A PIV study of a low Reynolds number pitch oscillating SD7037 airfoil in dynamic stall with CFD comparison

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Dynamic stall phenomena are associated with a highly separated unsteady boundary layer and energetic vortex formation and shedding. Modeling dynamic stall with pitch oscillating airfoils has been considered for many years because of its wide range of applications such as helicopter blade rotors, wind turbines, and maneuverable wings. Extensive experimental studies have been reported [1-5] since the review by McCroskey [6], but the physics of dynamic stall is not yet fully understood.

This study focuses on highly separated regions on the suction surface of SD7037 airfoil using non-intrusive phase averaged PIV measurements. Since no study on a pitch oscillating SD7037 airfoil exists in the literature, a transient numerical computational fluid dynamics (CFD) simulation was carried out in conjunction with the experimental work for comparison of flow features in dynamic stall. Aerodynamic loads are calculated from the CFD analysis.

A SD7037 airfoil was pitch oscillated at one quarter of the chord according to the sinusoidal motion prescribed by

\[ \alpha = \alpha_{\text{mean}} + \alpha_{\text{amp}} \sin(2\pi ft) \] (1)

where \( \alpha_{\text{mean}} \), \( \alpha_{\text{amp}} \) and \( f \) represent mean angle of attack, pitch oscillation amplitude, and oscillation frequency, respectively. For the current study \( \alpha_{\text{mean}}=11^\circ \), \( \alpha_{\text{amp}}=11^\circ \), and a reduced frequency \( k = (2\pi fC/\nu) \) of 0.085 were considered.

Dynamic stall can be divided into three stages, namely pre-stall, full stall and post-stall. All these stages are shown in streamline plots for varying upstroke and downstroke angles.

During upward pitch motion the flow starts to separate from the trailing edge at \( \alpha=5^\circ \). As the angle of attack increases, laminar separation bubbles (LSB) are created close to the leading edge. A further increase in the angle of incidence turns the LSB into a leading edge vortex (LEV). At \( \alpha=17^\circ \) the clock-wise LEV covers half of the suction side. Static pressure was determined and shows vortices affiliated with the low pressure waves. Hence, at \( \alpha=17^\circ \) the LEV yields a large pressure difference between the pressure and suction sides, resulting in high lift. The lift coefficient reaches the absolute maximum at the dynamic stall point.

After the airfoil stalls, shedding of the clockwise vorticity transfers the low pressure waves to the wake, leading to a quick drop in lift and full stall stage. During full stall a counter-clockwise vortex from the pressure surface forms and gradually rolls up at the trailing edge. At the end of full stall it reaches a maximum size and sheds into the wake.

As for the downward pitch motion, at \( \alpha=21.5^\circ \) the LEV from the numerical simulation is fully separated while the LEV from PIV starts to shed. The most marked discrepancy between the PIV and numerical results occurs during the downstroke motion at high angles of attack since the flow is significantly unsteady in this range of angles of attack and the development and subsequent separation of the LEV could happen within 0.5\(^\circ\). The LEVs during the downstroke motion are not as energetic as the upstroke counterparts and in turn do not significantly increase the aerodynamic loads.

Facilitated by the PIV technique with recent post processing methods, the current study explored the dynamic stall phenomena of a pitch oscillating SD7037 airfoil at low Reynolds number (40,000). During oscillation the airfoil experiences formation, development, and separation of pressure side and suction side vortices, which give rise to a severely separated boundary layer, as observed by both experimental and numerical methods. Although the latter predicts the stall point 0.2\(^\circ\) earlier during the upstroke motion, there is reasonable agreement between both methods in qualitatively and quantitatively capturing the flow characteristics. The calculated lift coefficient peaks to an absolute maximum at the stall point. Subsequently a rapid drop in lift to full stall is observed when the low pressure LEV is separated from the suction surface and enters the wake, followed by lift recovery due to the development of another LEV. Although there is a marked discrepancy between experimental and numerical results at relatively high angles of attack during the downstroke motion, overall the PIV technique was successful in identifying and analyzing the flow behavior associated with the dynamic stall phenomena.


