The unsteady flow field in the vicinity of a pitch oscillating SD7037 airfoil at a Reynolds number of 40,000 was investigated experimentally and numerically. The airfoil undergoes dynamic stall phenomena associated with a highly separated unsteady boundary layer and energetic vortex formation and shedding. The experimental part of the current study employed particle image velocimetry (PIV). The PIV results were based on averaging 500 images for each angle of attack. A computational fluid dynamics (CFD) simulation was performed for the same flow field with ANSYS Fluent 12, simulating laminar-turbulent transition using the transition SST model. Reasonable agreement was observed between the PIV and CFD methods in capturing both qualitative and quantitative flow characteristics.

Methodology

Experimental Setup

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

$$\alpha = \alpha_{\text{mean}} + \alpha_{\text{amp}} \sin(2\pi f t)$$

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 $k (\tau f c U)$ of 0.085 were considered.

The airfoil motion was actuated using a servo motor with a 2000 line encoder. A Galil CDS-3310 motion controller was used to interface with the servo motor and trigger the PIV image acquisition at user specified angles (Figure 1). The Reynolds number was fixed at 40,000. Images were obtained with a Dantec Dynamics PIV system utilizing a Nd:YAG laser. A beam splitter was used to separate the laser light in order to illuminate the top and bottom surfaces of the airfoil equally (Figure 2). The field of view was 5 cm by 5 cm with an image resolution of 2048 pixels by 2048 pixels. The time interval between frames was set to 4 μs with 500 images captured for each angle of attack. Image pairs were processed with adaptive PIV. Post processing was done with codes developed in house.

Numerical Setup

For the numerical simulation a commercial CFD flow solver package, ANSYS Fluent 12, was employed. A grid independence study was performed, concluding that a mesh resolution of 200,000 cells with 500 nodes around the airfoil was suitable. The whole computational domain was oscillated around the one quarter chord of the airfoil to serve as a dynamic mesh (Figure 3). The transition SST model was applied as a viscous model for the simulation.

RESULTS

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, Figure 4 at $\alpha = 15^\circ$. 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. Pressure contours scaled by the static pressure of the incoming flow calculated at one chord length ahead of the airfoil are plotted in Figure 6, which 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 stall angle is 18.8° by numerical prediction (Figure 7) or 19° according to PIV data. Figures 4 and 6 illustrate that at the dynamic stall point the LEV covers the entire suction side with very low pressure. After the airfoil stalls, shedding of the clockwise vorticity transfers the low pressure waves to the wake, leading to a quick drop in lift. During full stall a counter-clockwise vortex from the pressure surface forms. Following the numerical streamline plots, emergence of a second LEV is evident at $\alpha = 20.5^\circ$. The growth of the second LEV enhances the lift performance during the upstroke motion, though its strength subsides in comparison with the first LEV, as is evidenced by the higher inner pressure. At $\alpha = 21^\circ$, the first LEV separates while the second LEV undergoes further development (Figure 4). At $\alpha = 21.5^\circ$ the trailing edge vortex is shed while a third LEV emerges. At the same time the second LEV reaches the end of the airfoil, corresponding with a second peak lift during the upstroke motion. Since the numerical simulation slightly advances the aerodynamic events, at $\alpha = 22^\circ$ it shows the separation of the LEV and formation of the next trailing edge vortex whereas the PIV streamline plot shows only the developed LEV over the upper surface. 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 LEVs during the downstroke motion are not as energetic as the upstroke counterparts and in turn do not significantly increase the aerodynamic loads (Figure 7). At $\alpha = 7^\circ$ there is no sign of vortex formation, and the flow remains attached until the end of the cycle $\alpha = 0^\circ$. 

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