Investigation of the Orthogonal Blade-Vortex Interaction

1st Interim Report

by

J.M. Early* & R.B. Green†

Department of Aerospace Engineering
University of Glasgow
Glasgow
G12 8QQ
Scotland

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* Research student
† Principal Investigator

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J.M. Early, R.B. Green

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Department of Aerospace Engineering
University of Glasgow
Glasgow
Scotland
G12 8QQ

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Abstract

Steps towards the implementation of a stereoscopic particle image velocimetry (PIV) system for the investigation of the orthogonal blade-vortex interaction are described. The design of the stereo PIV system used is described, and details of the Scheimpflug camera mounts are provided. The necessary changes to the image capture and calibration procedures are described, and brief details of the stereo PIV analysis are given. This is essential preparatory work for the experimental study of the orthogonal blade-vortex interaction using stereoscopic PIV to take place later in this project.

1. Introduction

One of the mechanisms for noise generation and high impulsive loading on helicopter tail rotor blades is the orthogonal blade-vortex interaction (BVI). Here the vortex wake from the main rotor is skewed backwards by the oncoming flow, and the tail rotor blades cut across the vortex core; in the limiting orthogonal case the local vortex axis is normal to the plane of the blade. As opposed to the distinctive blade slapping sound of the parallel blade-vortex interaction, the orthogonal interaction is often characterised by a 'bubbling' sound. An understanding of the mechanism of the orthogonal BVI is essential if adverse vibration effects are to be reduced and quieter helicopters be developed.

Research conducted during the USARDSG-UK funded study on orthogonal blade-vortex interaction between 1st September 2000 and 31st August 2001 (Early et al. (2001)) applied a two-dimensional, two componentPIV system to an experimental model of the orthogonal BVI. Through the use of the PIV technique, the flow associated with the orthogonal blade-vortex interaction was examined, recording the progression of the interacting vortex over either side of the interacting blade. One of the most important features observed during this interaction process was the highly three-dimensional nature of the interaction process, which could not be fully accounted for using the current measuring system. The main disadvantage of the use of the 'classical' PIV system is that the recording obtained is only of the projection of the velocity vector in a two-dimensional plane, and any out-of-plane components are completely lost. In the case of flows where the out-of-plane component is significant, this can lead to an unrecoverable error in the local velocity vector. Although this projection error may be kept to a minimum by selecting a large viewing distance compared to the imaged region, it is still not possible to fully resolve both the in and out-of-plane components.Additional knowledge of this third component is required in many areas of investigation (Willert, 1997). For the current case, both the in-plane flow, determining the shape of the vortex core, and the core axial flow, which is modified during the interaction due to the blocking effects, need to be recovered, which is not possible using the two-component technique. Although there are a variety of techniques by which this may be accomplished (for example, holographic PIV and dual-plane PIV), the most straight forward to implement is through the use of an additional camera viewing from different viewing axis. This is commonly referred to as the stereoscopic PIV technique. The approach to the stereoscopic technique may be taken in two ways, either the use of the lens translation method, or the angular lens displacement with a tilted backplane (Scheimpflug condition). Due to problems with the maximum viewable area when applying the translational method (Prasad & Adrian, 1993), the angular displacement method is more appropriate for this application.

The current research project is to perform an investigation of the orthogonal BVI using a stereoscopic PIV technique, to follow on from the previous USARDSDG-UK sponsored study. This interim report describes the progress with the implementation of the stereoscopic PIV system.

2 Development of the stereoscopic PIV system

2.1 Angular displacement technique and the Scheimpflug condition

In the implementation of the angular displacement method the object plane is no longer parallel to the lens plane. In this case, it becomes increasingly difficult to obtain particle images that are well focussed throughout the image plane due to the perspective effects. This is overcome through the application of the Scheimpflug condition. The Scheimpflug condition states that for an object to be correctly in focus, the object plane, lens plane and image plane must all meet in a common line (Merklinger, 1996). Although this allows the object to be focussed correctly, it also leads to a non-uniform magnification across the image plane, which has to be accounted for in any calculation of the velocity vector. To achieve the Scheimpflug condition the camera and lens have to be on separate mounts to allow for tilt and shift of the image plane relative to the lens plane. Accurate calibration is essential if the non-uniform magnification is to be properly accounted for. The calibration is performed using a target of regularly spaced white dots on a black background in order to identify a set of known points in space to build up a relationship between the image and object planes. For reconstruction of the velocity field from the two sets of images recorded from the angular displacement method, the displacements of the particles in the images may be calculated using simple geometric relationships. This reconstruction of the three-dimensional data is approached through the back projection of the data from the imaging plane to the object plane. The most flexible approach is the use of the calibration method, then the use of a generalised function to project the data from the image to the object plane. The projection may then be performed in two ways, either involving the back projection of the image pixel data (known as mapping), or back projection of the displacement vector data (known as warping).

