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Tracking the Vortex Core From a Surface-piercing Foil by Particle Image Velocimetry (PIV) Using Fluorescing Particles

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Abstract

Hydrofoiling sailing yachts are becoming more prevalent and the use of hydrofoils are of critical importance within areas of maritime transportation where both speed and energy efficiency are the key drivers. For example the 2013 America's Cup was sailed on hydrofoiling catamarans, the next cup will be on similar vessels in 2017. Cavitation and ventilation are inevitable in such craft, due to the speed and loading of the hydrofoils, sparking a renewed interest in controlling such phenomena close to free surfaces. Indeed the higher these boats fly, the faster they go, prompting all proponents of these craft to push the limits of cavitation and ventilation. A mode of ventilation involving tip vortex ventilation has been identified, therefore tracking tip vortices is critical to understanding the effects of design changes.

To establish a method of tracking vortices near a free surface, the wake flow around the tip of a surface piercing flat plate at an angle of incidence was studied using 2D Particle Image Velocimetry (2D PIV) in the Australian Maritime College (AMC) towing tank. The results are compared to the benchmarking work presented by the Hydro Testing Alliance (HTA).

Issues affecting signal to noise ratio, such as specular reflections from the free surface and model geometry were overcome through the use of fluorescing particles and a high band pass filter on the camera. A bespoke periscope enabled in-situ control of camera aperture and focus, maximising image quality whilst providing underwater access to the area of interest and security for the optical equipment. These enhancements resulted in a very clean data set as compared to the benchmarking results provided by the HTA.

Images were captured at two image planes over run lengths exceeding 6 m. Uniform seeding was achieved with minimum interruption through the use of a seeding rake while returning the carriage for each subsequent test run. Images were post-processed and vector fields, vector core location and kinetic energy were calculated. Comparison of the mean flow fields, show the results of the AMC in agreement those of the HTA when studying flows in close proximity to either the free or model surfaces.

Introduction

Hydrofoils on sailing yachts operate in critical proximity to the sea surface. When foils operate in this regime, tip ventilation, where a pathway is formed through tip vortex interaction with the free surface has been observed [2, 4]. Small amounts of ventilation may result in a ventilated cavity either from the tip or flap termination, that may trail for a period of time before detaching [5]. More extensive ventilation via the same route will result in sheet ventilation of the foil and a catastrophic loss of lift resulting in the vessel crashing down, which with speeds often exceeding 20 ms^{-1} [1], the rapid deceleration elevates structural loadings and risk to on-board personnel.

This benchmarking study was undertaken to prove the capability of carriage mounted 2D PIV in the AMC towing tank to investigate the flow phenomena in a tip vortex, and as an aid to validating simulation results.

The tip ventilation inception point of hydrofoils in close proximity to the free surface might be altered through engineering of the tip vortex. PIV can be used to measure the effects of geometry modification and fluid structure interaction on tip vortex location and intensity, through the acquisition of instantaneous measurements across a flow field without the intrusion into the flow field required by Pitot tube measurement.

Experimental PIV results may be compared directly with numerical (CFD) results, thus enabling the validation of a comprehensive parametrical study and the setup parameters utilised.

The HTA investigated the flow around a vertical flat plate at incidence with the aim of providing a benchmarking strategy for hydrodynamic facilities targeting the repeatability of experiments having characteristics common to large test facilities that pose substantial challenges to PIV [3]. These experiments were conducted using stereo PIV in the deep water tank facilities of the Maritime Research Institute Netherlands (MARIN) and the Italian Ship Model Basin (INSEAN), and the Delft University of Technology (TUD) circulating water channel. The study found good agreement between results of similar facilities [7].

One of the greatest hurdles associated with PIV is maintaining good signal to noise ratio where specular reflection from test geometry, free surface or entrained bubbles is present [8]. Typical methods of minimising specular reflection are the use of low-reflectivity paint or an acrylic insert in certain instances. Image quality is compromised if excessive illumination causes glare which may affect a larger region than any localised reflection; where the light intensity used is at the minimum intensity required to illuminate particles [7].

Typically seeding media for PIV investigation of fluid flows such as glass, polymer, wax, fluid droplets and gas bubbles are illuminated by the laser pulse and reflect light to the camera. Fluorescing particles have been used for PIV seeding advantageously in proximity to the free surface or in multi-phase flows, increasing the signal to noise ratio through suppression of optical noise reflected from the laser source. These particles fluoresce at a different wavelength to the excitation wavelength from the laser; enabling filtering of reflected laser light from the acquired images [8].

