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Dynamic assessment of nonlinear typical section aeroviscoelastic systems using fractional derivative-based viscoelastic model

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ABSTRACT

Nonlinear aeroelastic systems are prone to the appearance of limit cycle oscillations, bifurcations, and chaos. Such problems are of increasing concern in aircraft design since there is the need to control nonlinear instabilities and improve safety margins, at the same time as aircraft are subjected to increasingly critical operational conditions. On the other hand, in spite of the fact that viscoelastic materials have already been successfully used for the attenuation of undesired vibrations in several types of mechanical systems, a small number of research works have addressed the feasibility of exploring the viscoelastic effect to improve the behavior of nonlinear aeroelastic systems. In this context, the objective of this work is to assess the influence of viscoelastic materials on the aeroelastic features of a three-degrees-of-freedom typical section with hardening structural nonlinearities. The equations of motion are derived accounting for the presence of viscoelastic materials introduced in the resilient elements associated to each degree-of-freedom. A constitutive law based on fractional derivatives is adopted, which allows the modeling of temperature-dependent viscoelastic behavior in time and frequency domains. The unsteady aerodynamic loading is calculated based on the classical linear potential theory for arbitrary airfoil motion. The aeroelastic behavior is investigated through time domain simulations, and subsequent frequency transformations, from which bifurcations are identified from diagrams of limit cycle oscillations amplitudes versus airspeed. The influence of the viscoelastic effect on the aeroelastic behavior, for different values of temperature, is also investigated. The numerical simulations show that viscoelastic damping can increase the flutter speed and reduce the amplitudes of limit cycle oscillations. These results prove the potential that viscoelastic materials have to increase aircraft components safety margins regarding aeroelastic stability.

1. Introduction

Modern aeroelastic systems may present nonlinearities and are subject to undesirable phenomena such as bifurcations, limit cycle oscillations (LCOs), and chaos [1]. It is known that nonlinear behavior, which can be induced by both structural and aerodynamic effects, are difficult to predict and are frequently associated with destructive structural responses [2]. For example, LCOs have caused persistent problems in many aircraft designs, such as the General Dynamics F-16 fighter [3]. In general, linear

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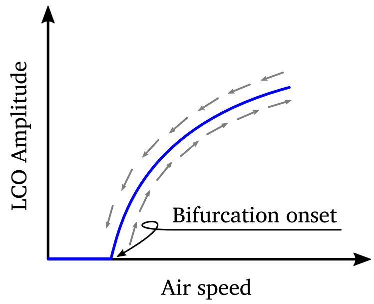

Fig. 1. Supercritical Hopf bifurcation typical of nonlinear aeroelastic systems.

models used for design are conservative and can comply with the requirements of stability safety margins even under the influence of nonlinear effects [4].

Among the sources of nonlinearities in aeroelastic systems, those of structural nature have been extensively studied by many authors during the last years. Concentrated nonlinear effects can be incorporated into numerical models through elastic restoring forces or moments. The traditional and well-understood types of concentrated nonlinearities are the hardening and softening springs [5], free-play [6] and hysteresis [7]. On the other hand, not as much is known about the fundamental mechanisms of damping and its impact on flutter and nonlinear aeroelastic responses [8]. Damping forces may also have a nonlinear relationship to the structural motion. As the derivation of accurate models is still a challenge, dissipation phenomena are usually oversimplified or represented empirically in aeroelastic models.

Bifurcation analysis indicates quantitative and qualitative changes in the system dynamics, such as the number and type of solutions, under the variation of one or more parameters [9]. Hopf bifurcation occurs when a nonlinear system response bifurcates to periodic equilibrium solutions such as LCOs. Fig. 1 depicts the classical Hopf bifurcation diagram for supercritical behavior. In general, if the system response is independent of the initial conditions and its stability changes only after the critical flutter velocity, the bifurcation is called supercritical.

LCOs can be associated with exceedingly large vibration amplitudes, which can provoke structural failure and penalize aerodynamic performance. Ideally, strategies for the improvement of aeroelastic stability margins must be used in early design phases, complying with certification requirements. However, it is not rare that corrective actions have to be undertaken in later phases as the result of unsatisfactory test results. In either situation, when compared to more sophisticated active techniques, aeroelastic passive control strategies are an appealing alternative due to inherent advantages related to simplicity, reliability, and cost.

In this sense, Lacarbonara and Cetraro [10] evaluated a visco-hysteretic vibration absorber introduced as an auxiliary single-degree-of-freedom system to improve the aeroelastic behavior of an airfoil in the pre- and post-flutter regimes.

Viscoelastic materials have long been used to mitigate noise and vibration in many types of mechanical structures, including machinery, automobiles, aircraft and civil engineering constructions [11]. However, only recently have those materials been considered for passive aeroelastic control. The first investigations have been reported in Refs. [12–15]. In fact, Hilton and collaborators seem to have been the first to use the term aeroviscoelasticity to describe the study of aeroelastic systems containing viscoelastic materials.

More recently, some studies have been devoted to the use of viscoelastic materials for panel flutter control under supersonic conditions [16,17]. In addition, Martins et al. [18] have addressed flutter control of typical section models under subsonic flow, presenting experimental results and validation of numerical models. All those contributions, which have been limited to linear aeroelastic systems, have confirmed the possibility of improving the aeroelastic behavior, especially in terms of increase of flutter speed, by exploring the viscoelastic behavior. However, the authors are unanimous in recognizing that the strong influence of temperature on the mechanical characteristics of viscoelastic materials is a factor that must be properly dealt with.

In the present paper, the authors present an investigation on the influence of viscoelastic damping to the aeroelastic behavior of a three-degrees-of-freedom typical section with hardening structural nonlinearities in pitch and control surface spring stiffness. This work provides further contributions to evaluate, both qualitatively and quantitatively, the benefits and shortcomings that can be engendered by viscoelastic materials in terms of nonlinear aeroelastic behavior. The formulation underlying the modeling of nonlinear aeroviscoelastic systems is developed for a typical section model, where the aerodynamics is represented by a linear state-space approximation from Theodorsen's method, and the viscoelastic constitutive model is based on fractional derivatives. Particular emphasis is devoted to the numerical procedures developed and implemented for the resolution of the equations of motion of the aeroviscoelastic system. Differently from linear aeroelastic systems, for which the aeroelastic behavior can be fully characterized by eigenvalue analysis to attain the onset of flutter instability, for nonlinear aeroelastic systems the post-critical behavior is also of utmost importance. Therefore, adequate theoretical framework