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On dynamic instability of a pressurized functionally graded carbon nanotube reinforced truncated conical shell subjected to yawed supersonic airflow

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ABSTRACT

The aeroelastic flutter characteristics of a functionally graded carbon nanotube reinforced composite (FG-CNTRC) truncated conical shell under simultaneous actions of a hydrostatic pressure and yawed supersonic airflow are scrutinized. The nonlinearity in geometry of the conical shell is considered in Green–Lagrange sense and the model is derived according to the Novozhilov nonlinear shell theory. The aerodynamic pressure is modeled based on the quasi-steady Krumhaar's modified supersonic piston theory by considering the effect of the panel curvature and flow yaw angle. Parametric studies are conducted to investigate the effects of boundary conditions, semi-vertex angle, distribution and volume fraction of CNT, Mach number and airflow yaw angle on the stability boundaries and flutter characteristics. The results show that the semi-vertex angle and CNT distribution may alter the stability boundaries. It is also found that the aeroelastic flutter responses of the structure can be significantly improved through a functionally graded distribution of CNT in a polymer matrix. Moreover, the aeroelastic characteristics of the FG-CNTRC truncated conical shell are found to be very sensitive to geometrical parameters and the airflow yaw angle. The results of this study shed a light into developing and using ultra-high-strength and low-weight composites reinforced with CNT for aerospace applications.

1. Introduction

Thin-walled structures have been widely used in various engineering structures, especially aircraft structures. External skins of high-speed aircrafts are mainly subjected to an external pressure, which results in the possible buckling instability. Essentially, the buckling instability does not indicate a structural failure, however, it may result in aerodynamic shape changes leading a reduction of the flight performance. On the other side, flutter is a kind of dynamic instability phenomenon, which is resulted from an interaction between the inertial, elastic and aerodynamic loads owing to the supersonic airflow. Predictions of the aeroelastic behaviors of lifting and control surfaces at high flow velocities are foremost from the perspective of both design optimization as well as safe testing of designs [1,2]. The onset of the flutter may be very sudden and hence may lead to a rapid destruction of the lifting surface, and thus it is perilous to the structural stability and safety. Therefore, investigations of the aeroelastic flutter instability of high-speed structures are significant steps in designing the external skins of high-speed structures.

There are a large number of researches in the literature on the buckling, vibration and flutter of thin-walled structures [3–26]. For instance, Shin et al. [18] conducted a numerical study based on the layerwise theory to investigate the aerothermoelastic responses of an aerothermally buckled cylindrical composite shell with different damping treatments. The aeroelastic stability of a geometrically imperfect cylindrical shell under a supersonic gas flow was addressed by Amabili and Pellicano [25] by employing Galerkin approach and Donnell shallow-shell theory. In their study, effects of viscous structural damping, asymmetric and axisymmetric imperfections of cylindrical shells were taken into consideration. It was shown that the onset of flutter is very sensible to initial imperfections of the shells. Recently, Asadi et al. [26] studied the nonlinear aerothermal flutter instability and investigated a

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possibility of enhancing the aerothermal stability boundaries and decreasing aerothermal postbuckling deflections of laminated composite beams using shape memory alloys fibers.

Recent years have witnessed a strong interest and intensive research activities in the design and analysis of advanced materials and structures, which have been widely used in engineering fields, particularly, in the aviation and aerospace sectors. Among several kinds of advanced materials, the extraordinary stiffness and specific tensile strength of carbon nanotubes (CNTs) make them well-suited as reinforcing components in next generation of high-performance multifunctional composites. In fact, their exceptional properties along with their high aspect ratio, low density have attracted enormous researches on developments of the advanced composites using CNTs.

Various studies assessed the influence of CNT on the dynamic and static responses of CNTRC structures [27–60]. An overview of the researches is presented hereafter.

