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Wave propagation across double-walled laminated composite cylindrical shells along with air-gap using three-dimensional theory

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ABSTRACT

This paper presents a complete model to calculate the sound transmission loss across laminated composite cylindrical shells based on three-dimensional equations of anisotropic elasticity. This model is included a double-walled laminated composite cylindrical shell with infinite length along with an air-gap impinged upon incidence oblique plane wave and immersed in a fluid. Therefore, the equations of motion are derived for each monoclinic anisotropic layer of both walls of double-walled laminated composite cylindrical shell; then, these equations are rewritten using the state space method. Hence, the state space governing formulation of each layer of both walls has been solved using the approximate laminate model along with the local transfer matrix approach. Finally, using the global transfer matrix method and considering the appropriate boundary conditions the transmission loss (TL) of the double-walled laminated composite cylindrical shell is calculated. Comparison of the presented results with those of other researchers for both single-walled and double-walled cylindrical shells indicates the accuracy and validity of the present study. Moreover, the effects of each parameter on TL are investigated. The results show the TLs of three-dimensional theory is of higher accuracy rather than other theories, because it doesn't consider any assumptions in simplifying the governing equations.

1. Introduction

In recent years, the composite structures are extensively applied in engineering structures as a result of the main factors including the weightless condition, the high stiffness and also the high capacity upon corrosive environments. These structures are manufactured in different configurations. The cylindrical composite shells are one of these configurations, can be practical in automotive, aerospace and petrochemical industries. The sound power reduction through these shells is of high importance particularly in the body of the fuselages in aerospace industry.

The acoustic transmission loss (TL) though the single-walled cylindrical shell have been studied by many researchers. Smith [1], studied sound transmission through thin cylindrical shells. In his study, the transmission of sound energy through a thin cylindrical shell by an oblique plane wave excitation was investigated. White [2], analyzed sound-insulation properties through a finite, closed, cylindrical shell. In this study, the ring and coincidence frequency have been introduced whereas the TL of the shell approaches into minimum values. Wilby and Scharton [3], analyzed the acoustic transmission through a fuselage sidewall. The vibrations of a thin-walled stiffened cylinder in an acoustic field are studied by Foxwell and Franklin [4]. Koval [5], studied the sound transmission into an isotropic and orthotropic cylindrical shell under flight conditions using the impedance method. He considered in his work an external air flow in the outer shell and also internal pressure for the cylindrical shell. He proved that in frequencies less than the ring frequency and between the ring and critical frequencies, the TL is more affected by cylindrical resonances and mass law behavior of the shells, respectively. In following, Blaise and Lesueur [6], extended Koval's [5] work to consider an orthotropic and multi-layered orthotropic shell excited by bevel plane sound wave with two independent incident angles in order to calculate the diffuse field transmission coefficient. Then Blaise and Lesueur [7–9], studied the acoustic transmission across an orthotropic multi-layered infinite cylindrical shell. They have considered three-dimensional displacement fields in the thickness. Analytical and experimental studies to understand the characteristics of power transmission through a thin isotropic cylindrical shell have been conducted by Lee and Kim [10], In their work the incident wave was a plane wave and also the inside cavity was assumed to be anechoic. Love's equations were considered to describe the shell vibration motions. In addition, they considered

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Nomenclature

c_1	speed of sound in external space
c_2	speed of sound in the space between shells
c_3	speed of sound in internal cavity
$\boldsymbol{D}_n$	global transfer matrix
E	module of elasticity
f_r	ring frequency
f_c	critical frequency
f_{coin}	coincidence frequency
G	module of rigidity
h_1	thickness of outer shell
h_2	thickness of inner shell
h_{gap}	air-gap thickness
H_n^1	cylindrical Hankel function of the first kind of order n
H_n^2	cylindrical Hankel function of the second kind of order n
i	$\sqrt{-1}$
J_n	cylindrical Bessel function of the first kind of order n
k_z, k_r	wave numbers in z and r direction
M	Mach number for external flow
n	mode number
P_1^I	incident wave in external space
P_1^R	reflected wave from external shell
P_2^T	incident wave in the space between shells
P_2^R	reflected wave from internal shell
P_3^T	transmitted wave through internal shell
P_o	amplitude of incident wave in external space
R_{p_1}	outer radius of external shell
R_{o_1}	inner radius of external shell
R_{p_2}	outer radius of internal shell
R_{o_2}	inner radius of internal shell
(r, φ, z)	components of cylindrical coordinate
t	time
$\boldsymbol{T}_n$	local modal transfer matrix
TL	transmission loss
u_r	displacement in the radial direction
u_φ	displacement in the circumferential direction
u_z	displacement in the axial direction
$\boldsymbol{U}$	state vector
V	velocity vector of external flow
W^I	incident power flow per unit length
W^T	transmitted power flow per unit length
$\boldsymbol{Y}_n$	modal state vector
θ	angle of fiber-reinforced layer
ρ	density of shell
ρ_1	density of external medium
ρ_2	density of air-gap
ρ_3	density of internal cavity
σ_{ij}	stress components
$\varepsilon_{ij}(\gamma_{ij})$	strain components
λ	dimensionless radial coordinate
υ	Poisson's ratio
ω	angular frequency
ε_n	Neumann factor
∇	Laplacian operator
α	sound incident angle

