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Aeroelastic flutter enhancement by exploiting the combined use of shape memory alloys and nonlinear piezoelectric circuits

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ABSTRACT

In this paper, the combined effects of semi-passive control using shunted piezoelectric material and passive pseudoelastic hysteresis of shape memory springs on the aerolastic behavior of a typical section is investigated. An aeroelastic model that accounts for the presence of both smart materials employed as mechanical energy dissipation devices is presented. The Brinson model is used to simulate the shape memory material. New expressions for the modeling of the synchronized switch damping on inductor technique (developed for enhanced piezoelectric damping) are presented, resulting in better agreement with experimental data. The individual effects of each nonlinear mechanism on the aeroelastic behavior of the typical section are first verified. Later, the combined effects of semi-passive piezoelectric control and passive shape memory alloy springs on the post-critical behavior of the system are discussed in details. The range of post-flutter airflow speeds with stable limit cycle oscillations is significantly increased due to the combined effects of both sources of energy dissipation, providing an effective and autonomous way to modify the behavior of aeroelastic systems using smart materials.

1. Introduction

The use of smart materials in aeronautical problems has been reported over the last years. In particular, smart materials have been employed in applications such as morphing structures [1], vibration control [2] and more recently wind energy harvesting [3,4]. Although different smart materials are available, review papers [1–4] show that piezoelectric materials and shape memory alloys (SMA) have received the most attention in aeronautical related applications. Piezoelectric materials can be used as sensors and/or actuators due to the direct and inverse piezoelectric effects, respectively. SMAs can be employed as an alternative to conventional actuators as well as provide energy dissipating and damping capabilities due to pseudoelastic hysteresis. In this work, particular attention is given to the use of nonlinear piezoelectric shunt circuits and pseudoelastic damping of SMAs to modify the aeroelastic behavior of elastic structures.

The nonlinear aeroelastic behavior of SMA fiber reinforced composite cantilevers subjected to simultaneous actions of thermal and aerodynamic loads has been investigated in the literature [5,6]. In another application of SMAs, Bachmann et al.

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[7] compare the effects of pseudoelastic hysteresis of SMA wires and piezoelectric shunt circuits for passive damping augmentation in open-rotor composite fan blade prototypes. Barzegari et al. [8] investigate the simultaneous use of piezoelectric actuators and embedded SMA wires (inducing in-plane loads) to improve the aeroelastic behavior of a cantilever wing. The effects of pseudoelastic hysteresis of SMA springs on post-critical aeroelastic oscillations of typical sections are also discussed in the literature [9–11].

The pioneering work on active aeroelastic wings using piezoelectric actuators was conducted by Crawley and his co-authors [12,13]. Later, the active control of dynamic aeroelastic phenomena was also demonstrated in the Piezoelectric Aeroelastic Response Tailoring Investigation (PARTI) [14] and in the Actively Controlled Response of Buffet Affected Tails (ACROBAT) [15]. Authors also investigated the effects of passive piezoelectric control (shunt circuits) on the aeroelastic behavior of a typical section [16] and also on the aeroelastic response of composite wings [17,18]. Although passive devices can effectively modify subcritical aeroelastic responses, they have a weak performance to improve the flutter boundary of the system. Since the frequencies involved in aeroelastic phenomena are typically low, the required inductances in passive aeroelastic control are extremely large and not practical.

The Synchronized Switching Damping (SSD) techniques [19–21] were developed in order to address some of the issues of passive damping methodologies. In the Synchronized Switch Damping on Inductor (SSDI) technique [20], the piezoelectric material is kept in open circuit condition except for a small period of time where voltage is inverted due to brief switch to an inductor. The nonlinear treatment of the electrical output of piezoelectric elements greatly improves the shunt damping effect of a host structure due to modified phase between voltage and structural velocity. Moreover, the required inductance is significantly smaller than that of resistive-inductive cases since it is adjusted according to the electrical resonance frequency. Therefore, the effects of the SSDI damping technique on the experimental aeroelastic behavior of a typical section [22] and also on the behavior of an elastic plate-like wing [23] were recently reported in the literature.

In this work, the concomitant effects of pseudoelastic hysteresis of SMAs and piezoelectric SSDI technique on the aeroelastic behavior of a two-degrees-of-freedom (2DOF) typical section are investigated. The governing aeroelastic equations are modified to include electromechanical coupling to the plunge DOF and SMA springs on the pitch DOF. Since the goal is to investigate the modified aeroelastic behavior, the model for SMA springs is based on Liang and Rogers [24] and the phase transformation kinetics is based on Brinson [25]. Although an ideal switch is assumed in the modeling of the SSDI technique, a new approach that accounts for the losses of a real switch circuit is presented, resulting in better agreement with experimental voltages (compared to the ideal modeling of an ideal switch usually found in the literature). The unsteady aerodynamic model follows [26] in order to model arbitrary motions. First, the individual effects of pseudoelastic hysteresis of SMAs and SSDI damping on the aerolastic behavior is briefly discussed. Although the effects of SSDI damping on the aeroelastic behavior of a typical section were experimentally investigated [22], a theoretical model and the analysis of parameters on the aeroelastic behavior have not been presented in the literature. Later, it is shown that the aeroelastic behavior is significantly modified due to the use of two different nonlinear mechanisms that results in enhanced damping of the aeroelastic system.

2. Model

A 2-DOF aeroelastic model is considered in this paper. Piezoelectric coupling, and consequently the switching circuit, will be modeled in the plunge DOF (adding electrical DOFs to the model). SMA helical springs will be modeled in the pitch DOF. Please note that piezoelectric coupling could be considered in the pitch DOF and SMA springs could be considered in the pitch DOF. Since the typical section is a coupled system (as will be discussed in next section), pitch and plunge motions are always present during flutter oscillations. This section first presents the model a 2-DOF typical section with linear steel springs that is later modified to include SMA springs and also electromechanical coupling. Later, the modeling of the SSDI technique developed in this work and the assumed SMA model (and both will be considered in the aeroelastic solution) are presented.

2.1. Piezoaeroelastic typical section model with SMA springs

A 2-DOF typical aeroelastic section is displayed in Fig. 1(a), where h and α denote the plunge and pitch displacements, respectively, b is the semichord length, x_α is the dimensionless distance from the elastic axis to the center of gravity (*e.a.* and CG in the figure), and U_∞ is the airflow speed. Please note that the typical section of Fig. 1(a) has a steel spring in the plunge DOF, where electromechanical coupling is also considered, and a torsion steel spring in the pitch DOF. The equations of motion are first presented considering steel springs on both DOFs. Later, the presence of a pair of SMA springs (replacing the torsion steel spring in pitch as displayed in Fig. 1(b)) and its effects on the pitch elastic restoring moment are also modeled.

The aeroelastic parameters are normalized by the airfoil length in the span direction, l. The spring constants per unit of span length are k_h (in the plunge DOF) and k_α (in the pitch DOF). The contribution of the piezoelectric element ("PZ" "in Fig. 1(a)) to the plunge stiffness is included in k_h. The aerodynamic pitch moment per unit length is M_α and the lift per unit length is L. Viscous damping is assumed in each DOF and represented by d_h and d_α (defined per unit length and omitted in the figure for clarity). In this paper, the elastic axis and the aerodynamic center (*a.c.* in the figure) are both located at the