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Frequency lock-in in pitch–heave stall flutter

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ABSTRACT

Coupled pitch–heave oscillations of a rigid but elastically mounted NACA0012 wing are experimentally investigated in a range of airspeeds corresponding to transitional Reynolds numbers (6.5×10^4–12.0×10^4). The elastic axis is set at 35% and the frequency ratio $\overline{\omega} = \omega_h/\omega_\theta$, is varied from 0.68 to 1.43. The system exhibits self-sustained large amplitude symmetric oscillations attributed to stall flutter in pitch. Pitch oscillation amplitudes are in the order of 40°, whereas the heave amplitude varies from 6% to 60% of chord length. For the most part the heave DOF plays a subordinate role as it is driven by the pitch dynamics; the system oscillates at a frequency determined by the pitch DOF. However, for a range of frequency ratios close to one, a strong coupling occurs from the heave to the pitch associated with a significant increase in heave amplitude and a lock-in of the LCO frequency onto the heave dictated frequency. This lock-in parallels classical observations of the elastically mounted cylinder in cross-flow interacting with its own wake in the form of von Kármán vortex street.

1. Introduction

Stall flutter is an aeroelastic phenomenon characterized by large amplitude limit-cycle oscillations (LCO). It occurs mainly in pitch although pure heave oscillations are theoretically possible. As a wing pitches in and out of the stall region, a hysteresis occurs between the aerodynamic loads and the angle of attack (AOA) which is largely influenced by the nonlinearity due to flow separation. This is known as dynamic stall (McCroskey, 1981). One consequence of dynamic stall is that the wing may extract energy from the flow for part of the cycle, hence negative aerodynamic damping. If the work done by the (non-conservative) aerodynamic loads over one full cycle is positive and its magnitude is larger than the work done by the structural loads, then the oscillations are self-sustained leading to LCO in the form of stall flutter (Fung, 1955). Dynamic stall is an aerodynamic phenomenon; stall flutter is an aeroelastic occurrence.

As pointed out by Dimitriadis and Li (2009), research on stall flutter has not been as frequent as on the related problem of dynamic stall. Nevertheless, some have inferred the existence of stall flutter by analyzing dynamic stall of an airfoil forced to undergo simple harmonic oscillations about a non-zero mean angle of attack, as Bhat and Govardhan (2013) for instance on a NACA0012. It appears that most of the dynamic stall experiments have been conducted about non-zero mean angles of attack in or close to the static stall regime, and with relatively small amplitudes of oscillations, as in McCroskey (1982). The aerodynamic problem of dynamic stall can also be investigated by means of a free oscillating wing, specifically in self-sustained motions, as is done by Dimitriadis and Li (2009), Goyaniuk et al. (2017) or Šidlof et al. (2016). It is relevant to point out that in the first two cases the dynamic stall being exhibited is due to stall flutter, whereas the latter is most likely caused by the classical coupled flutter problem.

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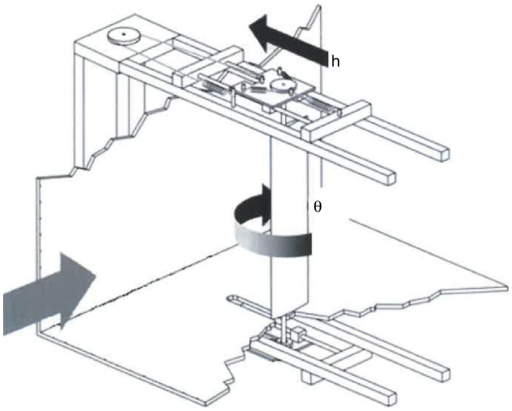

Fig. 1. Schematic of flutter rig.

In this work, we report experimental results of a rigid NACA0012 but elastically mounted airfoil in pitch and heave undergoing stall flutter at transitional Reynolds numbers, with the intent of interpreting the response from the point of view of frequency lock-in. The oscillations are generally symmetric about the zero angle of attack and have large amplitudes, certainly entering the deep stall regime during part of the cycle.

Previous results for the 1DOF pitch only motion were reported by Harris (2007) for an elastic axis (EA) at 27% c from the leading edge and by Peristy et al. (2014) for the EA at 35%. Different pitch stiffness coefficients, including no structural stiffness at all, were examined at different airspeeds (Reynolds numbers). Symmetric stall flutter oscillations, whose amplitude ranged from 22° to 35°, were reported. Still for the 1DOF stall flutter in pitch, Goyaniuk et al. (2017) provide a more in-depth analysis along with comparisons with LES based aeroelastic simulations. Initial results for the 2DOF pitch–heave problem were provided by Mendes (2016) for both EA locations; however in this case the large amplitude LCO were attributed to coalescence flutter, not stall flutter. In the current work, additional stall flutter results are presented for the 2DOF system for a range of Reynolds numbers (Section 3), and subsequently in terms of frequency ratio for the lock-in problem (Section 4).

2. Experimental method

The basic experimental set-up consists in a quasi-2D pitch–heave flutter rig. A rigid NACA0012 wing can pitch freely about an axis of rotation, or elastic axis (EA), which is mounted on two freely translating plates enabling the heave motion. A system of springs and pulleys provides the elastic restoring forces. For the current experiment, the axis of rotation is located at 35% c and the structural stiffness coefficient in pitch is set at a value $k_\theta = 0.3$ N m/rad. The structural stiffness coefficient in heave (k_h) is varied from 347 to 1534 N/m. Accordingly, the frequency ratio, defined as the uncoupled structural undamped natural frequency in heave over the uncoupled structural undamped natural frequency in pitch ($\overline{\omega} = \omega_h/\omega_\theta$), ranges from 0.68 to 1.43. The pitch only case, for which k_h is effectively infinite ($\overline{\omega} \to \infty$), is also considered as a basis of comparison. The mass moment of inertia of the wing about its EA (i.e. all the rotating parts) is 0.001 kg m^2; its mass is 0.77 kg whereas the mass of all the heaving parts is 2.50 kg. Note that the flutter rig has translating parts (heave) that do not rotate (pitch), hence the two different mass parameters. The center of mass is almost coincident with the EA giving a very small static unbalance $x_\theta = 0.004$ (or 0.2% of the chord), and making the structural system essentially uncoupled; x_θ is the normalized (by the half-chord length) distance between the CG and the EA) and positive when the CG is aft of the EA. Accordingly, most of the coupling originates from the aerodynamics. End plates are installed to minimize 3D aerodynamic effects. See Fig. 1. Note that the wing is mounted vertically. The wing has a chord $c = 0.156$ m and a span of 0.61 m, for an aspect ratio of 3.9. The wing surface is smooth and the freestream turbulence intensity in the wind tunnel test section is about 0.15%. More details can be found in Poirel et al. (2008).

Each test was conducted for about 80 secs, which is equivalent to about 200 LCO cycles. Extra care was taken to align the wing, both in pitch and heave, to minimize any biases. Special consideration was also given to initial conditions due to the highly nonlinear attribute of the problem, specifically due to Reynolds number and high angle of attack. The airspeed was recorded with a pressure transducer via a pitot-static tube located at the front of the test section, once steady-state aeroelastic oscillations were achieved. The pitch and heave motion were recorded simultaneously via rotary potentiometers connected to a National Instruments PCI-6034E A/D card using a LabVIEW based data acquisition system in which the sampling rate was set at a nominal value of 1 kHz. The raw data was filtered during the post-processing phase.