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Vibro-acoustic analysis of an elastically restrained plate duct silencer backed by irregular acoustical cavity

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ABSTRACT

Drum silencer is seemed as a novel passive mean for the low frequency noise control in duct, a lot of research work has been done for such panel silencer backed by regular cavity, while there is little effort devoted to the case with wall inclination. Motivated by such limitation, a three-dimensional vibro-acoustic coupling model for sound attenuation analysis of elastically restrained plate silencer backed by irregular acoustical cavity is established in a unified energy formulation. Coordinate transformation technique is employed to map the acoustical field description associated with the irregular-shaped cavity into those defined in a unit cubic volume. Boundary smoothed supplementary terms are introduced to the Fourier series to construct the corresponding admissible function, in conjunction with Rayleigh-Ritz procedure, the fully coupled matrix is derived, in which the concrete block can be specified for the irregular cavity subsystem. Numerical results are presented to illustrate the correctness and effectiveness of the proposed model through the comparison with those calculated from Finite Element Analysis. Based on the model established, the influence of geometry distortion of backed cavity on sound attenuation behavior of such drum silencer is studied and addressed. It is found that the wall inclination arrangement can modify the duct-panel-cavity structural-acoustic coupling pattern, and further serve as the optimal parameter to adjust the transmission loss frequency band. Experimental study is also carried out to verify the theoretical prediction from current model.

1. Introduction

Low frequency noise in duct is a major consideration in the quieter design of many applications such as marine engine and ventilation system. In air conditioning and ventilation systems, the low frequency noise generated by the operation of air-moving machine can propagate in the ductworks with long wavelength, transmit into various rooms, and cause the problem much hard to tackle with [1]. Generally, there are two means for the noise control, one is the active control with extra energy introduced into the primary system, and the other is passive way. Active control can be effective for low frequency noise attenuation in duct, however, it usually involves the use of electronic system as well as a specific signal processing algorithm, which will make this technique more expensive and also bring stability issues sometime [2]. In contrast, passive silencers are widely employed for the duct noise control due to their simplicity and reliability [3]. However, for the traditional silencers such as the resistance or impedance ones, there are also some disadvantages, for example, they work well mainly at mid to high frequency, and usually cause the environment issue due to the use of glass-fiber, as well as the bulkiness and aerodynamic loss [4–6], and so on. For these reasons, development of passive silencer with good sound attenuation performance in low frequency range has caused a lot of research interest in acoustics and noise control community.

During recent years, a novel drum-silencer has been proposed by Huang [7,8], in which sound attenuation is achieved through the interaction between sound propagation in duct and sound reflection from the flexible structure mounted as certain segment of the duct wall. Since there is no need of lining material or cross section variation like other traditional passive silencer does, such silencer is environmentally friendly, and has good flow-through characteristics. Subsequent theoretical and experimental studies [9–11] show that the drum-like silencer can realize a satisfactory sound attenuation from low frequency to medium over an octave band, and imply that membrane tensile force or plate bending stiffness can play a significant role for the silencing performance. With the aim to enhance the noise reduction, light composite plate configuration and micro-perforated plate (MPP) are further investigated as the flush-mounted structure in such structural-acoustic coupling silencer [12,13]. Active control of a pre-stretched Dielectric

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Elastomer (DE) is attempted for the improvement of sound energy absorption at system resonance [14,15]. Moreover, Du and Liu [16,17] investigated the influence of boundary restraints of flexible structure on sound attenuation performance of a duct-membrane silencer, and it was found that proper selection of boundary restraining stiffness and tensile force is helpful to obtain a better transmission loss for such duct-membrane system.

In order to achieve an effective design of such drum-like silencer, it is necessary to get a good understanding on the full vibro-acoustic coupling among the sound propagation in duct, transverse vibration of flexible structure, and the backed acoustical cavity. Literature review shows that much effort has been devoted to the transmission loss characteristics improvement, mainly through the modification and/or control of the flexible structure [12–17]. However, there is little work done to study the influence of backed cavity on sound attenuation performance, and most of current study is limited to the case of regular cavity, with the analysis emphasis on variation of cavity depth. In fact, the irregular enclosure, such as a trapezoidal cavity with an inclined rigid wall, will exhibit different modal characteristics comparing with those of regular one [18,19], and further affect the structural-acoustic coupling with the flexible structure significantly, as well as the corresponding active control and acoustic absorption behaviors [20–22]. From the viewpoint of optimal design, the irregular cavity with certain wall inclined will provide more potential parameter space, while in the current literature there is little attempt made toward this aspect. On the other hand, it is well known that the backed cavities occupy most of the space for such structural-acoustic silencer which limits its wider applicability in many occasions. Through the inclination of certain cavity walls, the installation space of such irregular silencer can be significantly confined, which will have great significance for the practical engineering. Then, it can be understood that accurate prediction and analysis of vibro-acoustic coupling for such plate-silencer with irregular cavity are essential for the purpose of its correct design. How will the wall inclination affect the structural-acoustic interaction among sound field in duct, flexible structural vibration and the backed cavity, as well as its silencing performance? There is a clear gap in current literature.

