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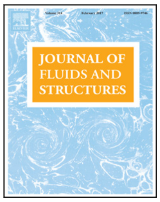

Active control of composite fuselage type structures with enclosed acoustic cavity

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ABSTRACT

An active structural–acoustic control system for a composite fuselage type structure is developed in this paper. The focus of the active control system is the global reduction of the sound field in an enclosed acoustic cavity using structure-integrated sensors and actuators. Active structural–acoustic control systems are commonly designed based on the acoustic radiation modes which diagonalize a radiation operator. In the case of interior sound radiation, this radiation operator is derived in this paper from the coupled acoustic modes, which take into account the boundary conditions of the coupled velocity from the fuselage type structure. This results in frequency-independent radiation modes which do not rely on the validity of the modal interaction approach. The latter one violates the continuity condition of the velocity along the coupling surface. Parameter studies regarding active control implementations are conducted in order to evaluate how many radiation modes need to be considered for achieving a global sound attenuation.

1. Introduction

Active control of structural sound radiation is an effective method to improve the low frequency acoustic insulation characteristics of lightweight aircraft structures. Especially global methods, e.g. active structural–acoustic control (ASAC), offer the potential to attenuate sound in entire fluid-filled volumes like aircraft cabins, termed cavities. ASAC approaches are often concerned with the control of sound radiation from infinitely baffled plates radiating noise into the far-field (Elliott and Johnson, 1993). For the sound radiation into cavities, cuboid cavities in contact with vibrating plates are commonly addressed (Bagha and Modak, 2017; Hesse et al., 2017a).

Realistic aircraft structures are formed by the circular cylindrical fuselage skin in connection with discrete frames and stringers as well as the floor. These structures are shown to exhibit a global vibrational behaviour in the low-frequency range (Herdic et al., 2005; Biedermann et al., 2017a) where structural waves stretch over a multitude of frames and stringers. In the mid-frequency range a superposition of the global vibration modes as well as local skin segment modes occurs (Biedermann et al., 2017b). The high-frequency range exhibits a high modal density and the local modes are statistically distributed. However, it is shown by Biedermann et al. (2017a) on the Acoustic FlightLAB demonstrator at the Zentrum für Angewandte Luftfahrtforschung (ZAL) in Hamburg that the sound radiation into the cabin is dominated by the low-frequency global fuselage modes even in the high-frequency range. This is due to the fact that these modes contain the vibrational waves with a lower wavenumber than the enclosed air and are consequently more efficient in radiating sound into the cavity.

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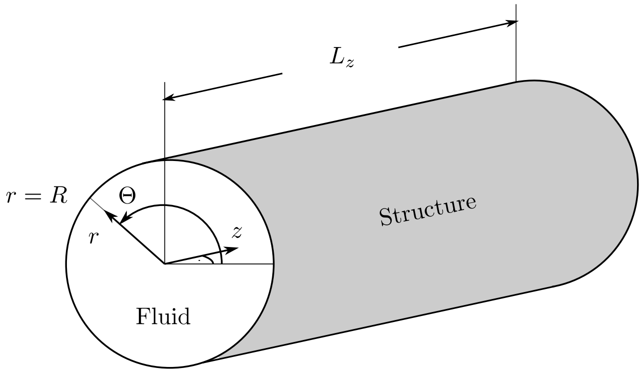

Fig. 1. Cylindrical shell (grey) with interior cavity.
Source: Reproduced from Hesse et al. (2017b).

Therefore, this paper addresses the active control of such global vibration modes of a circular cylindrical fuselage structure. For ASAC applications the structural contributions to the interior sound field are usually described in terms of the acoustic radiation modes (ARM). These are commonly calculated in order to diagonalize a radiation operator. For the interior ARMs they are derived in Cazzolato and Hansen (1998) and Johnson and Cunefare (2007) utilizing a singular value decomposition of the error weighting matrix. This formulation leads to ARMs that change with frequency and the need to sort the ARMs for each frequency step. In addition, diagonalizing the error weighting matrix which is formulated based on the uncoupled component modes can lead to eigenvalue veering over frequency, which is documented in Hesse (2016) and Davis (2017). This complicates implementation on real-time signal processing, especially when modal densities are high and therefore a lot of ARMs are needed to account for the entire acoustic energy.

A formulation of the frequency-independent ARMs for circular cylindrical shells is given in Hesse et al. (2017b) based on the uncoupled acoustic modes. The advantage of the frequency-independence originates from the reduced complexity for real-time implementations, which is demonstrated for the sound radiation into the far-field (Gibbs et al., 2000) and into cavities (Hesse et al., 2017a). However, due to acoustic modes of the cylindrical cavity which contain no information, this formulation may lead to a non-intuitive implementation for the cylindrical shell. These meaningless rigid walled acoustic modes occur in Hesse et al. (2017b) at a circumferential modal index of $m = 2, 4, 6, \ldots$ and radial modal index $n = 0$. Furthermore, the validity of coupling rigid-walled acoustic modes to the structure, termed modal interaction approach, is an often debated topic since the continuity condition of the velocity along the coupling surface is violated. The ARMs are therefore derived in Section 2 of this paper for a cylindrical composite test structure based on the real boundary conditions of the structural vibration on the skin surface of the cylinder rather than rigid-walled ones. The radiation efficiencies for the interior sound radiation are discussed in Section 3 as well as active control considerations using an optimal control law. Finally, Section 4 concludes this study.

2. Acoustic radiation modes

This section derives the ARMs for the composite fuselage type structure. The considered model of structural–acoustic interaction is that of a cylindrical shell coupled to an interior cylindrical cavity which is presented in Fig. 1. Since the stringers and frames change the vibrational behaviour of the structure, but only slightly affect the acoustic radiation properties into the enclosed cavity (Biedermann et al., 2017a), they are disregarded in this study. For simplicity, the cabin floor is disregarded as well. Ultimately, this section will derive the radiation operator, which describes the acoustic potential energy (APE) inside the cavity depending on the normal vibration of the structure.

The problem of interior sound radiation is described in a cylindrical coordinate system with r, Θ and z describing the radial, circumferential and axial coordinates. The acoustic sound pressure $p(r, \Theta, z, \omega)$ at the position (r, Θ, z) inside the enclosure is given by the wave equation

$$\left(\nabla^2 + \kappa^2\right) p(r, \Theta, z, \omega) = 0. \tag{1}$$

Here, the wavenumber is denoted by $\kappa = \omega/c$, with the circular frequency ω and the acoustic velocity c of the medium. The Laplacian operator ∇^2 is defined in cylindrical coordinates as

$$\nabla^2 = \frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \Theta^2} + \frac{\partial^2}{\partial z^2}. \tag{2}$$