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Time Resolved 3D3C Measurements of Shallow-water Island Wakes

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Abstract

The wakes behind islands subjected to strong oscillating tidal flows in shallow water are characterised by highly three-dimensional flow structures and significant cycle-to-cycle variability. As part of a broader study into the processes governing vertical and cross shelf mass exchanges in the topographically complex and strongly forced Kimberley coastal region, an experimental flume (the Shallow Oscillatory Flow Flume) has been designed and constructed to obtain time resolved, three-dimensional and three-component (3D3C) velocity field measurements of island wakes.

The facility makes use of the Synthetic Aperture Particle Imaging Velocimetry (SAPIV) approach, a light field imaging technique that utilises multiple cameras to digitally reconstruct a three-dimensional particle intensity field. Three-dimensional particle image velocimetry techniques are then used to obtain the velocity field. A specific advantage of SAPIV over other 3D techniques includes its unique ability to deal with occlusions, higher particle seeding densities and volume reconstruction efficiency.

This paper presents a description of the experimental facility and SAPIV system setup. The three velocity component SAPIV measurements are validated against co-located and synchronised ADV measurements.

Previous work by the authors has identified the importance of the Keulegan-Carpenter number and relative boundary layer thickness in governing the wake form of shallow islands subjected to tidal forcing. The new facility and SAPIV technique are utilised to investigate the wake form and evolution across a broad parameter range applicable to the Kimberley Region and provides a basis for quantitative model development of vertical and cross shelf mixing and exchange around islands.

Introduction

Characterisation of island wakes in the field is limited to observation by aerial photography and point source measurements. Whilst numerical simulations provide quantitative insight into wake dynamics, assumptions underpinning the parametrisation of bottom friction and the diffusion of momentum, in addition to the computational constraints imposed by spatial and temporal discretisation, put practical limits on the range of their application and resolving power.

Whilst there is some understanding of island wake formation in steady flows (eg. [15, 16]) the influence of flow unsteadiness and reversal on secondary circulation and wakes is an area that is very poorly addressed in the literature, particularly in shallow water environments. There exists only a handful of papers directly addressing oscillatory flow around islands in shallow water (i.e. [10, 7, 13]) where the influence of bed friction plays an important role in governing wake dynamics. A numerical modelling investigation of the time and length scales governing vortex generation around an idealised headland was undertaken in [9]. The study examined the dependence of eddy formation on the frictional Reynolds Number (island wake parameter of [16] and stability parameter of [7]) and identified that the behaviour was predominantly governed through relative value of two length scales, a tidal excursion length and a frictional length. Of the previous studies only [7] undertook laboratory investigations and they were limited to the measurement of surface velocities. The work of [7] suggested a model of shallow island wake form through dimensionless parameters that took account of the relative length scales of flow excursion and island size, however the study ignored the influence of time dependent bed friction, an essential element of unsteady flows.

Considering the limited success of [7] in separating the regimes of observed shallow island wake formation under oscillatory flow, an alternative model of wake form based on both the Keulegan-Carpenter number

$$KC = \frac{U_0 T}{D} \tag{1}$$

(where U_0 is the amplitude of the flow oscillation velocity and T the oscillation period) and the relative oscillatory boundary layer thickness

$$\delta^+ = h/\delta \tag{2}$$

(where h is the flow depth and δ is the boundary layer thickness) has been investigated [3]. The effects of bed friction in oscillatory flow are confined to a boundary layer and in laminar flow, the boundary layer thickness is defined as

$$\delta = 2\pi\sqrt{\frac{2\nu}{\omega}} \tag{3}$$

where ν is the kinematic viscosity of water and ω the angular frequency of oscillation ($\omega = 2\pi/T$). This represents the height at which the velocity deficit from the free stream velocity is less than 0.002. A re-examination of the results of [7] in the non-dimensional space defined by KC and the non-dimensional parameter $\delta^+ = h/\delta$ is shown in Figure 1.