Motivated by such limitation in literature, a three-dimensional vibro-acoustic coupling model for the interaction study of elastically restrained panel duct silencer backed by an irregular acoustical cavity is established in a unified framework of energy formulation, which will bring potential benefits that each acoustic or structural subsystem coincides with the corresponding block of final system matrix, and can be easily extended to include any multiple subsystems. The arbitrary hexahedral cavity is transformed into a rectangular enclosure through a coordination mapping scheme from x, y, and z to ξ, η and ζ. All the geometrical variation of backed cavity merely leads to the change of sub-matrix in system characteristic equation accordingly, without any reformulation of fully coupled system. Boundary smoothed supplementary functions are introduced to the standard Fourier series to overcome the differential discontinuities encountered on the panel edge as well as panel-cavity coupling interface. Numerical simulation is performed to validate the proposed model by comparing the calculated results with those from other approaches. Based on the model developed, influence of irregular cavity geometry on the silencing performance of such duct-panel-cavity coupling system is then studied and addressed. Experimental work is also performed to verify the theoretical analysis from the current model. Finally, some concluding remarks are made.

2. Theoretical formulations

2.1. Model description of drum silencer with irregular cavity

In this work, the plate duct silencer backed by a trapezoidal cavity is considered, as illustrated in Fig. 1. The coordinate system used for the vibro-acoustic coupling description is also presented, in which the

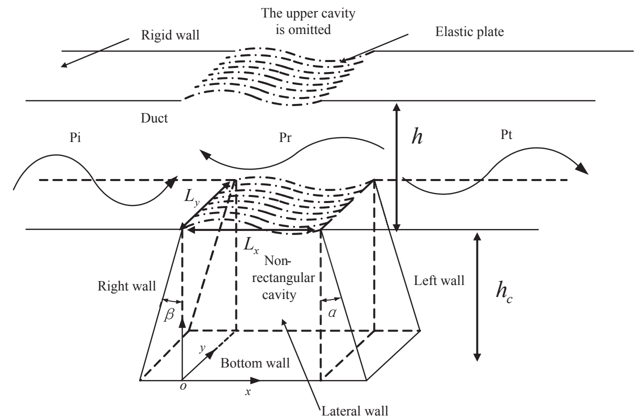

Fig. 1. Schematic illustration of the plate-silencer backed by irregular cavity with inclined walls.

origin O is located on the left corner of acoustical cavity. Two slightly inclined surfaces characterized by inclination angles α and β for an example are introduced to represent the geometrical distortion from the original rectangular geometry as shown in Fig. 1. Apart from the upper surface enclosed by the flexible panel, all the other surrounding walls are assumed to be acoustically rigid and set into certain inclination configuration. In this figure, two walls in the upstream and downstream of the backed cavity are inclined for illustration purposes, namely defined as the angles of α and β, respectively. A segment of duct with the cross section $L_y \times h$ is covered by the flexible plate $L_x \times L_y$ with general elastic edge restraints. In this work, any wall can be inclined, and the height of the cavity will be nonlinear function of spatial coordinate when the inclination configuration occurs at the bottom wall. Here, the notation h_c in Fig. 1 actually indicates the height of original rectangular cavity before this wall is titled. Two types of artificial springs are assumed to be distributed along each edge against the translation and rotation, then various boundary conditions can be easily simulated by setting the spring stiffness coefficients accordingly. In current model, symmetrical arrangement of backed cavities will be taken into account, while the upper one is omitted for simplification in this figure. In the upstream of duct, a predefined incident plane sound wave $P_i = p_i e^{-ik_0 x + i\omega t}$ with unit amplitude $p_i = 1$ is applied, in which $\omega = 2\pi f$ is the angular frequency of incident sound wave, and k_0 is equal to ω/c_0 with c_0 as sound speed in duct.

In order to treat such irregular cavity in a unified pattern, the coordination transformation scheme is employed for the mapping of irregular hexahedral cavity into a regular rectangular enclosure. As shown in Fig. 2, acoustic analysis of irregular cavity with various arbitrarily inclined walls can be analytically performed through the coordinate transformation from x, y and z to ξ, η and ζ, in which the adjacent surfaces will be perpendicular to each other. Sound pressure field in these two coordinate systems can be denoted as $p_{irr}(x, y, z)$ and $p_{rec}(\xi, \eta, \zeta)$, respectively.

Actually, for the current description framework, the backed cavity for plate silencer considered in Fig. 1 can be further evolved into more general case, such as pentahedron and tetrahedron geometrics, which can be uniformly achieved by moving the position of eight vertexes (x_i, y_i, z_i), where i is equal to1, 2, …, 8. The relationship between these two coordinate systems can be determined through the eight vertexes shown in Fig. 2, namely

$$x = N_1x_1 + N_2x_2 + N_3x_3 + N_4x_4 + N_5x_5 + N_6x_6 + N_7x_7 + N_8x_8, \tag{1-a}$$

$$y = N_1y_1 + N_2y_2 + N_3y_3 + N_4y_4 + N_5y_5 + N_6y_6 + N_7y_7 + N_8y_8, \tag{1-b}$$

and

$$z = N_1z_1 + N_2z_2 + N_3z_3 + N_4z_4 + N_5z_5 + N_6z_6 + N_7z_7 + N_8z_8. \tag{1-c}$$

where