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Sound transmission through a finite perforated panel set in a rigid baffle: A fully coupled analysis

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ABSTRACT

Sound transmission through a fluid-loaded finite perforated panel set in an infinite unperforated rigid baffle is considered. Using a fully coupled formulation in the 2-D wavenumber domain, the transmitted pressure due to an incident plane wave is obtained. The change in the panel resonances caused by the perforations is accounted for. The formulation also takes into account the self- and inter-modal coupling coefficients arising due to the fluid-loading effect. The derivation is almost entirely analytical with numerical computations done at the very end. Transmission loss (TL) curves are plotted for various cases and the physics is discussed. Along the way an uncoupled calculation is also done for the sake of comparison. The results are mainly for a light medium like air. For a light medium, in general, the perforate impedance is lower than the panel impedance. Thus, most of the transmission happens through the perforations. The panel velocity contribution is insignificant and hence the uncoupled calculation is adequate. In general, the absolute perforate impedance increases with increasing frequency. So does the TL. At low frequencies, because the resistive component of the hole impedance increases, the absolute perforate impedance rises. Thus, the TL curves rise at the lower frequencies. This effect is prominent for sub-millimeter hole radii, i.e., for micro-perforations. An important issue with the TL values for perforated panels is that they sometimes acquire negative values at low frequencies. This apparent anomaly is resolved by showing that at low frequencies there is an additional power component that flows from the baffle region onto the panel. Upon inclusion of this additional term, the TL values remain positive at all frequencies.

1. Introduction

Perforated panels are widely used in the design of structures for their ability to absorb sound over a wide frequency band [1]. They are robust in construction and hence can be used in extreme environments like the acoustic liners at the inlet and exhaust of aircraft nacelles [2]. Since the perforated panels themselves vibrate, one has to solve the acoustical and structural equations simultaneously to study the interaction between the panel and the surrounding acoustic field. It is the objective of this paper to analyze the transmission of sound through a finite flexible perforated panel set in an unperforated rigid baffle by including the fluid-loading effect (otherwise known as the fully coupled formulation).

Sound transmission studies through perforated screens gained momentum since the important work by Maa [1]. He developed an impedance model for the sound wave propagation through a single hole and used it to represent a uniformly perforated immobile screen having sub-millimeter size holes. The screen was backed by a cavity and extended up to infinity. Later, Taka-

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hashi and Tanaka [3] introduced the effect of panel flexibility by defining a mean velocity profile at the panel-fluid interface considering the continuity of flow and linear momentum within each hole. Their model assumed the pitch (hole separation length) to be smaller than the acoustic wavelength, which is the case in most of the applications. However, in the above studies, the panel was infinite in its dimensions.

Sound transmission and absorption properties of a finite flexible perforated panel backed by a cavity and a flexible wall were studied by Bravo et al. [2]. They used the average velocity scheme developed by Takahashi and Tanaka [3]. In a recent paper [4], Mana and Sonti incorporated the Takahashi and Tanaka model of average velocity [3] to find the sound radiation efficiency of a finite perforated panel set in a baffle when excited by a point harmonic force. These papers ([2,4]), however, assumed that the effect of fluid-loading on the panel is negligible.

For a water-loaded finite unperforated panel, Davies [5] derived an approximate expression for the radiated acoustic power spectral density (assuming fluid-loading). His expression was valid only at very low frequencies where the acoustic wavelengths are larger than twice the panel dimensions and the sound radiation is due to the corner modes alone. Later, Pope and Leibowitz [6] derived expressions for sound radiation by edge modes as well. Recently, Wang developed an approximate expression for the equivalent modal impedance incorporating the inter-modal coupling effects [7] and derived approximate expressions for the normal and diffuse field transmission coefficients using asymptotic methods [8].

