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Nonlinear aeroelastic analysis of an airfoil with control surface free-play using stochastic approach

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ABSTRACT

In this study the nonlinear aeroelastic of an airfoil with control surface free-play nonlinearity was analyzed using a stochastic approach. An unsteady aerodynamic flow based on the Theodorsen function was applied to model the aerodynamic load and moments. Using the stochastic approach, response variance against flow speed was analyzed where the flow speed of the maximum variance was taken as flutter speed. The results show that the effect of free-play nonlinearity on the decrement of the flutter speed is considerable if the flutter of the corresponding linear system is due to the flap motion instability. Moreover, the response variance of the nonlinear system experienced the flip bifurcation and chaos before the linear flutter speed and left the chaos through an intermittency road and tangent bifurcation. This tangent bifurcation led to jump phenomenon and abrupt change in response variance and was thus regarded as the nonlinear flutter speed. Tackling the challenge of aeroelastic analysis with free-play nonlinearity based on the stochastic approach is novel. We demonstrate that this approach is an efficient method which provides a better vision of types of bifurcation, chaos and jump phenomenon.

1. Introduction

Flutter Analysis of aeroelastic systems is one of the important issues which absorb a lot of researches in the recent decades. In the aeroelastic system, structural and aerodynamic loads interact and this mutual interaction may lead to flutter in some flight conditions. However if the aeroelastic system is nonlinear, some phenomena such as abrupt bifurcation, limit cycle oscillation and chaos may arise (Vasconcellos et al., 2014). One of the most significant nonlinearity in the aeroelastic systems is free-play, which plays an important role in the onset of flutter (Asjes et al., 2014).

The free-play nonlinearity is very common when the aeroelastic system is equipped with a control surface such as trailing edge flap or aileron in a wing (Borglund and Kuttenkeuler, 2002). The free-play nonlinearity arises from worn hinges and loosening of attachments (Vasconcellos et al., 2012) and produces a piecewise linear change in the structural stiffness of the control surface (Conner et al., 1997), i.e. within the free-play region the control surface experiences essentially no stiffness and outside the free-play region the stiffness is linear with a constant stiffness coefficient (Asjes et al., 2014).

There are semi-analytical and numerical methods which are used for the flutter analysis of nonlinear aeroelastic systems with free-play nonlinearity. Describing function (Bae et al., 2004; He et al., 2016; Yang et al., 2016), time–frequency (Dimitriadis and Cooper, 2003), harmonic balance (Liu and Dowell, 2005), Poincaré map (Zhao De-Min, 2010), perturbation (Dessi and Mastroddi, 2004), center manifold, Hénon (Conner et al., 1997) and time marching integration methods (Firouz-Abadi et al., 2013; Pereira et al., 2016) are of the main approaches which have used to investigate the aeroelastic systems

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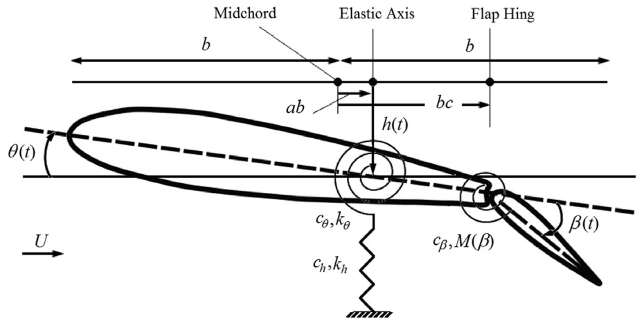

Fig. 1. Schematic model of an airfoil with flap.

with freeplay nonlinearity. However some of these approaches such as harmonic balance and describing function methods do not permit a full exploration of the effect of free-play nonlinearity (Conner et al., 1997). Some of them, like center manifold reduction, have serious limitations for treating the free-play nonlinearity (Grzędziński, 2005). The Hénon method requires multiple time integration and leads to a time consuming approach (Vasconcellos et al., 2012). Moreover the numerical continuation which uses the branch following procedure may also fail to analyze such systems due to very complex LCO behavior (Cavallaro et al., 2015; Chen and Liu, 2014; Cui et al., 2015; Grigorios, 2011).