the three displacement fields as well as both transverse and in-plane equations in order to depict the shell motion. In addition, they have applied a convergence algorithm to calculate the transmission loss. However, in their study the transverse shearing and rotational inertia were absolutely ignored. Sound transmission through infinite cylindrical sandwich shells illuminated by an oblique plane wave with two different incident angles has been developed by Tang et al. [11,12]. They considered the effects of external air flow and also the negative pressure difference between the inside and outside of the shell surfaces. In order to calculate TL, they utilized Naghdi–Berry theory and first order theory for thick and thin shells, respectively. Daneshjou et al. [13], analyzed sound transmission through laminated composite cylindrical shells. In this work, the classical thin shell theory (CST) is used to calculate the TL. In the following, Daneshjou et al. [14], applied the first order shear deformation theory (FSDT) to analyze the sound transmission through laminated composite cylindrical shells. They also compared their results with those obtained with the (CST) and then indicated the effects of transverse shearing at high frequencies. Sound transmission through orthotropic cylindrical shells with subsonic external flow has been developed by Daneshjou et al. [15], In other work done by Daneshjou et al. [16], the third order shear deformation theory (TSDT) is applied to analyze the sound transmission through relatively thick Functionally graded materials (FGM) in cylindrical shells. In this work, they calculated TL through thick FGM cylindrical shell, modeled by TSDT and then compared the results with CST and FSDT for different geometric ratios. They showed that third order shear deformation theory may lead into high precision results rather than the CST and FSDT particularly in thick shells or even for the thin shell in high frequency range. Shen et al. [17], analyzed the sound radiation of orthogonally stiffened laminated composite plates. In their study, the layer-wise shear deformable theory was employed to describe the model. They also concluded that, the coupling effects including flexural-extension and flexural-torsion could extensively influence on structure sound radiation. Talebitooti et al. [18], calculated the sound transmission across orthotropic cylindrical shells using third-order shear deformation theory. Recently, Talebitooti et al. [19], have derived three-dimensional exact equations of anisotropic elasticity for sound transmission though orthotropic cylindrical shells with arbitrary thickness. In this work, three-dimensional wave propagation is applied to calculate the TL considering state space method. The shell is assumed to be infinitely long and is subjected to an oblique plane wave. Moreover, an approximate laminate model along with the transfer matrix approach is used to solve the governing equations. They compared their results with those of previous models for thin shells. This model demonstrates more accurate results for thick shells because the shear and rotation effects become more significant in thick shells. In another work, Rajabi et al. [20], studied the scattering of a plane harmonic acoustic wave upon an anisotropic cylindrical shell based on the wave function expansion. In the following, they extended their last work and investigated on acoustic wave scattering from a laminated composite cylindrical shell based on three-dimensional exact equations of anisotropic elasticity [21]. In addition, they have used an approximate laminate model along with the local and global transfer matrix approach to solve the state space governing equations. Daneshjou et al. [22], studied the sound transmission loss though thick-walled isotropic cylindrical shell using three-dimensional elasticity theory. In their work, a thick-walled shell under obliquely plane incident wave is investigated. Firstly, the governing equation of the thick shell is derived; then, the equations are solved using Helmholtz decomposition. Also they compared their results with CST, FSDT and TSDT. There was reported that at high frequencies due to importance of rotational and shear terms the CST, FSDT and TSDT encounter insufficient accuracies. Talebitooti et al. [23], developed an analytical model to calculated sound transmission loss across laminated composite cylindrical