Mechanical Systems and Signal Processing 116 (2019) 900–915

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Modeling and dynamic characterization of nonlinear non-smooth aeroviscoelastic systems

Thiago de P. Sales [a,*], Daniel A. Pereira [a], Flávio D. Marques [b], Domingos A. Rade [a]

[a] Division of Mechanical Engineering, Aeronautics Institute of Technology (ITA), Brazil
[b] São Carlos School of Engineering, University of São Paulo, São Carlos, Brazil

ARTICLE INFO

Article history:
Received 29 September 2017
Received in revised form 2 June 2018
Accepted 1 July 2018

Keywords:
Nonlinear aeroelasticity
Typical section model
Free-play
Viscoelasticity
Subcritical bifurcation
Limit cycle oscillation

ABSTRACT

In this work, viscoelastic materials are adopted for handling aeroelastic features of typical section models with three degrees-of-freedom, which present non-smooth, free-play type nonlinearities in their control surface. A rotational viscoelastic damper is added to the resilient element associated to the control surface motion of the typical section. Equations of motion are derived accounting for the viscoelastic damper dependence on frequency and temperature. For this, a fractional derivatives-based viscoelasticity constitutive law is considered. Aerodynamic forces are introduced based on linear potential unsteady aerodynamics accounting for arbitrary airfoil motions. The aeroelastic behavior is investigated through time domain simulations, from which bifurcation diagrams are constructed. Numerical results show that the addition of viscoelastic damping can increase the flutter speed noticeably and reduce the amplitudes of limit cycle oscillations for the system under consideration. Another observed benefit provided by the viscoelastic damper is that undesirable subcritical behavior for the bifurcation onset can be eliminated or modified to have a supercritical character. The influence of temperature on the aeroviscoelastic behavior is also investigated. Using the proposed strategy, nonlinear instabilities can be controlled, improving the safety margins of aeroelastic systems.

1. Introduction

Aeroelastic systems may present nonlinearities that lead to undesirable behavior such as bifurcations, limit cycle oscillations (LCOs), and chaos [1,2]. Nonlinear behavior may be originated from either the structural dynamics or the unsteady aerodynamic effects [3] and linearized models used for aircraft design typically fail to predict problems under the influence of nonlinear effects.

Structural nonlinearities have been widely investigated due to their frequent occurrence in a variety of mechanical systems. They occur due to many circumstances such as large structural deflections, material behavior, partial loss of structural integrity and clearances in links or joints. Concentrated nonlinear effects, the most well-known type of structural nonlinearities, 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 – which can be approximated by polynomial functions –, free-play, and hysteresis [4]. However, the fundamental mechanisms of damping and its impact

* Corresponding author.
E-mail address: tpsales@ita.br (Thiago de P. Sales).

https://doi.org/10.1016/j.ymssp.2018.07.003
0888-3270/

on instability and nonlinear aeroelastic responses are still not fully known [5]. The internal damping forces may also have a nonlinear relationship to the structural motion, thus leading to a greater modeling challenge [6,7]. For instance, even for the case in which linear viscous and non-viscous damping models are considered, identification procedures have usually been adopted to overcome the lack of prior knowledge [8,9].

Aircraft control surfaces frequently involve complex drive mechanisms, making it almost impossible to avoid some kind of free-play or other concentrated nonlinearities. Several types of aircraft have experienced self-sustained LCOs as a result of control surface free-play. According to Dowell et al. [3], the effects of free-play represent a real concern for the industry. Croft [10] has reported the concern of the airworthiness certification authorities with self-excited LCOs as a result of free-play in the flaps and ailerons of the Airbus aircraft series. As consequence of that concern, the Federal Aviation Administration (FAA) requested modifications to the control surface systems of the A319, A320 and A321 aircraft, as well as the creation of a new directive for operators to measure elevator free-play every 18 months. Therefore, it is clear the importance of studying and improving engineering tools to model and analyze the nonlinear behavior of systems presenting free-play.