Preliminary application of this revised parameter space to a series of experiments conducted at UWA is presented in [3]. Three distinct flow regimes were identified in the study: (1) the bottom friction dominated regime ($\delta^+ < 1-1.2$) where the stabilising effect of bed friction prevents vortex shedding, (2) the timescale constrained regime ($KC < 7$) where the timescale of vortex evolution is greater than that of the flow oscillation, again preventing vortex shedding, and (3) the vortex shedding regime, where the flow has sufficient depth to exceed the stabilising effects of bed friction with in a cycle and the tidal excursion has sufficient length to allow vortex evolution.

The three dimensional structure of shallow water wakes presents specific challenges for their measurement and characterisation using traditional laboratory flow measurement techniques, in particular when the focus is the characterisation of

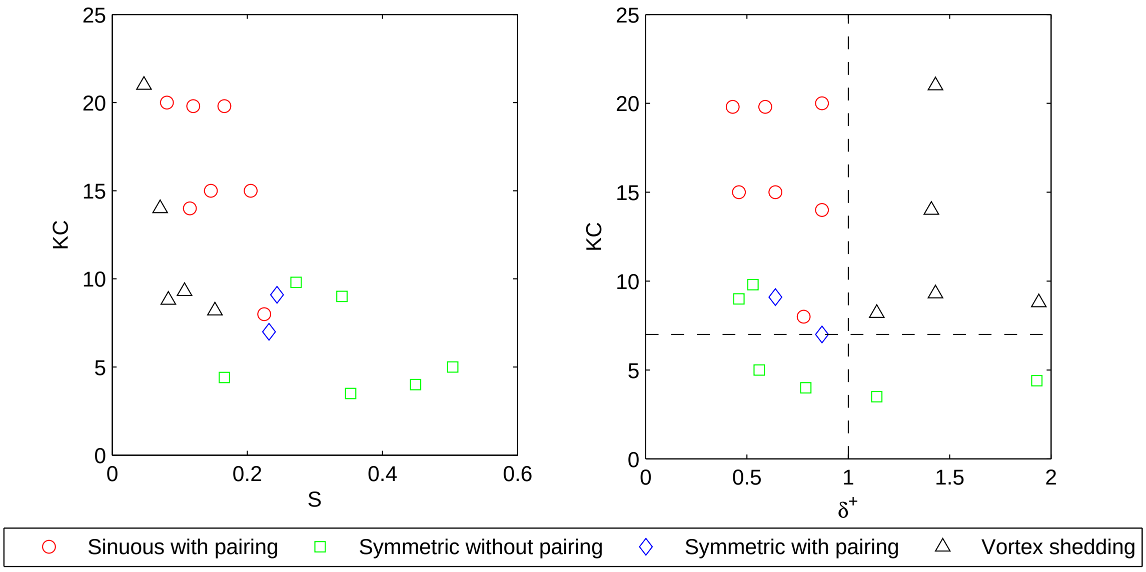

Figure 1: Results of [7] plotted in the parameter *KC* and *S* (left) and *KC* and δ^+ (right) dimensionless parameter spaces. Notice the improved separation of observed wake form on the right and the suppression of vortex shedding for δ^+ less than 1 and *KC* less than approximately 7 (indicated by the dashed lines).

upwelling due to islands in shallow flow. To examine this problem a purpose built shallow flow flume was constructed and a recently develop PIV technique implemented and validated for the three dimensional measurement of shallow island wakes.

Shallow Oscillatory Flow Flume

The shallow oscillatory flow flume is 1.85 m wide, 6.00 m long and 0.35 m deep. The working section of the flume is elevated 2.00 m off the ground and features a glass bottom to allow clear visualisation of the flow. The flume is recirculating and utilises a twin propeller, counter rotating thruster, motor and drive system that is controlled from LabView, allowing for arbitrary forcing signals to generate the unsteady oscillatory tidal flow. The drive system is able to achieve flow rates of up to approximately 150 L/s which provides a working section flow velocity of up to 40 cm/s in 25 cm flow depth. Predominantly the flume has been utilised in shallow flows (less than 10cm depth) and is able to consistently generate oscillatory flow signals with amplitudes as small as 0.5 cm/s.

