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Numerical and experimental investigation of aeroviscoelastic systems

Polliana C.O. Martins [a], Thiago A.M. Guimarães [b], Daniel de A. Pereira [c], Flávio D. Marques [d], Domingos A. Rade [e,*]

[a] Federal Institute of Education, Science and Technology of Goiás - Campus Valparaíso, Valparaíso, GO, Brazil
[b] Federal University of Uberlândia, Uberlândia, MG, Brazil
[c] Technological Institute of Aeronautics, São José dos Campos, SP, Brazil
[d] University of São Paulo, São Carlos School of Engineering, São Carlos, SP, Brazil
[e] Technological Institute of Aeronautics, Division of Mechanical Engineering, Praça Mal. Eduardo Gomes 50, 12.228-900 São José dos Campos, SP, Brazil

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ABSTRACT

Viscoelastic materials have been widely used for the purpose of passive vibration mitigation in various types of mechanical systems, including, industrial machinery, civil structures and vehicles. In this paper, the use of those materials in aeroelastic systems is investigated, with emphasis placed on the influence of the viscoelastic behavior on the flutter speeds of two-degree-of-freedom typical section models, in which viscoelastic elements are introduced in addition to elastic elements associated to heave and pitch motions. The equations of motion of the aeroelastic system are modified to account for the dependence of the viscoelastic behavior on frequency and temperature, by using the concepts of complex modulus and shift factor. The aerodynamic forces and moments in subsonic regime are modeled according to Theodorsen's method. Numerical simulations are conducted to evaluate the influence of the addition of viscoelastic elements on the flutter speed and elucidate the separated influences of stiffness and damping additions. An experimental wind tunnel setup consisting of a rigid wing supported by flexible elements in pitch and plunge motions has been modified to enable the introduction of viscoelastic elements in parallel to those flexible elements. For various configurations of viscoelastic additions, the flutter instability is characterized from vibration measurements performed for increasing flow speeds in the vicinity of the stability boundary. The experimental results are used to validate the numerical model derived for the aeroviscoelastic system and confirm both qualitatively and quantitatively the predictions of the simulations, especially the possibility of increasing the flutter speed by the inclusion of viscoelastic materials.

1. Introduction

To face the necessity of increased safety margins and improved load bearing effectiveness, techniques intended for the control of aeroelastic instabilities, especially flutter, have received a great deal of attention from the aerospace community

* Corresponding author.
E-mail address: rade@ita.br (D.A. Rade).

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lately. The techniques conceived for this purpose can be grouped into three main categories, namely: i) passive approaches, understood as those which do not require any input of external energy, such as the use of energy dissipation devices (viscous and friction dampers, for example); ii) active approaches, which are primarily based on the application of control forces, most often calculated from response signals and applied through actuators; the operation of these later require external energy; iii) semi-active approaches, in which actuation is exerted to modify some physical features of an inherently passive system. A comprehensive historic and scientific survey of a large number of research programs devoted to aeroelastic control up to 2004 is provided in Ref. [1].

Active control approaches have received a great deal of attention lately. Among the early works, the one by Nissim [2] described the general energy principle upon which active flutter suppression is based. Based on Nissim's theory, Sandford et al. [3] carried out experiments that demonstrated the concept of active flutter suppression on a delta wing. Since then, many other contributions have been devoted to active flutter control; many of them have been appraised by Librescu and Marzocca [4].

Active flutter control has gained great impulse as the result of the emergence of the so-called smart materials, which made possible the conception of novel sensor and actuator configurations, which can be fully integrated to aeroelastic systems. The report by Weisshaar and Rotea [5] provides fundamental understanding of integrated aeroservoelastic design when active materials are used as actuators to control the deformation of lifting surfaces. The study focus on the actuator material selection, the development of finite element models and optimization techniques to determine the conditions for optimal actuator configurations. Also, the research examines the conditions for the effective integration of control estimation theory into aeroelastic systems incorporating active materials.

Giurgiutiu [6] reviews, up to 2000, the achievements in the application of smart material actuators to counteract aeroelastic and vibration effects in helicopters and fixed wing aircraft. A variety of experiments of active flutter control, buffet suppression, gust load alleviation, and sonic fatigue reduction are discussed.

Scott and Weisshaar [7] examine the use of piezoelectric materials and shape memory alloys to control the flutter dynamic pressure of a flat, simply supported rectangular panel with one surface immersed in a supersonic flow. Two strategies are followed: in the first, piezoelectric actuators are used for active control based on a LQR feedback control law; in the second, which can be considered as a semi-active approach, piezoelectric and SMA actuators are electrically and thermally activated, respectively, to induce in-plane forces to increase the panel out-of-plane stiffness and, as a result, to control the flutter speed.

As compared to studies devoted to active aeroelastic control approaches, few works have explored passive or semi-active techniques. Reed et al. [8] introduce the concept of decoupler pylon for the aeroelastic control of aircraft having external stores. The pylon dynamically isolates the wing from the store pitch inertia effects by means of spring-damper elements assisted by a feedback control systems. This concept is validated by wind tunnel tests.

Viscoelastic materials have long been successfully used for the mitigation of vibrations in various types of mechanical systems, such as buildings, automobiles, airplanes and industrial equipment [9,10]. The main advantages provided by such strategy are the inherent stability, typical of passive control approaches, and moderate installation and maintenance costs. However, the viscoelastic behavior entails some modeling and characterization difficulties, especially due to the dependence of the dynamic behavior of those materials with respect to a number of operational and environmental factors, among which the vibration frequency and temperature are the most relevant [11]. As a result, specialized models and experimental procedures are necessary for the accurate prediction and characterization of dynamic systems containing viscoelastic materials.

Given the advantages of using viscoelastic materials for the attenuation of vibrations in the scope of structural dynamics, it would seem natural to consider the use of those materials for passive aeroelastic control. However, few research works addressing this possibility have been reported in the literature.

In the work of Lacarbonara and Cetraro [12], a visco-hysteretic vibration absorber (VA) is introduced as an auxiliary single-degree-of-freedom vibrating system to increase the flutter speed of an airfoil and enhance damping in the pre- and post-flutter regimes. The device consists of a parallel arrangement of a dashpot and a hysteretic element, represented by the Bouc-Wen differential model.

Notable contributions to the study of the aeroelastic behavior of viscoelastic panels and highly flexible aircraft have been given by Prof. Harry Hilton and collaborators [13]. It seems, by the way, that these authors coined the terms *aero-viscoelasticity* and *aero-servo-viscoelasticity* that are adopted in the present paper.

More recently, Martins [14] and Martins et al. [15], developed typical-section aeroviscoelastic models and investigated numerically the influence of viscoelastic material introduced into the model suspension on the flutter speed, also examining the influence of temperature.

Cunha Filho et al. [16,17] and present studies involving the application of surface viscoelastic damping treatments to cope with panel flutter in supersonic regime. According to the authors, the results show that it is possible to increase the critical flutter speeds by using surface viscoelastic damping treatments. They also conclude that the temperature and the thicknesses of the layers have significant effect on the flutter boundaries.

The scope of the previously mentioned papers is confined to theoretical foundations and numerical simulations most of them considering panel flutter in supersonic regime. Aiming at providing further contributions to the study of aero-viscoelastic systems, in the present paper the authors investigate, both numerically and also experimentally, the influence of viscoelastic damping on the flutter speeds of a typical section model of two degrees-of-freedom (pitch and heave motions),