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MEASUREMENT OF FREE SURFACE ELEVATION AND VELOCITY
SURROUNDING A SURFACE PIERCING FOIL

BY

JAMES J. SCHOCK

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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IN
OCEAN ENGINEERING

UNIVERSITY OF RHODE ISLAND

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MASTER OF SCIENCE THESIS
OF
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UNIVERSITY OF RHODE ISLAND

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ABSTRACT

Validation and verification of numerical experiments require data with which to compare the results. In particular, hybrid methods that involve grid interfaces between multiple numerical solutions on submerged boundaries or at the free surface require volumetric measurements for validation. In this study, two methods to obtain a comprehensive data set including volumetric three dimensional, three component (3D3C) fluid velocities, free surface profiles and drag force are compared for accuracy and economy. For the first method, a NACA 0012 surface piercing foil is evaluated at Froude numbers 0.19, 0.37 and 0.55. Velocity measurements are obtained using Stereo Particle Image Velocimetry (SPIV) with the interrogation plane parallel to the chord line of the foil. Free surface profiles are obtained using a GoPro camera positioned to observe the intersection of the free surface and the laser sheet. Force data is obtained through a load cell mounted on the tow carriage. The second method positions the SPIV interrogation plane perpendicular to the chord of the foil such that the volume is sliced transversely while the foil passes through the plane in time. Surface elevations for this method are again measured with a GoPro, mounted to capture the intersection of the laser sheet and the free surface. The transverse method is examined at Froude number 0.37. Results are presented based on the flow field statistics and the fundamental features of the data sets are compared using dynamic mode decomposition. Comparison between the two methods are made qualitatively, as well as quantitatively using RMSE and Dynamic Mode Decomposition. The difference between the two methods is less than 10% RMSE.

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PREFACE

The following work is a product of the authors listed. This thesis is formatted in accordance with the guidelines for a manuscript style thesis. The first manuscript is in preparation for submission to the Journal of Experiments in Fluids.

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MANUSCRIPT 1

**Measurement of Free Surface Elevation and Velocity Surrounding a
Surface Piercing Foil**

by James J. Schock and Jason M. Dahl

To be submitted to the Journal of Experiments in Fluids

1.1 Abstract

Verification of sea keeping prediction programs is typically performed using experimentally obtained velocity and free surface elevation data. Traditionally data are expensive to obtain due to the need for expensive equipment, a large number of experiments required to measure quantities in the volume in question or the significant processing time involved in calculating the flow properties. This paper describes two methods which can be used to obtain both velocity and free surface elevations surrounding a surface piercing foil. Both methods use Stereo Particle Image Velocimetry to measure the velocity of the flow and an off the shelf digital camera to measure the free surface elevations. The first method is performed using a vertical laser sheet in plane with the foil. The second method rotates the vertical laser sheet such that the foil is orthogonal to the laser sheet. The two methods are compared using dynamic mode decomposition and found to be substantially significant in the primary mode. Root mean square error is calculated between the two methods and a 9.6% difference is found.

1.2 Introduction

The wave field generated from a translating slender body at the free surface is an important component in the evaluation of the drag characteristics of slender bodies, such as ships or hydrofoils. This aspect of the generated flow field is critically important in the verification of sea keeping prediction programs, which aim to model these physics through computer simulation.

(Reliquet, 2013) developed a hybrid computational fluid modeling method similar to the hybrid Lattice Boltzmann Potential Flow solver under development at the University of Rhode Island (URI) by (OReilly et al., 2015). In order to verify the method in Reliquet, data from (Metcalf et al., 2006) was used. In Metcalf,

pressure and surface topography data was collected via pressure taps and wave sensors and assembled to describe the characteristic flow surrounding a surface piercing foil.

Although many techniques exist for separately obtaining velocity field or free surface measurements, one goal of this work is to limit the necessary equipment and experimental time needed to obtain an experimental data set using a stereo PIV system. Emphasis is placed on using a single laser for all measurements. Two methods are proposed and tested. The first method utilizes a vertically oriented planar field of view which is parallel to the chord line of the foil. This view makes it possible to slice the volume and obtain 3D3C measurements of velocity and free surface elevation with out disturbing the flow with wave probes or other equipment. In addition, by using a carriage to carry the SPIV equipment, such that the laser sheet and cameras are set a fixed distance, the need to calibrate between separate runs is eliminated. Second, a transversely sliced volume method using a 2D+T argument assuming a steady flow is explored, which significantly reduces the costs associated with obtaining the volumetric data set.

The vertical orientation of the laser sheet is of particular note. Past experiments use a horizontally oriented laser sheet to slice the volume. The resulting data is then viewed horizontally. For this set of experiments the laser sheet is oriented vertically and the data is visualized in the traditional horizontal format. By using the vertical orientation it is possible to only use one laser to image both the free surface and perform SPIV measurements simultaneously.

1.3 Background

In order to verify computational fluid solvers it is necessary to have empirical data to compare to the numerical results. Typically force or pressure data is

available and commonly used for comparisons. One problem with using force data for verification is that it is an integrated quantity in fluid flow. This means that force can be a non-unique, forces associated with a particular flow may match the computed forces even though the flow field may be slightly different. This can be particularly important in problems where phase is important, such as with free surface waves and vortex shedding. One goal of this experiment is to develop a data set that includes force on the body, 3D3C velocity surrounding the body, and wake elevations.

The Hybrid Lattice Boltzman Potential flow solver developed in (OReilly et al., 2015) utilizes potential flow theory to solve for flow characteristics in the general domain. Close to the body being evaluated, Lattice Boltzman methods are applied. In order to best verify the Hybrid Lattice Boltzmann Potential Flow Solver, it is desired to compare both the velocity field and the surface topography within the overlapping numerical domain in a non-invasive manner. Measurements of velocity, free surface elevations, and force are obtained simultaneously in order to construct the verification data set.

