FLOW STRUCTURES IN THE NEAR-WAKE OF A WING PITCHING UP IN STEADY CURRENT

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ABSTRACT: The flow fields in the near wake of a wing undergoing a pitch up motion has been investigated using a Digital Particle Image Velocimetry (DPIV) system. The wing has an aspect ratio of 4 or 6, pitches up to 45° for different durations of motion, in the presence of steady current with a Reynolds number of 10 000. The wing is either a rectangular plate or an NACA0012 airfoil. For the rectangular plate cases, the effect of both sharp and rounded edges has been investigated. Finally the pivot point is another parameter of the study; the wing rotates around either the leading edge or quarter chord from. The evolution of the flow structures has been studied for the aforementioned cases and the effect of the selected parameters has been identified.

INTRODUCTION: Biomimetics is attracting substantial and growing interest from a wide range of engineering disciplines recently. Micro air vehicles constitute probably the major application area of research related to biological flight. Human made air vehicle designs are inspired by birds and insects, but their functionality and efficiency are still far behind these natural fliers. Therefore, physical basis underlying natural flight should be examined in detail, in order to improve the effectiveness of the artificial flight. Biological flight is complicated; besides moving forward relative to the air, the wings also flap up and down, plunge and sweep [1]. Researchers usually simplify these special motions to make proper approximations to bird and insect flights.

Impulsively started wing and airfoils undergoing a pitch and plunge motion are simplified versions of start of the insect wing stroke [2, 3]. Strength and stability of the leading edge vortex (LEV) is also investigated in various studies and is considered to have significant effect on lift generation [4, 5]. Experimental results of flat plate wings in unsteady rotation [6] showed that three-dimensional effects are small and high lift is achieved during the first chord length of travel, due to the presence of a strong attached LEV. Reynolds number effect is also studied: the investigations [7] report that fundamental lift-generating flow structures on the waving wing do not appear to change significantly in the Reynolds number range of 10000-60000. Furthermore, in a non-dimensional time-scale, leading edge vortices appear to grow and shed more quickly at lower Reynolds numbers.

In this study, the flow structures in the near wake of a wing undergoing a pitch up motion have been investigated using a Digital Particle Image Velocimetry (DPIV) system. The wing is either a rectangular plate or an NACA0012 airfoil with an aspect ratio of 4 or 6. The Reynolds number is 10000 and constant for all cases while the wing pitches up to 45° for different durations of motion.

For the rectangular plate cases, the effect of both sharp and rounded edges has been investigated. Also as another parameter, the wing rotates around either the leading edge or the quarter chord from the leading edge. Spanwise variations are observed to determine three dimensional effects, mainly the effect of tip vortex, and laser plane is adjusted in mid-span and quarter-span positions. For the NACA0012 airfoil case, the effect of pivot point and duration of motion are investigated. The data has been obtained again at two different spanwise locations, namely mid-span and quarter-span. The evolution of the flow structures has been studied for the aforementioned cases and the effect of the selected parameters has been identified. Leading edge vortices are determined and their paths and strengths are tracked during the wing motion.

EXPERIMENTAL SETUP: Experiments were performed in the close-circuit, free-surface, large scale water channel located in the Trisonic Laboratories at the Faculty of Aeronautics and Astronautics of Istanbul Technical University. The cross-sectional dimensions of the main test section are 1010mm × 790mm. The model is mounted in a vertical cantilevered arrangement in the water channel about its leading edge or quarter chord. The connection rod connects the airfoil to the servo motor from its leading edge or quarter chord from the leading edge, to provide a ramp type pitch up motion via a coupling system. The chord length of the model is 10 cm with 20 cm span if it is not mentioned otherwise and it is manufactured of transparent plexiglas to allow laser light to illuminate both the suction and pressure sides. The model is either a thin rectangular plate (t=0.5cm) with sharp or rounded edges, or a NACA0012 airfoil (Figure 1). The experiments are conducted at Reynolds number of 10000 which simulate forward flight of small birds, this Reynolds number corresponds to a flow speed of U=0.1m/s.