In order to compute the three-component displacement vector field, the two- component vector field is first computed for each of the camera viewing angles using a standard PIV technique. The three component displacements are then calculated from the two component vector fields. This is done through a generalised back projection, which uses a generalised function to connect a point within the image plane to the object plane, and vice versa. Several functions have been suggested to accomplish this: second order polynomial (Soloff et al., 1997), second order rational polynomial for a two-dimensional calibration (Willert, 1997) and bicubic splines for a three dimensional calibration scheme (Van Oord, 1997). All of these methods are based upon using deviations from an ideal geometry. The following is the method by which this reconstruction is accomplished, as described by Willert (1997). This is an outline of the second order rational polynomial method.

If it is assumed that both cameras are focussed on a single region, the co-ordinates of the area in the sheet can be given by $L_1(x_1,y_1,z_1)$ and $L_2(x_2,y_2,z_2)$, where 1 and 2 refer to the two different cameras (assume pinhole lens). A point P (x_p,y_p,z_p) in the region of interest would be observed to have the displacements (dx_1,dy_1) and (dx_2,dy_2) from the two different viewing angles. The lightsheet may be assumed to be zero-thickness, since the distance from the imaging plane to the object plane will be of several orders of magnitude bigger. The angle that is enclosed by the lightsheet normal and the viewing ray is α_1 and α_2 for the separate camera viewing angles within the x-z plane, and similarly $\beta_1$and β_2 in the y-z plane.

These can then be reconstructed to give:

$$dx = \frac{dx_2 \tan\alpha_1 - dx_1 \tan\alpha_2}{\tan\alpha_1 - \tan\alpha_2}$$

$$dy = \frac{dy_2 \tan\beta_1 - dy_1 \tan\beta_{21}}{\tan\beta_1 - \tan\beta_2}$$

$$dz = \frac{dx_2 - dx_1}{\tan\alpha_1 - \tan\alpha_2} = \frac{dy_2 - dy_1}{\tan\beta_1 - \tan\beta_2}$$

This is only a general equation for the described arrangement, and given the conditions, it may be necessary to modify it. If the cameras (and hence the imaging planes) are at the same height, β_1 and β_2 will become very small, and as such, $\tan\beta_1$ and $\tan\beta_2$ will do so correspondingly. This means that only certain forms of these equations can then be used to determine the dy and dz components (which are both dependent upon β and $\tan\beta$).

There are two equations that may be used to determine the dz component, which makes the problem here easy to overcome. The equation governing dy may then be modified to:

$$dy = \frac{dy_1 + dy_2}{2} + \frac{dz}{2}(\tan\beta_2 - \tan\beta_1) = \frac{dy_1 + dy_2}{2} + \frac{dx_2 - dx_1}{2}\left(\frac{\tan\beta_2 - \tan\beta_1}{\tan\alpha_1 - \tan\alpha_2}\right)$$

To be able to use this reconstruction, there are a series of steps that need to be addressed first. The displacement data must first be converted from the image plane to the corresponding true displacements within the global coordinate system, which involves the implementation of a calibration technique.

The projection between the object plane (X_o,Y_o) and the image plane (X_i,Y_i) may be expressed as:

$$\begin{bmatrix} w_o X_o \\ w_o Y_o \\ w_o \end{bmatrix} = \begin{bmatrix} a_{11} a_{12} a_{13} \\ a_{21} a_{22} a_{23} \\ a_{31} a_{32} a_{33} \end{bmatrix} \begin{bmatrix} w_i X_i \\ w_i Y_i \\ w_i \end{bmatrix}$$

where w_o and w_i are both constants and a_{33}=1. This may then be used to express the standard coordinates in terms of non-linear expressions, which may then solved using the Levenberg-Marquardt method for non-linear least squares in order to obtain a first approximation for the reconstruction coefficients. By extending the expressions for the coordinates to higher orders, camera aberrations such as pincushioning and barrelling may be accounted for and the initial solution be used for calculation of the coefficients.

