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Nonlinear aeroelastic analysis of curved laminated composite panels

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ABSTRACT

Nonlinear aeroelastic behaviors of curved laminated composite panels are investigated in this paper.

The finite element co-rotational theory is applied to model geometrically nonlinear shell panels, and an Euler solver, instead of piston theory or other simplified aerodynamic theories, is utilized to solve for the unsteady aerodynamic pressure. Aeroelastic responses for thin panels, with which have two different sizes of curvature $H/h = 5$ and $H/h = 10$, as well as two different layer orientations, [0°/90°/0°/90°/0°] and [45°/−45°/45°/−45°/45°] are simulated under four Mach numbers at 0.76, 0.96, 1.2 and 1.67. The results, comprising the static aeroelastic deformation, limit cycle oscillation, non-periodic oscillation and chaotic behaviors are obtained and studied. Flutter dynamic pressure, amplitudes, and spectra of limit cycle oscillation are analyzed, and the nonlinear characteristics are discussed.

1. Introduction

Aeroelastic analysis of the flat panel flutter problem in supersonic flow regime has been investigated for many decades. Bolotin [1], Dowell [2,3], Gordnier [4] and Mei [5], to name a few, have contributed much to this topic. The main methods used in their works were based on Von Karman theory, Galerkin' method or finite element method in spatial variables accounting for the structural nonlinearity and quasi-steady aerodynamic theory, or piston theory accounting for the supersonic unsteady aerodynamics. The concrete behaviors, such as flat, buckled, limited cycle oscillation, periodic and chaos are obtained extensively in the published literature on flat panel flutter.

However, in the engineering practice of flight vehicles' design, the exposed skin of the structure always has a certain degree of curvature. Comparing with the flat panel, the static aeroelastic deformation will arise and the behaviors of the curved structure will present a more complex characteristic under aerodynamic loading. Some investigators have extended their studies to flutter of curved shell panels. Yates and Zeijel [6] studied flutter of curved panels and showed that curvature has a destabilizing effect on aeroelastic stability. Olson and Fung [7] did some research work on comparing the piston theory, the potential solution with experiment for the supersonic flutter of the circular cylindrical shell. Dowell [8,9] studied the flutter amplitude and boundary of two-dimensional and three-dimensional streamwise curved plates by a nonlinear Galerkin analysis based on Von Karman equations and quasi-steady aerodynamic theory, and pointed out that the static aerodynamic loading significantly affects the flutter boundary. Bismarck-Nasr [10] used a circular cylindrical shell element with a linear potential flow theory to solve supersonic flutter of circular cylindrical shell subjected to internal pressure and axial compression. Their numerical results were compared with experimental and analytical solutions. Nydick, Friedmann and Zhong [11] considered the flutter of shallow, curved, heated three-dimensional orthotropic panels exposed to hypersonic airflow. The equation, based on Marguerre's shallow shell theory, was solved using Galerkin's method combined with direct numerical integration in time to compute stable limit cycle amplitudes, non-simple harmonic complex motions were observed, and the aeroelastic behavior was found affected by aerodynamic heating, the presence of shock wave, and initial curvature. They also compared the aerodynamic loads predicted by 3rd order piston theory, the Euler equations, and the Navier-Stokes equations and suggested that the solution to the fully coupled aerothermoelastic problem may be necessary to fully understand the aeroelastic behavior of a panel in hypersonic flow. Krause and Dinkler [12] used finite element method (FEM) and third order piston theory to investigate the influence of curvature on flutter boundaries and flutter behavior for isotropic two-dimensional and three-dimensional panels. Their results showed that the flutter boundary drops significantly and the flutter motion becomes chaotic for larger curvatures. Librescu et al. [13] presented a theoretical investigation of the flutter and post-flutter behavior of circular, thin-walled cylindrical shell panels in a supersonic/hypersonic

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flow field. They used 3rd order piston theory and shock wave aerodynamics in conjunction with the geometrically nonlinear shell theory to analyze the character of the flutter instability boundary and outline the effects of the geometrical parameters. Azzouz and Mei [14] developed a finite element frequency domain method to predict the pre-flutter behavior and the flutter onset of curved panels in supersonic flow, the method was based on the first order shear deformation theory, the Marguerre's curved plate theory, the von Karman large deflection theory, and the quasi-steady first-order piston theory. Their results revealed that the pre-flutter static response of curved panels is fundamentally different from the one associated with flat plates and the curvature has a detrimental effect for 2-D cylindrical panels, but beneficial for 3-D at an optimum height rise. Ghoman [15] developed a finite element time domain method and the fluttering system was solved by a fourth-order Runge-Kutta numerical scheme to predict the pre/post-flutter behavior of curved panels under yawed supersonic flow at elevated temperature. Sabri and Lakis [16] used Sander's thin shell theory and piston theory to derive an aeroelastic equation in hybrid finite element formulation, and investigated the different boundary conditions of the shell, geometries, and flow parameter for the supersonic flutter of circular cylindrical shells. They concluded that the shell loses its stability due to coupled-mode flutter and observed a traveling wave during the dynamic instability. Abbas et al. [17] adopted Von Karman nonlinear strain-displacement relation in conjunction with the Kirchhoff plate-hypothesis and used Galerkin's approach to investigate a geometrically imperfect curved panel forced by a supersonic/hypersonic unsteady flow, and also discussed the thermal effects on flutter and post-flutter behavior. Yang [18] proposed a flow field modified local piston theory to analyze the static aeroelastic deformation and flutter stabilities of curved panels in hypersonic flow, and the results showed that with the larger curvatures, the static aeroelastic deformation is larger and the flutter stability boundary is smaller compared with those obtained by the curvature modified method.