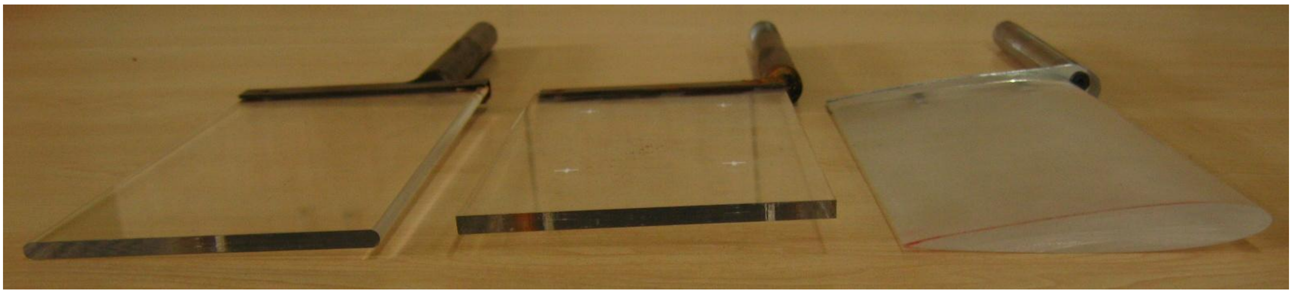

Fig. 1 The models used in the study, a NACA0012 airfoil and thin rectangular plates with round and sharp edges

Digital particle image velocimetry (DPIV) technique is used to record flow fields around the model and therefore to analyze the vortical structure. The flow is illuminated by a dual cavity Nd:Yag laser (max. 120mJ/pulse) and the water is seeded with silver coated glass spheres with a diameter of 10µm. Two 10-bit cameras with 1600×1200 pixels resolution are positioned underneath the water channel to obtain the images to observe the flow structures around the airfoil and in the near-wake. PIV images are interrogated using a double frame, cross-correlation technique with a window size of 64×64 pixels and 50% overlapping in each direction. The final grid resolution of velocity vectors is 3.5 mm × 3.5 mm in the plane of the flow. The resulting measurement plane is represented with approximately 3240 velocity vectors. The experimental setup is shown in Figure 2.

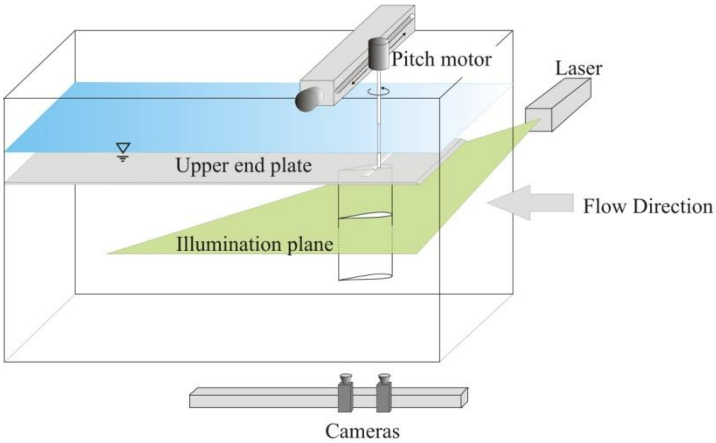

Fig. 2 Experimental setup showing the model and DPIV system

Since an endplate is used on the symmetry axis, the aspect ratio of the wings is either 4 or 6. The study considers two planes of illumination in spanwise direction. The flow fields are acquired at the mid-span and the quarter-span of the half wing as illustrated in Figure 3.

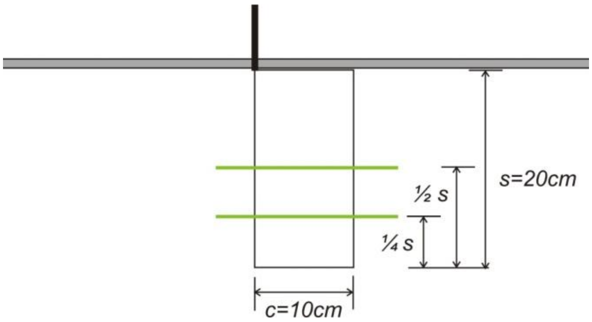

Fig. 3 Illumination planes in spanwise direction

RESULTS: The experiments were conducted for two different duration of motion; i.e. the model pitches up to 45° in one second or six seconds. In non-dimensional time scale, the active change of motion is achieved in 1 or 6 chord lengths of travel relative to fluid. To visualize the flow structures, mainly the leading edge vortex (LEV), vorticity contours are plotted. In order to analyze the evolution of leading edge vortices for the cases under investigation, their circulation values are also quantified around a certain and fixed level of vorticity contour.

The results obtained with thin rectangular plate are summarized in comparison for two illumination planes and are shown in Figure 4 and 5 when the wing is at the end of its motion.

