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Numerical analysis of acoustic radiation responses of shear deformable laminated composite shell panel in hygrothermal environment

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A B S T R A C T

In this article, the vibroacoustic responses of laminated composite curved panels subjected to harmonic point excitation in a combined temperature and moisture environment are investigated numerically using a novel higher-order finite-boundary element model. The hygrothermal dependent composite material properties are incorporated macroscopically in the formulation. The governing equations are derived using the higher-order shear deformation shell theory coupled with finite and boundary element approach. First, the Hamilton's principle is employed to obtain the stiffness, mass tensors and modal values of the vibrating structure subjected to hygrothermal stresses. The acoustic radiation responses are then computed by solving the Helmholtz wave equation discretized on the structure boundary using boundary elements coupled with the structural finite elements. Compared to those reported in open literature, the results for natural frequencies, critical buckling temperature, critical buckling moisture and sound power level values computed using the present scheme are found to be more accurate. The sound power values are also acquired via a simulation model implemented using commercial tools ANSYS and LMS. Virtual Lab and compared with present numerical results. The scheme is further extended to solve numerous numerical examples highlighting the influence of hygrothermal loads, geometry, curvature ratio, modular ratio, support conditions and lamination scheme on the hygro-thermo-acoustic responses of laminated composite shell panels.

1. Introduction

The laminated composite flat and curved panel structure are widely used in several engineering applications those demand superior materials for not only withstanding severe static and dynamic loading but also hold out when exposed to severe environmental conditions. Owing to the pre-stress effect and the variation in composite material properties due to the elevated temperature and/or moisture and/or combined hygrothermal loading, the stiffness of the structure/structural component is significantly altered. Consequently, the dynamic behaviour and thus, the vibration induced acoustic characteristics of the structure are significantly influenced. Therefore, the dynamic and the vibroacoustic analysis of laminated

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composite structure under individual and/or combined temperature and moisture environment has been a subject of acute interest in the recent past. However, acquiring the responses corresponding to specific hygrothermal conditions via physical testing is not only time-consuming and expensive but also necessitates repeatability for any specific configuration. Therefore, the numerical estimation of the structural responses has been dealt with great enthusiasm by the scientific community. Nevertheless, the precision of these numerical solutions is significantly reliant on the kinematic relations used in the computational models. Moreover, the incorporation of effective hygro-thermo-elastic composite material properties corresponding to different temperatures and moisture concentrations is very much essential to achieve more realistic responses expressly, for any multi-physical analysis under extreme hygrothermal load. In this aspect, several kinematic theories [1] including the classical laminated, the first-order and the higher-order shear deformation shell theories (CST, FSDST and HSDST) and other refined and mixed theories have been reported to predicted to dynamic and free vibration responses of composite flat and curved shell panels subjected to thermal/hygrothermal loading [2–9]. We note that the HSDST is frequently preferred over other available theories as it is capable of alleviating the necessity of shear correction factor, assumes more realistic distribution of shear stress and strain through the panel thickness [3,4,6,10,11] and thus results solutions consistent with those obtained via 3D-elasticity theory [12]. It is also reported that, in addition to the mid-plane kinematics, the structure geometry, excitation type and location, support conditions and numerous other factors also contribute to the sound radiation emission from the vibrating structures [13].

We also note that, in comparison to the conventional metallic counterpart the vibroacoustic behaviour of laminated composite flat and/or curved panel structure have got less attention. Moreover, most of the analysis is carried out in ambient conditions without considering the environmental effect [14–21]. The coupled finite and boundary element (FE-BE) technique has been implemented via commercial computational packages like ANSYS and SYSNOISE to study the sound radiation responses of mechanically excited isotropic flat panels with uniform [22] and varying thickness [23] and composite flat panels with inherent material damping [24] in a thermal environment. Li et al. [25] modelled the laminated composite flat panels using CST and FSDST and analysed the thermal buckling and acoustic radiation characteristics via Rayleigh's integral formulation. Zhou et al. [26] provided closed form solutions to the vibroacoustic problem of an orthotropic plate in a thermal environment. Geng and his colleagues studied the dynamic and sound radiation responses of flat panels [27] numerically via a FE-FE technique implemented in ABAQUS, laminated plates [28] with temperature variation along thickness direction and isotropic plates [29] using a FE-BE approach implemented using commercial software package (NASTRAN and VA One) in an elevated uniform thermal environment.

The shell structures not only provide excellent aesthetic value but also bear the greater bending load as they possess higher membrane strength due to their geometry (spatial curvature). However, the inclusion of curvature in the structures further increases the numerical complexity and make the solution more tough. The curved shell panels have also been probed for their sound radiation characteristics. Cao et al. [30] analysed stiffened cylindrical shells with constrained layer damping using Sander's thin shell theory and derived the solution in wavenumber domain. Ghinet and Atalla [31] analysed the sound transmission loss from curved laminates in the framework of statistical energy analysis approach. Chronopoulos [32] studied the transmission loss from composite aerospace structures experimentally and via wave finite element method (WFEM). Isotropic cylindrical shells subjected to uniform thermal loading are also analysed for the sound radiation characteristics [33] in the framework of FSDST using commercial FE-BE tools. Qu and Meng utilized the higher order zig-zag theory and presented a semi-analytical approach for predicting the vibration and acoustic responses of an arbitrarily shaped, multi-layered [34] and functionally graded [35] shells of revolution immersed in a light or heavy unbounded fluid. Yang et al. [36] presented a numerical solutions of the vibroacoustic response of stiffened isotropic conical shell using hybrid FEM-SEA approach. Successively, analytical studies on the influence of hygroscopic environment on the vibroacoustic behaviour of laminated composite flat [37], composite cylindrical shells [38] and orthotropic conical shells [39] have been reported in the recent past. Lyrintzis and Bofilios [40] presented an analytical approach to investigate the sound transmission characteristics of discretely stiffened composite panels exposed to hygrothermal environmental conditions.

The literature review suggests that various efficient numerical and analytical techniques have been developed every now and then to study the vibration and acoustic responses of isotropic and composite structure with or without considering the environmental effect. However, the laminated composite shells and shell panels have not been explored extensively for their vibroacoustic responses. Specifically, the sound emission behaviour of laminated composite structure under the influence of combined hygrothermal loading is an untapped dominion. In this work, coupled vibroacoustic analysis of laminated composite flat and curved shell panels under hygrothermal environment is performed using a coupled FEM-BEM scheme implemented via a customised computer code developed in MATLAB environment. To acquire more realistic responses, the structural mid-plane kinematic is modelled using the HSDST and the degraded composite material properties corresponding to elevated hygrothermal environment are incorporated in the model macroscopically. A nine-noded quadrilateral Lagrangian isoparametric element with each node having nine degree of freedom terms is utilized for discretisation of structural model followed by computation of acoustic responses via an indirect BEM. The validity of the proposed scheme is first established by comparing the present critical buckling temperature, critical buckling moisture, natural frequency and radiated sound power values with the available published results alongside those obtained using simulation model implemented via commercial tools. The vibroacoustic characteristic of laminated composite shell panel of various geometries (Cylindrical, spherical, elliptical and hyperboloid) subjected to incremental hygrothermal loading are analysed. The influences of hygrothermal conditions, geometry and other design parameters on the vibroacoustic response of laminated composite shell panel are discussed.