Traditionally, obtaining the free surface elevation and volumetric velocity measurements surrounding a surface piercing body require expensive specialized and possibly invasive equipment such as wave probes or pitot tubes which can cause issues with surface tension. These same methods also require large amounts of time devoted to testing in specialized facilities. Some methods split these two measurements into two separate problems; above and below the free surface such as in (Metcalf et al., 2006). SPIV is a common tool to measure the velocity field in this case. (Prasad and Adrian, 1992; Prasad, 2000) demonstrate an application of SPIV to fluid flows utilizing two cameras and a single light sheet. By tracking

and correlating the particles between two frames, it is possible to determine the three component velocity vectors of the observed flow. By using this technique and slicing the flow at varying locations in the volume, it is possible to develop a volumetric velocity profile. Although there are limitations in doing this, one must assume the flow can be time averaged.

Several techniques are developed which use imaging methods to determine the velocity of the free surface and the topography. (Fouras et al., 2006) describes a method where an etched glass plate is placed below the free surface and is imaged from above. A reference image is obtained followed by an image of the wavy surface. The two images are then compared using a PIV algorithm to determine the relative displacements of the etchings on the glass plate. A directly proportional relationship exists between the relative displacements of the etchings and the free surface heights. (Fouras et al., 2008b; Ng et al., 2009) build further on the work of (Fouras et al., 2006) by adding a second camera below the flow and taking both reference and distorted images simultaneously. (Fouras et al., 2007; Fouras et al., 2008a) build on this technique by removing the need for a calibration cycle through by the addition of a third paraxial camera and modified SPIV algorithm. By adding a third camera the calibration information is collected simultaneously with the measurement data. For this process to work, it is imperative that the third camera is able to image the field with minimal distortion.

(Gomit et al., 2012) used SPIV with three cameras, one located below the water channel and two above the water channel. By arranging the laser sheet such that the volume is sliced horizontally it is possible to obtain the surface heights, normal, and two dimensional velocity of the free surface. (Chatellier et al.,) used the cross-correlation of parametric shape and displacement image forms to determine the

three dimensional coordinates of the free surface.

These techniques focus primarily on measuring the free surface properties, however it would be expensive to implement these techniques with additional measurement of the 3-D velocity field and forces.

A more traditional approach is taken by (Metcalf et al., 2006) who measured the free surface topography and simultaneous pressure field surrounding a surface piercing foil using wave gauges and pressure sensors. In (Metcalf et al., 2006), a grid of pressure sensors are positioned on a foil to obtain the surface pressures acting on the foil. A Pitot-static tube is used to measure upstream surface pressure. To measure the free surface topography, three capacitance wire wave gauges are mounted on a dynamically positioned carriage. The carriage is moved around the foil to record slices of the wave field during the experiment. After conducting the experiment, the data is compiled into a pressure field on the surface of the foil and the free surface elevation field surrounding the foil. Although this experiment measures the free surface elevation and the pressure field at the foil surface, it does not measure the velocity field beyond the surface of the foil. In addition the wave gauges and pitot probe are invasive, which can affect the surface elevation measurements, particularly for low Fr and Re flows.

1.4 Experimental Setup

In order to gain the advantage of a single calibration while obtaining volumetric velocities and the elevation of the free surface, a traverse system was designed and constructed to fix the relative positions of the cameras and the light sheet used for PIV. Using this traverse it was possible to slice the volume vertically in planes parallel to the chord of the foil while only requiring a single initial calibration. To measure the free surface, a GoPro digital camera was mounted on the drive

carriage at a fixed distance from the laser sheet. The interaction between the free surface and the laser sheet results in light scattering which is detected as a high intensity light by the GoPro camera. The scatter pattern follows the curvature of the free surface and can thus be tracked and measured. The wake profile of the foil is assumed to be steady state since the transverse wave field is not significantly time varying. In assuming a steady state process, the data may be time averaged. Figure 1 and 3 show a schematic of the field of view of each camera used in the experiment. Vertical slicing of the velocity field parallel to the foil requires that multiple experiments must be repeated to obtain a volumetric measurement. This can be time consuming and expensive.

Figure 1: The Field of View of the SPIV cameras was located from the free surface to a depth of over one chord length. The GoPro field of view was located at the intersection of the laser sheet with the free surface and centered on the center of the foils chord length. Foil movement is parallel to the X axis.

A second 2D+T method is investigated to further reduce the necessary experimental time by fixing the cameras and light sheet such that the volume is sliced perpendicular to the long direction. By assuming that the flow is steady state, a relatively safe assumption for slender bodies, it is possible to treat time as a third spatial dimension. To employ this technique, the laser is aligned vertically and in an orientation orthogonal to the path of the foil. The foil is then "driven" through the laser sheet and the time series of images is collected. Figure 3 and 2 show the relative positions of the foil, laser sheet and cameras used for this method. The distance between each image is computed from the frame rate of the camera and the forward speed of the foil. This method allows for the experimental test matrix for a given Froude number to be reduced to a single experiment. Two experiments may be required, however, for an asymmetric body shape.