Seeding methods range from homogenising the seeded fluid using the test geometry, to the use of seeding rakes. The use of an in-situ seeding system is essential to maintain minimum levels of seeding concentration during ship model testing [9]. [6] suggested that a target for the wake fraction during data acquisition with a seeding rake should be 5% and as the wake fraction is constant flows can be compared.

Experimental Setup

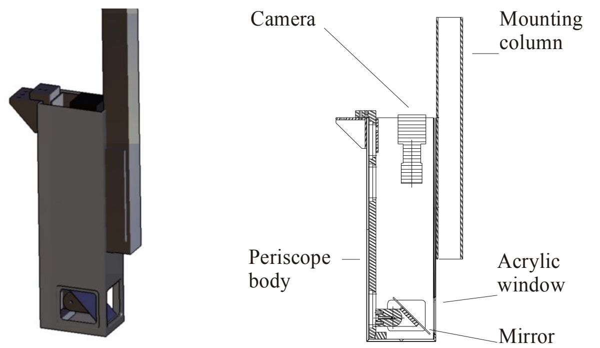
Experiments were carried out from the AMC towing tank manned variable speed carriage. The tank has a depth of 1.5 m, width of 3.5 m and length of 100 m.

Test geometry

The HTA benchmark model is rectangular, 500 mm wide by 800 mm high with a thickness of 6.35 mm manufactured from steel plate with leading and trailing edges radii of 3.175 mm. The model was rigidly mounted to the carriage, vertically at incidence of 20 degrees to the flow, with the tip immersed to a depth of 300 mm. In order to minimise specular reflection from the laser the model was coated with black low-reflectivity paint.

PIV setup

A carriage mounted New Wave Solo 120-mJ pulsing Nd:YAG laser with underwater sheet optics, and a LaVision sCMOS double shutter 16 bit camera with 2560 x 2160 pixels, 80 mm lens and high pass filter were used to capture 2D PIV data.



(a) (b)

Figure 1. Carriage mounted periscope (a) 3D view (b) Section view

Images normal to the flow direction were captured using a 2D PIV system with a free stream velocity of 0.4 ms^{-1}(Figure 2). An inverted periscope using a system of mirrors was used to keep the camera accessible above the free surface and to provide full in-situ manual camera control and adjustment.

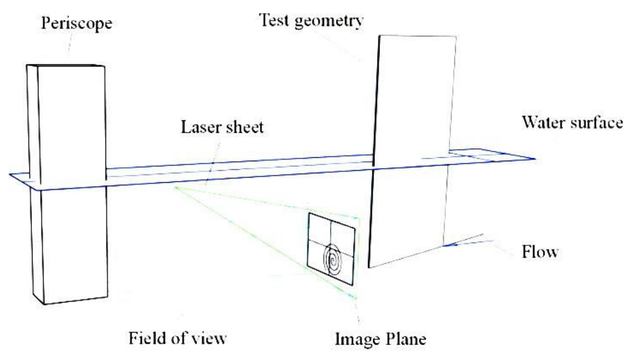


Figure 2. Experimental setup schematic for towing tank carriage mounted PIV

Fluorescent particles of diameter 38 – 75 microns manufactured in-house were deployed using a multi-fingered seeding rake which trailed the test geometry as the carriage returned to the start position after each test run. The seeding rake was lifted clear of the surface during each test run.

The shorter light path through water to the region of interest from the periscope, as compared to if the camera were mounted in a submerged housing, resulted in reduced light loss due to scatter and diffusion from suspended particles (Figure 1).

Measurements were recorded on two planes, 100 mm upstream and 100 mm downstream of the trailing edge by translating the test geometry backward and forward in the flow direction (Figure 3).

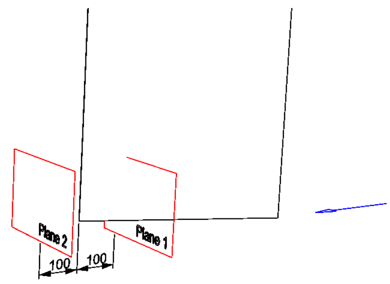


Figure 3. Position of planes captured in relation the trailing edge datum using 2D PIV.

