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Technical note

Coupling effects of boundary restraining stiffness and tension force on sound attenuation of a cavity-backed membrane duct silencer

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ABSTRACT

In this paper, the vibro-acoustic model for predicting the sound attenuation performance of a cavity-backed membrane duct silencer is established via an improved Fourier series method, in which the membrane vibration and cavity acoustic fields are both constructed as the superposition of standard Fourier series and supplementary polynomials to tackle the differential discontinuity issues encountered at such elastic edge restraint and/or coupling interface. The energy formulation is employed to describe the whole structural-acoustic interaction among the membrane vibration, cavity sound field as well as the sound propagation in duct environment. The coupled system response under the upstream plane wave excitation is then solved through the Rayleigh-Ritz procedure. Numerical examples are then presented to illustrate the correctness and effectiveness of the proposed model. The predicted results from the current method are compared with those derived from other approach and experimental measurement available in literature, satisfactory agreements are observed for these validation studies. Based the model established, the coupling effects of boundary restraining stiffness and tensile force on the sound attenuation performance of such cavity-backed membrane duct silencer are discussed and analyzed, the results show that there exists an optimal window of these two parameters matching. This work can provide some useful insight for the effective design of such membrane silencing system.

1. Introduction

Low frequency noise control in duct is often a challenge in various engineering occasions, such as air conditioning and ventilation system [1]. Active control may be used for the low frequency noise control, while it always involves the introduction of error sensor, secondary actuator as well as the electric controller [2], which will make the system complicated and expensive, even cause stability and reliability issues at some circumstance. For this reason, continuous research effort has been made to pursue the low frequency noise control effectiveness through the passive means. However, the traditional resistance silencer just works well for the medium-to-high frequency range, which dissipates the sound energy into heat through the absorbing material lined in duct, such as fibers. Although the impedance silencer, such as the expansion-chamber-type muffler, is much more effective in low frequency, it still has some disadvantages, such as the existence of passbands, the bulkiness and the aerodynamic loss.

Recently, a novel membrane duct silencer is proposed by Huang [3], in which tensioned membrane is located as a segment of the duct wall to reflect the grazing incident noise, and the structural-acoustic coupling mechanism generates the low frequency noise attenuation in duct. Comparing with the above two types of passive silencers, there is no need of lining material and/or cross section variation, such duct-membrane silencer is environmentally friendly, and also has good flow-through characteristics. Inspired by the practical silencer design, the backed cavity is further introduced to the membrane structure by Huang [4–6], and his theoretical and experimental studies show that such 'drum silencer' can realize a satisfactory attenuation from low frequency to medium over an octave band. Subsequently, the three-dimensional model was further considered by Huang and Choy [7], their results illustrated that the silencing performance had a strong relationship with the lateral tension of membrane with four edges fixed. Chiu et al. [8] utilized the magnetic force to change the tension of membrane and the stiffness of cavity to extend the effective bandwidth of the transmission loss. Choy and Huang [9] introduce the multiple drum-like silencer with partitioned membrane to reduce the high level required tension. Some other investigations include that the replacement of membrane to flexible panel with simply supported and clamped boundary conditions [10,11], as well as the flow effect [12], and so on.

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As mentioned above, since such membrane silencer achieves the sound attenuation in duct based on the structural-acoustic coupling, especially for the interaction between the flexible structure and sound field in duct. From the viewpoint of subsystem, the structural-acoustic coupling is highly dependent on the modal characteristics of structure and acoustic cavity, respectively [13]. For the membrane silencer, the acoustic characteristics is fixed for the given duct dimension, the modal characteristics of membrane can be affected and improved through the tension force and introduction of backed-cavity, as demonstrated in Refs. [4–7]. Actually, as one of another important structural parameters, boundary condition also has a significant influence on the modal property of flexible structure, and further cause the resultant sound attenuation performance improvement of such duct silencer. Some effect of boundary condition has been investigated by Huang et al. [10,11], and they found that for a uniform plate, the optimal stop band is narrower than that of the simply supported configuration. Ramamoorthy et al. [14] also considered the sensitivity of performance to structural boundary conditions in three-dimensional finite element simulation through different combination of the simply supported and clamped cases. Their work both indicate that the boundary conditions can play a significant role for the sound attenuation performance of such drum-silencer, while these previous studies are just limited to the classical cases as mentioned above. More recently, Du et al. [15] investigated the influence of boundary restraint on sound attenuation performance of a duct-membrane silencer, and the results implies that proper selection of boundary restraining stiffness is helpful to obtain a better transmission loss for such duct-membrane system. For the cavity-backed membrane duct silencer, the application of membrane into the duct as a segment, there are two factors, namely boundary restraining stiffness and tensile force, which will affect the sound attenuation performance of such silencer. What effect will be caused by these two coupling variables? What are the guidelines to be followed for improving the sound attenuation performance of such silencing system? Obviously, this is a lack of general understating of this coupling effect in the current literature.