2.2 Implementation of stereoscopic capability into existing PIV system

The basic PIV system at Glasgow consists of the illumination and image capture systems as follows. Illumination is provided by two frequency doubled, double-pulsed Spectra-Physics Nd:YAG lasers (model Lab 130-10), and the lasers can be used independently or together. The laser light sheet is delivered into the working section of the wind tunnel (in this project a 3′ x 3′ low-speed return tunnel) by a system of mirrors, a beam shaping telescope and a cylindrical lens. Two Kodak Megaplus ES1 digital video cameras (operating in triggered double exposure mode) with dedicated National Instruments PCI-1424 digital frame grabbers are used for image capture, and the lasers, cameras and frame grabbers are synchronized using a National Instruments PC-TIO-10 counter timer card with buffered output. The frame grabbers and counter timer card are fitted into a desktop PC, and the PIV image capture system is programmed using LabVIEW®. The Scheimpflug mounts are assembled from off-the-shelf optical mounts, and allow for accurate setting of camera azimuth, lens shift and azimuth of the whole system relative to the laser sheet plane. The two cameras and mounts are supported on a single piece of precision optical rail to allow for fine and accurate adjustment of camera separation distance.

Minor amendments to the image capture system had to be made for the stereoscopic PIV. For the normal mode of operation of the PIV system the user may choose single or dual camera mode PIV; the dual camera mode PIV has been used previously for capturing transient phenomena in different areas of the flow field (e.g. Green et al. (2000)), for example. For the stereoscopic system the dual camera system was set up as the default, and as the cameras would be trained on the same area of the flow field the cameras would be triggered simultaneously. This is a hardware side problem, and simply requires that the camera and frame grabber triggers be connected into the same respective output timer channels on the camera/ laser/ frame grabber synchronizer interface. Raw PIV images are saved to disk in TIFF format, and the filenames are given a unique identifier for the camera they were recorded with.

Careful spatial calibration is essential for stereoscopic PIV. The calibration is required not just for mapping the image plane onto the physical plane, but also for providing data for the image de-warping transfer function which is an essential step in calculating the out-of-plane velocity component. A calibration grid consisting of 1mm diameter holes drilled through a 20cm square, 2mm thick aluminium plate has been manufactured. The holes are spaced at 5mm intervals over a square grid covering the plate. To allow fine alignment of the calibration grid with the laser sheet the plate is fixed onto a lockable ball and socket mount fixed on short rails. The plate is black anodized and backlit so that the holes stand out when illuminated. An essential part of the de-warping procedure is that the calibration images from the two cameras are aligned. To achieve this three of the holes in an L-shaped pattern in the centre of the calibration plate are drilled to a larger diameter than the others; these are the control points, and when the calibration plate is backlit they stand out clearly. The LabVIEW® system is programmed to display the images from the two cameras simultaneously when the system is being set up. Once the calibration images are captured they are processed using the LabVIEW® system; the centroids of the illuminated dots are determined, the user selects the control points manually, and the data are saved in a file on the hard disk.

2.3 Stereoscopic PIV analysis methodology

The raw data is processed to produce PIV vector maps basically by a standard cross-correlation technique. The Forward-Reverse Tile Test scheme (Green at al. (2000)) is used to enhance vector map quality before a more traditional nearest neighbour vector map post-processor is applied. Super-resolution and particle tracking are also possible using the PIV analysis system. The PIV processing methodology is programmed using MATLAB, which allows a multi-platform capability for PC, UNIX and MacOSX. A graphical user interface (GUI) provides ease of use of the PIV processor. The stereoscopic analysis described above is included into the MATLAB GUI by means of a button which simply calls up a function that performs the various operations to extract the out-of-plane velocity component. The stereo analysis code has yet to be completely debugged and tested.

3. Research plans for remainder of contract period

At present the camera mounts are complete. Owing to wind tunnel usage, however, the system has not been tested yet (the tunnel is occupied by undergraduate laboratories throughout October and November). The image capture system itself has been tested, so the system testing can focus upon use of and familiarisation with the camera mounts. For the calibration system standard PIV images available on the internet have been used as test images, and the actual calibration images from the present system will be similar

4. Administrative actions (staffing)

The significant administrative action was the appointment of the research student, Ms. Juliana Early, onto the current project. She was employed during the initial USARDSG-UK sponsored study from 1st September 2000 to 31st August 2001, in which the groundwork for the current project was laid down.

Technician support for the project is provided by a mechanical technician, Mr. D. Perrins. He assists with any adjustments to the mechanical operation of the test facilities, i.e. the wind tunnel and the rotor rig, and with the construction of the camera mounts.

5. References

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Appendices

A. Financial statement

A breakdown of the funds so far used is as follows. The exchange rate of £1=$1.51 was valid on 28th November 2002.

Equipment	£2438
Studentship + fee	£3373
Consumables	£655
Technician salary + overhead	£441
Total	£6907 ($10429)

Balance remaining **$21571 = £14285**

B. Important property acquired during present report period

No significant property was acquired during the present period. The equipment expense is for lenses and mounts for the construction of the Stereo PIV system.