1.4.1 Tow Tank Characteristics

A tow tank with a usable length of 2.6 meters, depth of 0.68 meters and width of 0.90 meters is used to conduct the experiments. The tow tank is fitted with an automated top carriage which can be programmed to position the foil dynamically within the tank. For the purposes of this experiment, the foil is fixed at a zero degree angle of attack and shifted transversely from center line out to 0.5 chord lengths in increments of 0.036 chord lengths. The carriage is capable of speeds up to 0.5 m/s. The sides and bottom of the tow tank are constructed of tempered glass and the frame is extruded aluminum. Full details of the tow tank and top carriage can be found in (Reilly-Collette, 2014). As part of this investigation, a second traverse was designed and fitted to the tow tank to enable the SPIV equipment to traverse the length of the tank.

Figure 2: The 2D+T method is shown above. This method allows for the free surface elevations and fluid velocities to be obtained rapidly. The laser sheet and cameras are fixed in position both relative to each other and the tank. Foil movement is parallel to the X axis.

An important feature of this tow tank is the ability to conduct highly repeatable experiments. The movement of both carriages is fully automated using servomotors with 0.1 mm repeatability, ensuring easily replicated experiments. This allows for volumetric measurement of the time averaged velocity field.

1.4.2 Foil Parameters

For this investigation, a NACA 0012 section with a chord length of 70mm was used. The foil was mounted to the top traverse of the tow tank such that 3.5 chord lengths of the foil were submerged below the free surface. With the foil submerged to this depth the infinite length assumption is used to neglect foil tip effects. The

foil was constructed of aluminum and anodized flat black to reduce the reflection from laser light, provide a smooth test surface, and avoid corrosion.

1.4.3 SPIV System Arrangement, Control and Calibration

The SPIV system used for this investigation is a LaVision SPIV system consisting of two Phantom V10 high speed cameras, pulsed Nd/Yag laser, timing controller, and DaVis 8 software package.

The high speed cameras used were two Phantom V10 high speed CMOS cameras capable of a frame rate of 480hz with a resolution of 2400 x 1800 pixels. The cameras were mounted in a traditional stereo piv arrangement; on the same plane with an angular separation of approximately 30 degrees. Each camera was equipped with Nikon lens mounts and scheimpflugs. 3 shows a schematic of the camera setup with the field of view.

Two different lenses were used, one for each version of the experiment. For the longitudinal experiments, Nikkor 50mm f1.2 lenses were used. For the transverse experiments, Nikkor 105mm f 2D lenses were utilized. In both cases, the lenses were manually focused on the region of interest using a calibration plate.

A timing controller is used to control the two Phantom cameras as well as the laser timing. It is a LaVision HighSpeed controller. An optical trigger is also integrated into the timing controller. The trigger was mounted on the rail of the PIV system traverse and activated when the cart passed over the trigger. The trigger initiated the SPIV imaging acquisition.

A Photonix model DM30-527PIV pulsed Nd Yag laser which emits 527 nm green light and 1053 nm ultra-violet light as used.

SPIV Fields of View

Figure 3: Camera positions for each configuration. The cameras are separated by an angle of approximately 30 degrees.

DaVis 8.1 software was used as the primary control interface for the SPIV system as well as the initial processing of the fluid velocity fields. Utilizing the included calibration work flow, SPIV images were able to be calibrated using a 3rd order polynomial calibration. The GoPro images were calibrated using a pinhole camera model calibration included as an option in the workflow. The calibration plate used for all cameras is a LaVision 204-15. The 204-15 is a two-level plate measuring 204 mm x 204 mm square, with white marks spaced in 15 mm increments covering each of the two levels. There is a 3 mm separation between the two levels.

1.4.4 Free Surface Camera Arrangement, Control, and Calibration

In order to visualize the wake at a given position, it was necessary to mount a camera close to the foil, above the free surface, at an angle that allows for capturing the full wave elevation without obscuring the view of the free surface. In addition, for ease of repetition, the camera must be fixed in relation to the laser sheet. Ideally the laser sheet should be as thin as possible to provide better resolution for the free surface measurements, however, in order to perform SPIV simultaneously it is necessary to have some thickness to the laser sheet. For this set of experiments the laser sheet was set to a thickness of approximately 2.0 mm.

A GoPro Hero4 Black edition was used to visualize the free surface. This small high definition camera is capable of frame rates of up to 240 Hz. For this set of experiments the camera was set to record images at 240 Hz with an image size of 1280 by 720 pixels using the option for a "narrow" view angle. Triggering for this camera was performed using the GoPro iPhone application via bluetooth.

In order to calibrate the GoPro camera, a set of images showing the LaVision 204-15 calibration plate was recorded. These images were used by DaVis to complete a calibration using the built in pinhole camera model. In order to avoid changing the location of the camera a wireless bridge was established using the built in WiFi adapter of the GoPro. This allowed the images to be downloaded to the processing computer after each experiment.

The GoPro images were synced to the velocity data in two different manners. The longitudinally sliced free surface measurements were synced to the velocity measurements by locating the foil position in the images collected while the laser sheet was on the center line of the foil. Using this information ProAnalyst tracking

lines, described below, were developed relative to this zero position. The same tracking lines were used for each slice to maintain the known position of the foil. For the Transversely sliced data, the image frame where the leading edge of the foil crosses the laser plane is set to the zero location. Using the frame rate of the camera and the foil speed, the distance for subsequent frames is calculated and applied to the topography measurements.

1.4.5 ProAnalyst

Motion tracking software, ProAnalyst, was used to determine the location of the free surface in images collected by the free surface camera. ProAnalyst can be used to track both $1 - D$ and $2 - D$ movement within a video. For the purpose of this investigation only $1 - D$ tracking is necessary. In $1 - D$ tracking mode, lines are placed on the video and set to track the characteristics of the object which is of interest.

