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Influence of a hysteretic damper on the flutter instability

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ABSTRACT

The influence of a hysteretic damper on the airfoil flutter instability is investigated. In particular, its effect on the post-critical limit cycle oscillations (LCOs) is emphasized. For that purpose, an aeroelastic model including large amplitude motions and dynamic stall phenomenon, is considered for a rigid flat plate having two degrees of freedom in pitch and plunge motions. The hysteretic behaviour is modeled thanks to a generalized Bouc-Wen formulation. A parametric study of aeroelastic as well as hysteresis model parameters, allows one to draw a complete picture of the bifurcation scenario, highlighting the capacity of the hysteretic damper in precluding the occurrence of stall. The special case of shape memory alloy (SMA) springs is then used numerically and experimentally for controlling the flutter oscillations of a flat plate. The study reveals the ability of the SMA springs to drastically reduce the amplitudes of the LCOs caused by the flutter instability.

1. Introduction

Undesired mechanical vibrations are a major issue in many industrial applications. Multiple strategies exist to avoid them, depending on the type of vibration or the expecting operating range. This paper focuses on the control of the airfoil classical flutter instability. This phenomenon results from an interaction between two modes of the structure and an axial flow, which gives rise to strong or even fatal deformations. The flow velocity for which the instability arises is called flutter velocity. The goal of the control is then to increase the flutter velocity and reduce the amplitude of vibrations developing in the post-critical regime.

Flutter control is an important research topic in aeronautics. In the last decades, the most explored strategy to prevent flutter was to actively control the unsteady aerodynamic loads on the airfoil, see e.g. Karpel (1982), Ko et al. (1999), Vipperman et al. (1998), Dowell (2004). Nevertheless some studies have investigated passive control strategies, like the implementation of a nonlinear energy sink by Lee et al. (2007b), Lee et al. (2007a) acting on both modes of the wing or a tuned mass damper by Kwon and Park (2004) acting on a bridge deck.

In the present study, the passive control is realized by means of a hysteretic damper which consists of springs made of shape memory alloys (SMA) acting on the plunge motion. Indeed, in their pseudo-elastic regime, SMA are known to dissipate an important amount of energy due to the presence of an hysteresis loop in their stress-strain relationship, see e.g. Ould Moussa et al. (2012), Doaré et al. (2012).

Carpineto et al. (2014), Carboni and Lacarbonara (2015) have studied numerically and experimentally the dynamical behaviour of hysteretic damper partly made of SMA wires. These studies have shown promising results regarding the capacity of such damper to mitigate unwanted vibrations.

Besides the study of the SMA hysteretic behaviour, a particular attention is paid in this work on the estimation of the

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aerodynamic loads developing around the airfoil. Indeed, in the post-critical regime, the airfoil is subjected to large amplitude motions and a nonlinear approach must be considered to estimate the aerodynamic forces. Especially a phenomenon called *dynamic stall* arises for large amplitude motion as remarked by Amandolèse et al. (2013) or Razak et al. (2011). This phenomenon is estimated by means of a phenomenological model.

The use of hysteretic damper to mitigate the flutter instability has already been explored in previous studies. For example, Candido de Sousa and De Marqui Junior (2014) considered SMA springs acting on the airfoil pitch motion. They used a refined material modeling of the SMA behaviour in order to express the restoring force. However a linear model was used to describe the aerodynamic loads. Another investigation by Lacarbonara and Cetraro (2011) also used a hysteretic damper, however it was implemented as a vibration absorber, which means that an additional degree of freedom was added to the system. Preliminary results have also been reported by Malher et al. (2015b), Malher et al. (2015a). In this case, the SMA restoring force was estimated with a simple heuristic model, and the nonlinearity of the aeroelastic system by using cubic stiffness. The results presented in this study thus extend all the existing studies on the subject, by considering realistic aerodynamic nonlinear loads together with a versatile expression of the hysteretic damper, which is estimated by a generalized Bouc-Wen model.

The paper is organized as follows. In Section 2, the structural model used to describe the airfoil motion along with the aerodynamic forces estimation is presented. Then, in Section 3, the modeling of the dynamic restoring force of the SMA springs is established. In Section 4, an experimental set-up inspired from Amandolèse et al. (2013) is used to investigate the influence of the SMA springs on the flutter instability. Eventually, in Section 5, the complete numerical model is used to explore the influence of the aerodynamic loads and the SMA springs on the flutter instability.