In this paper, plane harmonic wave incidence and transmission through a fluid-loaded finite simply-supported perforated panel set in an infinite rigid unperforated baffle is studied. The coupled acoustic and structural equations of motion are derived in the wavenumber domain using the 2-D Fourier transforms. The organization of the paper is as follows: In Section 2, we present the expressions for the total pressure fields on the incident and the transmitted sides of the perforated panel in terms of an average interface velocity field called the locally averaged fluid particle (LAFP) velocity. The LAFP velocity takes into account both the panel vibration and the flow through the perforations. Section 3 gives a detailed derivation of the double Fourier transform of the LAFP velocity over the panel-baffle plane. The formulation is general and is capable of handling the discontinuity in the perforate impedance along the panel-baffle plane. The response of the perforated panel to the total sound field is derived in Section 4. The modified natural frequencies and modeshapes derived using the Receptance method are used to compute the panel response. Due to the coupling of acoustic and structural domains, the panel response turns out to be a function of the LAFP velocity. In Section 5, a coupled equation of motion is derived combining both the acoustic and the structural domains and solved for the panel response modal amplitudes. The uncoupled formulation (that ignores the effect of the radiated pressure on the panel response) is derived in Section 6. In Section 7, the integral expression for the transmitted power and the definition of the TL are presented. The TL for different cases is discussed and compared in Section 8 and a few conclusions are drawn in Section 9.

2. The incident and the transmitted pressure fields around a perforated panel set in a baffle

Consider a flexible perforated panel of finite extent lying in the $z = 0$ plane, in the region $-a/2 \le x \le a/2$ and $-b/2 \le y \le b/2$. The panel is placed in a rigid baffle of infinite extent in the $z = 0$ plane, as shown in Fig. 1. A harmonic plane wave of frequency ω, wavenumber k and amplitude $\widetilde{P}_i$ is incident upon the panel-baffle surface from the $z > 0$ region, from the direction θ and ϕ (θ, polar angle and ϕ, azimuthal angle). This creates flexural vibrations in the perforated panel which transmits the sound to the $z < 0$ region. Let $p_1(x, y, z, t)$ and $p_2(x, y, z, t)$ be the resulting pressure fields in the transmitted ($z < 0$) and the incident ($z > 0$) regions, respectively (see Fig. 1). The transmitted pressure field $p_1(x, y, z, t)$ is due to the vibrating perforated panel and the direct transmission of sound through the holes in the panel. Whereas, on the incident side the total pressure field $p_2(x, y, z, t)$ comprises of the incident and the reflected pressure terms. Let the incident pressure field $p_i(x, y, z, t)$ be

$$p_i(x, y, z, t) = \widetilde{P}_i e^{ik_x x + ik_y y - ik_z z} \ e^{-i\omega t}, \tag{1}$$

where $k_x = k \ \sin\theta \ \cos\phi$, $k_y = k \ \sin\theta \ \sin\phi$ and $k_z = k \ \cos\theta$. The total pressure field on the incident side is given by

$$p_2(x, y, z, t) = \widetilde{P}_i e^{ik_x x + ik_y - ik_z z} \ e^{-i\omega t} + p_r(x, y, z) \ e^{-i\omega t}, \tag{2}$$

where $p_r(x, y, z)$ is the reflected pressure field. In the following derivations, the dependence on time $e^{-i\omega t}$ is suppressed.

The transmitted pressure $p_1(x, y, z)$ comprises of only the radiated pressure $p^-(x, y, z)$ in the $z < 0$ region. $p^-(x, y, z)$ accounts for both the radiation of sound by the panel vibration and the direct transmission of sound through the perforations. The $p^-(x, y, z)$ satisfies the 3-D Helmholtz equation

$$\left(\nabla^2 + k^2\right) p^-(x, y, z) = 0. \tag{3}$$

On taking a *double Fourier transform* of the above equation in the x and y directions we get

$$\left[\frac{d^2}{dz^2} + \left(k^2 - \lambda^2 - \mu^2\right)\right] P^-(\lambda, \mu, z) = 0, \tag{4}$$

where $P^-(\lambda, \mu, z)$ represents the double Fourier transform of $p^-(x, y, z)$ and is defined as

$$P^-(\lambda, \mu, z) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p^-(x, y, z) \ e^{i\lambda x + i\mu y} \ dx \ dy. \tag{5}$$