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Nonlinear aero-thermal flutter postponement of supersonic laminated composite beams with shape memory alloys

M. Samadpour [a], H. Asadi [a, *], Q. Wang [b, c]

[a] Thermoelasticity Center of Excellence, Department of Mechanical Engineering, Amirkabir University of Technology, Tehran 15875, Iran
[b] Department of Mechanical and Manufacturing Engineering, University of Manitoba, Winnipeg, MB, Canada
[c] Department of Mechanical Engineering, Khalifa University, Abu Dhabi 127788, United Arab Emirates

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ABSTRACT

The nonlinear aerothermal flutter instability of a shape memory alloy (SMA) fiber reinforced composite beam subjected to simultaneous actions of thermal and aerodynamic loads is investigated. The Brinson model is used to simulate behaviors of the SMA fibers and the Euler-Bernoulli beam theory along with nonlinear von-Karman strain field are used for modeling of the beam. Thermomechanical properties are assumed to be temperature-dependent. The aerodynamic pressure is modeled based on the quasi-steady first-order piston theory. The governing equations are solved by means of the Galerkin approach, and flutter and buckling boundaries, natural frequencies and damping ratios are obtained. Effects of various pivotal factors such as SMA volume fraction, prestrain of SMA fibers, location and orientation of SMA fibers on critical flutter dynamic pressure, damping ratio and bifurcation points and paths are studied. The results show that the aerothermal flutter characteristics of the laminated beam can be significantly enhanced by embedding SMA fibers. Moreover, the presence of aerodynamic flow and SMA fibers results in postponement of the bifurcation point and a reduction of the postbuckling deflection. The results of this study are expected to shed a light into enhancing the stability boundaries efficiently by increasing the SMA fiber volume fraction and prestrain.

1. Introduction

Thin-walled structures are extensively used in aircraft structures. External skins of high-speed aircrafts usually experience a high temperature rise due to aerodynamic heating, which can induce thermal buckling. In general, thermal buckling does not indicate a structural failure, however, it may bring a change of aerodynamic shape, causing a reduction of the flight performance. On the other hand, flutter is a type of dynamic instability phenomenon, which is resulted from an interaction between the inertial, thermoelastic forces of an aircraft structure and aerodynamic loads due to the supersonic gas airflow. Flutter is a critical dynamic problem and very dangerous to the structural safety and stability. As a result, investigations of aerothermal flutter and postbuckling of supersonic structures are significant steps in designing the external skin of supersonic aircraft vehicles.

There are a large number of studies in literatures on thermal buckling, vibration and flutter of thin-walled structures (Song and Li, 2012; Li and Song, in press; Zhao and Zhang, in press; Ibrahim et al., 2007; Asadi and Aghdam, 2014; Kuo, 2011; Li, 2012; Zhao and Cao, 2013; Asadi et al., 2014; Li et al., 2011; Oh and Lee, 2006; Song and Li, 2011; Nikrad and Asadi, 2015; Xue and Mei, 1993; Dowell, 1966; Liao and Sun, 1993; Nikrad et al., 2015; Shin et al., 2009; Koo and Hwang, 2004). For example, Li et al. (2011) investigated active aeroelastic flutter behaviors of supersonic beams using piezoelectric materials. It was found that the aeroelastic flutter characteristics of beams can be efficiently improved by virtue of piezoelectric materials. Liao and Sun (1993) employed a finite element method to study flutter stability of stiffened laminated composite plates and shells subjected to aerodynamic loads. In this study, natural frequencies of the plates and shells were obtained based on the classical plate theory and 2-D linear quasi-steady piston theory. The aerothermoelastic response of an aerothermally buckled cylindrical composite shell with different damping treatments was presented by Shin et al. (2009) using layerwise theory. In this work, the complex modulus was adopted to take into consideration of influence of viscoelastic damping.

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* Corresponding author.
E-mail addresses: m.samadpour@aut.ac.ir (M. Samadpour), hamed_asadi@aut.ac.ir (H. Asadi), quan.wang@kustar.ac.ae (Q. Wang).

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Fazelzadeh and Hosseini (2007) studied aerothermoelastic behaviors of supersonic rotating thin-walled functionally graded (FG) beams. The quasi-steady aerodynamic pressure forces were calculated based on the first-order piston theory. Effects of Mach number and geometric parameters on natural frequencies were examined.

Shape memory alloys (SMAs) belong to a class of smart materials, which have drawn specific attention in engineering fields, especially in the aerospace and aviation industries. SMAs have a mechanical-temperature coupling that confers the materials with superior adaptive behaviors to change properties due to environmental changes. The remarkable features of SMAs are related to phase transformations responsible for different thermomechanical characteristics of these alloys. SMAs are characterized by a solid state phase transformation between the parent phase (Austenite) and the product phase (Martensite) in response to either mechanical stresses or temperatures (Lagoudas, 2007). SMAs could recover their original shape at certain characteristic temperatures, known as shape memory effect (SME) and undergo large strains without plastic deformation or failure, which is called pseudoelasticity. These unique features of SMA materials have promoted their application in morphing the shape of aerospace structures (Lagoudas, 2007). For instance, NASA has recently developed self-heating SMAs that can repair themselves when they are damaged (Granath, 2013).

The ability of SMA materials to control structural specifications like bifurcation points, paths and vibration, motivates investigations on various applications. Hereinafter we will provide a brief literature review on the stability and dynamic responses of SMA structures.