The free surface appears in each frame of the video as a line of peak intensity where the laser sheet intersects the free surface. This interface is approximately 7 to 10 pixels thick and directly proportional to the thickness of the laser sheet. To determine the free surface location, each tracking line was set to detect the location of highest intensity along the tracking line. Figure 4 shows how the tracking lines are arranged along the high intensity laser sheet - free surface intersection. In order to establish a baseline for the still water free surface, a tracking line was placed forward of the foil in the still water region. ProAnalyst calibration was performed using calibrated marks placed on each frame of the video by DaVis. Using the calibration marks, ProAnalyst can establish a relationship between pixel and world coordinates, in this case 10.4 pixels per mm. The tracking function will locate the highest intensity pixel along each tracking line, however, because the free surface

is between 7-10 pixels in thickness this leads to variability in the free surface on the order of 0.5 mm.

Figure 4: This screen shot from ProAnalyst shows the arrangement of the tracking lines and the free surface. The laser sheet intersecting the free surface is the high intensity line of approximately 10 pixels in thickness. The vertical lines are the tracking lines which track the peak intensity. In this image, the scale is 10.4 pixels per mm

1.4.6 Additional Measurements

In addition to the free surface elevation and velocity data, force measurements, foil position, and velocity were also collected for each experiment. Force measurements were made using a 6-axis ATI Gamma force sensor, model SI-130-10, mounted between the foil and top carriage. Position and velocity were recorded using the feed back from the motion control system and Labview. Velocity was also independently measured using a Unimeasure HX-VP1010-200-E1-L7M spring potentiometer.

1.5 Longitudinal Slicing

1.5.1 Experimental Design

As a free surface flow with a long slender body, Fr and Re are the dominant non-dimensional parameters. The Froude number, as defined in equation 1, is necessary to scale model free surface flows. In equation 1, U is the characteristic velocity of the flow, g represents standard gravity, and l is the characteristic length of the body, in this case the chord length. Froude numbers 0.19, 0.37, and 0.55 were chosen in order to provide a comparison to the Froude numbers used in (Metcalf et al., 2006), although a different NACA section was used. Experiments

were conducted in two sets. First, Fr 0.37 experiments were conducted in sequence from 0 to one half chord length between the slice and foil in increments of 0.035 chord lengths. Second, Fr 0.19 and 0.55 were completely randomized for both Fr and distance from foil. Table 1 is the experimental layout used. The numbers under each froud number indicate the number of the experiment.

$$Fr = \frac{U}{\sqrt{g * l}} \quad (1)$$

Table 1: Experimental Layout, the numbers below the Fr number indicate the run sequence of the individual experiment. First, Fr 0.37 was run starting at the centerline of the foil out to a half chord length. Second, Fr 0.19 and 0.55 were fully randomized in both speed and distance from the foil.

Distance (mm)	Froude Number		
	0.19	0.37	0.55
0.0	19	1	17
2.5	23	2	10
5.0	1	3	18
7.5	8	4	5
10.0	14	5	24
12.5	28	6	13
15.0	26	7	2
17.5	11	8	3
20.0	7	9	7
22.5	12	10	21
25.0	29	11	4
27.5	6	12	20
30.0	30	13	25
32.5	22	14	27
35.0	15	15	16

1.5.2 Approach

A time resolved 3-D velocity field is difficult to measure with out a tomographic PIV system or comprably expensive technology. For this reason, it was necessary to make 2-D measurements and then reconstruct the 3-D field. In order to reconstruct

the volume from the slices it is assumed that the phenomena surrounding the foil are steady state and that separation of the wake from the foil is minimal. Figure 5 shows the orientation of the slices and foil as well as a sample of reconstructed data. As mentioned in section 1.4.1 the tow tank is capable of highly repeatable experiments. This allows the volume to be "sliced" at specific distances from the center line of the foil. A similar technique is used in (Metcalf et al., 2006) to obtain the free surface elevations. In the Metcalf paper, a wave gauge was dynamically positioned in the wave field during the experiment. By averaging free surface heights in time, Metcalf was able to reconstruct the wave field. The longitudinal slicing method used is similar, in that the volume is sliced by the SPIV plane of view, averaged in time, and assembled with successive experiments to represent the 3-D volume surrounding the foil.

1.5.3 Image Collection

Each experiment followed the same procedure. First, the SPIV system, free surface camera, and control computer were programmed and placed in the "ready" mode. Once the seeding in the tank was adequate and the free surface was calm, the experiment commenced. The foil was set to accelerate using a half second ramp function, hold a steady speed, then decelerate using a half second inverse ramp function. SPIV and free surface camera systems were triggered remotely as the foil crossed the optical sensor which was located in the steady state zone of the speed profile. After the foil finished each run, the imaging systems downloaded all of the recorded data for archiving. Simultaneously, the foil would reset to the original position. Each experiment cycle lasted approximately 20 minutes, due to the download speed for the SPIV data and the necessity to wait for the tank to calm to a still water condition.

Figure 5: The volume surrounding the foil is sliced to obtain velocities and free surface elevations within the plane of the slice. The slices are then aggregated to obtain the volumetric average velocities within the volume.

1.5.4 Calculations

DaVis 8.1 software by LaVision was used to process the collected images and develop average velocity fields. Images were corrected using the calibration data obtained during the experimental set up. The SPIV calculation is performed using a 48 x 48 pixel square interrogation panel followed by a 32 x 32 pixel square secondary interrogation panel to determine the velocity field vector. The time average and standard deviation are calculated for the vector field based on the entire series of images. The final result yields a 2-D vector field of average velocities at a particular distance from the center line of the foil. By combining all of the slices performed at a specific Froude number it is possible to construct a three

dimensional average velocity field surrounding one side of the foil. This same process is followed for all three of the selected Froude numbers.

