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Numerical investigation of the effects of structural geometric and material nonlinearities on limit-cycle oscillation of a cropped delta wing

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ABSTRACT

This article presents numerical simulations of the limit-cycle oscillation (LCO) of a cropped delta wing in order to investigate the effects of structural geometric and material nonlinearities on aeroelastic behavior. In the computational model, the structural part included both the geometric nonlinearity that arises from large deflections, and the material nonlinearity that originates from plasticity. The Euler equations were employed in the fluid part to describe the transonic aerodynamics. Moreover, the load transfer was conducted using a 3-D interpolating procedure, and the interfaces between the structural and aerodynamic domains were constructed in the form of an exact match. The flutter and LCO behaviors of the cropped delta wing were simulated using the coupling model, and the results were compared with existing experimental measurements. For lower dynamic pressures, the geometric nonlinearity provided the proper mechanism for the development of the LCO, and the numerical results correlated with the experimental values. For higher dynamic pressures, the material nonlinearity led to a rapid rise in the LCO amplitude, and the simulated varying trend was consistent with the experimental observation. This study demonstrated that the LCO of the cropped delta wing was not only closely related to geometric nonlinearity, but was also remarkably affected by material nonlinearity.

1. Introduction

Modern military aircraft being developed, such as unmanned combat air vehicle configurations, will need to be highly maneuverable while allowing for increased flexibility in the wing structure. The aeroelastic behavior for this type of aircraft may involve a few sensible nonlinear characteristics, of which the most typical feature is wing limit-cycle oscillation (LCO) (Dowell et al., 2003, 2004). As a simple dynamic bifurcation, the LCO phenomenon is considered to be closely linked to classical flutter, except that the coupling of structural vibrations and unsteady aerodynamics is nonlinear in nature, resulting in a limited amplitude, self-sustaining oscillatory motion. The primary physical sources of the nonlinearities essential to the LCO are a subject of current debate among experts in aeroelasticity. The candidate sources are several: (i) for the structure, free-play (Marsden and Price, 2005), nonlinear damping (Dowell et al., 2003) and geometric nonlinearity (Demasi and Livne, 2009); and (ii) for the fluid, shock wave motion (Dietz et al., 2006) and flow separation (Sarkar and Bijl, 2008; Poirel and Yuan, 2010). Because the LCO phenomenon is associated with the nonlinear factors of the structure and/or aerodynamics, the investigation of wing LCO is of great theoretical and engineering importance.

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The numerical simulation for a complex aeroelastic problem normally has advantages over wind-tunnel testing and real flight because of less expense and lower technical risks. With the progress in research methods and computing resources, a high-precision analysis based on the coupling of finite element method (FEM) and computational fluid dynamics (CFD) technologies has been capable of predicting the LCO behavior. Subsequently, the analysis of wing LCO quickly became a research hotspot. Attar et al. (2005) simulated the LCO of a delta wing in low subsonic flow and revealed the effects of structural geometric nonlinearity. The results obtained through the use of a high-fidelity structural solver, ANSYS, coupled with a linear vortex lattice aerodynamic scheme agreed with the experimental results. On this basis and in combination with a slender-body theory for modeling store aerodynamics, Attar et al. (2008) further investigated the flutter and LCO of a delta wing-store configuration. Gordnier and Visbal (2005) have provided a good review on the CFD/FEM coupled solution for nonlinear fluid–structure interaction (FSI). They also presented simulations of several areoelastic problems, including panel flutter, delta wing LCO and buffet. Parker et al. (2007) performed aeroelastic calculations by integrating a linear modal structural scheme into a general purpose CFD solver, FLUENT, to simulate the LCO of a rectangular wing and clarify how under-wing and tip stores worked on LCO. They found that the addition of stores directly contributed to LCO amplitude, but it did not relate to LCO frequency. Bendiksen (2008, 2009) reported that transonic LCO of a high-aspect-ratio swept wing had been successfully predicted by the coupling of a Euler CFD solver and the shell-element model with geometric nonlinearity. The aeroelastic mechanism for this LCO behavior could be explained in terms of a structural washout effect, which was strongly stabilizing in the transonic region.

