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Subcritical, nontypical and period-doubling bifurcations of a delta wing in a low speed wind tunnel

Banu Korbahti [a], Emile Kagambage [b], Thomas Andrianne [b], Norizham Abdul Razak [b], Grigorios Dimitriadis [b,]*

[a] Engineering Faculty, Department of Mechanical Engineering, Istanbul University, Turkey
[b] Aerospace and Mechanical Engineering Department, University of Liège, Belgium

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ABSTRACT

Limit Cycle Oscillations (LCOs) involving Delta wings are an important area of research in modern aeroelasticity. Such phenomena can be the result of geometric or aerodynamic nonlinearity. In this paper, a flexible half-span Delta wing is tested in a low speed wind tunnel in order to investigate its dynamic response. The wing is designed to be more flexible than the models used in previous research on the subject in order to expand the airspeed range in which LCOs occur. The experiments reveal that this wing features a very rich bifurcation behavior. Three types of bifurcation are observed for the first time for such an aeroelastic system: subcritical bifurcations, period-doubling/period-halving and nontypical bifurcations. They give rise to a great variety of LCOs, even at very low angles of attack. The LCOs resulting from the nontypical bifurcation display Hopf-type behavior, i.e. having fundamental frequencies equal to one of the linear modal frequencies. All of the other LCOs have fundamental frequencies that are unrelated to the underlying linear system modes.

1. Introduction

Nonlinear aeroelasticity is a research area that has attracted a lot of interest in recent years. Increases in computational power and improvements in simulation methods, coupled with a willingness to address novel aeroelastic problems have rendered investigations of nonlinear phenomena quite popular within the research community. The most important phenomena arising from the presence of nonlinearity in aeroelastic systems are Limit Cycle Oscillations (LCO), which are self-induced oscillations at constant or approximately constant amplitude. The vast majority of the work carried out has been simulation-based, although some important experimental research has also been accomplished. Most investigators have categorized the sources of nonlinearity in aircraft into structural, aerodynamic and control nonlinearities. Most of the fundamental research has centered on simple aeroelastic systems with structural nonlinearities (Tang et al., 1998; Lee et al., 1999b).

More recently, significant research effort has been devoted to aeroelastic problems involving aerodynamic nonlinearities and, more specifically, the phenomenon known as transonic LCO or 'transonic buzz' (Dowell et al., 2003; Kholodar et al., 2004; Henshaw et al., 2007). Other work has centered on dynamic stall and stall flutter (Spentzos et al., 2005; Laxman and Venkatesan, 2007; Li and Dimitriadis, 2007; Dimitriadis and Li, 2009).

Another important area of nonlinear aeroelastic research centers around the phenomenon of buffeting. Buffeting oscillations of a lifting surface due to flow separation on itself are an inherently nonlinear phenomenon because the structural oscillations

* Corresponding author.
E-mail address: gdimitriadis@ulg.ac.be (G. Dimitriadis).

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affect the aerodynamic excitation function and *vice versa* (Becker and Luber, 2003; Anderson et al., 2006). A significant experimental investigation of this phenomenon was carried out by Zan (1992). The authors measured the wing root bending moment responses of swept and unswept wings caused by flow separation at high angles of attack. The wings were stiff but not rigid and the measurements were used to estimate a buffet excitation parameter. The nature of the experiment was such that the wings' structural response was assumed not to affect significantly the aerodynamic excitation force.

Buffeting is still not a fully understood phenomenon. There is no consensus over the exact mechanisms that cause self-excited buffeting oscillations and their relationships with other nonlinear aeroelastic phenomena such as stall flutter and transonic flutter. For example, Raveh (2009) uses the term buffet to describe large amplitude shock wave oscillations around an airfoil. However, such shock oscillations have also been linked to transonic LCOs due to shock oscillation (Vio et al., 2007). For low subsonic Mach numbers investigators have studied the flutter and LCOs of a delta wing using potential flow theory based upon vortex lattice models for the aerodynamic modeling and a Von Karman plate theory for the nonlinear structural modeling. Several experimental investigations have also been performed (Tang et al., 1999; Tang and Dowell, 2001; Attar et al., 2003).

