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# Acoustic radiation from shear deformable ring-stiffened laminated composite cylindrical shell submerged in flowing fluid

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Acoustic radiation from a point driven, infinite, periodically ring-stiffened, laminated composite cylindrical shell submerged in flowing fluid is investigated theoretically. Both the effects of in-plane and out-of-plane vibrations of the ring-stiffeners and the effects of fluid convection on far field acoustic radiation behaviors are concerned. The equations of motion of the laminated composite cylindrical shell is presented on the basis of the first order shear deformation theory. Fourier transform and Poisson summation formula are used to transform the equations into a set of infinite algebraic equations expressed in the wavenumber domain. After truncation, the response of the laminated composite cylindrical shell is solved, and the stationary phase approximate is employed to find the expression for the far field sound pressure. Convergence analysis of the numerical solutions is conducted. The theoretical model and numerical method proposed in this paper are validated by comparison with those presented in available literature. Finally, numerical results are presented to demonstrate the effects of various parameters such as the size and spacing of the ring-stiffener, the thickness and the radius of the cylindrical shell, the lamination angle and the lamination scheme of the composite materials as well as the Mach number on the far field sound pressure.



## 1. Introduction

Periodically rib-stiffened laminated composite structures are extensively used as structural components in various engineering fields, such as aviation and aerospace engineering, naval architecture and ocean engineering as well as mechanical and transportation engineering due to their excellent performance in structural strength and stiffness. In order to avoid the unpleasant, energy dissipating and even structurally damaging vibroacoustic problems encountered in practical engineering, vibroacoustic characteristics of periodically rib-stiffened laminated composite structures are of significant interest for designers and engineers. Up to now, a great many researchers have developed many theoretical or numerical models to study vibroacoustic characteristics of laminated composite structures, including laminated composite plates and cylindrical shells.

A laminated composite structure is usually considered as a two-dimensional model of a single layer, so the well-developed uniform isotropic plate/shell theory can be conveniently extended to the laminated plate/shell theory. The classical laminated plate theory is based on the Kirchhoff-Love hypothesis which states that the straight lines, initially normal to the middle plane before bending, remain straight and normal to the middle surface during the deformation. This hypothesis ignores the transverse shear strain and transverse normal strain, and consequently, it introduces two inconsistencies in transverse shear stress and transverse normal stress. Taking into account the effects of rotary inertia and shear deformation, Mindlin [1] and Soedel [2] respectively presented a more accurate theory for plates and shells, known as the first order shear deformation theory (FSDT), which introduces a shear coefficient to account for the non-uniform distribution of the shear stresses over the thickness of the plate and the shell. More refined theories, such as second and higher-order plate theories, which expand the displacement components over the thickness of the plate into higher-order polynomials, are proposed by Reddy [3], Reddy and Liu [4] and Lee and Reddy [5].

Dynamic characteristics of plates and shells reinforced by stiffeners are quite different from those of the uniform ones, and they are also extensively investigated by numerous researchers. For periodically stiffened plates, one of the pioneering works was done by Maidanik [6], who analyzed the response of ribbed panels to a

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reverberant acoustic field and revealed the fact that the periodic line supports attached to an infinite plate increase the acoustic radiation efficiency at frequencies below the critical frequency. Subsequently, Maidanik [7] and Crighton and Maidanik [8] found the role of the stiffeners in converting high, non-radiating, subsonic wavenumbers into low, radiating, supersonic wavenumbers. By means of the wavenumber transform method, Mace [9] investigated sound radiation from an infinite isotropic plate with two sets of parallel periodic stiffeners and obtained the far field sound pressure with the method adopted by Greenspon [10]. Mead and Pujara [11] analyzed the response of the periodically supported beams under random convection loading with the employment of the space harmonic expansion method, by which Rumerman [12] and Mead and Yaman [13] analyzed the response of the ribbed plates. Based on the stiffened uniform isotropic plate theory proposed by Mace and taking into account the normal forces of the stiffeners to the plate. Yin et al. [14] investigated acoustic radiation from a point-driven, infinite fluid-loaded, laminated composite plate which is reinforced by doubly periodic parallel stiffeners and the results show the effects of the spacing of the double parallel stiffeners on the acoustic radiation of the laminated composite plate. Cao et al. [15] studied sound radiation from shear deformable stiffened laminated plates theoretically. The equations of motion for the composite laminated plate with two sets of parallel stiffeners interact with the laminated plate only through the normal line forces were derived on the basis of the first-order shear deformation plate theory. And then, the far-field sound pressure was described analytically by using the Fourier wavenumber transform and the stationary phase method. Finally, the effects of force location, stiffeners and angle-ply layers as well as the lamination schemes on sound radiation from the shear deformable stiffened laminated plates were presented. Shen et al. [16] developed an analytical periodic model to study sound radiation from orthogonally stiffened laminated composite plates under airborne and structure borne excitations on the basis of a layer-wise shear deformable theory, which demonstrates the significant influence of both flexural-extension and flexural-torsion coupling upon acoustic radiation from the composite plate. Wang et al. [17] presented an analytical solution for the vibration and acoustic responses of a finite stiffened plate covered with decoupling layers and the results reveal that the loss factor and the thickness of the decoupling layer significantly affects noise reduction of the stiffened plate. Jin et al. [18] developed a general theoretical model to investigate sound radiation from an infinite orthogonally stiffened plate under point excitation force. A recent study was done by Xin [19], in which an exact elasticity model was developed for a fluid-loaded periodically rib-stiffened plate covered by a decoupling acoustic coating layer based on the plain strain elasticity theory and the results show the significant effect of the decoupling acoustic coating layer on the noise reduction of the periodically rib-stiffened structures.