Synthetic Aperture Imaging

Sythetic aperture imaging is based on the light field imaging concept and involves the sampling of a large number of light rays in a scene from multiple view points. If the geometry of the imaging system is well known, it is possible to re-parameterise the scene [6]. Two common approaches to obtain light field images are to utilise a micro-lens array over an image sensor (a so called Plenoptic camera) or to utilise an array of cameras. Application of light field imaging and the re-parameterisation process to three–dimensional Particle Image Velocimetry (3D PIV) for development of the technique into a flow measurement system was demonstrated in [2]. There, the synthetic aperture refocussing technique [6] was applied to re-parameterise the captured light field into a number of discrete focal planes located arbitrarily in the imaged volume using the Map-shift-average algorithm [11]. A comprehensive evaluation of the physical constraints and sources of error relevant to the technique was completed in [2], and these findings were applied to carefully design a cost-effective synthetic aperture imaging system for the study of shallow island wakes. Some limitations on the technique arise due to the overall field of view, camera array spacing and depth of field for each individual camera. However, geophysical flows are particularly suited to application of the synthetic aperture technique, as they are characterised by having larger horizontal than vertical length scales. This allows the out-of-image plane axis to be aligned vertically which can ideally position the relatively flat measurement volume within a narrow depth of field, with large camera apertures consequently improving the overall optical efficiency of the system.

Imaging System

The synthetic aperture camera array system consists of 9 Basler ACE acA1600-20gm 2.0 mega-pixel monochrome GigE cameras with a maximum frame-rate of 20 fps. At maximum resolution, bit-rate and frame rate the total data throughput of the camera system is approximately 5.8 Gbit/s (721 MBytes/s). The data is streamed via a bank of high speed PCI-express network cards to a array of 4 solid state disks in raid-0 configuration. The 1TB SSD array allows for approximately 30 minutes of continuous measurement. Data is backed up to a large capacity institutional data store prior to transfer to the Pawsey Supercomputing Centre for processing and analysis.

The camera array is positioned below the flume at a distance of approximately 1.2 m. The cameras are arranged in a 3 x 3 grid layout with approximately 0.37 m spacing between each camera. The cameras are aligned on a 340 x 260 x 70 mm^3 measurement volume. The horizontal and vertical size of each voxel is 0.22 mm and 0.5 mm respectively, with a total volume size of 280.6 million voxels.

Camera array calibration is achieved by placing a target within the measurement volume. The multi-camera self-calibration technique of [1] was applied. The technique involves initially placing the calibration target flush against the glass bed, which defines a reference co–ordinate system for the three dimensional volume. Subsequently the calibration target is positioned at a number of arbitrary planes within the volume and coincident points across the camera array identified. A total of 275 points on the calibration target are identified in each camera and a bundle adjusting non-linear least squares optimisation is performed with the Levenberg-marq algorithm on a pin hole camera model that includes the refractive water–glass–air transformation [1]. A mean reprojection error of 0.11mm was obtained across the 9 cameras in the array.

Three–dimensional Particle Imaging Velocimetry

The flow is seeded using Pliolite AC80 with a particle size range of 300 - 450 μm, approximately double the pixel resolution. Image pre-processing, volume reconstruction and particle imaging velocimetry is performed on a supercomputer using custom developed C++ code that makes use of MPI and OpenMP parallel processing to scale across multiple nodes. The three–dimensional particle imaging velocimetry code applies an iterative, multi-grid, image deforming approach to reduce the inplane loss of pairs and ensemble averaging in the correlation space to overcome non-uniformity in seeding density [8]. Subpixel displacement estimates are obtained using a three point Gaussian fit to the correlation peak in three dimensions. The universal outlier detection algorithm of [12] is applied after each pass to remove outliers.

The iterative analysis is applied for a total of 8 passes, with the first three passes progressively refining the interrogation volume from 256 x 256 x 48 voxels through to 96 x 96 x 16 voxels with 75% overlap. This results in a three dimensional vector field of 64 x 48 x 33 (101376) vectors with physical spacing of 5.28 mm horizontally and 2 mm vertically.

