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Effect of perforation on the sound transmission through a double-walled cylindrical shell

Qunlin Zhang, Yijun Mao*, Datong Qi

School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, PR China

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ABSTRACT

An analytical model is developed to study the sound transmission loss through a general double-walled cylindrical shell system with one or two walls perforated, which is excited by a plane wave in the presence of external mean flow. The shell motion is governed by the classical Donnell's thin shell theory, and the mean particle velocity model is employed to describe boundary conditions at interfaces between the shells and fluid media. In contrast to the conventional solid double-walled shell system, numerical results show that perforating the inner shell in the transmission side improves sound insulation performance over a wide frequency band, and removes fluctuation of sound transmission loss with frequency at mid-frequencies in the absence of external flow. Both the incidence and azimuthal angles have nearly negligible effect on the sound transmission loss over the low and middle frequency range when perforating the inner shell. Width of the frequency band with continuous sound transmission loss can be tuned by the perforation ratio.

1. Introduction

Reducing the interior noise of the cabin of an aircraft or a high-speed train is crucial in the design stage. The cylindrical shell is popularly selected as a simplified model to investigate the sound transmission characteristics of the cabin in analytical studies. Koval analytically studied the sound transmission through a thin cylindrical shell [1] and the effect of stiffening with rings and stringers on its sound insulation ability [2–4]. White [5] investigated experimentally the sound transmission through a closed cylindrical shell with finite length using the concept of averaging energy and energy flow and gave a comparison with the analytical results. Lee et al. [6] also developed an analytical model by solving the classical shell vibration equations and the acoustic wave equations and validated its fidelity by experimental measurements. In the context of an automotive muffler, Lee et al. [7] then combined a one-dimensional model and a two-dimensional model to solve the sound transmission loss through a double-walled cylindrical shell due to the compression and bending waves in the shells, respectively. Reasonable agreements were achieved when compared with the experimental results. Tang et al. [8] used a modal expansion technique and the Galerkin approach to derive a solution of the sound transmission through the double-walled cylindrical structure excited by the external turbulent boundary layer (TBL) pressure fluctuations.

Though the double-walled shell shows superior sound insulation performance against the single-walled one, there still exists “dips” at some frequencies where the resonant response of the shell structure governs the sound transmission. The damping material is typically added to the annular space between the skin wall and trim wall to form a sandwich structure

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* Corresponding author.
E-mail address: maoyijun@mail.xjtu.edu.cn (Y. Mao).

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Nomenclature

a	Shell radius [m]
c	Speed of sound [m s^{-1}]
d	Aperture diameter [m]
E	Young's modulus [Pa]
h	Shell thickness [mm]
i	Imaginary unit
k	Wavenumber
k_{MPP}	Perforation constant
M	Mach number
p	Acoustic pressure [Pa]
p_0	Amplitude of the incident wave [Pa]
u	Displacement in the axial direction [m]
v	Displacement in the circumferential direction [m]
v_p	Panel velocity [m s^{-1}]
v_f	Particle velocity [m s^{-1}]
$\bar{v}$	Mean particle velocity [m s^{-1}]
W	Acoustic power [W]
w	Displacement in the radial direction [m]
Z_0	Impedance of an aperture [kg m^{-2} s^{-1}]
Z_{react}	Reactance of an aperture [kg m^{-2} s^{-1}]
Z_{resist}	Resistance of an aperture [kg m^{-2} s^{-1}]
α	Incidence angle [deg]
ε	Neumann factor
η	Fluid viscous coefficient
μ	Poisson's ratio
ρ	Fluid density [kg m^{-3}]
ρ_s	Shell material density [kg m^{-3}]
τ	Acoustic power transmission coefficient
χ	Auxiliary angle [deg]
ψ	Azimuthal angle [deg]
ω	Angular frequency [rad s^{-1}]
Superscripts	
I	Incidence
R	Reflection
T	Transmission
Abbreviations	
MPP	Micro-perforated panel
TBL	Turbulent boundary layer
TL	Transmission loss

which can enhance the sound transmission loss at these resonant frequencies. Zhou et al. [9] solved the sound transmission through the double-walled cylindrical shell lined with poroelastic materials by employing the Love's thin shell theory, the Biot's model and the wave equation to describe the shell vibration, the wave propagation in the porous material and in the fluid media, respectively. Three configurations of the porous material including unbonded-unbonded, unbonded-bonded, bonded-bonded were compared to explore the effect of the external mean flow on the sound transmission of this sandwich structure excited by the incident plane wave. In his study, the presence of the external flow had the potential of increasing the transmission loss above the ring frequency and the air gap was a vital factor to determine the sound insulation of the sandwich cylindrical shell. Liu and He improved [10] and extended [11,12] Zhou's work to a more general case by taking both the incidence and azimuthal angle into consideration in a diffuse field while Zhou just discussed the effect of different incidence angles of the plane wave. Additionally, the internal reflection within the porous material layer was highlighted in Liu's work due to the discontinuous acoustic impedance in different wave propagation regions of the sandwich system. Thus, a limiting incidence angle might occur in a diffuse incidence field.

Though the porous elastic material is commonly used in the double-walled structure to increase sound insulation performance due to its lower cost and convenience, it may produce fibers which would be a threat to the environment and human health [13]. The micro-perforated panel, first developed by Maa [14] in the 1970s, appeared to be a promising