2D DPIV of a Pitching Aerofoil

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ABSTRACT

This paper presents experimental results from DPIV measurements over a sinusoidally pitching aerofoil with quasi-elliptical cross-section and aspect ratio of 3.3. The aerofoil was oscillated about its mid-chord at representative Strouhal and Reynolds numbers to investigate the generation and development of the flow structure, and the corresponding dependence on these non-dimensional parameters. Results include far-field images that capture both the development of vorticity over the aerofoil and morphology of the wake downstream of the trailing edge, and near-field images of one flow case that detail the interaction of the dynamic stall vortex and the shear layer over the top of the aerofoil.

1. INTRODUCTION

The understanding and manipulation of the flow behind a moving airfoil has potential in applications to modern marine technology. In the case of carangiform and thunniform motion, the cross-section of the caudal fin (tail) can be approximated by an airfoil, and therefore much insight into the thrust production of efficiently swimming fish can be gained by studying the unsteady fluid dynamics of a heaving and pitching airfoil. Studies have shown that efficiencies up to 80\% can be obtained using a propulsive mechanism involving a pitching and heaving aerofoil\textsuperscript{[4]}.

Past experimental work has investigated the structure of the wake and its relationship to thrust generation. Motions for which drag dominates thrust are marked by a Karman street and velocity deficit in the wake. Conversely, a wake consisting of a reverse Karman street indicates the dominance of thrust over drag. Reverse Karman streets are generated, and consequently the greatest efficiencies occur, when the motion falls into a range of the non-dimensional Strouhal number between 0.25 < St < 0.35 \textsuperscript{[1]}. Further investigation into the generation and structure of the wake and its dependence on the variation of non-dimensional parameters is critical and will help in the development of more efficient aquatic vehicles.

In order to obtain quantitative velocity data from airfoil wakes, Digital Particle Image Velocimetry (DPIV) is often used as a non-intrusive measurement technique. In the experiments presented here, 2D DPIV is used to define the velocity field in a single 2D plane of the wake. The airfoil used is 3D and measurements are taken at the mid-span, so any 3D effects in the present results are not pursued. A study of the 3D flow around a pitching and heaving airfoil can be found in \textsuperscript{[2]}.

The motion considered in these experiments was a simple sinusoidal pitching motion. A range of frequencies and external flow velocities were chosen to illustrate Reynolds number and Strouhal number effects on the pitching wake structure. Additionally, a magnified velocity field is also obtained for one flow case in order to obtain a more refined investigation of the dynamics close to the leading edge and the aerofoil surface.

2. EXPERIMENTAL TECHNIQUE

2.1 Apparatus and Method

The experiments are conducted in a water tunnel at the Laboratory for Turbulence Research for Aerospace & Combustion. The working section measures 500mm x 500mm x 1000mm. The turbulence intensity levels in the core region are less than 0.35\%. A full description of the experimental rig is provided in \textsuperscript{[2]}.

A quasi-elliptical cross-section airfoil with chord, \( c = 31 \text{ mm} \) and \( 4R = 3.3 \) is suspended vertically from above the test section. The airfoil performs angular (pitch) oscillations about the mid-chord position using stepper motors. The pitch motor drives the airfoil directly. A motion control program was created in such a manner to allow different motion parameters, such as frequency and maximum pitch oscillation amplitude, to be independently varied, thereby allowing for various motion profiles. The actuation of the motion follows the equation,

\[ \theta = \theta_0 \cos(2\pi ft) \]

where \( \theta_0 \) is the oscillation amplitude and \( f \) is the pitch frequency. All pitching motions were performed symmetrically around the mid-chord point.

Potentiometers are mounted along the pitch axis to provide accurate feedback of the output trajectory of the foils. Optical triggers have been placed at various locations along the airfoil trajectory to provide the trigger signals to the laser and cameras.

The entire oscillating mechanism is mounted on a railing system above the water tunnel, allowing the airfoil setup to be moved to different locations, while the cameras and laser arrangement is kept fixed.

2.2 Data Acquisition

In order to quantitatively analyse the flow, digital particle image velocimetry is utilized. DPIV measurements are conducted for far field regions, which have dimension 2.3c (x-direction) by 1.8c (y-direction), and are captured at a magnification of 0.12. Near field images that investigate the leading edge have a field with dimension 0.89c (x-direction) x 0.71c (y-direction) with a magnification of 0.31.

Images of the pitching motion were collected in a phase locked sense. Real Time Linux was utilized to synch the laser and camera and acquire images at prescribed phase angles of the motion. Eight phases were chosen corresponding to the
zero degree, half amplitude, and full amplitude points on both the upward and downward stroke. At each phase, 100 images were taken, the resulting velocity fields of which were ensemble-averaged.

One Pixelfly CCD camera with an array size of 1280px x 1024px is mounted vertically below the test section. 11µm hollow glass spheres are used as seed particles, and are illuminated by laser light from a dual-cavity New Wave Nd:Yag laser, pulsing 532nm light at 32mJ. A 3mm thick horizontal light sheet is created in the mid-span region of the airfoil using the necessary collimating optics. The DPIV setup is optimised for good image quality. A beam collector is placed on the far side wall of the test section to collect light from the laser.