In (Willert and Gharib, 1991) the accuracy of PIV measurements is quantified based on the interrogation window size and the number of seed particles present in the window. Based on the PIV algorithm characterization of (Willert and Gharib, 1991) it is possible to make a conservative estimate of the error present in the PIV measurements. (Willert and Gharib, 1991) use an interrogation window of 32 by 32 pixels to obtain the information and plot the RMS fluctuation as a function of seeding density per window. In the experiments in this paper, a final interrogation window of 32 by 32 pixels with an average seeding density of 6 particles per window. At this density, a vertical RMS fluctuation of 0.013 pixels and a horizontal fluctuation of 0.026 pixels is estimated. To increase the number of computed vectors, four processing passes were conducted on each set of images. The first two processing passes were made with an interrogation window size of 48 pixels square. The second two passes were 32 pixels square and the interrogation windows were overlapped by 50% in all passes allowing for more velocity vector calculations per image. In the calibration of the longitudinally sliced data, 1.0mm is equal to 8 pixels. This translates to a theoretical variability of $\pm 2.08 \times 10^{-4}$ m/s in the horizontal direction and $\pm 1.04 \times 10^{-4}$ m/s in the vertical direction, using the estimates in algorithm error from (Willert and Gharib, 1991).

1.5.5 Free Surface Elevations

In order to obtain free surface measurements based on tracking the intersection of the free surface and the laser sheet, the SPIV images cannot be used since the curvature of the free surface combined with the perspective of distortion of the cameras results in regions where the near free surface blocks the view of the laser

intersection. By mounting the camera just above the still water free surface, at an approximate 30° angle behind the foil and fixed in reference to the laser sheet it is possible to obtain a clear image of the entire wave profile. Figure 6 illustrates the location of the camera in relation to the foil. Experiments are conducted in a dark room, where the only light present is the laser sheet, such that there is a very prominent line which is easily recorded by the camera as seen in Figure 7a.

Figure 6: This figure demonstrates the positioning of the GoPro camera in relation to the foil. The camera was mounted just slightly above the still water free surface to avoid the camera from interfering in the wave field. (A) Camera (B) Camera field of view (C) Laser sheet intersecting the free surface (D) Foil.

The video of the free surface was trimmed such that only the wave profile was shown to reduce file size and speed the processing of images. The video was then separated into individual frames and loaded into DaVis. The images were corrected

(a) Raw image

(b) Corrected image

Figure 7: Raw and corrected images obtained using the camera arrangement in figure 6 and calibrated using the DaVis pinhole camera model correction.

by using the calibration information calculated based on the methods described in section 1.4.4. To ensure that the calibration was accurate, the length of the foil in the image was compared to the actual chord length of the foil. A geometric mask was used to isolate the free surface profile from the surrounding image. ProAnalyst was then used to track the free surface as described in section 1.4.5. An example of the calibrated image can be seen in Figure 7b.

The free surface measurements were collected in slices, similar to the method used to collect the velocity measurements because the laser was moving. To establish the free surface position at the location of the slice, each tracking line height was averaged over all of the frames for that slice. The free surface was reconstructed by plotting each average height relative to the foil position which was determined from the slice along the center line of the foil. By using this method

and aggregating all 15 slices, it is possible to recreate the free surface topography as shown in Figure 11.

1.6 Transverse Slicing Method

A second method was investigated with the light sheet oriented perpendicular to the chord line of the foil as seen in figure 8. By orienting the sheet in this direction and assuming the fluid flow is steady, the foil passing through this sheet will behave like a 2D+T experiment, where the third spatial dimension is reconstructed from time, frame rate and foil velocity. By imaging the phenomenon in this manner it is possible to obtain the full velocity field and elevations in one experiment, significantly reducing the cost of obtaining this information.

Figure 8: This figure shows the orientation of the laser plane to the foil as well as the location of successive frames taken with the transverse method.

Transverse slicing required that the SPIV cameras be placed at the end of the tow tank, positioned such that they are at an approximate 20 deg angle away from the path of the foil. This also required the foil to be moved 5.0 cm off of center away from the cameras. The laser sheet was then positioned in the tank such that it intersected the path of the foil at the focal length of the camera lenses. The laser sheet intersected the path of the foil at a 90 deg angle.

To capture the free surface, the GoPro was affixed to the side of the tank using a suction cup mount and flexible arm. This allowed the camera to be fixed relative to the laser sheet but not interfere with the movement of the foil or track. The camera was positioned to look forward, toward the foil and laser sheet intersection. This allowed the collection of one side of the foil and resulting wake profile.

One challenge of this method is that the seed particles are at rest to start and the disturbance caused by the foil is minimal. To overcome this, the frame rate of the SPIV cameras was increased to 1094 hz to better capture the displacement of the particles. Seeding density was similar to that of the longitudinal method. For the transverse slice experiments, a Froude number of 0.37 was used. It is also important to note that in this orientation the U velocities are being measured by the stereo calculation, as opposed to the W velocities in the longitudinally sliced data.

1.6.1 Calculations

Utilizing DaVis 8.1, image sequences were pre-processed in the same manner as the longitudinally sliced experiments. It was necessary to reduce the sample rate of the collected images by a factor of 3 based on the displacement of the particles in each frame. At the full frame rate, the displacement of the particles was not large enough to provide an accurate velocity calculation. A first pass window size

of 64 x 64 pixels with 50% overlap was used. The two final passes were made with windows of 48 x 48 pixels and 50% overlap. For this experiment, the average and rms velocities were not calculated because time is used to reconstruct the third spatial dimension for the velocity field assuming a steady flow. The time series of images was then stitched together to recreate the volume in question. Each image is separated by a distance calculated by equation 2.

$$\delta d = \frac{U}{n} \text{ where } n = \text{framerate} \quad (2)$$

The transversely sliced elevation calculations were performed in the same manner to the longitudinally sliced measurements.