The cropped delta wing model, which was tested in the wind tunnel by Schairer and Hand (1999), is another typical research subject for transonic LCO. In recent years, the LCO behavior of the cropped delta wing has been studied based on theoretical models that vary in fidelity for the verification of aeroelastic analysis method and the reveal of physical mechanism of this LCO. Gordnier and Melville (2001) first presented calculations of the LCO of the cropped delta wing using a computing technique that coupled the Navier–Stokes solver to a linear modal structural scheme. The nonlinear mechanism for the development of this LCO was identified as the leading-edge vortex. This vortex acted like an aerodynamic spring, which limited the growth of structural oscillation. Because of the lack of nonlinear structural effects, the computed LCO amplitudes were significantly higher than the experimental measurements. In subsequent work (Gordnier, 2002, 2003), the same author replaced the modal structural scheme with a von Karman nonlinear plate model to study the effects of geometric nonlinearity. Although lower than the experimental values, the computed LCO amplitudes were obviously better than the earlier ones (Gordnier and Melville, 2001). Gordnier (2002, 2003) found that the LCO was induced by geometric nonlinearity and the influence of aerodynamic viscosity was moderate. Based on a Euler finite difference solver that was coupled to the general purpose FEM program ANSYS, Attar and Gordnier (2006) continued to investigate the effects of geometric nonlinearity on the LCO behavior. The excellent capability for the modeling of geometric nonlinearity resulted in an improvement of LCO simulations over past results (Gordnier, 2002, 2003), especially for higher dynamic pressures. Terashima and Ono (2006) conducted a detailed discussion of the use and choice of structural models for the simulation of the LCO of the cropped delta wing. An aeroelastic solver that resembled the existing one (Attar and Gordnier, 2006) was used to complete the calculations. In the work of Cui and Han (2010), a 3-D interpolating procedure was suitably processed besides the modeling of geometric nonlinearity and transonic aerodynamics. The computed LCO responses of the delta wing agreed with the experimental values for lower dynamic pressures. However, the amplitudes of the LCO still had a slower rate of growth with increasing dynamic pressures.

The previous works mentioned above have greatly promoted research on the nonlinear mechanism of the LCO of the cropped delta wing. In comparison with aeroelastic experiments, numerical simulations are still insufficient for the measurement of the LCO phenomenon. Schairer and Hand (1999) noted that a rapid rise in LCO amplitude occurs in the delta wing wind-tunnel tests for the highest dynamic pressure. They also suggested that this interesting phenomenon might be caused by the structural stress that exceeded the proportional limits of the material. In other words, the material plasticity, which is a general form of the nonlinear characteristics of metallic materials, may play an observable role in the structural responses of the cropped delta wing. To the best of present authors' knowledge, there is little information available in the literature about the influence of material nonlinearity on aeroelastic behavior. Furthermore, current investigations have not succeeded in capturing the phenomenon of a mutation in the LCO amplitude of the cropped delta wing.

The principal focus of this article is on transonic LCO behavior of a cropped delta wing. As motivated by the experimental phenomena, this article presented numerical simulations to study the effects of structural geometric and material nonlinearities on the LCO. Based on a general purpose FSI program ANSYS/CFX, the developed aeroelastic model involved the structural nonlinearities, which arise from both large deflections and material plasticity, and the transonic aerodynamics described by the Euler equations. Also, fluid–structure coupling was accomplished by a 3-D interpolating procedure that occurred at the exact-match interfaces. We first conducted the flutter analysis of the cropped delta wing, and then performed the detailed computations of the transonic LCO behavior. The numerical results were compared with experimental measurements. A discussion of the effects of geometric and material nonlinearities was reported to clarify the proper physical mechanism for this LCO.

2. Computational approach

Aeroelastic behavior involves the coupling of structural vibrations and unsteady aerodynamics. This effect is represented by compatibility and equilibrium conditions that are imposed on the interface. Therefore, the basic equations