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Research paper

Nonlinear aeroelastic analysis of an airfoil-store system with a freeplay by precise integration method

Y.M. Chen*, J.K. Liu

Department of Mechanics, Sun Yat-sen University, 135 Xingang Road West, 510275 Guangzhou, China

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ABSTRACT

The aeroelastic system of an airfoil-store configuration with a pitch freeplay is investigated using the precise integration method (PIM). According to the piecewise feature, the system is divided into three linear sub-systems. The sub-systems are separated by switching points related to the freeplay nonlinearity. The PIM is then employed to solve the sub-systems one by one. During the solution procedures, one challenge arises when determining the vibration state passing the switching points. A predictor-corrector algorithm is proposed based on the PIM to tackle this computational obstacle. Compared with exact solutions, the PIM can provide solutions to the precision in the order of magnitude of 10^{-12}. Given the same step length, the PIM results are much more accurate than those of the Runge–Kutta (RK) method. Moreover, the RK method might falsely track limit cycle oscillations (LCOs), bifurcation charts or chaotic attractors; even the step length is chosen much smaller than that for the PIM. Bifurcations and LCOs are obtained and analyzed by the PIM in detail. Interestingly, it is found that multiple LCOs and chaotic attractors can exist simultaneously. With this magnitude of precision and efficiency, the PIM could become a solution technique with excellent potential for piecewise nonlinear aeroelastic systems.

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1. Introduction

The aeroelastic system of an airfoil is one of the typical self-excited oscillators. The airfoil may continue vibrating stably or unstably by extracting energy from the wind. Due to the nonlinearities resulting from structural stiffness and/or aerodynamics, flutter is usually characterized by motions with certain amplitudes, i.e., limit cycle oscillation (LCO). A LCO can be classified as supercritical due to a supercritical Hopf bifurcation or as subcritical due to a subcritical bifurcation. One category of research dealing with airfoil flutter was based on a so-called typical section with two-dimensional aerodynamics (Lee et al., 1999a, 1999b; Coller and Chamara (2004)). This model usually has two structural degrees-of-freedom (dofs), i.e., the plunge and the pitch. In these studies, the subsonic aerodynamics acting on an airfoil was usually modeled by steady/quasi-steady or unsteady flow, and the aerodynamics acting on the airfoil can be explicitly expressed. Another kind of research focused on developing CFD/CSD coupling techniques to solve nonlinear flutter problems directly, in which the aerodynamics are numerically computed coupled with structural motions (Hall et al., 2000; Thomas et al., 2004; Dowell and Tang, 2002).

* Corresponding author. Tel.: +86 2084114211; fax: +86 2084114212.
E-mail address: chenyanmao@hotmail.com (Y.M. Chen).

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Quantitative research on LCOs via analytical or semi-analytical techniques has been an active area for many years (Lee et al., 1999a). Overall, there are two categories of solution approaches for the nonlinear equations. The time domain method is to use integration techniques to generate transient responses numerically for a long time based on state space equations, and then to extract a LCO solution in one approximate period when steady responses are reached. The other approach is called the frequency domain method, which usually involves seeking a LCO solution using truncated Fourier series with unknown coefficients.

Numerical techniques based on time domain analysis mainly include the finite difference scheme (Lee and LeBlanc, 1986), the Runge–Kutta (RK) integration method (Lee et al., 1998), and the cyclic method (Beran and Lucia, 2005). As exact solutions are generally not evident, the RK method was widely applied as the benchmark for comparison. At the early stage, the analytical or semi-analytical analysis was primarily based on the describing function technique, the harmonic balancing technique (Lee et al., 1999a), etc. Lee et al. (1997) obtained a purely analytic solution of a nonlinear aeroelastic equation subject to a sinusoidal external excitation. During the past decade, several methods were developed for nonlinear aeroelastic analysis, such as the high dimensional harmonic balance method (Liu et al., 2007), the incremental harmonic balance method (Chen et al., 2012a), the reduced cyclic method (Beran and Lucia, 2005), and the homotopy analysis method (Chen and Liu, 2008), to mention a few.

Note that the above studies modeled the considered nonlinearities as continuous and smooth functions, usually as lumped ones. In order to analyze discontinuous nonlinearities such as bilinear and piecewise stiffness, the point transformation method (Liu et al., 2002) and the incremental-perturbation method (Chung et al., 2007, 2009) were developed, respectively.

Generally speaking, there should be a criterion for judging whether the breathing crack opens or closes during numerical simulations. The criterion will lead to an unavoidable switching point. It is worth noting that a troublesome problem in a freeplay model lies in determining switching points (Lin and Cheng, 1993; Conner et al., 1997). Lin and Cheng (1993) found that an entirely incorrect asymptotic behavior can occur due to an error in tracking the switching point in the RK method. Significant discrepancies between the exact motion and the numerical solution may sometimes be observed. Though the switching point can be approximated very accurately as the step length is chosen refined enough, the computational cost is sometimes too high, even unacceptable under some working conditions such as real time structural health monitoring or damage detection. Therefore, it is worth proposing some more efficient approaches to tackle this problem.

The precise integration method (PIM) was initiated by Zhong and Williams (1994) and Zhong (2004) two decades ago. The most outstanding merit of PIM lies in its high precision and efficiency. Theoretically, it can even reach computer precision with an acceptable amount of computational resources. It has been developed and applied in various problems such as dynamical systems, wave propagation, optimal control, structural mechanics, electro-magnetic wave guide problems (Wang, 2011), bio-medical engineering problems (Lin et al., 2013), and soil mechanics (Huang et al., 2007). It can be applied not only to initial-valued problems but also to boundary-valued problems (Zhang and Huang, 2013).

Aeroelastic systems with a freeplay have stimulated the curiosity and interest of many aeroelasticians (Liu and Dowell, 2005; Marsden and Price, 2005; Firouz-Abadi et al., 2013; Li et al., 2012). As is well known, the PIM is very suitable for linear initial-valued problems. We are motivated by its high precision and efficiency to apply this technique in an aeroelastic system with a freeplay. In this study, we will propose an effective algorithm, based on the PIM, to precisely simulate the nonlinear aeroelastic responses of an airfoil-store configuration with piecewise pitch stiffness.

2. Equations of motions

Fig. 1 shows the physical model of a two-dimensional airfoil with an external store. The airfoil oscillates in pitch and plunge degrees-of-freedom (dofs). The pitch angle about the elastic axis (E), denoted by α, is positive with the nose up; the plunge deflection denoted by h is positive in the downward direction. The external store is located at a distance $\bar{L}b$ from the mid-chord. Its motion is modeled as a varying pitch angle (β) about F, called the store dof. The span length of the airfoil is assumed as a unit, the mid-chord length as b and the wind speed as V. The elastic axis is located at a distance ab from the mid-chord, while the mass center (G) is located at a distance $x_\alpha b$ from the elastic axis. The distance from the mass center of the external store to the aerodynamic center is denoted as $x_\beta b$. All the distances such as ab, $x_\alpha b$ and $x_\beta b$ are positive when measured towards the trailing edge of the airfoil.

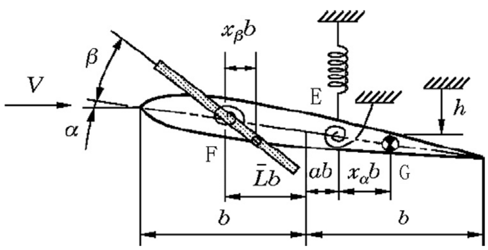

Fig. 1. Sketch of an airfoil with an external store.

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