1.7 Results

1.7.1 Longitudinal Slicing

The component velocities U, V, and W resulting from the longitudinal slicing method for all three Fr are shown in figure 9. U velocity for all Fr show a region of increased speed at the location of maximum thickness as expected. V velocities indicate velocities in the downward direction from the leading edge of the foil transitioning to upward velocities at the trailing edge. W velocities show that the fluid is moving outward from the foil at the leading edge, and toward the foil at the trailing edge.

In addition to analyzing velocity near the free surface it is also possible to slice the data at various locations along the span of the foil. Figure 10 shows the U velocity at several consecutive slices starting at just above the free surface to one chord length below.

Figure 9: Non-dimensional velocities for all directional components and froude numbers. Velocities are non-dimensionalized by Fr number.

Figure 10: $Fr = 0.37$. Slices along the chord of the foil, starting at the mean free surface and extending to one chord length below the free surface. Velocities have been non-dimensionalized by Froude number

The compiled free surface measurements are shown in figure 11. At each Fr the wake profile expected of a slender body is observed and the elevations are of reasonable proportions relative to the size of the foil. Observations of the free surface disturbance are comparable in shape to the measurements obtained in figure 5 of (Metcalf et al., 2006). Metcalf uses a NACA 0024 foil and therefore the magnitudes of the free surface can't be directly compared, however, the general wake patterns can be expected to show resemblance to each other.

Table 2 shows the time averaged drag force. The drag coefficient (C_d) was calculated using Equation 3 for each froude number as well. In (Laitone, 1997) the C_d for a NACA 0012 is provided for a range of Re ranging from $20,700 \leq Re \leq 64,000$ and a straight line approximation is provided as Equation 4. Using 4 the C_d at the appropriate Re may be extrapolated from data presented in figure 6 of (Laitone, 1997). Table 3 compares the extrapolated C_d of Laitone to those of this experiment. As seen in Table 3 there is some difference between (Laitone, 1997) and this experiment. This difference is present for two reasons. First, the force sensor used in this experiment is rated to measure upto 130 newtons at a resolution of 1/40 N resolution. The measurements made during this experiment are at the very low end of its range which will introduce error in the form of noise to the force readings. The second reason for the differences, is due to the low Reynolds number. Existing data at Reynolds numbers lower than 10×10^4 could not be found, and thus, no direct comparison can be made.

$$C_d = \frac{F_x}{\frac{1}{2}U^2SC} \text{ where } S = \text{span length and } C = \text{chord length} \quad (3)$$

$$C_d = 0.11Re^{-0.125} \quad (4)$$

Free Surface Elevation

Figure 11: Free Surface Elevations

Table 2: Force in Newtons. The drag coefficient is for drag in the X direction based on the chord length of the foil.

	Froude Number		
Mean Force	0.19	0.37	0.55
F _x	0.0112	0.0118	0.0273
C _d	0.0339	0.0095	0.0100

Table 3: C_d for this experiment and extrapolated from Laitone are compared at corresponding Reynolds numbers.

	Drag Coefficient		
Froude Number	0.19	0.37	0.55
Reynolds Number	1.1288×10^3	2.1851×10^3	3.2407×10^3
This Experiment	0.0339	0.0095	0.0100
Laitone	0.0457	0.0421	0.0400

1.7.2 Transverse Slicing

The component velocities U, V, and W resulting from the transverse slicing method are shown in figure 12. This plot offers greater resolution in all directions due to the increased frame rate of the image collection. U velocities (chord-wise direction) are shown slowing at the front of the foil, increased along the chord, returning to free stream velocity at the trailing edge and leaving an unsteady wake. V velocity (span-wise direction, in and out of plot plane) are shown positive in front of the foil, negative along the chord and rising in the wake. W velocity (orthogonal to the chord) demonstrates the fluid moving away from the foil initially and then filling in around the foil toward the trailing edge. There is more variability in the W velocity measurements because the W dimension corresponds to the stereo calculation. All of these observations are what would be expected from this foil geometry at this Froude number.

Transverse Slicing, $Fr = 0.37$, $y/c = -0.334$

Figure 12: Transverse Slice Component Velocities. Velocities are non dimensionalized by the Fr number.

Elevation measurements obtained using the transverse slicing method are promising. Figures 13 show the elevations observed. Qualitatively the plots agree with velocity measurements and demonstrate an elevated zone at the leading edge, depressed surface elevations along the chord and finally the elevation returning to that of surrounding free surface.

Figure 13: Free surface elevations, non dimensionalized by the average free surface height, surrounding a NACA 0012 surface piercing foil at Froude number 0.37. The data for this plot was obtained using the transverse slicing technique.

1.8 Discussion

Ideally the longitudinal and transverse methods would yield high resolution, accurate and precise results for both velocity and free surface elevation. Two methods are used to compare the two experimental sets. First a qualitative comparison is made through direct comparison. Figures 9 and 12 can be compared to observe that similarities are present between the two methods. In both methods the velocities follow accepted patterns for flow over a slender body. The difference is in the resolution of the measurement. In the longitudinally sliced data, W velocities are a challenge to resolve due to the orientation of the imaging plane as well as the fact that they are the smallest in magnitude. In the transversely sliced data, U velocity becomes the more challenging component; however, the effects are offset due to the greater magnitude of the velocity. Also the direct relation to the Froude number allows the error to be more easily assessed and accounted for.

