Wake Measurements of a Pitching Plate using Multi-component, Multi-dimensional PIV Techniques

A-J. Buchner¹, N. A. Buchmann¹ and J. Soria¹

¹Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC)
Department of Mechanical and Aerospace Engineering
Monash University, Victoria 3168, Australia

Abstract
Unsteady aerodynamics in the low Reynolds number domain is of great importance to the development of Micro Air Vehicles (MAVs). The low Re flow over, and in the wake of, pitching aerofoils is not well understood. This paper extends previous work [11] to multi-dimensional (3D), multi-component (3C) measurements of this phenomenon by using Tomographic Particle Image Velocimetry (Tomographic PIV). The three-component, three-dimensional (3C-3D) velocity fields in the wake of a flat plate undergoing a pitch-hold-return motion is investigated. The experiments are conducted in a water tunnel at a Reynolds number of 7,500 and a dimensionless pitching rate of $K_c = 0.93$. The evolution of the trailing edge vortices is investigated, highlighting the three-dimensional organisation of the coherent vortex structure.

Introduction
This paper presents the results of an experimental investigation into the low Reynolds number flow in the wake of a rapidly pitching flat plate with rounded leading and trailing edges. By applying tomographic PIV to a canonical pitch-hold-return problem, the three dimensional topological evolution of the wake can be studied in the context of already existing two-dimensional data. Understanding of the nature of such flows has application in the design of biomimetic inspired micro air vehicles (MAVs) and builds upon the more traditional work done in unsteady and transient flows over foils which has in the past been mainly focussed on the higher Reynolds number regime with application to dynamic stall, manoeuvre and gust response. Previous work [1, 16, 22, 6] has concluded that at low Reynolds it becomes necessary to use separation induced leading edge vortices in the production of lift and thrust. By combining pitching and heaving motions the desired vortices, and hence forces, can thus be produced.

Conventional aerodynamic models do not easily account for the phenomena observed in low Reynolds number transient flows, and only basic knowledge of the physics involved exists at this time. Early experiments investigating the effect of time varying pitching motion reported the production of a normal force vector with fluctuating thrust and lift components depending on the instantaneous angle of attack [1]. More recent studies by Eldredge et. al. [6] have investigated the sensitivity of leading and trailing edge vortex structures to variations in pitch pivot point, and pitch rate. The former was found to have a significant effect mainly on the formation of the leading edge vortex and its size while the latter tends to produce a tighter leading edge vortex if increased. For higher dimensionless pitch rates, a counter-rotating vortex pair dominates the trailing edge vortex structure whilst at lower rates the flow field tends to exhibit a stream of smaller vortices with less domination by any particular structures. Both the trail of smaller vortices, and the larger counter-rotating pair were also observed in the stereoscopic PIV investigation of Kilany et.al. [11]. Under these conditions the leading edge vortex has a tendency to be more diffused and of lower peak vorticity than an equivalent vortex produced at the trailing edge at the same axial location [12]. The current set of results correlates well with those already published on 2D data, whilst extending the work to look more in-depth at the 3D effects expected within the vortical wake structures.

Principle of Tomographic PIV
The tomographic PIV technique allows the reconstruction of a 3C-3D velocity field, and thus also yields all nine components of the velocity gradient tensor. A volume of the seeded flow is illuminated by means of a thick light sheet, and the intensity distribution is recorded by three or more cameras (in this case, four). Triangulating the intensity distributions recorded by each camera allows individual particles to be located in three-dimensional space, a process is carried out by the Multiple Line of Sight Simultaneous Multiplicative Algebraic Reconstruction Technique (MLOS-SMART) algorithm [3]. The use of this algorithm significantly speeds up the reconstruction process when compared with the currently ubiquitous Multiplicative Algebraic Reconstruction Technique (MART) algorithm by excluding voxels containing zero return intensity. In the same manner as for planar or stereoscopic PIV, the intensity distribution is segmented into interrogation windows, or volumes in the three-dimensional tomographic case, and cross correlated to determine the 3C-3D velocity field.

Proposed by Atkinson and Soria [3], the MLOS-SMART algorithm significantly reduces the computation cost of 3C-3D velocity field reconstruction. The volume fraction of voxels with significant intensity within the reconstruction volume will typically be of the order of only 5% as it has been shown that 10-15 particles per interrogation region is sufficient for obtaining a valid displacement vector estimate [10]. This means that approximately 95% of the reconstructed volume will have a negligible intensity and can be excluded from the reconstruction process, thus reducing computational and data storage requirements (see Atkinson and Soria [3] for more details). Following the volume reconstruction, the 3D particle intensity fields are evaluated with a 3D spatial cross-correlation routine [25] to determine the instantaneous 3C-3D velocity fields.

