to address the acoustic–acoustic/acoustic–elastic coupling problem. The coupling conditions of pressure and forces were applied at a node of the FEM/BEM interface, and a relaxation parameter is introduced in the iterative coupling procedure to accelerate the convergence. Desmet [28] proposed a wave-based method (WBM) for a structural-acoustic system by expanding the field variables as the sum of exact wave functions and particular solution functions. Subsequently, a hybrid FE-WBM and a hybrid BE-WBM were developed [29,30]; this hybrid method broadened the adaption of the WBM for problems of complex geometry. Xuan et al. [31] extended the finite volume method (FVM), which has been applied in structural analysis for structural-acoustic coupling problems. At the coupling interface, the normal components of a particle acceleration continuity condition and a normal traction equilibrium condition were applied.

The literature review indicates that the analytical and numerical modeling methods that employ a sub-structuring approach or discretization techniques for vibro-acoustic problems can be broadly categorized into three groups. In the first group, which includes the numerical methods that employ matched grids, the continuity conditions are exactly satisfied at the coupling interface. In the second group, a structural member with non-mass and non-stiffness is assumed to be located at the acoustic-acoustic coupling interface, as in Refs [21,24]. By setting this virtual member, the acoustic-acoustic coupling problem can be solved with the framework of a structural-acoustic coupling procedure. In the third group, the continuity conditions at the coupling interface are enforced by an alternative method, such as the Lagrange multiplier method; refer to Refs [23,25]. Therefore, while the analytical methods are capable of providing accurate results and delivering physical