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Active control of radiated sound power of a smart cylindrical shell based on radiation modes

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A new approach is proposed in this paper based on radiation modes to control the radiated sound pressure of a smart cylindrical shell equipped with piezoelectric sensor and actuators. The radiation modes determine the specific distribution of normal velocity of the shell that independently radiates sound to the surrounding space. In this study, the first radiation mode is controlled since it is the most effective mode in terms of the radiated power. The results indicate that most of the sound power is attenuated by controlling only this mode. The extended Hamilton's principle, the Sanders shell theory and the assumed mode method are used to derive the equations of motion in a state space form that is suitable to design the controller. The radiated sound pressure is calculated using the simplified Kirchhoff-Helmholtz integral along with a Kalman filter to observe the system states, and a modified higher harmonic control (MHHC) is designed to attenuate the sound power. A numerical simulation demonstrated the effectiveness of the proposed approach compared to active vibration control (AVC) in attenuating the radiated sound in the low frequency domain.

1. Introduction

Many researchers have recently studied active low-frequency noise and vibration control in smart structures. A smart structure is equipped with sensors and actuators that are made of different materials, such as shape memory alloys, piezoelectric materials, magnetorheological fluids, and fiber optics, to respond to both external disturbances and internal changes. Of these, piezoelectric materials have gained popularity because they are highly robust, compact, resistant to both temperature and humidity, easy to implement, and offer dual use as either sensors or actuators. In particular, this study investigates the control of the sound power radiated from a smart cylindrical shell equipped with piezoelectric sensors and actuators with a new approach based on the radiation modes.

Researchers have suggested different methods to attenuate unwanted sound and vibrations in smart cylindrical shells. One of these approaches is based on the reduction of structural mode amplitudes. This method is referred to as active vibration control (AVC). Since vibrations are the source of radiated noise, the attenuation of such vibrations usually leads to a decrease in the radiated noise. Tani et al. [1] and Qiu and Tani [2] controlled the vibration of a cylindrical shell by using distributed piezoelectric sensors and actuators and a robust controller. Young and Hansen [3] controlled the flexural vibration in stiffened structures using piezoelectric stack actuators. Dogan and Vaicaitis [4] theoretically controlled the nonlinear cylindrical shell vibration under random excitation by using collocated sensors/actuators and a velocity feedback controller. Liu et al. [5] attenuated the interior noise in box structures such as cabins of vehicles and aircrafts using the structural intensity method. Kwak et al. [6], Kwak and Yang [7] and Kim et al. [8] utilized macro fiber composites (MFC) that are flexible piezoelectric transducers to suppress the vibration of simple and ring-stiffened cylindrical shells. Sohn et al. [9] and, Biglar et al. [10] optimized the location and orientation of the MFC and the piezoelectric transducers, respectively, in the active vibration control of cylindrical shells. Ma et al. [11] attenuated the radiated sound of an elastic cylindrical shell by using active-passive vibration isolation system. Loghmani et al. [12] through a FXLMS feedforward controller and piezoceramic disks reduced the vibration of a cylindrical shell.

However, there is no guarantee that the AVC will achieve the attenuation of radiated noise. For example, consider the case where there are two structural modes that have destructive effects on each other in an acoustic medium. By eliminating one of these modes without having an effect on the other, the total vibration

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level can decrease while the radiated noise can increase [13]. Furthermore, there are some structural modes that they don't have any influence on the radiated noise. Therefore, it is not efficient to suppress this kind of structural modes. Thus, specialists have introduced an alternative approach referred to as active structural acoustic control (ASAC).

In the ASAC, the controller focuses directly on attenuating the radiated noise unlike the AVC that decreases the sound pressure as a byproduct of suppressing the structural vibrations. Therefore, in this method it is required to calculate the radiated sound based on the structural vibrations. Guyader and Laulagnet [14] predicted the radiated noise from structures on the basis of structural modal method. Maillard and Fuller [15] proposed an approach referred to as discrete structural acoustic sensing (DSAS) to estimate and control the sound that is radiated form a cylindrical shell by an adaptive feedforward FXLMS controller. Modal structural acoustic sensing (MSAS) was proposed by Loghmani et al. [16] to estimate the sound that is radiated from cylindrical shells. This new approach resolved the disadvantages of DSAS such as the high number of required sensors, and they obtained a more accurate pressure estimation compared to the DSAS. The structural and acoustic signature of a stiffened cylindrical shell closed by truncated conical shells was studied by Caresta and Kessissoglou [17] that can be used for active structural acoustic control.

