Journal of Fluids and Structures 61 (2016) 431–449

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Limit cycle oscillation behavior of transonic control surface buzz considering free-play nonlinearity

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ARTICLE INFO

Article history:
Received 8 April 2015
Accepted 20 November 2015
Available online 21 January 2016

Keywords:
Control surface buzz
Transonic flow
Aerodynamic nonlinearity
Free-play
Single degree of freedom flutter
Limit cycle oscillation

ABSTRACT

The limit cycle oscillation (LCO) behaviors of control surface buzz in transonic flow are studied. Euler equations are employed to obtain the unsteady aerodynamic forces for Type B and Type C buzz analyses, and an all-movable control surface model, a wing/control surface model and a three-dimensional wing with a full-span control surface are adopted in the study. Aerodynamic and structural describing functions are used to deal with aerodynamic and structural nonlinearities, respectively. Then the buzz speed and buzz frequency are obtained by V-g method. The LCO behavior of the transonic control surface buzz system with linear structure exhibits subcritical or supercritical bifurcation at different Mach numbers. For nonlinear structural model with a free-play nonlinearity in the control surface deflection stiffness, the double LCO phenomenon is observed in certain range of flutter speed. The free-play nonlinearity changes the stability of LCOs at small amplitudes and turns the unstable LCO into a stable one. The LCO behavior is dominated by the aerodynamic nonlinearity for the case with large control surface oscillation amplitude but by the structural nonlinearity for the case with small amplitude. Good agreements between LCO behaviors obtained by the present method and available experimental data show that our study may help to explain the experimental observation in wind tunnel tests and to understand the physical mechanism of transonic control surface buzz.

1. Introduction

Buzz is an aeroelastic phenomenon that occurs on the aircraft control surface in transonic flow, which is treated as a kind of the single degree of freedom flutter. It was firstly observed in aircraft flight around 1945 according to Lambourne (1964). During the flight test of a P-80 jet fighter aircraft (Lambourne, 1964), a low amplitude control surface buzz was encountered, and in the following flight tests of the P-80 aircraft, a violent control surface buzz occurred and resulted in permanent damage to the control surface. Bendiksen (1993) noted other possible control surface buzz phenomena, which happened on Bell X-1 and X-1A aircrafts. The Bell X-1 aircraft encountered severe buffeting and control surface (aileron) buzz around Mach 0.86, however, as the aircraft accelerated over about Mach 0.95, the buzz phenomenon disappeared. A similar situation happened to X-1A aircraft, and the pilot saw the shocks rippling across the wing surface and felt the control

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http://dx.doi.org/10.1016/j.jfluidstructs.2015.11.014
0889-9746/

surface (aileron) buzzing like mad. From above flight tests, we can see that the control surface buzz is dangerous, since it usually causes control surface vibrating suddenly and violently, and may result in a permanent damage on the structure.

In the next two decades after the first observation of control surface buzz, wind tunnel tests were conducted to explore the physical mechanisms of this dangerous vibration. The study presented by Lambourne (1964) is one of the most important researches. Based on systematic wind tunnel tests, Lambourne suggested that control surface buzz could be classified into three types, namely Type A, Type B and Type C, according to Mach number and shock wave location on the control surface. Type A buzz typically occurs slightly above the critical Mach number when the shock stands forward of the control surface hinge, and this type buzz is thought to be related to shock-induced airflow separation. Type B buzz occurs at a higher Mach number, and it is associated with the shock oscillation on control surface. Type C buzz occurs at a even higher Mach number. The supersonic flow extends over the entire control surface and the shock attaches to the trailing edge. This classification for control surface buzz is still used in aircraft engineering nowadays. In 1990s,a series of transonic control surface buzz tests for National Aerospace Plane (NASP) wings were conducted in NASA Langley's Transonic Dynamic Tunnel. Parker et al. (1991) reported that control surface buzz is associated not only with Mach number but also with dynamic pressure, which disagrees with Lambourne's opinion that the occurrence of control surface buzz depends primarily on the Mach number rather than on the airspeed.

