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Characterization of nonlinear behavior of an airfoil under stall-induced pitching oscillations

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ABSTRACT

This work presents an investigation on the embedded dynamics of experimental aeroelastic signals of an airfoil under the influence of stall-induced oscillations. Helicopter blades or wind turbines are severely imposed to vibrate in stall conditions, which motivates this research. Despite a significant effort to model the unsteady aerodynamics associated with the stall phenomenon, nonlinear aeroelastic behavior prediction and analysis in such flow regime remain formidable challenges. This modeling requires proper knowledge of the physical events during stall regime, what can be better attained from experimental data. In this work a pitching airfoil is tested in a wind tunnel model. Due to the stall influence the airfoil presents sustained periodic and limit cycle oscillations at high angles of attack. The influence of wind-off preset incidence angles are also included in these analyses. The aeroelastic signals are evaluated using techniques from time series theory and spectral analysis. The method of delays approach is used to reconstruct the state space, revealing indications to possible bifurcations and complex dynamics. Changes in amplitudes of stall-induced oscillation due to airspeed and preset angles increases were also investigated. Frequency domain analysis through power spectra evolutions and higher-order spectra was used to identify and confirm nonlinear couplings and other complex features.

1. Introduction

Vibrations caused by separated flows can be encountered in a variety of engineering applications. Blunt bodies immersed in flow fields are subjected to vibrations induced by the frequency of the shedding vortex; the so-called vortex-induced vibrations [1,2]. For airfoils, flow separation and stall-induced vibrations may lead to highly nonlinear phenomena when the unsteady aerodynamics gives a significant contribution to the system complexity. With respect to airfoil aeroelasticity in stall regime, rotorcraft and wind turbines provide substantial motivation to investigate and predict undesired effects.

In rotorcraft industry, complex effects related to flow separation and vortex phenomenon are mostly due to dynamic stall per blade revolution, particularly in forward flight [3,4]. Vibrations in helicopters may disturb passenger–crew comfort, increase structural and components fatigue, and decrease rotor performance with impact to the aircraft flight.

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In wind turbines, complexity comes from the operational environment due to atmospheric turbulence, boundary layer effects near the ground, and variations in the wind shear [5]. Moreover, modern blade design with large rotor diameters (slender blades) has also contributed to let stall-induced vibrations a significant aeroelastic problem [6–8].

Design measures to avoid the drawbacks related to stall-induced vibrations have been considered [7,4]. By doing so, the understanding of physical features of the phenomenon is desired. Non-linear behavior is inherent to aeroelastic systems and can be associated with aerodynamic sources (*e.g.*, compressibility and separated flows) [9] and structural sources (*e.g.*, effects of aging, loose attachments, material features, and large deformations) [10,11]. Aeroelastic systems can face those effects, for instance, in transonic flight, or at high angles of attack maneuvers. Moreover, due to nonlinearities, aeroelastic systems would be subjected to multiple equilibrium points, bifurcations, limit-cycle oscillations, and chaotic motion [12,13].

Separated flows and dynamic stall are substantially complex physical events. This process influences the unsteady aerodynamic loading on the airfoil, largely controlling aeroelastic responses. Mathematical modeling to pursue nonlinear aeroelastic characterization under separated flow fields represents a considerable challenge. Models are typically validated or verified to their accuracy with experimentally acquired data. Experimental data furnishes sequences of measurements that correspond to signals containing embedded dynamics [14]. For a system dynamics with a high level of complexity, it is reasonable to proceed analyzes of the measured signal to retrieve as much information as possible to support a mathematical model. In such context, techniques from time series and signal processing analyzes become necessary.

Therefore, from experimental data alone, information on embedded nonlinear behavior can be extracted, providing a basis for characterization and system identification. As an example of this approach, in Ref. [14] aeroelastic signals related to a flexible wing aeroelastic responses at high angles of attack were examined, and the observed behavior was characterized as chaotic. There exists some techniques applied to characterize embedded system dynamics, to classify on stationarity, determinism, and if the signals are representative of a linear or nonlinear system. The following methods are widely reported in the literature: the run-test method, the surrogate data test [14,15], state space reconstruction (pseudo-state space) [16,17], recurrence plots, and higher-order spectral analysis (HOS) [18].

This paper presents analyses of nonlinear features of stall-induced aeroelastic vibration signals acquired from a pitching airfoil in wind tunnel tests. The test model comprises a rigid airfoil supported by an elastic suspension permitting pitching motion only. By exposing the airfoil to flow field, periodic and limit cycle oscillations can be observed, and aeroelastic signals are collected for analysis. Aeroelastic tests have also considered a preset incidence angle at the wind-off condition, that is, the airfoil would be oscillating admitting different equilibrium states (depending on the preset angle of attack). To retrieve and infer on the embedded dynamics of these signals, techniques from time series theory and spectral analysis were used. From aeroelastic time histories, bifurcation diagrams were achieved in terms of airspeed evolution per airfoil preset incidence angle. Moreover, pseudo- or reconstructed state spaces from each experimental time series were computed using the method of delays. An analysis in the frequency domain was also performed and power spectra evolution with respect to airspeed were analyzed to identify complex harmonics arrangements. The higher-order spectral analysis is also used to investigate nonlinear couplings and their properties. Results demonstrate that the stall-induced oscillations combined with inherent structural nonlinearities provide complex dynamics.

2. Stall-induced vibration phenomenon

Stall-induced vibrations in airfoils are dictated by dynamic stall phenomenon. Loading variation around the airfoil due to complex trailing and leading edge vortex promotes nonlinear aeroelastic responses that may lead to limit cycles or even chaotic behavior. In this section, the events related to dynamic stall and the impact in aeroelastic vibrations of airfoils are briefly described. In the literature, research works such as in Refs. [19–21] and, more recently, Refs. [22,23] provide reviews and more details on dynamic stall physical events.

Typical airfoils experience dynamic stall effects in a very similar manner. Therefore, nonlinear aeroelastic responses in stall-induced excitation also follow similar patterns. An airfoil elastically sustained in pitching will move depending on the unsteady aerodynamic loading. At a certain low angle of attack, unsteady loading permits the airfoil to pitch up. If that happens continuously, the angle of attack increases until the stall delay effects get more pronounced.

At unsteady motions below the static stall condition, airfoil normal force behaves with very little difference from linear inviscid attached flow. Important stall delay effects start to act after the static stall condition being passed for a pitching airfoil, where normal force keeps growing, and attached flow behavior still observed. Concurrently, as the angle of attack grows a flow reversal region expands upstream from the trailing edge towards the leading edge of the airfoil. Moreover, in the leading edge a vortex will also appear and increase in intensity as the angle of attack gets higher. All these events determine a delay in loading degradation as one could expect. Adversely, the unsteady normal force keeps growing higher to the static stall condition, with no substantial change in pitching moment.

Reverse flow evolution upstream coincides with an increase in the leading edge vortex intensity. This progress depends on various parameters such as airfoil shape, pitch rate, Reynolds and Mach numbers, for example. When the leading edge vortex gets enough energy, it is also large enough and starts moving downstream. This physical event is the beginning of the dynamic stall phenomenon. The immediate consequence of a large leading edge vortex convecting downstream is a sudden increase in both airfoil normal force and negative pitching moment. Such condition is also referred as lift stall effect [20,21]. The large vortex over the airfoil will follow this way downstream into the wake. Consequently, complete flow separation is