Wuite and Adali [28] performed a multiscale analysis of the stresses and bending deflection of the CNTRC beam. The influence of CNT volume fraction and nanotube diameter on the transverse deflection was studied, and comparisons were made with carbon fiber reinforced composites. Yas and Samadi [30] analyzed free vibration and buckling responses of a nanocomposite beam reinforced with SWCNTs resting on Pasternak elastic foundation by means of generalized differential quadrature (GDQ) method. Their results indicated that embedding CNTs in a polymer matrix could result in an increase in the buckling strength. Lei et al. [34,35] investigated large deflection and buckling of FG-CNTRC plates under various in-plane loads by employing the element-free kp-Ritz method. In these works, the effective material properties were calculated in accordance with either the Eshelby–Mori–Tanaka or the extended rule of mixture. Effects of CNT and elastic foundation on the onset of the buckling of FG-CNTRC skew plate were examined by Liew and his colleagues [37–39] by means of element-free IMLS-Ritz method. The first shear deformation theory (FSDT) was used for formulation of energy functional to incorporate the influence of the transverse shear deformation and rotary inertia. Liew et al. [40,41] presented a numerical study using the element-free kp-Ritz approach to study dynamic stability and postbuckling characteristics of FG-CNTRC cylindrical panels under axial compressive load. According to kernel particle approximations for the field variables, the Ritz method was used to develop the discretized governing equations and the bending stiffness was evaluated by a stabilized conforming nodal integration scheme. Linear thermal and mechanical buckling of FG-CNTRC conical shells were studied by Kiani and his colleagues [42,43] using Donnell shell theory in conjunction with the first-order shear deformation theory (FSDT). Sankar et al. [56] studied dynamic instability behavior of sandwich panels with CNT reinforced face-sheets under in-plane periodic load by employing a shear flexible QUAD-8 serendipity element. They found that HSDT predicts a narrow instability region and the onset of primary instability zone happens at lower forcing frequency compared to the FSDT. The flutter characteristics of sandwich plates with CNT reinforced face-sheets was investigated by Sankar et al. [57] using QUAD-8 shear flexible element in conjunction with HSDT. Their results showed that the occurrence of type of flexural/extensional modes in the thickness direction depends on the position of the structures. Recently, Asadi et al. [59] investigated buckling and free vibration responses of FG-CNTRC truncated conical shells according to nonlinear Novozhilov shell theory. Their results indicated that the circumferential mode number associated with the fundamental natural frequency is independent of the CNT volume fraction and distribution as opposed to stability characteristics in which volume fraction and distribution of CNT may change the buckling configuration. Most recently, Zhang et al. [60] presented a comprehensive research on an active control aerothermoelastic flutter of FG-CNTRC plates using piezoelectric actuators and sensors. In their work, the optimal area and location of piezoelectric patches were also determined using the genetic algorithm. It is found that the aeroelastic flutter stability may be enhanced where the CNTs are concentrated near the neutral plane of the FG-CNTRC plates.

The above literature review clearly indicates that despite various attempts to study effects of CNT on the structural responses of flat and curved structures, a rigorous investigation for examining effects of CNT on the aeroelastic flutter response of CNTRC flat and curved structures seems to be absent. It is noteworthy that the incorporation of CNT may significantly enhance the strength and stiffness of the composites with a minimal increase in weight. Since Young modulus of CNTs are superior to all carbon fibers with value greater than $1\,(\mathrm{TPa})$ and their density may be only $1300\,(\mathrm{Kg/m^3})$. This motivates us to conduct the present research.

The main purpose of the present research is to fill this important gap in the literature. The present work scrutinizes the aeroelastic flutter characteristics of a FG-CNTRC truncated conical shell subjected to hydrostatic pressure and exposed to yawed supersonic external airflow. Nonlinear equations of motion of the FG-CNTRC truncated conical shell are derived according to the Novozhilov nonlinear shell theory and Green–Lagrange geometrical nonlinearity via Hamilton principle. The Krumhaar's modified supersonic piston model is adopted to evaluate the aerodynamic pressure. A detailed parametric study is carried out to investigate the effect of all geometrical parameters, CNT distribution and volume fraction on the supersonic aeroelastic flutter behavior of the FG-CNTRC truncated conical shell. The main contribution of the present work is to reveal an efficient application of CNT to enhance the aeroelastic flutter characteristics of supersonic curved structures.

2. Basic formulation

2.1. Modeling of FG-CNTRC

As illustrated in Fig. 1A, a FG-CNTRC truncated conical shell is considered in the cylindrical coordinate system (x, θ, z). The truncated conical shell is shown with the thickness h, length L, semi-vertex angle α and end radii $R_1 < R_2$. It is assumed that the truncated conical shell is subjected to a hydrostatic pressure (q_H) and yawed supersonic airflow (see Fig. 1B).

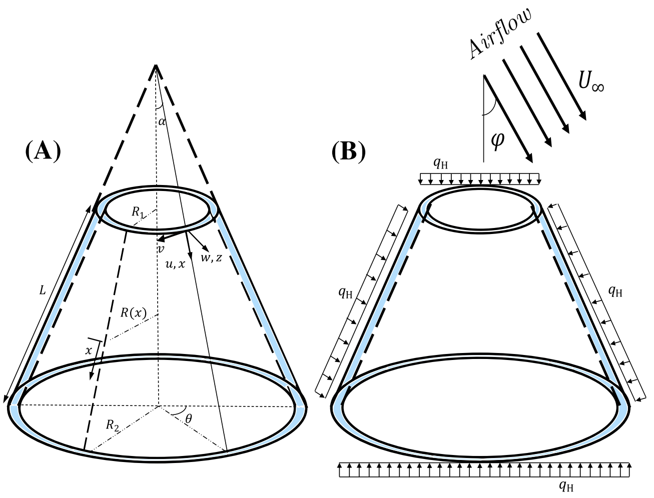

Fig. 1. Schematic and geometric characteristics of the FG-CNTRC conical shell.