Each data set consisted of 128 instantaneous velocity fields captured at a frequency of 15 Hz, using an inter-frame interval of 2.5 milliseconds. With these settings and a light sheet thickness of approximately 4 mm it was estimated that 75% of particles would remain within the light sheet for each image pair. A 200 mm high by 300 mm wide field of view was obtained.

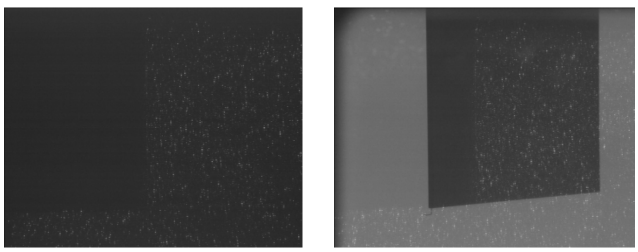
Image calibration was carried out using Davis software with a 3rd order polynomial fit model, resulting in a standard deviation for the fit of 0.61 pixels.

Post-processing

Davis 8.1.3 software was used to post process the PIV data with a multi-pass cross correlation and decreasing window size from 32x32 to 24x24, with 50% overlap. Test geometry was masked as required.

Discussion and Results

The RAW images of measurement plane 1, 100mm forward of the trailing edge where there is intersection between the test geometry and light sheet (Figure 4), show that due to the extended exposure time of the second frame some additional ambient light is captured, though insufficient to interfere with image processing. In contrast to the HTA results no reflection can be observed.



(a) (b)

Figure 4. Double frame raw images from measurement plane 1 showing the absence of reflection from the test geometry and dense high contrast seeding (a) First pulse and (b) Second pulse

INSEAN MARIN AMC

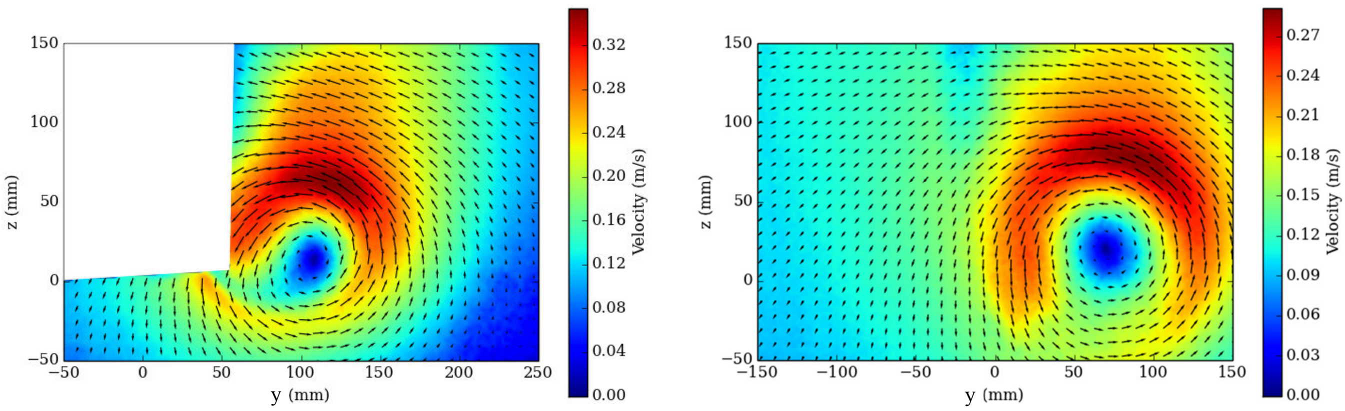
Figure 5. Raw images where the light sheet does not intersect the test geometry from the HTA study [7] and AMC.

The RAW images presented in Figure 5, aft of the trailing edge show a significant reduction in reflection for all institutes as there is no intersection between the laser sheet and geometry. The seeding in the MARIN image appears inhomogeneous with considerable variation in particle illumination that might be attributed to inconsistent particle size or foreign matter suspended in the tank water. The INSEAN image shows homogeneity and appears to be seeded at a high density. The lower illumination of the particles indicates either low laser power or small particle size. The AMC image shows homogeneous seeding, with particle illumination somewhere between that of the other institutions.

