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Computational aeroelastic investigation of a transonic limit-cycle-oscillation experiment at a transport aircraft wing model

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ABSTRACT

Aeroelastic measurements of a three-dimensional wing model, the so-called Aerostabil wing, were conducted in the Transonic Windtunnel Gottingen. This clean, backward-swept wing allowed the experimental investigation of limit cycle oscillations in a certain transonic parameter range. In this paper, a detailed insight into the observed physical phenomena, especially the measured limit cycle oscillations, is presented by means of CFD–CSM coupled simulations. These simulations on the basis of a detailed structural finite element model reveal the specific properties of the Aerostabil wing and furthermore allow investigating the unstable behavior of this windtunnel model for transonic flow settings. The aerodynamic characteristics include a two-shock system and large flow separation areas, further increasing the complexity of the aeroelastic problem. A structural single degree-of-freedom system is used for the prediction of the experimental stability range and the limit cycle oscillation investigations. Due to the good agreement of simulation and experiment the limit cycle oscillations can be explained by means of nonlinear aerodynamic effects.

1. Introduction

For the construction of modern aircraft the flutter boundaries are an increasing limiting factor in the development progress. To minimize the operational cost of aircraft, new materials like carbon fiber reinforced plastic are used to reduce the structural weight. Furthermore the structural stiffness is reduced to achieve passive load reduction, but also to optimize the aircraft weight, additionally.

Although current flutter analysis methods, using linear structural models and linearized aerodynamics, are reliably capable of predicting classical flutter cases for standard aircraft designs, nonlinearities in the structure or subcritical flutter due to strong aerodynamic nonlinearities (see Bendiksen, 2004) can lead to catastrophic flutter or, as small amplitude case, limit-cycle flutter, limit-cycle oscillations (LCO), respectively.

Limit cycles oscillations are usually defined as self-sustained oscillations with limited amplitudes. For LCOs to occur, nonlinearities have to be present in the system, stemming either from nonlinearities in the structure, in the aerodynamics, in the flight control system or as a result of a combination of those. Previous publications divide LCOs into types triggered by structural or aerodynamics effects. Examples for structural LCOs are induced by free-play, as shown by Lee and Kim (1995),

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geometric nonlinearity, see Tang and Dowell (2004) or additional material nonlinearities as presented by Peng and Han (2011). An industrial example is given by Banavara and Newsom (2010), discussing nonlinear actuators plus free-play in a complete aircraft model. Nonlinear aerodynamic effects, which are also subject of the present work, are the other focus. Several experiments, for example by Dietz et al. (2003, 2004); Schewe et al. (2003) and mainly computational or combined investigations were performed, e.g. for three-dimensional cases by Bendiksen (2008), Edwards et al. (2001), Gordnier and Melville (2001); for two-dimensional case: by Poirel et al. (2011), Raveh and Dowell (2011) or Wang and Zha (2011). The aerodynamic LCO-limiter in these publications is either connected with flow separation or transonic shock-(buffet) influences.

The motivation of the present work is a series of measurements, which were performed on the so-called Aerostabil wing (model B) to develop a thorough understanding of the static and especially the dynamic behavior of an elastic wing under aerodynamic loading close to the flutter speed, see Dietz et al. (2003). It allowed the measurements of LCOs for a certain parameter range. This experiment has also motivated O.O. Bendiksen, who has done detailed LCO research on a very similar, theoretical model, called the “G-wing”. In Bendiksen (2008, 2009) several investigations of this Aerostabil-similar wing with an identical planform but different airfoil shape and an inviscid Euler CFD-solver are presented. The amplitude limitation is explained with the “structural washout” effect, which is shown to be especially important under transonic flow conditions. The term “structural washout“ is used for the combined heave and pitch motion of the first structural bending mode of a backward-swept wing, which results in a reduced local angle of attack on the wing for increased wing bending. It was shown that the load-decreasing pitch motion supports the transition from continuous to intermittent shock motion (Tijdeman type A→B, see Tijdeman (1977)), which decreases the aerodynamic work performed on the structure.

Schewe (2013) uses the landau equation to model LCOs. The Aerostabil experiment is one of the three cases that are discussed in this paper. It mentions the similarity of the Aerostabil LCOs to another 2D LCO experiment in the same windtunnel.

In the present investigation a Reynolds-averaged Navier Stokes solver and a detailed, but linear structural model are applied. It turns out that the maturity of the structural model is a very important requirement for the correct simulation of the Aerostabil experiments. By the use of a dynamical single-degree-of-freedom model, derived from this structural model, a detailed computational insight into the measured LCOs and the measured stability boundaries can be obtained. A single-degree-of-freedom flutter was also the outcome of investigations by Isogai (2012) for a different windtunnel experiment.

Additionally, the Aerostabil experiment is a demanding validation case for the application of fluid–structure interaction (FSI) methods, because not only amplitudes, but also unsteady pressures were measured.

This document starts with the description of the experiment, the applied methods and the structural model, followed by steady FSI results to validate the applicability of the structural model, but also to discuss the influence of turbulence modeling. Next by the use of classical flutter analysis methods the unstable region, in which LCOs occur, is identified, and LCO simulation results are presented. The final section answers the question, if a detailed structural model of the wing is also important for the unsteady aerodynamic excitation of the wing.

2. Experiment

The main experiment including the Aerostabil wing is described by Dietz et al. (2003). This paper presents results on static aeroelastic measurements and preliminary results about the observed transonic flutter phenomena. Furthermore features and details of the wing model and their structural properties are described.

The main aim of the experiments was to study the static aeroelastic effects and in particular the flutter behavior of generic elastic swept wing.

Thus a geometry of low complexity was selected as sketched in Fig. 2. The model has a supercritical airfoil and is equipped with 93 pressure transducers in three wing sections. In addition, accelerometers were installed to obtain information about the oscillating wing deflections. Pressure and acceleration measurements were measured for static and oscillating experimental settings. The experiments were performed in the adaptive test section (size: $1 \times 1\ m^2$) of the Transonic Windtunnel in Gottingen (DNW-TWG).

The presented experimental results are focused on a special case in the transonic regime, where the amplitudes of the limit cycle oscillations were maximal. This case is also the key aspect in the following numerical investigations.

The wing model was mounted on a turntable device. Between the root of the wing and the attachment at the turntable a rigid piezoelectric balance was applied for measuring the global forces. The span, without wing tip, amounts to $s = 600.9$ mm and the reference chord length is $c_{ref} = 183$ mm, the sweep angle of the spar axis is 27°. The wing thickness related to local chord length is nearly constant along the span and amounts to approximately 10 percent. To force the laminar/turbulent transition, a transition strip was applied on the upper and the lower side at 7.5 percent of the local chord length. The first bending mode of the wing has an eigenfrequency of 37.2 Hz, further characteristic frequencies can be found in Table 1 of Section 4. The wing-model could be forced by means of a hydraulic rotation actuator to perform pitch oscillations around the swept spar axis. Laser triangulators were used to measure the angle of incidence α at the root, related to the spar axis. Two accelerometers considered in this study were located at $y/s = 0.795$. To obtain displacement information, the signals were filtered and integrated twice.

The flutter experiment was conducted in the following way: at constant Mach number, the pressure in the windtunnel was adjusted to a value slightly below the assumed critical point for the onset of the flutter oscillations. Then the angle of incidence was increased in small steps of $\Delta\alpha = 0.1°$ by the hydraulic actuator. The boundary of stability was reached, when

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