Differences also exist in the SPIV processing of the velocity fields. The longitudinally sliced data has a final processing window of 32×32 square pixels and the transverse sliced data was processed with a final window size of 48×48 square pixel size, both with a 50% overlap in window. According to (Willert and Gharib, 1991) window size does not have a direct effect on accuracy, however, the particle density in the image does. As the seeding is similar for each data set, the larger window size of the transverse data set allows for more particles to be present in each interrogation window, which results in less error. To quantitatively compare the two methods, the root mean square error (RMSE) was calculated using equation 5 where L denotes the longitudinal sliced data, T denotes transverse data and N is the total number of data points. U, V, and W are the component velocities with L and T indicating the longitudinally or transversely sliced data point respectively. The results of the calculations show an RMSE equal to 9.65%.

$$RMSE = \sqrt{\frac{\Sigma(U_T - U_L)^2 + \Sigma(V_T - V_L)^2 + \Sigma(W_T - W_L)^2}{N}} \quad (5)$$

In addition to better resolution in the component velocities, there is a difference in spatial resolution between the two methods. The longitudinal slices were taken in increments of $0.036 * CL$ (where $CL = \text{Chord Length}$) from the foil where as the transverse method resolves the entire volume in increments of $0.014 * CL$ which is limited by frame rate.

A third difference in the data is that the longitudinally sliced data is time independent. The imaging sequence obtained through the longitudinal slices measured a steady state time invariant phenomenon. The average of the SPIV series was then taken and that result was used to obtain the velocity profile. For the transverse slicing data, the imaging series is time dependent and each frame of data is observing a time dependent evolution of the flow field.

Since one data set is time averaged and one data set is time dependent, we want to measure whether the underlying flow structures of the two data sets are the same. To do this, we use dynamic mode decomposition. (Schmidt, 2010) calculates the eigenvalues of the approximated evolution matrix that describes how a time series moves from one snapshot to the next. First the component velocities are assembled into a matrix (V_1^N) containing the 3D3C velocities as seen in equation 6 where N references the snapshot and M references the point with in the snapshot. Then, two comparison matrices are assembled as described by equation 7 and 8. Using the two comparison matrices QR decomposition is applied and the companion matrix S is found. Eigenvalues and vectors are calculated from S and then plotted. The mode shape which exists only in the real domain is the primary and most

important mode shape.

This method allows the comparison of the mechanical processes occurring in the flow fields as they vary in time. For the 2D+T measurements DMD is applied directly. In order to apply this method to the longitudinally sliced data snapshots of the volume were taken along the Z axis. To consider the methods to be of similar quality, the mode shapes present in each must be sufficiently similar in pattern as well as in magnitude. As seen in Figure 14 the mode shapes do share similar shapes as well as magnitudes to each other and can be considered to be measuring the same phenomenon.

$$v_1 = \begin{bmatrix} U_M^N \\ V_M^N \\ W_M^N \end{bmatrix} \quad (6)$$

$$V_1^N = \{v_1, v_2, v_3 \dots v_{N-1}\} \quad (7)$$

$$V_2^{N-1} = \{v_2, v_3, v_4 \dots v_N\} \quad (8)$$

Based on the results of both methods, the 2D+T method provides the best for an economical measurement of free surface elevations and 3D3C velocities surrounding a surface piercing foil. The longitudinal method, although similarly accurate, requires many more individual experiments and corresponding processing time.

1.9 Conclusions

SPIV is a very powerful tool to obtain volumetric velocities of fluids, however the expense of such measurements is prohibitive for many applications. By changing the orientation of the SPIV field of view from horizontal to vertical, it is possible to reduce the expense by eliminating the need to re-calibrate the system

before each individual slice of the experiment. The results obtained by this experiment show that by using a vertically oriented laser sheet, parallel to the chord line of the foil, it is possible to obtain a robust and accurate measurement with only one calibration of the cameras.

Even greater economy can be found by slicing the volume transversely. The transverse method allowed the number of experiments to be reduced to one in this case. In the event that an angle of attack or asymmetrical body were to be used, two experiments would be needed, one for each side of the body. The reduction of the number of experiments brings a significant savings in time and computing expense.

The longitudinal method is useful for measuring time averaged data when the body under investigation is symmetrical and the flow is steady with no separation. The transverse method will allow for a more economical representation of the fluid volume as only one or two experiments are required to determine the velocities through out the volume. If the longitudinal method is used on an asymmetrical body the number of experiments and processing time required to develop the volume is doubled as SPIV must be carried out on both sides of the body.

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Figure 14: The most significant mode as calculated using DMD.

APPENDIX A

Longitudinal Slicing Set Up and Experiment Execution

A.1 Setting up the Tank

In order to set up the tank do the following:

1. Clean and fill tank with fresh water to the desired level.
2. Install Foil to load cell.
3. Home all axis of the tank drive system using the homing routine on the control computer.
4. Seed the tank with particles, for this experiment 50 micron particles were used.

A.2 Setting up the PIV system

1. Phantom Cameras should be mounted on the cross arm of the trolley. They should be close together and pointed toward the same field of view.
2. The laser head should be positioned on the breadboard of the trolley.
3. The laser sheet should be adjusted so that it is slicing the tank longitudinally. The laser should be positioned such that the laser sheet follows the center line of the foil.
4. The trigger switch that is mounted to the side of the tank should be positioned such that it is triggered after the foil reaches steady state velocity.
5. Connect the PIV cameras, Laser head, timing controller, and PIV computer as instructed by the LaVision manual.

