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Active control of sound transmission into an enclosure using structural modal filters

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ABSTRACT

This paper deals with active control of sound transmission through a flexible structure into an enclosed space. The control system consists of sensors and actuators used to measure and control the vibration of a flexible structure for reducing sound transmission. However, since the structural modes mutually contribute to the acoustic potential energy in the enclosure, evaluating the contribution of each structural mode independently is not straightforward. Hence, it is not clear which structural modes should be measured and controlled. In this paper, a formulation for expressing the contribution from each structural mode to the acoustic potential energy via interaction between structural modes is developed. Though the formulation is not a closed form, it enables one to evaluate the contribution of each structural mode independently. Once the highly contributive structural modes are identified, these structural modes can be measured and controlled independently without spillover to other structural modes by using structural modal filters. It is found that the proposed control method can effectively reduce the acoustic potential energy and can avoid an increase in the vibration of the flexible structure. The theory is developed for an arbitrarily-shaped enclosure. A numerical simulation for a rectangular enclosure is also conducted to verify the theory.

1. Introduction

Active control of sound transmission through a flexible structure into an enclosed space is examined in this study. The control system discussed here consists of sensors and actuators that are used to measure and control the vibration of the flexible structure for reducing sound transmission. In the control system design, it is essential to know which structural modes are highly contributive to the acoustic potential energy in the enclosure. However, the contribution of each structural mode is difficult to evaluate independently, because the structural modes mutually contribute to the acoustic potential energy [1,2]. Moreover, it is known that vibration control using actuators to minimize sound transmission does not necessarily lead to a decrease in vibration and can even increase vibration [3–5]. Though the radiation mode is known as an independent contributor to the acoustic potential energy and is useful for control system design [6–8], minimizing the amplitude of the radiation mode can increase the vibration significantly [9].

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In analogy with an enclosed space, the interaction between structural modes occurs in sound transmission through a flexible structure into an open space. The structural modes mutually contribute to the sound transmission coefficient, and thus it is difficult to evaluate the contribution of each structural mode independently. However, Wang [10,11] recently developed a formulation for expressing the contribution from each structural mode to the sound transmission coefficient via interaction with the other structural modes. To realize this formulation, a recursive relationship in the structural mode equation is removed by partially neglecting the interaction between the structural modes. Though the formulation is not in closed form, it enables one to evaluate the contribution of each structural mode independently. This modal contribution is referred to as the modal sound transmission coefficient. In earlier work [10], numerical examples were also presented to verify whether the aforementioned approximation is acceptable. The sum of modal sound transmission coefficients, i.e., the approximation of the sound transmission coefficient, and the exact solution of the sound transmission coefficient were compared, and good agreement was observed.

The modal sound transmission coefficient was used to design an active control system for the sound transmission into an open space [12]. By observing the frequency response of the modal sound transmission coefficient, the contribution from each structural mode to the sound transmission coefficient can be evaluated individually. Once the highly contributive structural modes are identified, these structural modes can be measured and controlled independently without spillover to other structural modes by using structural modal filters composed of sensors and actuators [13–18]. Moreover, a vibration increase can be avoided, because this control method independently suppresses the targeted structural modes and does not affect the other structural modes.

The purpose of this study is to expand the methodology of the modal sound transmission coefficient from an open space to an enclosed space. In other words, the primary objective is to formulate the acoustic potential energy in an enclosure as a simple superposition of the structural modal components, referred to as the structural modal acoustic potential energies in this paper. The secondary objective is to design an active control system that can effectively reduce sound transmission into the enclosure without increasing the vibration of the enclosure, by using knowledge on the structural modal acoustic potential energy.

In Section 2, a general theory is provided for an arbitrarily-shaped enclosure. The structural modal acoustic potential energy is formulated under the assumption that the modal interaction is partially neglected in an analogous fashion to the modal sound transmission coefficient. Then, a control system that independently suppresses the structural mode possessing a high structural modal acoustic potential energy by using structural modal filters is described, and the expected control performance is discussed. In Section 3, the theory is applied to a rectangular enclosure as an example, and the results from a numerical simulation are presented. The validity of the aforementioned approximation and its use in deriving the structural modal acoustic potential energy is verified by comparing the sum of the structural modal acoustic potential energies, i.e., the approximated acoustic potential energy, and the exact solution of the acoustic potential energy. Moreover, by reference to the frequency response of the structural modal acoustic potential energy, which structural mode should be measured and controlled is determined. A control system is designed which independently suppresses the targeted structural mode by using structural modal filters, and the obtained control performance is presented. In Section 4, the findings of this study are summarized.

2. Theory

In this section, a general discussion is presented for an arbitrarily-shaped enclosure. In Section 2.1, the basic theory of sound transmission into an enclosure [1,2,19,20], which is employed in this study, is reviewed. In Section 2.2, the structural modal acoustic potential energy is formulated, and the control system design based on it is described. In Section 2.3, a control system with structural modal filters composed of point sensors and point actuators is modeled as an example of the proposed control system design. This model will be used to conduct the numerical simulation in Section 3.

2.1. Basic theory of sound transmission into an enclosure

As illustrated in Fig. 1, the cavity is surrounded by a flexible structure and an acoustically rigid wall. A harmonic plane wave is incident on the flexible structure. The sound pressure over the exterior surface of the flexible structure is assumed to be dominated by the blocked pressure of the incident wave [21]. A force distribution is applied to the flexible structure as the control input. The linear Helmholtz equation and isotropic thin plate theory are assumed for the enclosed acoustic field and the flexible structure, respectively. The force distribution and normal vibration velocity of the flexible structure are set to be positive when they direct inward to the cavity. The response of the coupled fluid–structure system is assumed to be expressed in terms of the uncoupled acoustic modes, i.e., *rigid-walled* acoustic modes, and the uncoupled structural modes, i.e., *in vacuo* structural modes. The coupled response is then described as follows [20]. Although the materials presented in this section are not new, they are presented here, with outline derivations when appropriate, to provide a self-contained and unified account of the theory.

The sound pressure in the enclosure and the normal vibration velocity of the flexible structure are then written as