As can be seen from the above literatures, the materials of these curved panels are isotropic. When considering anisotropic material in panel structure, especially for composite material, which has higher stiffness and strength-to-weight ratio, the complexity of aeroelastic problem arises from the added difficulties associated not only from the curvature, but also material nonlinear effects. Some researchers have focused their study on the aeroelastic characteristic of the composite panel in supersonic flow. Shiau and Lu [19] investigated the nonlinear flutter behaviors of a composite laminated plate at high supersonic Mach number. The results showed that the anisotropic properties have significant effects on the behavior of both limit cycle nonlinear oscillations and chaotic motions. Gray and Mei [20] presented a finite element approach to determine the nonlinear flutter characteristics of three-dimensional thin laminated composite panels using the full third-order piston theory and von Karman large-deflection plate theory; this nonlinear flutter analyses were performed for different boundary support conditions and for various system parameters. Ganapathi et al. [21] modeled an orthotropic and laminated anisotropic circular cylindrical shell in supersonic flow using finite element based on the field-consistency approach and studied the effects of aspect ratio, thickness, internal pressure, axial compression, the number of layers and lamination scheme on the flutter boundaries. Chowdary et al. [22] used eight-noded isoparametric elements and linearized piston theory to study the effects on dynamic instability for different geometric laminated composite skew panels in supersonic flow. Shin et al. [23] used the finite element method based on zig-zag layerwise shell theory and Kumhaar's modified piston theory to analyze the flutter of cylindrical composite panels considering structural damping effect. Singha and Mandal [24] used the 16-noded isoparametric degenerated shell element and a linear potential flow theory for solving the effects of curvature, laminate stacking sequence, air flow direction and boundary condition on the supersonic flutter characteristics of laminated composite cylindrical panels. Kouchakzadeh et al. [25] employed Galerkin's method with a direct numerical integration technique to investigate the panel flutter of a general laminated composite plate in supersonic airflow, and discussed the effects of in-plane force, static pressure differential, fiber orientations and aerodynamic damping on the nonlinear aeroelastic behavior. Castro et al. [26] presented a semi-analytical model with Krumhaar's modified supersonic piston theory to predict the aeroelastic response of laminated composite stiffened panels under supersonic flow, and the results showed that the stiffener base significantly affects the panel aeroelastic behavior.

In recent years, there has been considerable development in improvements in the dynamic and aeroleastic behaviors of composite structures by utilizing active and passive control strategies. Leão et al. [27,28] studied the possibility of increasing the supersonic flutter boundary of a composite flat panel by the passive control. They applied a multimode shunted piezoceramic in series topology to affect the flutter speed of a typical section under an unsteady airflow. Cunha-Filho et al. [29,30] investigated the possibility reducing the effects of the supersonic aeroelastic instability of rectangular plates by applying passive constrained viscoelastic layers and addressed the description of a numerical study on the flutter analysis of a three-layer sandwich plate. The results showed that it is possible to increase the critical flutter speeds of flat panels using surface viscoelastic damping treatments. Donadon and Faria [31] investigated the aeroelastic stability boundary of flutter in Shape Memory Alloy Hybrid Composite laminates, and studied different geometric configuration, laminate stacking sequence, boundary conditions and curvatures. The results indicated that the stiffening effect of the shape memory alloy increases the rate of occurrence of flutter, stabilizing the plate.

To the best of the authors' knowledge, there are few published works on the nonlinear aeroelastic behavior of curved composite panels in subsonic, transonic and low supersonic flow regime. The nonlinearity, arising from curvature effect, large deformation, material property, shock wave movement and flow separation has not been thoroughly understood. This paper intends to simulate the nonlinear aeroelastic behaviors of curved laminated composite panels. In order to model geometrically nonlinear structure, a finite element co-rotational theory with OPT + TMT elements is developed and a nonlinear Newmark numerical method is applied to solve the structural responses. In the interest of obtaining the unsteady aerodynamic loads in the case of shock motions and flow separation, an Euler solver, which incorporates a flux splitting scheme, implicit time marching technique and geometric conservation law, is utilized. The two solvers are validated separately, and connected by a second order loosely coupled procedure to calculate the nonlinear aeroelastic response of the curved laminated composite panels in subsonic, transonic and supersonic flows. The effects of the curvature, composite fiber angle, shock wave movement and flow separation on the aeroelastic behavior are analyzed.

2. Geometrically nonlinear structure modeling

The co-rotational (CR) approach, differing from the total Lagrangian (TL) and updated Lagrangian (UL) approaches, has generated an increased interest and viewed as an effective way to describe the geometric nonlinear problems with small strains but large-rotations. Many important works related to the development of this method can be found in Crisfied [32], Battini [33] and Pacoste