Experimental Conditions

Apparatus
The Monash University horizontal water tunnel facility operated by the Laboratory for Turbulence Research in Aerospace and Combustion (LTRAC) was used for these experiments. The tunnel has a long, 5000mm, test section with a $500mm \times 500mm$ square cross-section. The freestream turbulence level is less than 0.5%, and the velocity profiles are uniform over the test section by 4000mm from the contraction [16]. This is where the experiments are conducted, at approximately the centreline of the tunnel. A carbon fibre flat plate, dimensionally similar to that used by Ol [14], with rounded edges, chord length 100mm, span 470mm and thickness of 2.3mm is used for the current experimental investigation.

Figure (1c) gives an overview of the experimental setup. The vertically mounted flat plate is driven by a Rorze stepper motor (figure (1b)) with a drive resolution of 80,000 steps per revolution to pitch around the half chord point. The stepper motor is controlled by an in-house program for a Motion Architect AT6400 multi-axis motor controller.

Optical Arrangement
The imaging equipment consists of five PCO.4000 digital CCD
The free-stream velocity and the seeded flow (54nm nylon spheres, \( \rho = 1.01g/cm^3 \)). A 240mJ pulsed, dual-cavity Nd:YAG laser is used to illuminate the use of water filled glass prisms. As the image plane and subject plane are not parallel, the Scheinplug condition is invoked to correct the image focus gradient. The cameras are calibrated using the method described by Soloff et al. [23] through a thickness of 12mm and the resulting calibration error of approximately 1-2 pixel. A more detailed description of the tomographic PIV parameters are reduced via self calibration [27] to between 1-2 pixel. The cameras are calibrated to yeild a 12mm thick light sheet with well defined boundaries. Optical refraction effects are minimised through the use of water filled glass prisms. As the image plane and subject plane are not parallel, the Scheinplug condition is invoked to correct the image focus gradient. The cameras are calibrated using the method described by Soloff et al. [23] through a thickness of 12mm and the resulting calibration error of approximately 10 pixels is reduced via self calibration [27] to between 1-2 pixel. A more detailed description of the tomographic PIV parameters is given in Table (1).

A 240mJ pulsed, dual-cavity Nd:YAG laser is used to illuminate the seeded flow (54nm nylon spheres, \( \rho = 1.01g/cm^3 \)). It is focussed into a thick light sheet which is truncated through a slit to yeild a 12mm thick light sheet with well defined boundaries. The lightsheet is shone lengthwise through the test section of the tunnel, from the downstream direction. The double-shutter exposure delay of 6ms is set to give a freestream average particle displacement of 12 pixel (0.48mm). The thick laser sheet minimises through-plane velocity reconstruction errors as less particles are lost or gained to the lightsheet during the exposure delay.

**Pitching Plate Motion Profile**

Each cycle, the plate pitches linearly to a maximum angle of \( \theta = 40^\circ \), holds for 0.05 \( t/T \), and returns to its zero position. This is repeated after a pause of 20 time periods (\( T = 1sec \)). The transient pitch-hold-return motion of the flat plate is shown in Figure (2) and characterised by the non-dimensional velocity ratio:

\[
K_c = \frac{c\theta}{2U_\infty}
\]

where \( \theta \) is the constant angular velocity of the flat plate, \( U_\infty \) the free-stream velocity and \( c \) the chord length. The Reynolds number is defined as \( Re = \frac{U_\infty c}{\nu} \). A summary of the current experimental parameters, which are identical to those used in previous stereoscopic PIV experiments by Kilany et al. [11], is given in Table (2).

**Data Processing and Analysis**

To take full advantage of the MLOS-SMART algorithm, it is desirable that the background intensity is removed to increase the number of zero-voxels. Background subtraction, band-pass filtering and then Gaussian smoothing are applied to help equalize the particle intensities across the image and between cameras. Volume reconstruction is performed with 10 iterative corrections of the MLOS-SMART technique and an initial solution and relaxation parameter of unity. The volume over which the particle intensities are reconstructed and cross-correlated is 3500 \( \times \) 2250 \( \times \) 350\text{pixels} (table (1)).

The velocity fields are calculated with an in-house developed multigrid multi-pass FFT-based cross-correlation algorithm [25]. Interrogation volumes of 64\(^3\) voxels (\( \approx 2.56\text{mm} \)) with 50\% overlap are used to provide fields of 98 \( \times \) 65 \( \times \) 9 vectors. A normalised local median filter [26] and a maximum displacement constraint are used to validate vectors and a maximum displacement limit.