Results for the AMC velocity vector fields on measurement planes 1 and 2 (Figure 6) indicate a reduction in flow strength between the measurement locations.

Visibility of flow features near the specimen show compression of the flow field by the plate resulting in an ellipsoidal vortex.

The HTA used through plane velocity to locate the centre of the vortex. In this study in–plane velocities were measured, and the point of minimum kinetic energy used as the vortex centre location. There is good agreement between the AMC and HTA results based on V and W velocities (Table 1). The HTA location for the vortex centre based on through plane velocity or U velocity contours shows considerably more variation which may be due to the sensitivity of measuring the U component to experimental setup. The peak magnitude of the V and W velocities shows excellent agreement with the HTA results (Figure 7), the location of which was normalised with relationship to the vortex centre due to variation in position between the different institutions with reference to the geometric datum.



(a) (b)

Figure 6. 2D velocity vectors plots averaged over 128 double frames on an 8 x 8 grid for (a) Plane 1 (b) Plane 2

Test Facility	Based on U velocity		Based on V & W velocities	
	Y [mm]	Z [mm]	Y [mm]	Z [mm]
AMC	-	-	69	19
MARIN	75	30	69	15
INSEAN	65	30	68	25

Table 1. Location of vortex centre, calculated from U, V and W velocities

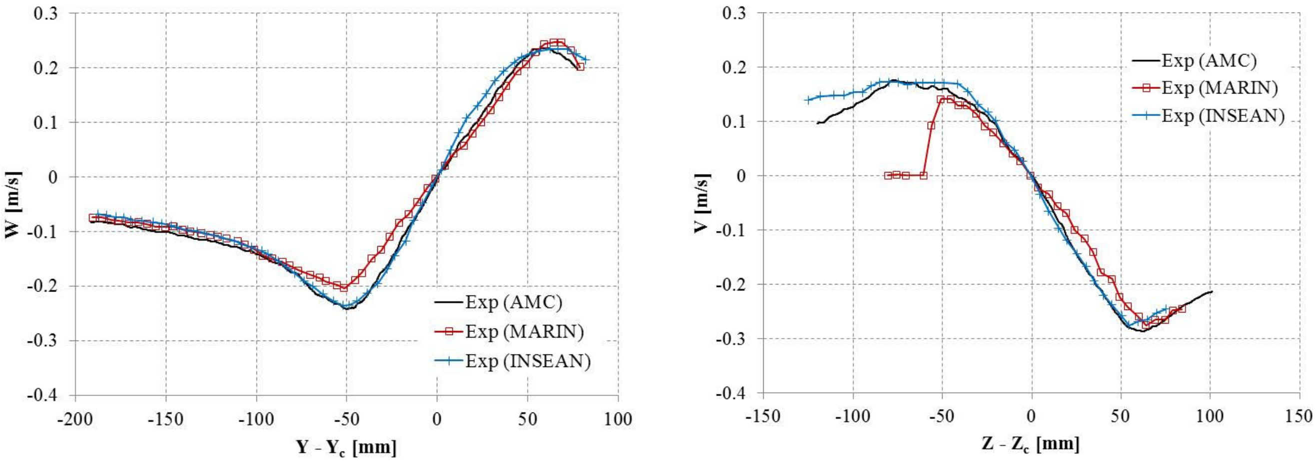


Figure 7. Experimental results from the HTA and AMC showing the magnitude of the W and V vectors with reference to the vortex centre.

Conclusions

This study benchmarked the use of 2D PIV in the AMC towing tank. The combination of fluorescing particles, high band pass filter, short light path, low-reflectivity paint and full size camera resulted in an improved signal to noise ratio removing the requirement to mask or process out reflections.

The model scale of the HTA trial has been shown to be suitable for PIV benchmarking in a broad range of towing tank facilities. The study was useful in that it demonstrated that the AMC has the capability to perform PIV experiments with quality results. The results obtained in the AMC towing tank demonstrate an equal capability to the much larger facilities of MARIN and INSEAN used by the HTA.

This study demonstrates the capability of PIV in the AMC towing tank to be used for the purpose of validating results from a simulation based study measuring hydrofoil tip vortex intensity and location.

The magnitude of the velocity vectors is comparable between all institutions however the positional accuracy of flow features remains to be confirmed.

Recommendations

An investigation of the repeatability of positional measurements for flow phenomena should be undertaken.

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