By far the most computationally expensive calculation are the fast-Fourier transforms of the 3D PIV processing. The image pre-processing and volume reconstruction through synthetic aperture refocussing are completed in 4% of the time required for the 3D PIV.

Results

The overall Synthetic Aperture Particle Imaging Velocimetry (SAPIV) process was validated against measurements obtained with an ADV positioned within the PIV measurement volume. Figure 2 presents the u, v and w velocity time series in the wake of a cylinder. The agreement between the ADV and SAPIV measurements is excellent. Whilst there appears to be some minor under estimation of the peaks in velocity by the PIV it should be noted that during those times of very strong shear and vertical motion the ADV correlation score and signal-to-noise ratio also drop due to the less than ideal seeding conditions for the ADV.

The system has been applied to quantify a broad range of parameters in the KC and δ^+ space. An example of the shallow island wake in the vortex shedding regime is presented in Figure 3. The streamlines are seeded on a grid at a level of 5 mm above the bed and are coloured by elevation. The vertical upwelling and wake vorticies are clearly visible. The variation of vertical velocity in the wake with KC is shown in Figure 4 through time-series of mean, ninety-fifth percentile and fifth percentile vertical velocity. The flow depth is 53 mm and δ^+ held constant at 1.36. There is a non-linear increase in vertical velocity with the onset of vortex shedding. A total of 24 experiments have been completed in the parameter range $6 < KC < 24$ and $0.5 < \delta^+ < 2.0$. Similar to [14] a range of rich wake forms is demonstrated across the parameter space and these are described in detail in [4]. The dependence of lateral and vertical mixing on KC and δ^+ is detailed in [5].

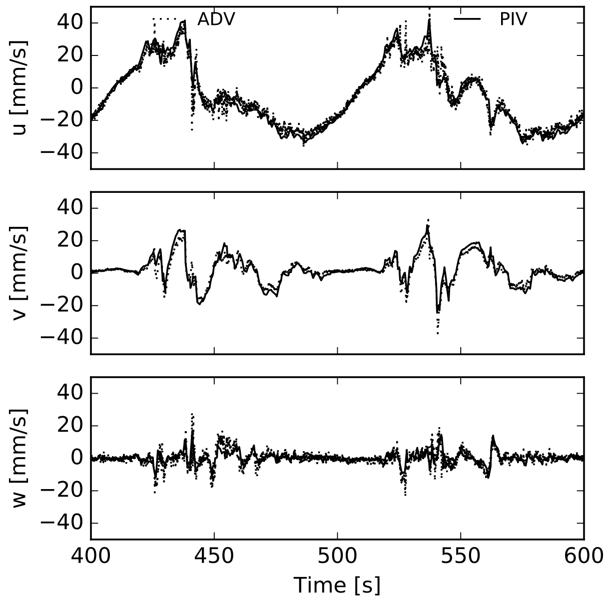

Figure 2: Comparison of SAPIV measurements for co-located ADV measurements in the wake of a cylinder subjected to oscillatory flow.

Conclusions

A shallow oscillatory flow flume has been designed and constructed to study the dynamics of shallow island wakes across a broad parameter space representative of islands subjected to strong tidal forcing. A novel PIV technique has been implemented to obtain 3D3C velocity measurements in the wake of shallow islands and validated against ADV measurements. An example of the rich three dimensional velocity measurements is demonstrated through streamlines seeded at the bed which highlight areas of upwelling in the wake.

