Journal of Fluids and Structures 76 (2018) 592–605

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Mitigation of flutter vibration using embedded shape memory alloys

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HIGHLIGHTS

- A fluttering silicone plate with embedded shape memory alloy is tested.
- Vibrational response of the fluttering plate is observed over varying temperatures.
- Shifts in 3 different mode shapes of the plate captured and displayed in real time.
- Decrease in vibration amplitudes of 34–60% observed in the cantilevered plate.
- Embedded SMA wire successfully mitigates vibrational response of flutter.

ARTICLE INFO

Article history:
Received 5 January 2017
Received in revised form 7 September 2017
Accepted 26 September 2017
Available online 23 November 2017

Keywords:
Flutter
Aeroelasticity
Shape memory
Flat plate flutter
Flutter suppression
Elastomer plate
Fluid structure interaction

ABSTRACT

Aeroelastic flutter is a major concern for designers of planes, boats, turbines and other systems that experience aerodynamic loading. The typically undesirable phenomenon can cause aircraft instability, high cycle fatigue, excess noise, and in some cases catastrophic failure. This research aims to quantify the effect of embedded shape memory alloys (SMA) as an active suppression system to mitigate vibrations induced by aeroelastic flutter through an experimental investigation. A silicone plate with embedded SMA wire was designed. A subsonic wind tunnel was utilized to actuate flutter vibration. Control samples were created using the same dimensions and silicone material. One control sample contained embedded aluminum wire while the other sample contained no embedded material. Frequencies at the tip of the fluttering plates were calculated using a Fast Fourier Transfer (FFT) at varying temperatures. Experiments resulted in an average natural frequency shift of 44.6% at the sample tip upon actuation of the SMA material. Two dimensional vibrational scanning tests revealed three vibration modes in the fluttering flags. A first bending mode revealed a tip amplitude decrease of 34.4% upon actuation of the embedded SMA material. A second bending mode revealed a tip amplitude decrease of 33.6%. A torsional mode revealed a tip amplitude decrease of 60.7%. The frequency of the embedded aluminum wire sample remained relatively constant at low and high temperatures, leading to the conclusion that the frequency shift of the SMA sample was a result of the shape memory effect.

1. Introduction

Flutter is defined as the aeroelastic instabilities of a structure produced by the interaction of aerodynamic, inertial and elastic restoring forces (Bisplinghoff, 1955). The presence of flutter in any non-energy harvesting system is undesirable as

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https://doi.org/10.1016/j.jfluidstructs.2017.09.013
0889-9746/

the vibrations produced can create problems ranging from the tolerable to the catastrophic (Bir and Jonkman, 2007). The tolerable cases include the mild wing flutter experienced in passenger aircraft that can cause passenger and pilot discomfort. More severe cases can cause structures to suffer from high cycle fatigue and produce microfractures in materials. Severe cases of flutter cause catastrophic structural failure when the amplitude of the oscillations increase at an exponential rate. Examples of flutter can be seen in jet engine nacelles, energy harvesting and even as the driving effect of oronasal snoring (Huang, 1995). It is imperative for engineers to design structures to resist the actuation of flutter, with the government issuing specific standards for the critical flutter speed of airfoils and bridges.

The research presented herein seeks to quantify the effectiveness of using embedded shape memory alloy (SMA) as an active controller in the mitigation of flutter. SMA is a smart material that has been well studied with its large work capacity contributing to numerous applications ranging from thermal actuators to aerospace components (Jani et al., 2014; Huang, 2002; Schetky, 1991).

1.1. Flutter mitigation techniques

The design of any structure that encounters aerodynamic loading must include the consideration of aeroelastic flutter. Designing of a system that is structurally stable and resists flutter may also carry disadvantages such as increased weight or complicated and expensive design. Some aircraft designers simply create stronger lifting surfaces that are less stiff, causing flutter to occur at airspeeds below that required by government regulations (Hager et al., 1991). In this case, the avoidance of wing flutter requires the typically undesirable solution of reducing the maximum operating speed of the aircraft. In order to keep a design that is optimal and conforms to a desired structural property range, an active system must be used to mitigate flutter. Such a system would alter the structural properties and vibrational behavior of the design leading to an increase in the critical fluid flow speed required to induce flutter.

Current active flutter mitigation technology include systems aimed at induced blade twist. Servo-hydraulic actuators, embedded piezoelectric actuators (PZT) and active fiber composites have all been used to actuate a smooth and continuous twisting deformation along blades/rotors. Theoretical and experimental studies have shown that the induced blade twist results in a reduction in vibration (Giurgiutiu, 2000). Surface bonded piezoelectric actuators are also being heavily researched as a solution to flutter mitigation. An experiment by NASA Langley Research Center's Flutter Research and Experimental Device (FRED) included two 1.5 in. by 1 in. piezoelectric wafer actuators. The device was created in a wind tunnel and included a flexible mount system and a rigid wing. The flexible mount system measured plunge depth with two spring tines while pitch angle was measured with a single pitch spring. The two piezoelectric actuators were adhered to either side of the base of one of the spring tines. Upon activation of the actuators, a flutter speed increase of 20% was observed (National Aeronautics and Space Administration and Heeg, 1998). Another experiment implemented servo motors as delayed controllers to alter trailing edge properties of a fluttering wing. The experiment successfully increased the flutter actuation speed of the wing from 36.5 to 39 m/s (Huang et al., 2015). Experimental analyses of SMA wire embedded in elastomer beams where conducted in Garafolo and Collard (2017a). The beams underwent forced oscillations intended to simulate flat plate flutter. Actuation of the embedded SMA wire revealed a vibrational frequency shift from 13 to 17.91 Hz (44.7%) and a maximum amplitude displacement reduction from 292.5 to 192.1 μm (34%).

The selection of SMA materials involves the material's advantages in the areas of power consumption and work output. Piezoelectric actuators, a similar smart material, come with the disadvantages of high power consumption and low displacement ranges. SMAs thermal actuation properties may also lead to future use as a passive flutter mitigation actuator in high heat applications such as the early stages of a turbine engine.

1.2. Airfoil theory

The study of the flutter phenomenon acting on airfoils can be dated back to the first studied case of the horizontal tail on the Handley Page O/400 bomber in 1916 (Bisplinghoff, 1955). Investigations of these violent vibrations led to the discovery of two modes of oscillation which are typically studied in classical airfoil theory; a bending mode and a torsional mode about the pitch axis. When the coupled modes lose stability, the amplitude of oscillation increase significantly. This sudden increase in amplitude is what is known as flutter.

A classical flutter analysis of an airfoil can be executed using a free body diagram of an airfoil cross section which depicts the aerodynamic center, elastic axis, and center of gravity of body. The bending displacement with respect to the elastic axis, bending stiffness, torsional stiffness, deflection angle with respect to the elastic axis and dimensionless quarter chord must be identified. Two forces can be applied to the airfoil; a lifting force in the y direction and a bending moment, both located at the elastic axis. Equations of motion can be derived from a summation of forces as the uncoupled natural frequencies of the two modes. In linear systems, the amplitude of oscillation grows at an exponential rate until failure. In non-linear systems, the motion initially grows at an exponential rate, but may settle into limit cycle high amplitude oscillations. Details of this analysis can be found in Hodges and Pierce (2002).