Tang et al. (1999) demonstrated experimentally that LCOs can be obtained at low airspeeds as a result of the interaction of structural geometric nonlinearity with attached flow aerodynamics. The experiments concerned plate-like Delta wings made from plastic and aluminum sheet. Tang and Dowell (2001) performed a numerical investigation of the effect of the steady state angle of attack. They found that the LCO amplitude decreases as the angle of attack increases; they stated that such behavior had been observed in flight flutter tests but they did not perform any specific experiments to investigate the phenomenon.

Attar et al. (2003) performed a set of experiments on a Delta wing which showed that the amplitude of the LCOs increases for a given airspeed with increasing steady angle of attack of the Delta wing. The study was both theoretical and experimental and the authors concluded that structural nonlinearity is dominant at low angles of attack. Gordnier (2003) studied the zero angle of attack LCO of a moderately swept cropped delta wing in high subsonic flow. For the wing configuration and Mach number range studied, Gordnier found that viscous effects were limited. In the absence of separation, vortex breakdown or shock wave motion LCOs cannot be termed buffeting but they could certainly look like buffeting. Subsequent investigations by Attar et al. (2004) showed that the inclusion of higher fidelity structural models in the theoretical simulation of LCOs of delta wings improves the agreement with experiment. The simulations and experiments concerned again a flexible Delta wing at low airspeeds subjected to different steady state angles of attack. It was found that the LCO onset airspeed increased with angle of attack. Furthermore, the LCO amplitude also increased with angle of attack for a given airspeed. Attar and Gordnier (2001) also showed that higher fidelity fluid models helped in improving the correlation between theoretical and experimental results.

It should be noted that the phenomena investigated by Tang and Dowell (2001) and Attar et al. (2003) occurred at small steady wing angles of attack (up to 5°). LCOs occurring at much higher angles of attack (up to 30°) were modeled by Gordnier and Visbal (2004) and by Attar et al. (2006, 2008) using aerodynamic models that included detailed vortex breakdown calculations. The theoretical results were compared to experimental data by Gray et al. (2003) and other authors. It was shown that the LCO amplitude increases with steady angles of attack up to 20° but decreases at higher angles for a half-wing Delta. For a full wing, at angles higher than 20°, the LCO amplitude increases at a much higher rate. The experimental and numerical results presented by Gordnier and Visbal (2004) show that the LCO amplitude increases up to a steady angle of attack of 27.5° and indicate that this increase is due to the progression of vortex breakdown over the wing. At higher angles of attack the flow over the entire wing is completely separated and the vibration amplitudes drop.

Gursul (2005) wrote a comprehensive review of the behavior of vortex flow over Delta wings oscillating at high angles of attack. It is clear that vortex breakdown and the spatial oscillation of the location of the vortex breakdown over a period of oscillation constitute a considerable nonlinearity that should affect the aeroelastic response of a Delta wing.

The experiment studied in the present work consists of a flexible flat plate Delta wing in a wind tunnel. The stiffness of the plate is chosen to be low, such that the LCOs span a significant range of airspeeds. In most of the previous experimental work published on this subject the limit cycles occur over a range of less than 10 m/s, so that the number of LCO observations is low and the study of the evolution of the oscillations with airspeed is of limited scope.

Furthermore, by expanding the airspeed range over which LCOs can occur, it is hoped that a richer bifurcation behavior can be observed. The work reported to date on Delta wing experiments in low speed wind tunnel has concerned only supercritical bifurcations. Such bifurcations have been extensively studied by researchers in nonlinear aeroelasticity (Chen and Liu, 2008). However, in fluid structure interaction problems subcritical bifurcations can also occur, especially in cases involving flow separation. An additional objective of the present work is to attempt to observe subcritical bifurcation behavior (as well as other types of bifurcation, if present) on a flat plate Delta wing.

2. Experiment

In this research, a flexible low-sweep half-Delta wing was tested in a low speed wind tunnel in order to investigate its dynamic response. The wing was cut directly from 1 mm thick aluminum flat plate. The dimensions of the wing were 500 mm root chord and 705 mm span, giving a sweep angle of 35.3°. This wing geometry was chosen following the flutter data for Delta wings by Doggett and Soistmann (1989). In their work, the flutter speeds of four Delta wings with four different sweep angles were experimentally determined and tabulated. It was shown that a particular nondimensional flutter speed parameter varies linearly with sweep angle. According to these results, the wing geometry chosen for the