The active structural acoustic control of cylindrical shells has been studied by some researchers. Clark and Fuller [18] proposed the sensors that are shaped to observe the supersonic wavenumber of radiated noise in the structural acoustic control. Clark and Fuller [19] compared the usage of PVDF[1] strips and microphones in the active noise control system. They demonstrated that the PVDF strips can be used instead of microphones in the accordion type vibration of cylindrical shells to attenuate the noise. Pan et al. [20,21] theoretically investigated the active feedforward control of low-frequency noise from the cylindrical hull and a submarine, respectively, under axial excitation of the propeller. They proposed a new actuator configuration based on piezoelectric stacks and compared the effectiveness of the ASAC with that of the axial vibration control on the radiated sound power. Cao et al. [22] studied the same approach with a different piezoelectric stack actuator. They showed that the proposed actuator leads to a decrease in the control force. Both the AVC and the ASAC with inertial actuators was investigated by Caresta [23] to attenuate the radiated sound of a submarine in bending vibration under harmonic excitation from the propeller.

In all previous studies mentioned above, concerning the ASAC of cylindrical shells, they assumed that the disturbance force exists and they used feedforward controllers to obtain the control force, however, in many real applications there is no prior information about the disturbance force, and using the reference signals to get the disturbance force has various problems such as being affected by the control force or making the controller non-causal.

In our previous work [24] a virtual microphone was designed and implemented to estimate the radiated sound of cylindrical shell and then it was used in the control algorithm. However, in this paper a new approach is proposed for the ASAC of cylindrical shells based on the radiation modes and a feedback controller. The effectiveness of the proposed approach compared to the AVC is demonstrated through numerical simulations. This approach leads to a sharp decrease in the control dimensionality.

The radiation modes of cylindrical shells are obtained using the singular value decomposition (SVD) method to decompose the radiation matrix derived based on far-field radiation, unlike previous studies that derive radiation modes of beams and plates based on near-field radiation (e.g. [25–27]). The obtained eigenvectors that are referred to as the radiation modes are specific distributions of normal velocity of the structure that radiate independently to the acoustic medium. The eigenvalues of the radiation matrix are radiation efficiencies. In a low frequency domain, the radiation efficiency of the first radiation mode has the main effect in the sound radiation, and by controlling this mode, most of the radiated power will be attenuated. This leads to a sharp decrease in the control dimensionality of ASAC. A feedback controller along with a Kalman filter is designed to evaluate the efficacy of eliminating the first radiation mode that is the most efficient mode, on the total radiated sound power. The motion equations of a cylindrical shell are derived using the extended Hamilton's principle and the Sanders shell theory. The continuous equations are discretized using the assumed mode method. For the first time, all the circumferential modes including the breathing mode ($n = 0$), are considered to derive the shell equations of motion in a state space form unlike previous studies that only considered $n \geqslant 1$ circumferential modes (n is the number of circumferential nodes). The simplified Kirchhoff-Helmholtz integral is used to estimate the sound pressure in the far-field. The results demonstrate that to achieve a good sound power reduction we can control just the first radiation mode.

The remainder of this paper is organized as follows. The equations for the vibration motion of the cylindrical shell are derived in Section 2, and the structural mode shapes and natural frequencies are also presented in this section. Section 3 presents the acoustic modeling, radiation modes and radiation efficiencies of the cylinder. Section 4 proposes the controller, and finally, Section 5 concludes this paper.

2. Vibration equations of motion

The dynamic model of a smart cylindrical shell is derived based on the extended Hamilton's principle. The relation between the strains and the displacements of the cylinder is described using the Sanders shell theory, which is more accurate than the Donnel-Mushtari shell theory [28]. Continuous equations of motion are then discretized using the assumed mode method.

Consider a cylinder with length L, radius R and thickness h. A polar coordinate is attached to the cylinder, as shown in Fig. 1 where θ is the angle with respect to the vertical axis, x is the axis along its length, and u, v, and w are the displacements in the x, θ, and z directions, respectively. z is the distance from the middle surface of the shell thickness to an arbitrary point on the shell, and various piezoelectric sensors and actuators have been bonded to the cylinder.

The continuous form of Hamilton's principle is expressed as follows [29].

$$\int_{t_0}^{t} [\delta(T - V) + \delta W_{ext}] dt = 0, \tag{1}$$

where δT, δV and δW_{ext} are the variations in the kinetic energy, potential energy and work of external forces, respectively. The total kinetic energy consists of kinetic energies of both the shell and piezoelectric patches, and it is expressed as

$$T = \frac{1}{2}\int_{V_s} \rho_s(\dot{u}^2 + \dot{v}^2 + \dot{w}^2) dV_s + \frac{1}{2}\sum_{i=1}^{N_p}\int_{V_{pi}} \rho_p(\dot{u}^2 + \dot{v}^2 + \dot{w}^2) dV_{pi}, \tag{2}$$

where ρ_s is the cylinder density, ρ_p and N_p are the density and number of piezoelectric patches, V_s and V_{pi} are the shell and the i-th piezoelectric patch volume, respectively, and $dV_s = dV_{pi} = Rd\theta dz dx$. The total potential energy consists of

[1] Polyvinylidene fluoride.