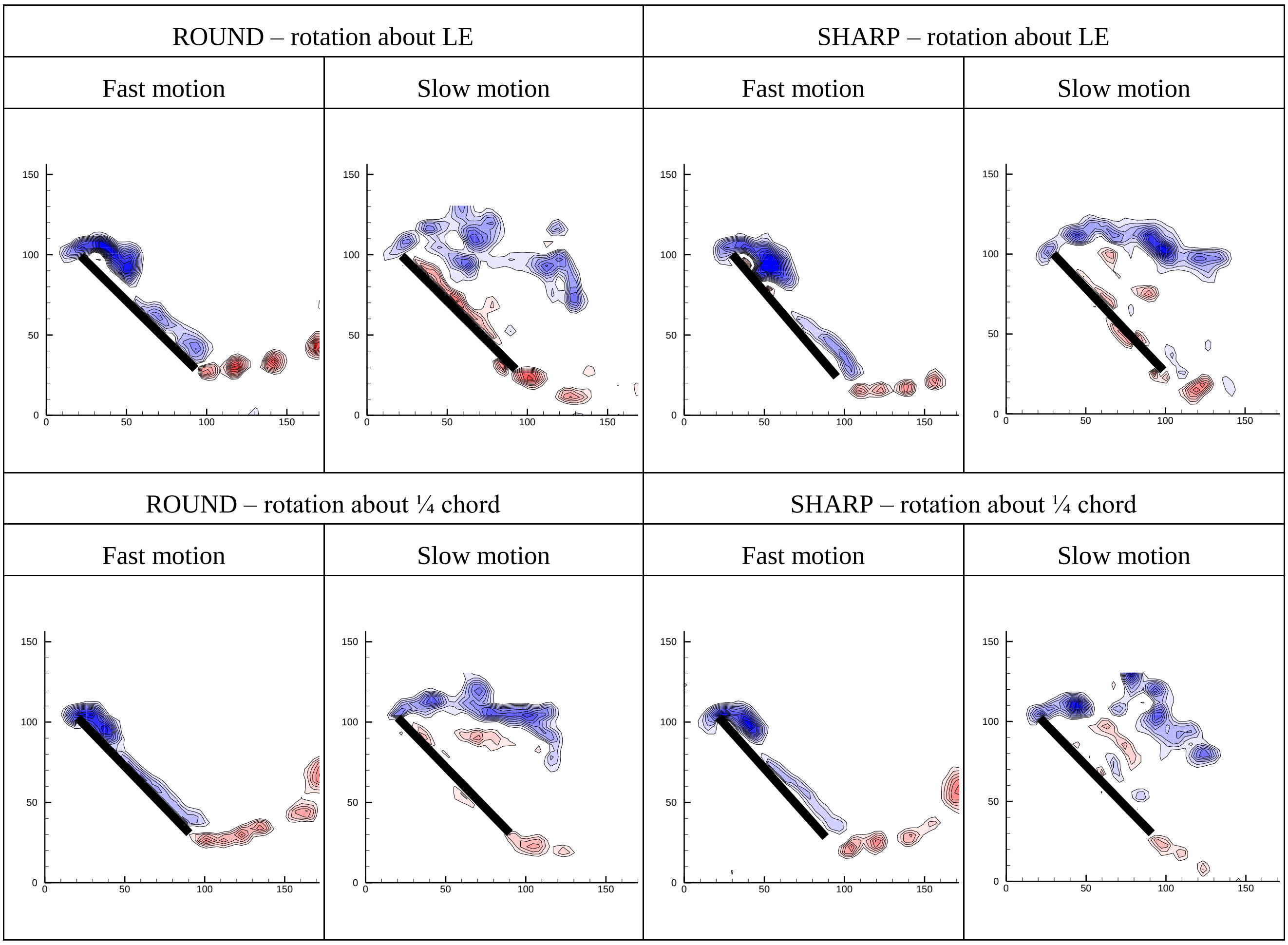

Fig. 4 Patterns of vorticity for thin rectangular plate when the mid-span location is illuminated