2. Airfoil model and dynamic stall characterization

In this section, the equation of the aeroelastic system as well as the aerodynamic loads are established. A particular attention is paid to the nonlinear behaviour of aerodynamic forces, in order to derive a predictive model able to take into account dynamic stall.

2.1. Aeroelastic model

The classical pitch and plunge model is used to describe the airfoil motion (see e.g Dowell (2004) for more details). The plunge (resp. pitch) motion depicts the first flexural (resp. torsional) mode of the airfoil. Pitch and plunge are respectively described by the heave h and the angle of attack α as shown in Fig. 1, where EC refers to the elastic center, AC to the aerodynamic center and GC to the gravity center. U is the upstream flow speed, c the chord and b the mid-chord of the plate. The distance between AC and EC is denoted by e. K_h and D_h (resp. K_α and D_α) refer to the plunge (resp. pitch) stiffness and viscous damping. The inertia moment is denoted by I_α, the airfoil mass by m and the static moment by S_α. The static moment is proportional to the distance between GC and EC and is responsible of the coupling. The kinetic energy reads $\mathcal{T} = \frac{1}{2}m\dot{h}^2 + \frac{1}{2}I_\alpha\,\dot{\alpha}^2 + S_\alpha\cos(\alpha)\dot{h}\dot{\alpha}$, and the potential energy which comes from the pitch and plunge stiffnesses reads $\mathcal{V} = \frac{1}{2}K_\alpha\alpha^2 + \frac{1}{2}K_h h^2$. By means of a Lagrangian formulation, the equations of motion writes:

$$\begin{bmatrix} m & S_\alpha\cos(\alpha) \\ S_\alpha\cos(\alpha) & I_\alpha \end{bmatrix}\begin{bmatrix} \ddot{h} \\ \ddot{\alpha} \end{bmatrix} + \begin{bmatrix} D_h & 0 \\ 0 & D_\alpha \end{bmatrix}\begin{bmatrix} \dot{h} \\ \dot{\alpha} \end{bmatrix} + \begin{bmatrix} K_h & 0 \\ 0 & K_\alpha \end{bmatrix}\begin{bmatrix} h \\ \alpha \end{bmatrix} = \begin{bmatrix} -L + S_\alpha\sin(\alpha)\dot{\alpha}^2 \\ M \end{bmatrix}, \tag{1}$$

where $\dot{(\cdot)}$ denotes the time derivative. In equation (1), L is the lift and M the aerodynamic moment. The detailed expressions used for L and M, taking into account dynamic stall, are examined in the next section.

2.2. Dynamic stall

For small amplitudes, L and M are assumed to depend directly on an equivalent unsteady angle of attack $\alpha + \dot{h}/U$ (see e.g. Dowell, 2004). However as we are interested in the post-critical behaviour of the wing, the airfoil may encounter large amplitude motions. Thus nonlinearities have to be taken into account in the aerodynamic forces. Whereas a structural polynomial nonlinearity

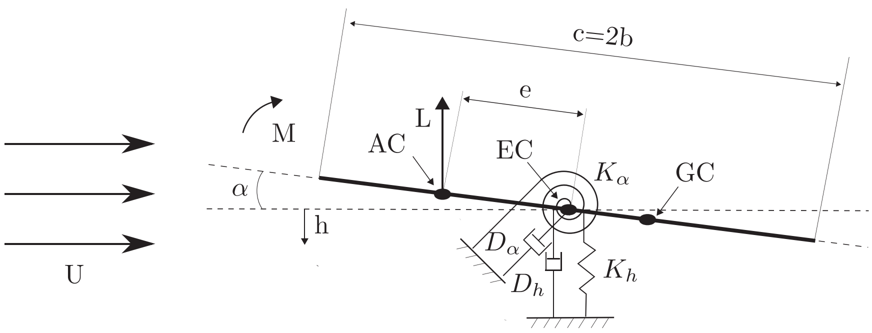

Fig. 1. Two degrees of freedom flat plate section model.