Acknowledgements

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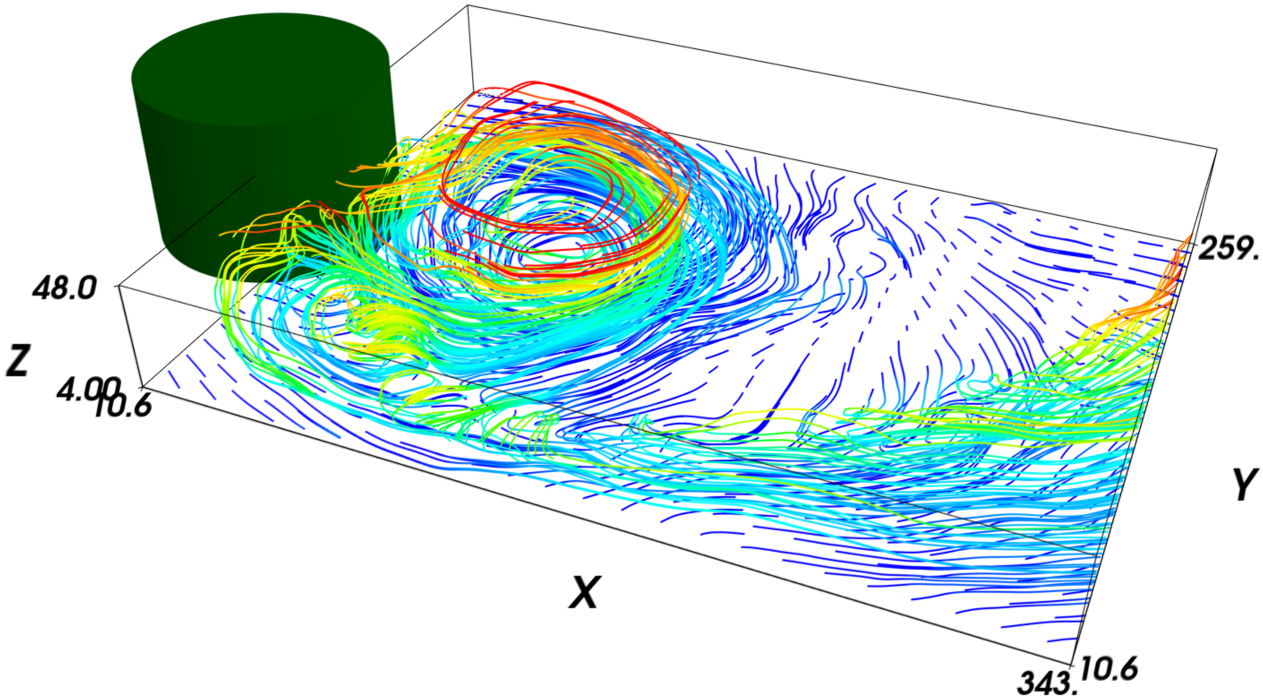

Figure 3: Example island wakes visualised through a grid of streamlines seeded at 5mm above the bed and coloured by elevation for $KC = 24$, $\delta^+ = 2.0$

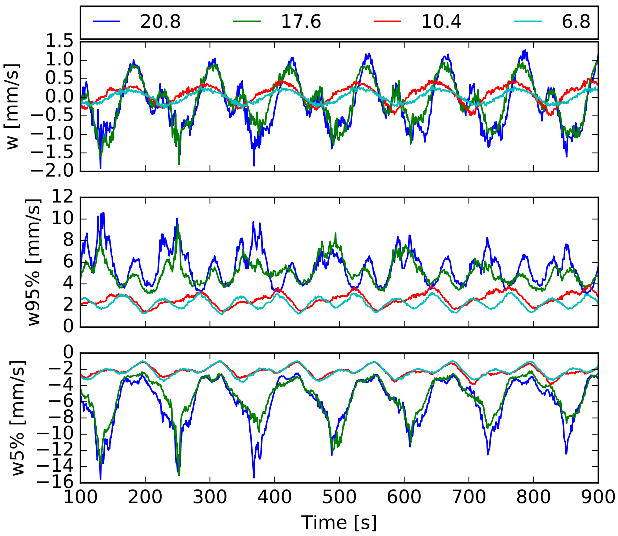

Figure 4: Example of the variation in mean (*top*), ninety-fifth percentile (*middle*) and fifth percentile (*bottom*) vertical velocity with KC for $\delta^+ = 1.36$

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