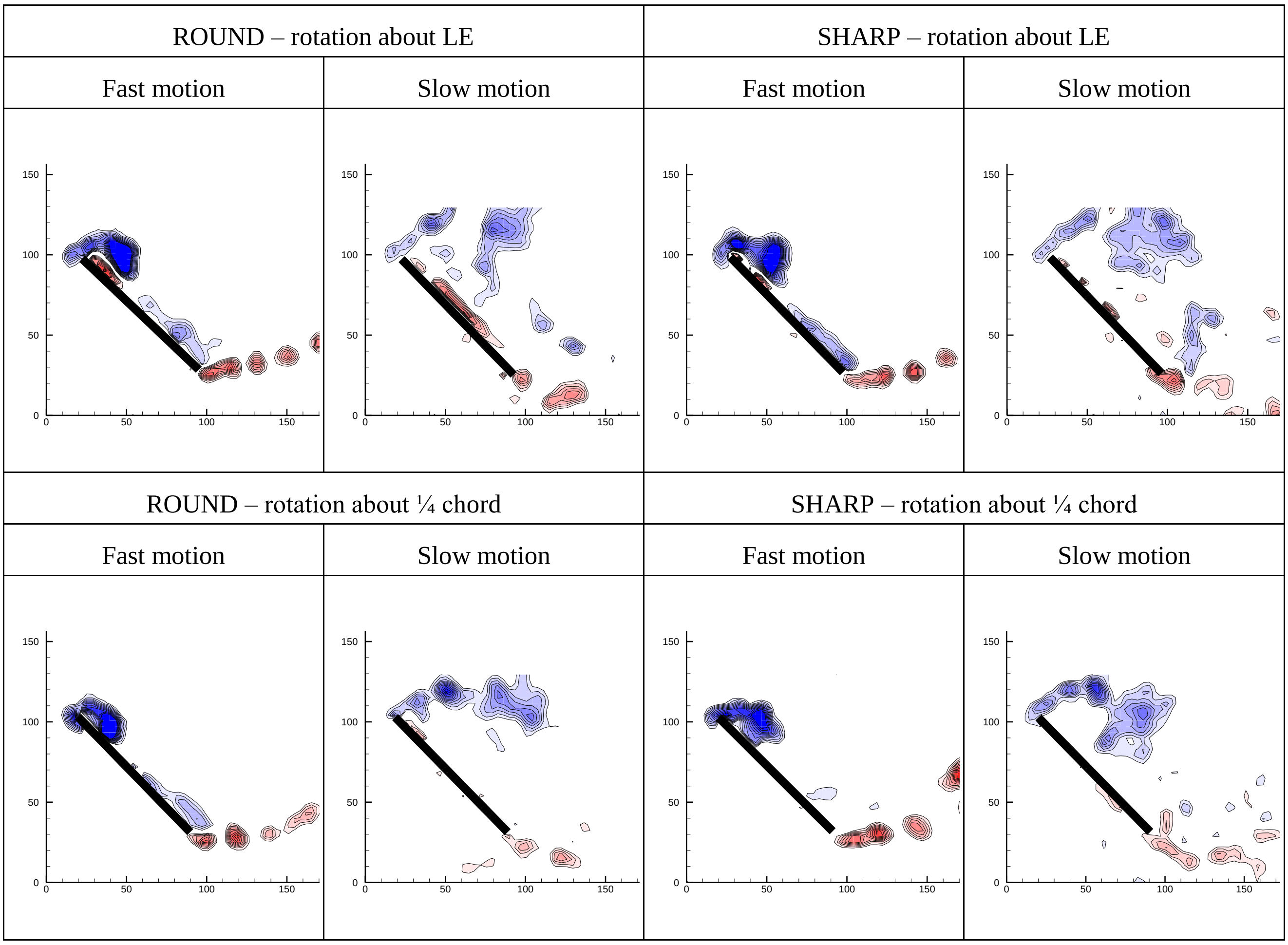

Fig. 5 Patterns of vorticity for thin rectangular plate when the quarter-span location is illuminated

Comparing the fast and slow motion cases, it is possible to conclude that the evolution of the LEV cannot follow the motion speed or scaled to the motion duration. The negative vorticity patterns form closer to the surface when the wing rotates about its quarter chord from the leading edge. These negative vorticity contours include both the LEV and shear layer instabilities and this fact complicates the identification of LEV. Although there are not clear differences between vortical structures of sharp or round leading edge cases, they are stronger when the wing rotates about its leading edge.

The major difference observing the results on two spanwise illumination planes is that the extension of the vorticity patterns in chordwise direction is shorter for quarter-span views. The roll-up of the LEV is evident especially for sharp leading edge cases and when the wing rotates around its quarter chord.

For the investigated cases of thin rectangular plate, the distance of the LEV to the leading edge of the wing and its strength has been plotted with respect to time and illustrated in Figures 6 to 8. Figure 6 shows a plateau for approximately 2 < chords traveled < 3. LEV is found to be more distant to the leading edge for sharp leading edge model especially after the plateau, when the LEV is definitely shed in the wake. Rotation about quarter chord yields similar results for sharp or rounded leading edges, especially for chords traveled less than 3.

When the same plot is obtained for the illumination plane at quarter-span (Figure 7), the slope is milder indicating a slower motion of the LEV. In between the parameters studied, a clear difference cannot be identified for this spanwise location where LEV and tip vortex is assumed to have a stronger interaction.