### Table 1: Parameters of the Tomo-PIV system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cameras</td>
<td>4008 ( \times ) 2672\text{px} ( \times ) 16\text{bit}</td>
</tr>
<tr>
<td>Laser</td>
<td>Nd:YAG, 240mJ</td>
</tr>
<tr>
<td>Flow Seeding</td>
<td>54nm nylon spheres, ( \rho = 1.01g/cm^3 )</td>
</tr>
<tr>
<td>Imaging Properties</td>
<td></td>
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<tr>
<td>Magnification</td>
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<tr>
<td>Resolution</td>
<td>25\text{px/mm}</td>
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<tr>
<td>FoV(( \Delta x \times \Delta y \times \Delta z ))</td>
<td>3500 ( \times ) 2250 ( \times ) 350\text{px} ( ^3 )</td>
</tr>
<tr>
<td>Depth of field</td>
<td>( \approx 12\text{mm} )</td>
</tr>
<tr>
<td>Particle image diam.</td>
<td>( \approx 2.3\text{px} )</td>
</tr>
<tr>
<td>Max. Displacement</td>
<td>12\text{px}</td>
</tr>
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</table>

### Table 2: Experimental parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c )</td>
<td>100mm</td>
</tr>
<tr>
<td>( U_\infty )</td>
<td>75mm/s</td>
</tr>
<tr>
<td>( \theta )</td>
<td>0 – 40\text{deg}</td>
</tr>
<tr>
<td>( Re )</td>
<td>7,500</td>
</tr>
<tr>
<td>( K_c )</td>
<td>0.93</td>
</tr>
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</table>

Figure 2: Measured pitch angle of the flat plate as a function of \( t/T \), with flowfield acquisition points marked. (a) \( t/T = 0.24 \), (b) \( t/T = 0.47 \), (c) \( t/T = 0.77 \), (d) \( t/T = 1.0 \), (e) \( t/T = 1.5 \), (f) \( t/T = 2.5 \) with \( T = 1sec \).
Invalid vectors (approx 2% of total) are replaced via a mean vector interpolation. For visual representation of the data, the velocity fields are filtered with a $3 \times 3 \times 3$ Gaussian kernel ($\sigma = 1$) to suppress noise fluctuations in the velocity gradients [20, 29]. As the filter kernel is equal to the interrogation window size, the spatial frequency response remains unaffected.

Results and Discussion

The instantaneous flowfields in figure (3) demonstrate the instantaneous flow structure in the wake of the pitching plate. Significant regions of circulation are shed during both the pitch, and reverse, motions and convect downstream at roughly the velocity of the freestream. These regions are indicated in the figure by blue and red shading, denoting vorticity of opposing sign. The overlaid black contour lines are lines of constant spanwise velocity ($w$), and illustrate the true three-dimensional nature of this ‘nominally’ two-dimensional experiment. The dashed lines represent negative (into page) velocity. They are spaced at intervals of $w = 2$ mm/s.

At $t/T = 0.24$ (figure (3a)), circulation has begun to be produced by the angular acceleration from a standstill of the plate trailing edge. The circulation produced convects downstream and is replaced by circulation of the opposite sign produced by the plate as it pitches back to its resting position. The evolution of these vortex structures as they move away from the trailing edge is complex. In the phase averages, it is clear that what are initially well structured strings of vortex filaments begin to coalesce into more disparate counter-rotating vortex pairs as they move downstream. Though the length of this paper prohibits the publication of phase averaged plots, this effect can be seen quite clearly in the evolution of the instantaneous fields from figure (3c-d) to figure (3e). The topology of these flows compares well with previously published data [11, 14]. The leading edge vortex does not enter the field of view until approximately $t/T = 2.5$. This vortex is of significantly larger size than the vortices produced at the trailing edge.

It can readily be observed that regions of high vorticity are accompanied by associated spanwise velocity components, and also high gradients of such. This could be indicative of the presence of vortex stretching as described in [18]. The spanwise velocities are apparent right from the point of circulation production, at the trailing edge, but become more concentrated with time and convection downstream until the magnitude of spanwise flow drops off by $t = 1.5T$. During the pitching motion cycle the maximum spanwise component to be expected is of the order of 10% of the stream velocity. Figure (3f) shows an instantaneous flowfield at $t = 2.5T$. The leading edge vortex has begun to move into the field of view and, associated with it, are strong spanwise velocity gradients. Most of the region within the leading edge vortex core displays strong spanwise flow, which peaks at approximately 85% of the freestream velocity. It is interesting to note that with phase averaging these regions of strong spanwise flow tend to cancel and so it is observed that the spanwise velocity is not of constant sign over a number of phases.

Concluding remarks

Investigations to date such as Parker et al. [15] show the three-dimensionality of flows past a finite span pitching aerofoil, but fail to address the existence of three-dimensional structures within the unsteady vortex sheet produced by a nominally infinite oscillating aerofoil. In employing tomographic PIV techniques to this problem, these flows were shown to contain significant spanwise axial flow components indicative of the presence of vortex stretching, as described in Petitjeans and Wesfried [18]. The 3C-3D flow fields provided by the tomographic PIV methods in the present study show this phenomenon qualitatively as well as quantitatively, and provide the basis for further investigations into the substructure of the vortex filaments.
Acknowledgments
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References