

# Bifurcation Behavior of Airfoil Undergoing Stall Flutter Oscillations in Low-Speed Wind Tunnel

Grigorios Dimitriadis\*

Université de Liège, 4000 Liège, Belgium

and

Jing Li†

University of Manchester, Manchester, England M60 1QD, United Kingdom

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**Stall flutter is a nonlinear aeroelastic phenomenon that can affect several types of aeroelastic systems such as helicopter rotor blades, wind turbine blades, and highly flexible wings. Although the related aerodynamic phenomenon of dynamic stall has been the subject of many experimental studies, stall flutter itself has rarely been investigated. This paper presents a set of experiments conducted on a NACA0012 airfoil undergoing stall flutter oscillations in a low-speed wind tunnel. The aeroelastic responses are analyzed with the objective of characterizing the local bifurcation behavior of the system. It is shown that symmetric stall flutter oscillations are encountered as a result of a subcritical Hopf bifurcation, followed by a fold bifurcation. The cause of these bifurcations is the occurrence of dynamic stall, which allows the transfer of energy from the freestream to the wing. A second bifurcation occurs at the system's static divergence airspeed. As a consequence, the wing starts to undergo asymmetric stall flutter bifurcations at only positive (or only negative) pitch angles. The dynamic stall mechanism itself does not change but the flow only separates on one side of the wing.**

## I. Introduction

**T**HE subject of this paper is the experimental study of the aeroelastic behavior of a wing undergoing stall flutter. A series of experiments carried out on a wing with pitch and plunge degrees of freedom in a low-speed wind tunnel are described and the results are analyzed to attempt a characterization of the stall flutter phenomenon.

Classical bending-torsion flutter involves the interaction between two or more modes of vibration (or degrees of freedom) to give rise to catastrophic self-excited vibrations of exponentially increasing amplitude. The phenomenon is treated using linear assumptions, and methods for its prediction are at a quite advanced stage.

Stall flutter is a nonlinear dynamic phenomenon that can involve only a single degree of freedom. It is associated with large areas of dynamically separating and reattaching flow over a lifting surface. Stall flutter is closely related to galloping; in fact, Blevins [1] treats the two phenomena simultaneously because they are both oscillations of limited amplitude, induced by unsteady separated flows. Stall flutter involves stalled flow over wings, whereas galloping involves separated flow over bluff bodies. The main difference between the two is that, in stall flutter, the flow reattaches instantaneously during an oscillation cycle, whereas flow over bluff bodies is always separated. In this paper, only stall flutter will be considered, that is, the work will concern a wing.

Essential to the occurrence of stall flutter is the phenomenon of dynamic stall, even though these two are quite distinct phenomena. As this distinction is central to the present work, the definitions of the two phenomena is given here.

*Dynamic stall:* The significant and abrupt loss of aerodynamic loads (lift and/or pitching moment) due to flow separation on wings undergoing unsteady motions. It is an unsteady aerodynamic phenomenon.

*Stall flutter:* Self-excited oscillation of limited amplitude, caused by the interaction of a dynamic stall event with the inertial and elastic characteristics of a wing. It is an aeroelastic phenomenon.

Dynamic stall is a purely aerodynamic phenomenon because no feedback from the aerodynamic forces to the motion of the wing is necessary for it to occur. In dynamic stall experiments, the motion of the wing is prescribed using motors and the wing itself is usually completely rigid. Stall flutter, on the other hand, is an aeroelastic phenomenon because the dynamically stalling aerodynamic forces interact with the structural restoring forces of the wing and the motion is a free self-excited oscillation of limited amplitude. In the nonlinear dynamics literature, such oscillations are called limit cycle oscillations (LCOs). In other words, dynamic stall is an aerodynamic nonlinearity. Stall flutter is a LCO occurring as a result of the existence of this nonlinearity.

Nevertheless, dynamic stall is the phenomenon that has been most investigated in the past. Halfman et al. [2] produced one of the first truly thorough investigations of dynamic stall. Experimental results in a wind tunnel were obtained using an airfoil oscillator, that is, a mechanism for forcing a nearly 2-D rectangular NACA wing to oscillate sinusoidally in a wind-tunnel section. Time-varying lift, drag, moment, and position were measured along with various inertia quantities.

Ericsson and Reding [3–5] carried out a significant amount of work on dynamic stall in the 1970s. Among other things, they developed a quasi-steady aerodynamic model for dynamic stall of a 2-D airfoil with unsteady terms represented by a single lumped vortex “spilled” from the trailing edge. The authors’ quasi-steady approach was further improved by including in the analysis the effect of this spilled leading-edge vortex [6].

McCroskey [7] defined two dynamic stall regimes: light stall and deep stall. Light stall is a phenomenon similar to static stall and is characterized by very negative pitch damping values. Deep stall is essentially the phenomenon whereby a large vortex is shed at the leading edge and travels downstream. The passage of this vortex over the airfoil’s upper surface produces maximum lift and moment values far in excess of their static counterparts.

Several other experimental investigations of dynamic stall were carried out since then, including particle image velocimetry measurements [8,9], culminating in a nearly complete visualization of the dynamic stall phenomenon [10].

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\*Assistant Professor, Département d’Aérospatiale et Mécanique, B52/3, Chemin des Chevreuils, 1; gdimitriadis@ulg.ac.be. Member AIAA.

†Researcher, Post Office Box 88.