2.3 Data Analysis
Images were analysed using multi-grid cross correlation digital particle image velocimetry (MCCDPIV) software, developed in-house and described in [4]. Analysis was performed on 100 pairs of single-exposed images per phase-averaged data set. An interactive correlation scheme was employed with a smallest interrogation window of 16 px². Data was reduced using a global histogram filter, a dynamic mean value operator check, and a 4-point Hart filter.

A masking boundary file was created for each set of images to be used by the MCCDPIV software so that areas such as those in the shadow of the aerofoil would be ignored by the analysis. A thin region along the aerofoil surface was included in the masking boundary, as scattering at the surface made this data from this area of the images unreliable.

3. DISCUSSION OF RESULTS
The eight images in Figure 1 (a)-(h) show the $uv$ vector fields for shaded by spanwise vorticity for the ensemble-averaged data obtained from phase-locked image acquisition at the determined angles in the aerofoil motion. This motion is for $St=0.3$ and $Re=1500$. The aerofoil is approximated by an ellipse with major and minor axis appropriately representing the chord and aerofoil thickness, but it should be noted that the leading and trailing edges are sharp in reality, not blunt.

Red vectors areas indicate positive (out of plane) vorticity, while blue indicates negative (into plane) vorticity. The area directly below the aerofoil shows no data, as this area was in the shadow of the aerofoil, and data was unobtainable. The axes are non-dimensionalised by $c$, and the vorticity is non-dimensionalised by $c/U_\infty$.

These plots clearly depict the shedding of oppositely signed vorticity each half cycle of the aerofoil motion. A distinct pairing of oppositely signed vorticity indicating thrust or drag generation is not immediately apparent.

Also clearly shown is the dynamic stall vortex (DSV) created at the sharp leading edge. It is observed that the DSV is generated during the downward stroke of the leading edge of the aerofoil, but as the aerofoil begins to pitch upward, it weakens and the shear layer toward the rear of the aerofoil becomes more apparent. To further investigate whether these two phenomena were related, near-field experiments were performed.

In these images, it is clear from the phases shown in (f) and (g) that the weakening of the DSV and the strengthening and upstream movement of the shear layer are not independent. Image (g) in particular shows the two constructively merging. As the aerofoil continues its upward stroke, the DSV disappears completely and only the thickened shear layer remains, covering the entire upper surface of the aerofoil in image (h). To further describe the event, data from phases at smaller time intervals would need to be obtained. In

![Figure 1](image1.png)

![Figure 2](image2.png)

**Figure 1.** $uv$ vector field, shaded by spanwise vorticity, which is non-dimensionalised by $cU_\infty$, at $Re=500$, $St=0.3$: Downward stroke: (a) 20°, (b) 10°, (c) 0°, (d) -10°, (e) -20°. Upward stroke: (f) -10°, (g) 0°, (h) 10°.

**Figure 2** (a)-(h) shows the $uv$ vector field, shaded by spanwise vorticity for the same flow case and non-dimensionalisation as in Figure 1. However, these images were obtained with twice the resolution in an attempt to resolve the vortical structures and interactions on the upper surface of the aerofoil.
Figure 2. $uv$ vector field shaded by spanwise vorticity, which is non-dimensionalised by $c/U_\infty$, at $Re=500$, $St=0.3$: Downward stroke: (a) $20^\circ$, (b) $10^\circ$, (c) $0^\circ$, (d) $-10^\circ$, (e) $-20^\circ$. Upward stroke: (f) $-10^\circ$, (g) $0^\circ$, (h) $10^\circ$.

particular, information about the activity between the phases shown in Figure 2(f) and (g) would help to describe the interaction in more detail.

Initial results relating to the parameter study are shown in Figure 3. These plots are for five successive phases in the aerofoil motion, and the two columns present a comparison

Figure 3. Comparison of the $uv$ vector fields shaded by spanwise vorticity, which is non-dimensionalised by $c/U_\infty$, for flows at conditions (a) $Re=1500$, $St=0.2$, and (b) $Re=1500$, $St=0.3$ between the wake generation for two flows at the same Reynolds number, but at different Strouhal numbers. It is seen here that the motion of a higher $St$ (b) produces a symmetrical wake, while the motion of a lower $St$ (a) produces an oblique wake. The oblique wake includes pairings of oppositely signed vorticity that would induce jets in the upstream direction, indicative of drag production. A distinct pairing of
vorticity is not apparent for the high St, and it is inconclusive whether this motion produces thrust or drag.

4. CONCLUSIONS

2D DPIV was performed on a purely pitching aerofoil. Data was collected in a phase locked sense, and the presented data for each phase was ensemble averaged over 100 instantaneous fields. Initial images were taken of the far field to investigate the full wake generated by the unsteady aerofoil. Additional experiments were performed to resolve interaction between the dynamic stall vortex and the aerofoil shear layer. It is concluded that there is a marked interaction between the two, but further experiments are needed to fully describe the event. Initial parameter studies also indicate that the wake structure has a marked dependence on Strouhal number, with lower St motion generating an oblique wake and higher St motion generating a symmetric wake. Future experiments will also work to resolve the velocities subsequently the vorticity at the aerofoil surface.

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REFERENCES