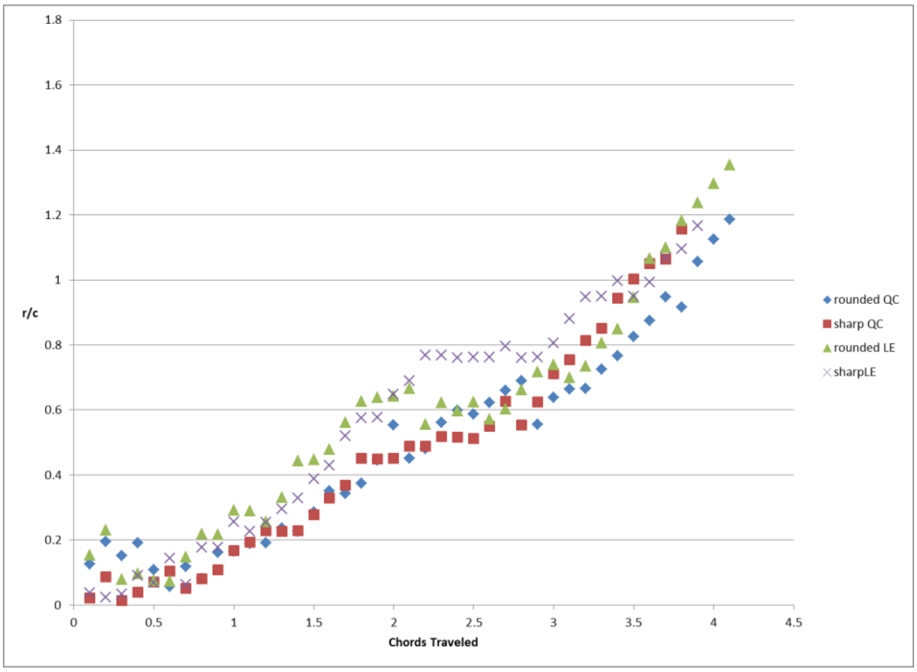

Fig. 6 Variation of the distance of the LEV core to the leading edge of the wing with respect to time when the mid-span location is illuminated for fast motion case

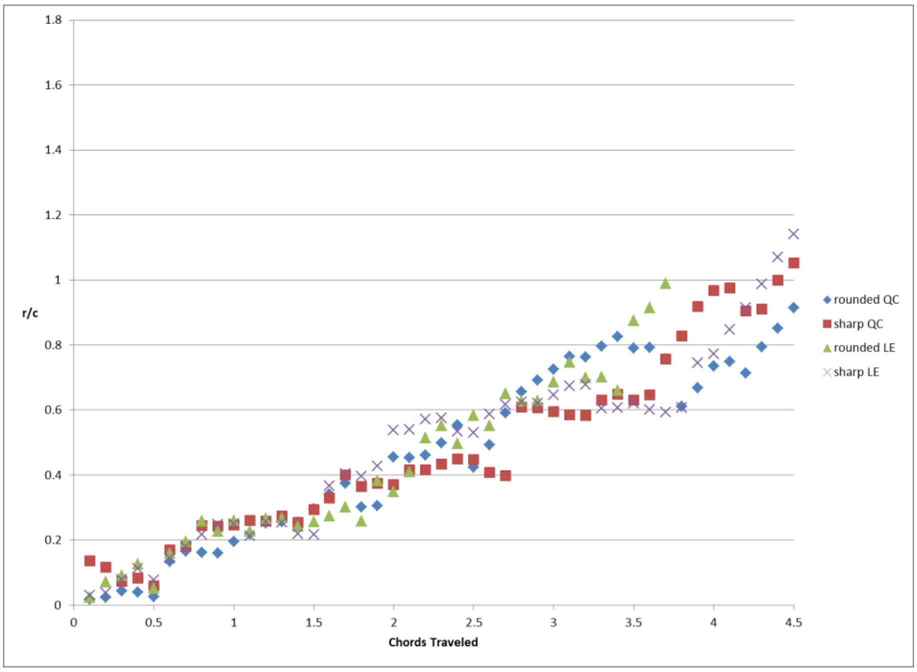

Fig. 7: Variation of the distance of the LEV core to the leading edge of the wing with respect to time when the quarter-span location is illuminated for fast motion case

It becomes difficult to track the LEV studying the slow motion cases. Shear layer instabilities and the contours showing continuously a detachment and reattachment of cells of vertical structures worsen the identification of LEV. However, LEV stays longer in the field of view and it is still possible to conclude that the LEV is slower in the slow motion case in comparison to the fast case as the slope of the plot is milder in Figure 8.