Some of the experiment phenomena reported by Parker are of great interest. Some experiment models showed constant amplitude oscillations and divergent oscillations, and the other exhibited relatively low amplitude and heavily damped control surface oscillation just prior to divergent oscillations. Besides, the control surface buzz frequency increased by about 20–30% compared with a wind-off condition, which is called aerodynamic stiffening by Parker et al. (1991). Reasonable explanations for these interesting phenomena could contribute to understand the mechanisms of transonic control surface buzz.

As a high-fidelity technique to simulating shock wave and flow separation in transonic flow, computational fluid dynamics (CFD) is usually employed to predict the control surface buzz. Steger and Bailey (1980) firstly used the numerical method to simulate control surface buzz based on Navier–Stokes equations, and their calculations indicated that control surface buzz did happen at a certain Mach number and showed good agreement with the results of wind tunnel tests. Pak and Baker (2001) applied CFL3D and CAPTSD codes to predict the initiation of control surface buzz at some Mach numbers according to those tested in wind tunnel. Constant amplitude buzz boundaries were captured during their simulation, and the buzz dynamic pressures and frequencies showed reasonably good agreement with those obtained by wind tunnel tests. A Hopf-bifurcation analysis method was employed to predict the transonic control surface buzz for a delta-wing model with a full-span control surface base on Navier–Stokes equations by Liu and Bai (2002), and the results achieved by the Hopf-bifurcation analysis were consistent with those obtained by the time integration calculations and wind tunnel tests. A fully implicit multi-block aeroelastic solver, which coupled thin-layer Navier–Stokes equations with structural equations of motion, was implemented to simulate control surface buzz for a supersonic transport model by Yang and Obayashi (2003). Although the first six structural modes were taken into account in their simulations, the dominant mode was still the control surface oscillation mode when the control surface buzz occurred.

With respect to Type B and Type C buzz, though boundary layer separation was also observed in the experiments, shock wave would be the dominant factor rather than separation (Bendiksen, 1993; Fusi et al., 2012). So solutions of Euler equations, which neglect the viscosity effect, are also sufficient to predict Type B and Type C control surface buzz. Bendiksen (1993) used Euler equations to simulate the aeroelastic behavior of a wing/control surface model, and the results suggested that control surface buzz could be caused by the interaction between shock motion and control surface vibration. In addition, wing flexibility in both bending and torsion, as well as camber bending, was modeled in his work. Based on Euler equations, Fusi et al. (2012) conducted a numerical study for Type B buzz aimed at drawing attention on grid details for accurate results. It can be seen from the above studies that Euler equations are also effective to simulate the control surface buzz of Type B and Type C.

In essence, control surface buzz is a kind of single degree of freedom nonlinear flutter. According to Thomas et al. (2004), three possible types of limit cycle oscillation (LCO) behavior can be observed when nonlinearity is considered in the aeroelastic system, as illustrated in Fig. 1. The supercritical bifurcation is sometimes referred as soft flutter or benign LCO, in

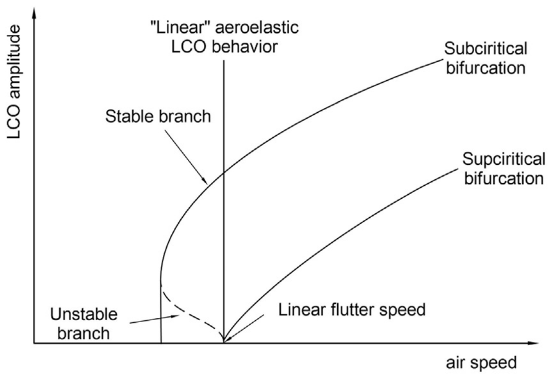

Fig. 1. LCO behavior trends for nonlinear aeroelastic system from Thomas et al. (2004).