The free-play nonlinearity can be modeled as piecewise linear function. Therefore another major problem for utilizing the mentioned methods during the analysis of the system with free-play nonlinearity, lies in determining the switching point (Chen and Liu, 2014). To tackle this computational obstacle some researchers used a predictor–corrector algorithm to identify the switching point (Chen and Liu, 2014; Cui et al., 2015). They also divided the system into three linear sub-systems and employed the precise integration method to solve the sub-system one by one. Another approach for overcoming the switching point problem is to approximate the free-play nonlinearity with the polynomial expansion, hyperbolic tangent representation or third-order rational function. In some cases these approximations especially the polynomial expansion may lead to imprecise results (Vasconcellos et al., 2012).

One of the latest approaches proposed for analyzing the aeroelastic system is the stochastic approach. In this method, apart from the aerodynamic lift and moment deduced from the aerodynamic theories, one Gaussian white noise is also added to the lift force. The flutter speed is obtained by investigating the variation of the response variance against the air speed. The maximum of the response variance represents the flutter speed (Irani and Sazesh, 2013). Adding a noise with constant spectral density to the lift force provides an opportunity to use the capability of random vibration analysis in aeroelastic system. In aeroelastic system the flow speed affects the dynamics of system and this affection is reflected in the response variance. Therefore, the dynamics of system can be investigated using the response variance.

This stochastic approach was shown to be applicable to nonlinear aeroelastic systems with cubic nonlinearity (Irani et al., 2016). Therefore the main goal of this study is to evaluate the stochastic approach in dealing with the free-play nonlinearity. In this regard, a three degrees of freedom airfoil with control surface free-play nonlinearity under an unsteady incompressible flow is investigated by the stochastic approach. The response variance of the system versus the flow speed, shows a jump phenomenon and a tangent bifurcation before the linear flutter speed. This bifurcation is a sudden onset of destructive instability and regarded as nonlinear flutter speed. The stochastic approach needs no guess for initial conditions and has no limitation for identification of switching point. The achieved results show that the stochastic approach is an efficient method to tackle the aeroelastic problems with free-play nonlinearity. Also it provides a better vision of the intermittency and chaotic behaviors of the system. The main limitation of using stochastic approach is for systems with strong nonlinearities because the statistical linearization is not accurate for systems with severe nonlinearities.

2. Aeroelastic model

The aeroelastic model is a three degrees of freedom airfoil with plunge, pitch and control surface (flap) angle which are denoted by h, θ and β respectively (Fig. 1). The chord and semi-chord of the airfoil are, respectively, denoted by c and b. The dimensionless parameter, a, determine the location of elastic axis from the mid-chord.

The aeroelastic equations of motion can be written as follows (Dessi and Mastroddi, 2004)

$$\begin{cases} m\ddot{h} + S_\theta\ddot{\theta} + S_\beta\ddot{\beta} + c_h\dot{h} + k_h h = L \\ S_\theta\ddot{h} + I_\theta\ddot{\theta} + \left(I_\beta + b\,(c-a)\,S_\beta\right)\ddot{\beta} + c_\theta\dot{\theta} + k_\theta\theta = M_\theta \\ S_\beta\ddot{h} + \left(I_\beta + b\,(c-a)\,S_\beta\right)\ddot{\theta} + I_\beta\ddot{\beta} + c_\beta\dot{\beta} + M\,(\beta) = M_\beta, \end{cases} \tag{1}$$

where m is the airfoil mass, S_θ and S_β are the static moments of the airfoil and flap, k_h and k_θ are the translational and torsional stiffnesses,c_h is translational damping, c_θ and c_β are rotational dampings of airfoil and flap, I_θ and I_β are the moments inertia of the airfoil and flap, respectively. $M\,(\beta)$ denotes the restoring torque of the flap. The free-play nonlinearity can be modeled as a piecewise linear function (Fig. 2).