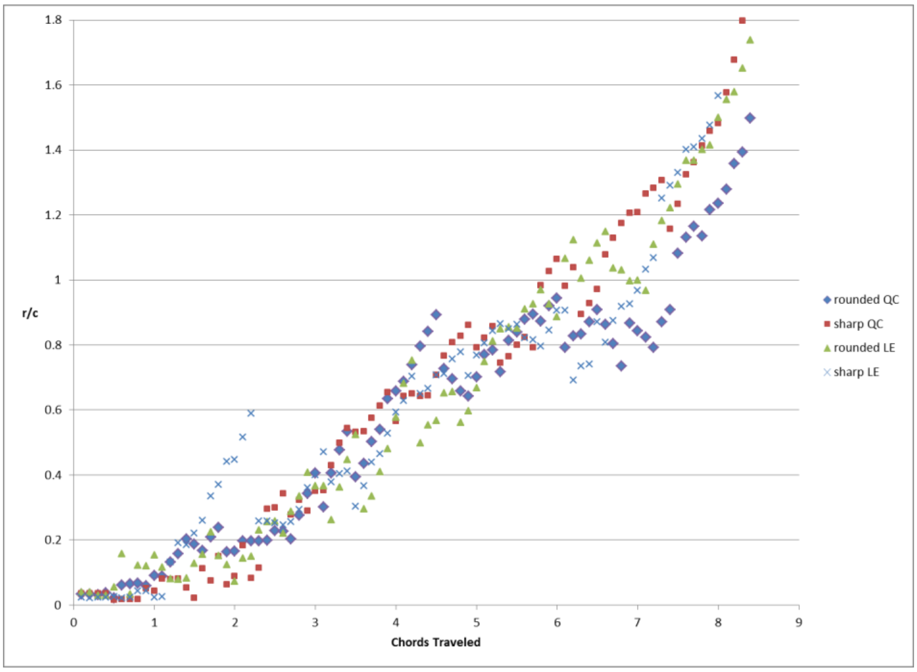

Fig. 8 Variation of the distance of the LEV core to the leading edge of the wing with respect to time when the mid-span location is illuminated for slow motion case

Figures 9 to 11 show the LEV strength with respect to time for the thin rectangular plate. For both illumination planes, the fast motion yields a stronger LEV when the wing rotates about its leading edge. The plots for fast motion cases exhibit a sharp increase followed by a maximum for different cases. This maximum is observed later in time for the wings rotating about quarter chord and indicates the shedding or detachment of the LEV. As a major difference, a second maximum is not apparent for the data obtained illuminating the quarter-span. As aforementioned and can also be concluded from the plot for the slow motion case (Figure 11), it is difficult to identify and track the LEV. However, it is still evident that the LEV gets stronger for the slow motion case and the maximum value is observed before the motion ends.

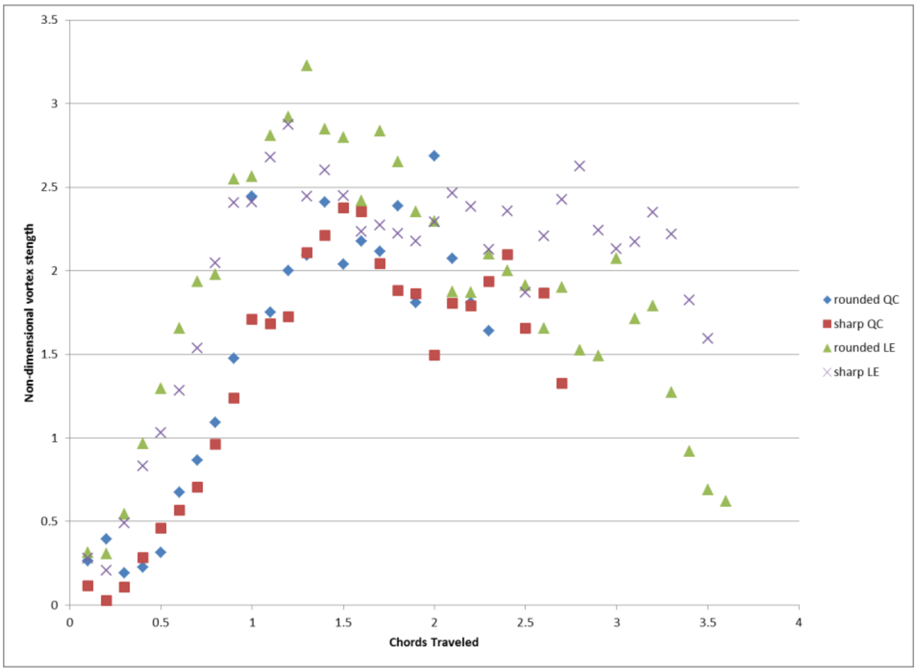

Fig. 9 Variation of the LEV strength with respect to time when the mid-span location is illuminated for fast motion case