In this paper, an attempt will be made to answer these questions with a cavity-backed membrane duct silencer. A fully coupled vibro-acoustic model for predicting the sound attenuation performance of membrane silencer backed by a cavity in duct is established via an improved Fourier series method. Energy formulation is employed to describe the coupling system dynamics, with the supplementary functions introduced to overcome the differential discontinuities encountered at the elastic boundary restraint and coupling interface [16–18]. All unknown expansions coefficients including system coupled response information are found through the Rayleigh-Ritz procedure. The current model is validated by comparison with those data from the theoretical and experimental studies in literature. Based on this, the coupling effects of the boundary restraining stiffness and tension force on the silencing performance of such cavity-backed membrane duct silencer is discussed and analyzed based on the developed model. Finally, concluding remarks are presented.

2. Theoretical formulation

2.1. Model description

Consider a cavity-backed membrane duct silencer as shown in Fig. 1, two segments of the rigid duct wall are replaced with membrane backed by cavities. For simplicity of analysis, the two-dimensional model will be used in this work, and the coordinate system used is also illustrated in Fig. 1, in which the origin O is located on the left end of the membrane. L is membrane length, and h is duct height. The membrane is backed by two cavities of depth h_c and length L. F is the membrane tension.

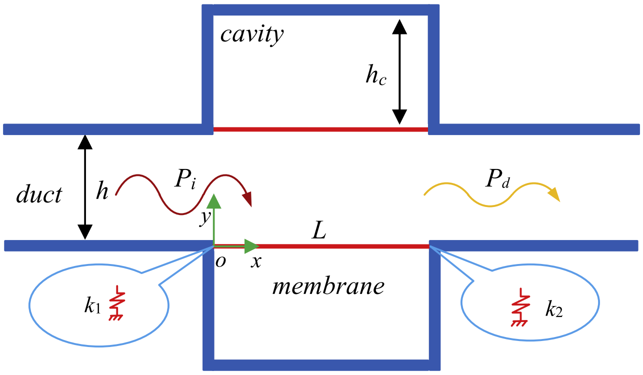

Fig. 1. Configuration of the duct-membrane silencer backed by acoustical cavity.

In the current simplified model, the membrane will actually behaves as the one-dimension string. Boundary conditions are simulated through the introduction of elastic springs to the both ends of spring, with the stiffness coefficients defined as k_1 at $x = 0$ and k_2 at $x = L$ (see Fig. 2). In the current framework, arbitrary boundary condition can be easily obtained by adjusting the spring coefficients accordingly. Based on the force balance and displacement coordination at both ends, the boundary conditions can be written as the following forms:

$$\tau\frac{\partial u(x,t)}{\partial x}\bigg|_{x=0} = k_1 u(0,t) \tag{1-a}$$

$$\tau\frac{\partial u(x,t)}{\partial x}\bigg|_{x=L} = -k_2 u(L,t) \tag{1-b}$$

here, τ is the constant stretching force, u is the flexural displacement of membrane. As mentioned above, any classical boundary condition can be easily obtained by setting the stiffness coefficient into an infinity or zero. For example, when both two spring stiffnesses are taken as infinity (a very large number in numerical calculation), the familiar fixed boundary condition will be obtained. When median value is set, it will be actually elastic boundary restraint. In reality, the flexible structure is usually mounted by batten and/or bolt. When the bolts are not tightened with extreme strength, the boundary condition is then elastic with finite supporting stiffness. On the other hand, the controlled boundary supporting stiffness apparatus may be developed based on the smart material such as magnetorheological elastomer.

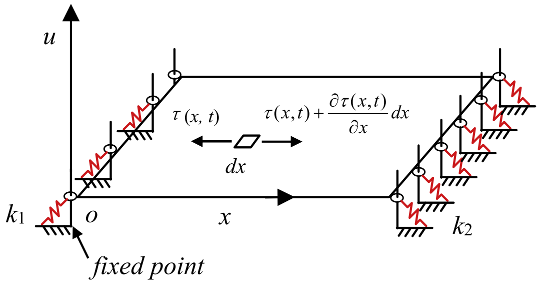

Fig. 2. Tensile membrane with elastic boundary restraints.