A few studies have been devoted to structural behaviors of SMA hybrid structures (Birman, 1997; Choi et al., 1999; Lee and Lee, 2000; Loughlan et al., 2002; Tawfik et al., 2002; Roh et al., 2004; Park et al., 2004, 2005; Ibrahim et al., 2009; Kumar and Singh, 2009; Kuo et al., 2009; Ibrahim et al., 2011; Kim et al., 2011; Wang and Wu, 2012; Asadi et al., 2013a; Khalili et al., 2013a; Asadi et al., 2013b; Panda and Singh, 2013a; Khalili et al., 2013b; Panda and Singh, 2013b; Asadi et al., 2015a, 2014a, 2014b; Savi, 2015; Asadi et al., 2015b; Samadpour et al., 2015; Asadi et al., 2015c; Alebrahim et al., 2015; Asadi et al., 2015d; Abdollahi et al., 2015; Liang, 1990; Rezaei et al., 2012; Asadi et al., 2015e; Jani et al., 2014; Forouzesh and Jafari, 2015). For instance, Lee and Lee (2000) studied influence of embedded SMA fibers on buckling and postbuckling responses of a laminated composite beam under thermomechanical loadings using the commercial finite element (FE) computer code ABAQUS code. Loughlan et al. (2002) proved that by embedding SMA fibers within laminated composite plates, lateral deflection can be reduced. It was concluded that the postbuckling deflection could be declined even by applying a small SMA volume fraction. Park et al. (2004) introduced a nonlinear finite element approach to investigate vibration of a thermally postbuckled laminated composite plate with embedded SMA fibers. The governing equations were developed based on the FSDT by taking the nonlinearity in von Karman sense. Results indicate that a recovery stress in pre-strained SMA wires improves the buckling and postbuckling behaviors of laminated composite plates. Influence of non-uniformly distributed SMA fibers on the linear mechanical buckling of an SMA fiber reinforced composite plate was investigated by Kuo (Park et al., 2005) by means of an FE method. Ibrahim and co-authors (Tawfik et al., 2002; Ibrahim et al., 2009, 2011) investigated static and dynamic instabilities of a laminated panel reinforced with SMA fibers subjected to a combined aerodynamic and thermal loadings. A nonlinear FE method based on the von Karman strain displacement relation was used to study thermal bifurcation points, bifurcation paths, free vibration and flutter boundary. They used approximate curves based on the experimental data to determine the recovery stress of SMA fibers. Thermal postbuckling analysis of a geometrically imperfect and perfect laminated composite beam reinforced with SMA fibers were conducted by Asadi et al. (2014b) and (2015b). It was concluded that the SMA fibers may significantly diminish or completely eradicate the postbuckling deflection of both perfect and imperfect laminated beams. Samadpour et al. (2015) investigated vibrations of a thermally pre/post buckled sandwich plate with an SMA fiber reinforced composite face sheet. It was shown that reinforcement of face sheets with SMA fibers has a considerable effect on vibration and postbuckling responses of the sandwich plate for both compressible and incompressible type of substrates. Forouzesh and Jafari (2015) studied radial vibrations of simply supported pseudoelastic shape memory alloy cylindrical shells under time-dependent internal pressure based on the classical shell theory. It was found that when the phase transformation occurs, the frequency response graphs shows a softening behavior in the system. Panda and Singh (2010) and (2013c) introduced a nonlinear finite element approach using Green–Lagrange nonlinear kinematics based on the higher-order shear deformation theory to investigate thermal postbuckling and large amplitude vibration of doubly curved panels and spherical shells reinforced with SMA fibers. In spite of all above-mentioned literatures, there are just few studies on the flutter analysis of plates and panels subjected to supersonic gas flows. Further comprehensive studies are still indispensable for understanding the dynamic instability of SMA structures.

In this paper, nonlinear flutter and thermal postbuckling responses of a shape memory alloy hybrid composite beam subjected to simultaneous thermal and aerodynamic loadings are investigated by utilizing the Galerkin method. The SMA fibers are actuated by aerodynamic heating created by presence of shock waves. The one-dimensional constitutive equation of SMAs proposed by Brinson (1993) is used to model the characteristics of SMA fibers. The Euler-Bernoulli beam theory is used to describe the displacement field of the structure by considering the geometrical nonlinearity by the von Karman equation. The supersonic piston theory is adopted to calculate the aerodynamic pressure. The aerothermal flutter and buckling bounds are obtained via the derivations of the natural frequencies, damping ratios and thermal bifurcation points. The main contribution of the present work is to reveal an efficient application of SMA fibers to improve the flutter behaviors of supersonic aerospace structures.

2. Structural and aerodynamic modeling

2.1. Kinematics and constitutive equations

A straight hybrid laminated composite beam in Cartesian coordinate system with a length L in the x direction, width b in the y direction and total thickness h in the z direction is considered in Fig. 1. The SMA embedded fibers is in parallel to the fibers of the composite medium in the arbitrary layers. Zhong et al. (1994) claimed that the material properties of fiber/matrix composite with embedded SMA fibers could be determined by utilizing micromechanics of conventional composites and considering the fiber/matrix composite and SMA fibers as matrix and fiber, respectively. Furthermore, It is well known that material properties of a fiber-reinforces composite may be derived from general micromechanics schemes. While the following aspects do not follow considerably from the rule of a mixture, several SMA parameters deviate from the regular rule according to the thermomechanical constitutive law. Hence, the multi-cell micromechanics approach is used to determine the effective thermomechanical characteristics of each layer (See Appendix A). The efficiency of this