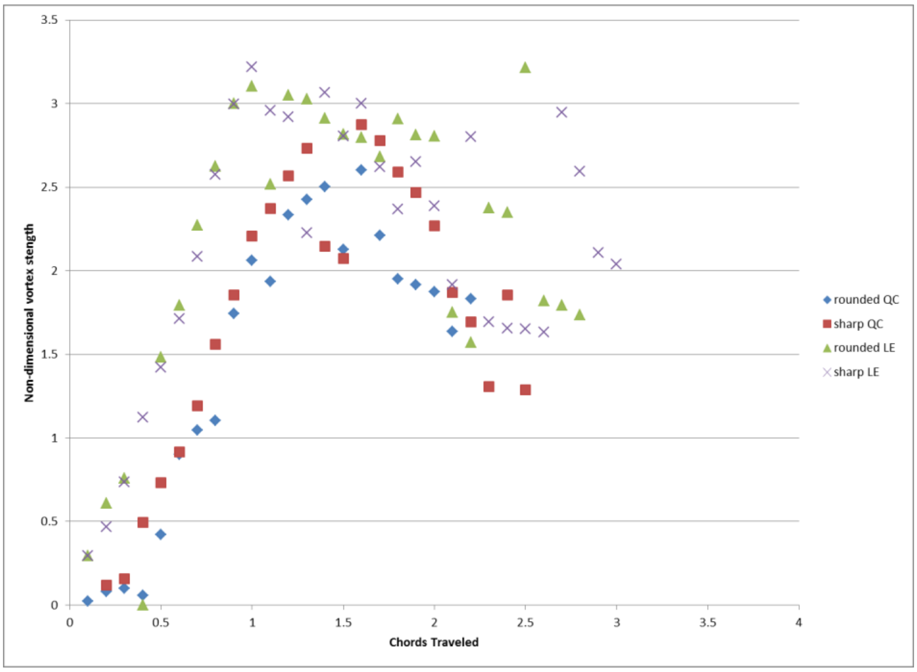

Fig. 10 Variation of the LEV strength with respect to time when the quarter-span location is illuminated for fast motion case

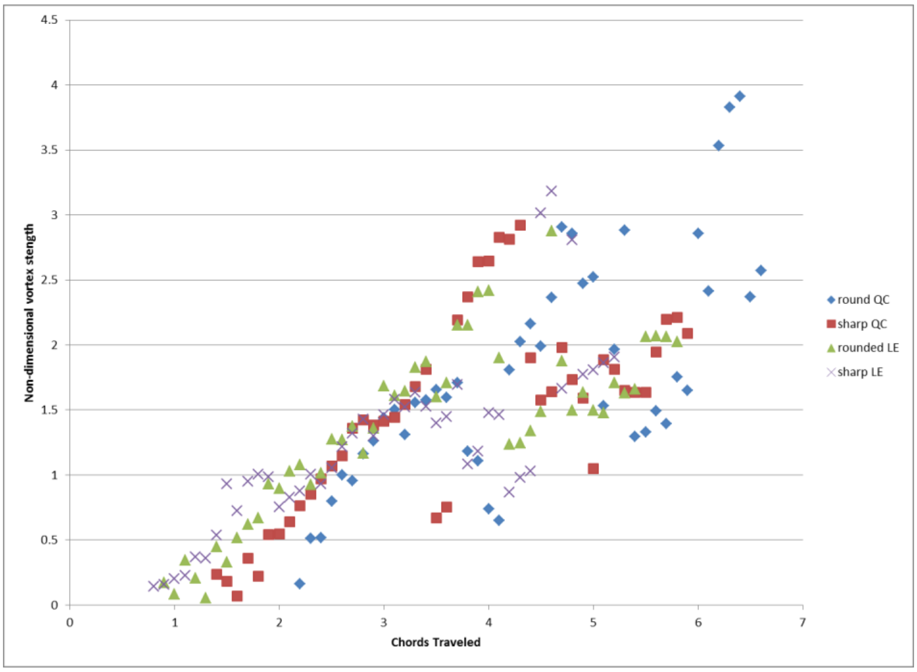

Fig. 11 Variation of the LEV strength with respect to time when the mid-span location is illuminated for slow motion case

Finally the effect of the aspect ratio is visualized for the NACA0012 wing. Figure 12 shows the wing at its end of its motion and the laser illuminates the mid-span for all cases presented. For both aspect ratios, the difference between the fast and slow motion cases is the same as in the thin rectangular plate results; the distance of the LEV to the leading edge is greater at the end of the stroke for the slow motion case. On the other hand, the effect of the aspect ratio is only evident for slow motion case where a roll-up of the LEV is observed for AR=6 whereas the LEV appears more compact and its core is much closer to the leading edge of the airfoil for AR=4.