The effect of unstable LCOs and other problems due to the free-play in control surface hinges have been reported by a great number of researchers. From experimental tests, Trickey et al. [11] have associated free-play nonlinear effects with transitions from damped motion, to periodic LCOs, to quasi-periodic aeroelastic responses, and then to chaotic motions. Vasconcellos et al. [12] have shown that the use of hyperbolic tangent functions to represent discontinuous nonlinearities is appropriate for detecting different nonlinear responses, including experimentally observed LCOs, chaos and transitions.

During the design of an aeroelastic system, it might be a requirement to improve stability margins and reduce LCO amplitudes related to flutter conditions and avoid the appearance of subcritical behavior, which is known to be associated with free-play nonlinearity [13,14]. Subcritical and supercritical systems are properly investigated through bifurcation analysis, which 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 [15]. When a nonlinear system bifurcates to periodic solutions such as LCOs, the phenomenon is called a Hopf bifurcation. In general, if the system depends on the initial conditions and has different solutions when the air velocity is increased and decreased near the nonlinear critical velocity, the bifurcation is called subcritical, i.e., LCOs may also exist below the flutter boundary. However, if the system is independent of the initial conditions and its stability changes only after the critical flutter velocity, the bifurcation is called supercritical. As an example, Magri and Galvanetto [16] have investigated a non-smooth Hopf bifurcation in an aeroelastic system while considering the Leishman–Beddoes semi-empirical nonlinear dynamic stall model. In another study, Kalmár-Nagy et al. [17] performed a nonlinear analysis of a two degree-of-freedom typical section aeroelastic system, taking into account a bilinear relationship between aerodynamic loads and the effective angle of attack of the airfoil. Results obtained by those authors, including bifurcation diagrams and phase portraits, showed rich dynamic behavior, in the form of discontinuity-induced bifurcations, as well as transition towards chaotic behavior.

Viscoelastic materials have already been proven as a viable solution for several vibration-related engineering problems [18]. These materials combine the behavior of elastic solids and Newtonian fluids, in the sense that they not only store, but also dissipate energy in a passive manner. However, their application requires carefulness, since the material properties are dependent on several environmental and operational conditions. These encompass, among others, temperature, frequency, and static pre-load [6]. Several modeling strategies have been put forward for the design and prediction of complex viscoelastic damping effect in engineering systems [19]. For passive control of flutter, the use of passive strategies has been investigated in the literature. Lacarbonara and Cetraro [20] proposed a visco-hysteretic vibration absorber to increase the flutter speed and to improve the damping in the pre- and post-flutter regimes of a one degree-of-freedom typical section. Many of the first contributions to the study of the aeroelastic behavior of panels containing viscoelastic materials have been given by Hilton and collaborators [21,22]. It seems, by the way, that those authors were the first to use the term aeroviscoelasticity. Martins et al. [23] performed experimental and numerical analyses of two degrees-of-freedom typical section presenting viscoelastic damping in pitch and plunge motions, revealing that viscoelastic materials can increase considerably the flutter speed. Other authors have reported the use of viscoelastic damping treatments to control panel flutter in supersonic regime [24]. Despite their contributions, these studies have been limited to cases of linear aeroelastic systems. Only more recently have viscoelastic dampers been considered as an alternative to improve the onset of LCOs and reduce their amplitudes in aeroelastic systems containing a smooth nonlinearity [25].

Based on the previous introductory discussion, the use of viscoelastic materials for mitigating undesired aeroelastic responses when free-play nonlinearity is included in control surface hinges is assessed in this work. To perform investigations, a typical aeroelastic section model including plunge, pitch, and control surface motions is adopted. The free-play nonlinearity is introduced in the control surface hinge and accounted for through an approximation based on hyperbolic tangent functions. A viscoelastic damper is installed in the control surface hinge and its contributions to the equations of motion result from considering a constitutive law based on fractional derivatives [26]. For dealing with unsteady aerodynamic loads, the classical Theodorsen's theory, accounting for arbitrary airfoil motions, is adopted. While these modeling strategies are reviewed in Section 2, results and discussion of numerical simulations are provided in Section 3. Concluding remarks are finally presented in Section 4.