With respect to periodically ring-stiffened cylindrical shells, the basic theories and fundamental methods are similar to those used to study sound radiation from the periodically stiffened plates. Based on the space harmonic expansion method, Lee and Kim [20] investigated sound transmission through the periodically stiffened cylindrical shells subjected to an incident plane wave with the stiffeners considered as a combination of the lumped mass in conjunction with translational and rotational springs. Yan et al. [21] analyzed acoustic radiation characteristics of an infinite periodically stiffened cylindrical shell excited by a harmonic line force acting along the radial direction with the employment of the space harmonic expansion method. Subsequently, Efimtsov and Lazarev [22,23] developed an effective method to study vibroacoustic characteristics of an orthogonally stiffened cylindrical shell on the basis of the space harmonic expansion method. Then, based on the classical laminated shell theory (CLST), Yin et al. [14] investigated acoustic radiation from a point-driven infinite laminated cylindrical shell stiffened by doubly periodic rings with the effects of the two sets of rings on radial displacement of the laminated cylindrical shell identified by means of the helical wave spectra. Afterwards, based on the shear deformation theory, Cao et al. [24] presented an analytical model of acoustic radiation from shear deformable laminated cylindrical shells with initial axial loadings and doubly periodic rings with the consideration of the rotary inertia and the normal forces of the rings acting on the laminated cylindrical shell. Recently, Hemmatnezhad et al. [25] investigated the free vibration characteristics of stiffened composite cylindrical shells using experimental, numerical and analytical techniques, among which the theoretical formulation is established on the basis of Sanders' thin shell theory and the numerical results are obtained by the Ritz method. Besides, both the theoretical formulation and the numerical results are validated by the experimental modal analysis and the finite element model.

For fluid loaded structures, there are also lots of related literature, which mainly take the simple structure of flat plate as the subject of study. Koval [26] theoretically studied the effects of external air flow, panel curvature and internal fuselage pressurization on sound transmission through aircraft fuselage panels, which shows that the external air flow and panel curvature can effectively increase the sound insulation performance of the aircraft fuselage panels, while the internal fuselage pressurization exerts an opposite influence exactly. Berry [27,28] analyzed the dynamic response and acoustic radiation of baffled rectangular plates elastically restrained against deflection and rotation along the four edges and exposed to a half-space of dense fluid. Sgard et al. [29] analyzed the effects of the mean flows on vibroacoustic behaviors of planar structures by coupled FEM-BEM approach with the term corresponding to the mean flow effects concerned as an explicit form in the expression of sound transmission loss. Then, Atalla and Nicolas [30] extended the formulation developed by Berry to the one for the transverse vibrations of the plate coupling with the inviscid, uniform subsonic flow. The extended formulation shows explicitly the effects of the flow in terms of added mass and radiation resistance. Wu and Maestrello [31] investigated the vibroacoustic characteristics of the simply-supported plate under turbulent flow excitations. By approximately simplifying a section of an aircraft fuselage as a flat plate. Howe and Shah [32] studied the vibroacoustic behaviors of a thin elastic plate by straight edges transverse to the mean flow direction of the high, subsonic turbulent flow. Graham [33] described the initial form model of sound radiation from a single, flat, elastic plate under boundary layer excitation, and then Graham [34] extended the abovementioned model to include the influence of the cabin interior treatment on boundary layer noise levels. The results show that increasing the structural damping and decreasing the skin stiffness and number of reinforcements, the radiated sound will be reduced. Frampton and Clark [35] and Frampton et al. [36] established a state-space model for aeroelastic panels with aerodynamic loading of the linearized potential flow. With the model, Clark and Frampton [37], Frampton and Clark [38] and Frampton [39,40] analyzed sound radiation from the flat plate with boundary layer excitations. Besides, Schmidt and Frampton [41] studied the effect of in-plane forces on sound radiation from convected, fluid loaded plates. The results show that the in-plane forces exert a tremendous influence on sound radiation characteristics of the plate and that the increase of the amplitude of the in-plane forces contributes to eliminating the translation of the radiation power curves. Based on Koval's model, Xin et al. [42] established a theoretical model for noise transmission through a double-leaf aeroelastic plate and analyzed the influence of the external mean flow. Subsequently, Xin and Lu [43] presented an analytical solution for sound transmission through finite aeroelastic panels in convected fluids. Recently, Zhou et al. [44] studied sound transmission through a sys-