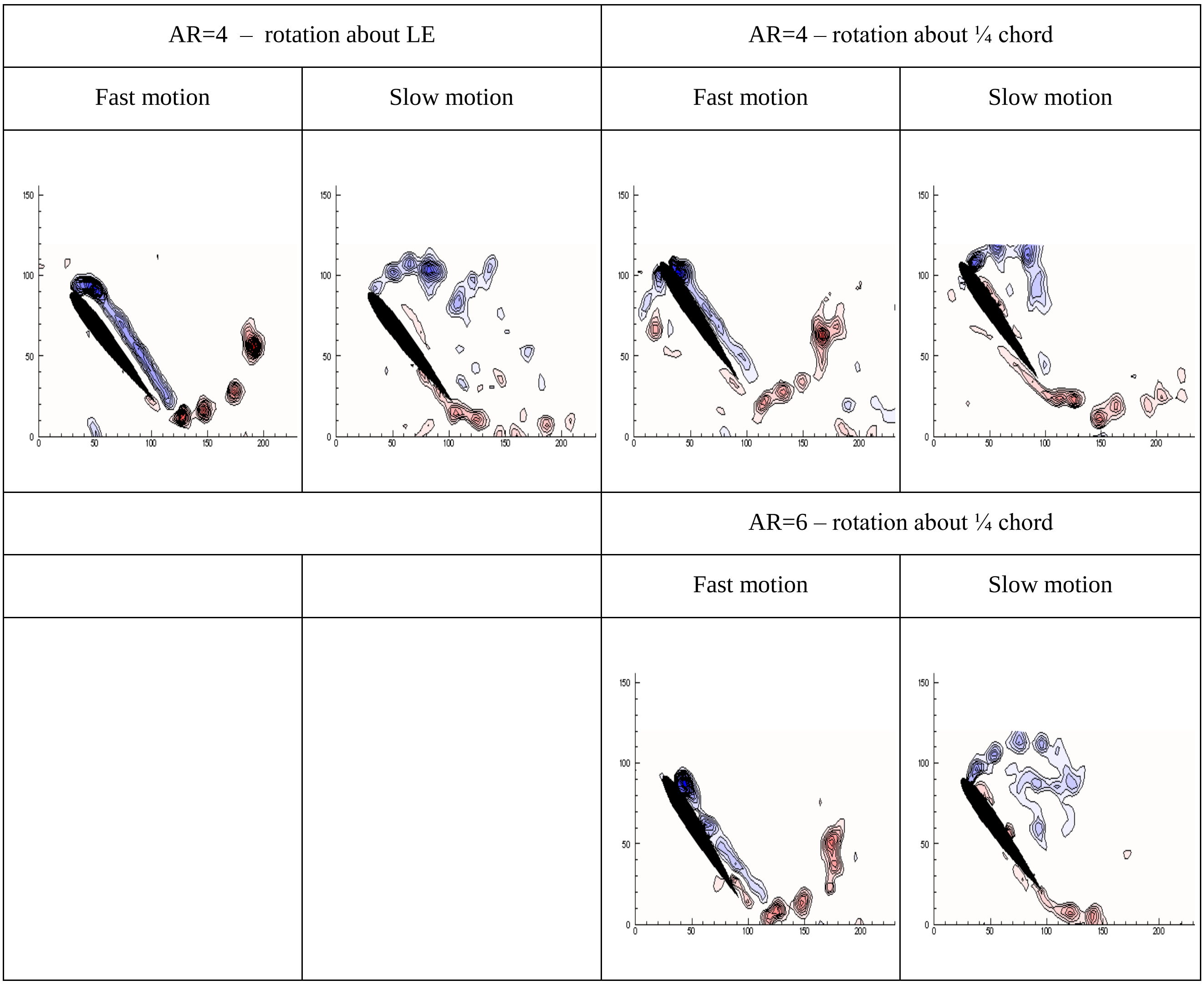

Figure 12: Patterns of vorticity for NACA0012 when the quarter-span location is illuminated

CONCLUSION: The flow structures in the near wake of a wing undergoing a pitch up motion have been investigated using a Digital Particle Image Velocimetry (DPIV) system. The wing is either a rectangular plate or an NACA0012 airfoil with an aspect ratio of 4 or 6. The Reynolds number is 10000 and constant for all cases while the wing pitches up to 45° for different durations of motion. The roundness of the leading edge for the thin flat plate and the rotation axis constitute the other parameters of the study.

Although there are variations for leading edge vortex location and strength between cases studied with different parameters, there are three major concluding remarks which are summarized as follows:

- The leading edge vortex evolution is not scaled with the duration of motion.
- Although three-dimesional effects are present for quarter-span illumination plane, planes closer to the wing tip need to be investigated to establish the interaction of the leading edge and tip vortices.
- As the vorticity patterns include both the shear layer instabilities and the leading edge vortex, a vortex identification method is necessary to better spot and track the leading edge vortex.

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