Journal of Fluids and Structures 74 (2017) 19–34

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

On limit cycle oscillations of typical aeroelastic section with different preset angles of incidence at low airspeeds

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HIGHLIGHTS

- Bifurcation regions with the dominance of structural and aerodynamics nonlinearities were distinguished.
- Jumps from damped oscillations to LCOs were detected.
- The computational model have successfully characterized the dynamic stall loads during LCOs.
- The flutter onset velocity increases for preset angles from zero up to ten degrees and then reduces quickly.

ARTICLE INFO

Article history:
Received 20 April 2017
Received in revised form 26 June 2017
Accepted 7 July 2017

Keywords:
Aeroelasticity
Dynamic stall
Flutter
LCO
Stall-induced oscillations
Hopf bifurcation
Semi-empirical model

ABSTRACT

Helicopter blades and wind turbines are examples of aeroelastic systems that can reach high angles of attack and can vibrate due to the effects of the dynamic stall, thereby leading to fatigue problems or performance loss. Structural and aerodynamic nonlinearities influence the aforementioned behavior and their modeling is crucial for phenomena characterization. Such system modeling requires proper knowledge of the physical events during the stall, which can be better achieved by validating the model with experimental data. This work investigates the nonlinear dynamics of a NACA 0012 airfoil under the influence of structural and aerodynamic nonlinearities due to dynamic stall effects at high angles of attack. Experimental and numerical analyses are carried out. Moreover, different preset incidence angles for the typical aeroelastic section are also considered. The aeroelastic signals are used for estimating the Hopf bifurcation onset and to build the bifurcation diagrams. By using a typical section model with two degrees of freedom coupled to the Beddoes–Leishman aerodynamic model, numerical results have been able to capture with good precision experimental features. The onset of the Hopf bifurcations allows the determination of the flutter critical airspeed. Results for zero preset angle show that limit cycle oscillations from small to moderate displacements are mostly driven by the hardening nonlinearity. After reaching larger angles of incidence the dynamic stall nonlinearities supplant those from structural sources. For higher preset angles, the dynamic stall effects tend to increase the energy associated with pitching motion and to reduce amplitudes in plunge motion. Another effect related to the aerodynamic nonlinearities relies on the increase of the flutter velocity by around 10% for preset angles ranging from zero up to

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http://dx.doi.org/10.1016/j.jfluidstructs.2017.07.008

ten degrees. For higher preset angles an abrupt reduction in the flutter onset velocity is observed.

1. Introduction

Nonlinear aeroelastic phenomena can arise from structural or aerodynamic sources. Limit cycle oscillations (LCO) initiating at the Hopf bifurcation point have been often observed in aeroelastic systems (Dowell et al., 2003). Nonlinear structural behavior is usually related to concentrated or distributed influences resulting from large geometric displacements or material properties. Concentrated structural nonlinearities have been widely used in aeroelasticity research in the form of hardening and softening stiffness effects (Pereira et al., 2016). Either viscous or compressibility effects influence nonlinear aerodynamic loading. For instance, flow separation during pre- and post-stall is driven by viscous behavior effects, while shock excursion in unsteady transonic regime leads to typical nonlinear behavior due to compressibility effects (Dowell and Tang, 2002).

The design of rotary wings admitting combined effects of structural and aerodynamic nonlinearities represents a formidable challenge, including the prediction of regimes of operation subject to dynamic stall effects. From the authors' best knowledge, it is still important to investigate simplified concepts, such as typical airfoil sections and wings.

Aeroelastic analysis of combined structural and aerodynamic nonlinearities for finite wings has been explored by Tang and Dowell (2002), where a highly flexible, long aspect ratio wing with a tip concentrated mass was tested. Supercritical and subcritical LCOs were found over a range that involved the stall regime. Stanford and Beran (2013) have used the same slender wing to explore a direct formulation to the Hopf bifurcation point and to construct the bifurcation diagram without the need for extensive time integration of aeroelastic equations of motion. Zakaria et al. (2015) have observed the influence of preset angles on the energy harvesting from an oscillating composite beam. When exposed to a flow field, the beam reaches self-excited motion with large geometric deformations associated with a nonlinear aerodynamic loading.

Regarding nonlinear aeroelastic investigations, Camilo et al. (2013) presented a numerical study on the behavior of a typical section by considering structural nonlinearities and transonic flow regime. At low airspeeds, an important source of aerodynamic nonlinearity is associated with the flow separation at high angles of incidence. Dimitriadis and Li (2009), Razak et al. (2011), and Vasconcellos et al. (2016) have shown experimental results where LCOs driven by dynamic stall effects were observed. Such nonlinear phenomenon leads to responses that are related to complex trailing and leading edge vortex interactions (McCroskey, 1982; Carr, 1988; Mulleners and Raffel, 2013; Choudhry et al., 2014).

This paper presents an experimental and numerical investigation on structural and aerodynamic nonlinear effects on a two-degree-of-freedom typical aeroelastic section for different preset angles of incidence. The preset angle of incidence must be understood as a fixed incidence to the airfoil from which the aeroelastic oscillations occur. The aerodynamic nonlinear behavior is expected when higher angles of attack are attained, while the structural nonlinearity comes from the hardening effect present in the pitch spring stiffness. The experimental procedure is carried out with a rigid wing in a suspension prepared to ensure pitch and plunge motions. Adjustments to the airfoil incidence guarantee a range of preset angles. Aeroelastic signals are acquired and used for validating a numerical model based on the typical section equations of motion and unsteady aerodynamics computed through a semi-empirical approach, that is, the Beddoes–Leishman dynamic stall model. Limit cycle oscillations are observed by exposing the airfoil to the flow field, and aeroelastic signals are collected from this motion for subsequent analysis. Bifurcation diagrams are achieved from aeroelastic time histories, regarding the airspeed evolution for different preset angles of incidence. The results demonstrate that the effect of stall-induced oscillations can surpass the effect of inherent structural nonlinearities when the angle of attack is higher than the stall angle of attack for the NACA 0012, by changing considerably the behavior of the system and the flutter onset velocity. Simulations using the numerical model allow the assessment of bifurcation onset points and inferences on the physical aspects that occur in the aeroelastic system.

2. Experimental apparatus

The experiments were performed in a blower-type wind tunnel (open jet) with an output section of 0.5 × 0.5 m and able to reach approximately 23 m/s maximum airspeed. The experimental apparatus comprises a rigid wing with a NACA 0012 airfoil profile with a span length of 0.6 m supported by an elastic suspension. The device is supposed to be correlated with the typical aeroelastic section considering pitch and plunge motions. Fig. 1 sketches the wing and its elastic suspension. While the plunge motion is restrained by four elastic steel beams (two on each side at the top and at the bottom), the pitching motion is restrained by a piano wire going through the elastic axis. Nonlinear structural behaviors coming from pitch and plunge elastic features were characterized, and are presented further in this text. Structural damping effects estimations were also included in the dynamical model.

A preset angle of incidence is defined as the structural equilibrium position of the airfoil in wind-off condition, including non-zero incidences. Therefore, aeroelastic oscillations will occur about this angle. Fig. 2 depicts the plate used for adjusting the preset angle, thus enabling a fixed initial condition in incidence to be set, which is responsible for enhancing the effect of aerodynamic nonlinearities.