6. Mount the calibration plate so that the laser sheet is in plane with the front of the plate and the the plate is located in the same location as the center line of the foil.
7. Start DaVis 8.0 and choose the record setting, enable both cameras and then choose "live mode".
8. Use the calibration plate to adjust the cameras so that they are imaging the same area. Do not move the calibration plate, it is important for the next part of the set up.

A.3 Setting up the GoPro

1. Prior to setting up the camera, download and install the GoPro app onto a smart phone. This will allow you to view the camera image prior to the testing as well as trigger the camera during testing. The GoPro website www.gopro.com has full instructions and information on how to download, install, and connect the camera to a smart phone.
2. The GoPro will be mounted on top carriage of the tank on the side of foil closest to the center of the room. Use the flexible arm and 80/20 components to fix the camera in position.
3. Prior to setting up the camera ensure that the following settings are chosen in the camera: (use the manual to set them if you are not familiar with the camera)
 - Invert the image
 - Use the narrow field of view
 - Set the frame rate to 240 hz
 - Choose the highest resolution available at 240hz.

4. Position the GoPro such that it can image the front of the calibration plate which should still be located in plane with the laser sheet. The camera can be flipped upside down to get the best viewing azimuth.
5. Ensure that half of the calibration plate that is above the water is visible in the camera image.
6. Once the camera is mounted, record a series of images of the calibration plate to use for calibration. DO NOT MOVE THE CAMERA after these are taken, or you will have to re-take the images.

A.4 Calibration

Once the cameras are set up, focused, and ready to record images, run a few test runs to ensure that the trigger, camera angle, and frame rate are suitable. Once you are satisfied with the image quality and field of view, use DaVis to calibrate the PIV cameras in accordance with the DaVis Manual and Wizard.

The calibration for the GoPro video will be done separately as part of the processing to determine the elevation of the free surface.

A.5 Experiment Execution

Once the system is calibrated, use the control computer and Matlab to control the foil movement.

1. First, set DaVis to "record on TTL input"
2. Open Matlab
3. Open 'JJ Test' folder on the desktop or external hard drive.
4. Open 'tankloop.m' and 'experimentalsetdefinition.m'

5. 'experimentalsetdefinition.m' contains the motion profiles for the foil. choose the appropriate profile (the experiments done for this thesis were conducted using set 1).
6. Set 'Foil y distance' parameter to $0cm$.
7. Set 'speed' to the speed which corresponds to the Froude number in question.
8. Save 'experimentalsetdefinition.m'
9. Run 'tankloop.m'
10. Repeat these steps for each Froude number and distance combination to be tested.

This will start the controller and run the system through one experiment. It is necessary to use the GoPro smart phone application to trigger the go pro. Trigger the GoPro early as extra frames may be deleted during processing. After the experiment has run, ensure that the data is complete and download all images from PIV cameras.

Downloading GoPro Data Images from the GoPro may be downloaded via WiFi as follows:

1. Ensure GoPro WiFi is turned on.
2. Connect the PIV computer to the "DahlGoPro" WiFi network, the password for the network is the same as the control computer.
3. Use Chrome to access <http://10.5.5.9:8080> this will allow a backdoor into the gopro file system.

4. Navigate to "dcim" folder and the various videos stored on the GoPro will be visible
5. Right click on the file to be downloaded and choose "save destination file as", select where you want to save it, and click ok.
6. the file should now download.

APPENDIX B

Longitudinal Slice Elevation Processing Procedures

B.1 Introduction

In order to take the raw mp4 video from the GoPro and calculate the elevations, the video must be processed. During the processing the images in the video will be calibrated, the free surface tracked, and then plotted.

B.2 Creating Frames from Video Files

Each mp4 file downloaded from the GoPro should be placed into a folder within the Matlab path. A copy of 'splitmp4.m' should be placed on the same level as the video files. In Matlab run 'splitmp4.m' to create separate folders with the video files split into individual frames. This is also a good time to trip any unnecessary frames from the files, this will conserve computing and processing time.

B.3 Import Video to DaVis

The folders created in the last section need to be imported back to DaVis. DaVis has an "import" function which will allow the importation of folders of image frames. Follow the DaVis Manual to import the images, including the calibration images.

B.4 Calibration

Once imported, use the calibration wizard to establish the calibration curve for the images. Instead of capturing images, use the folder button on the image acquisition page of the wizard to locate the calibration frames imported in the last step. When prompted for the type of calibration algorithm, choose the "pinhole camera" option. Once the calibration is complete click "OK". Verify that the calibration of the images is correct by comparing the length of the foil in the

image to the actual length of the foil.

B.5 Correction

Once the images are calibrated, click on the processing tab at the top of the screen in DaVis. By right clicking and choosing "hyperloop" it is possible to batch process many experiments at once. Once the appropriate folders have been chosen, click on the "Parameter" button at the bottom of the page.

On the parameter page select the first processing step and choose,

This will apply the calibration function to each image. This is also a good time to mask any parts of the image that are not necessary to the calculation of the free surface. Using the various masking tools, exclude all of the image with the exception of the high intensity line which will be tracked in future steps. Leave adequate room above and below the line such that any deflections will be retained after masking.

B.6 Export from DaVis to ProAnalyst

Once the frames are corrected and masked, use the hyperloop tool to export the frames as .avi videos. Export all of the frames and ensure that your naming convention is still intact. Once exported, the .avi files can be directly imported to ProAnalyst using the "add file" option on the toolbar.

B.7 Establishing Scale and Origin

Once a file is open in ProAnalyst, the first task is to establish the scale and origin of the image.

Set the first point as one of the tick marks on the Y axis of the image. Set the second point as the tick mark above or below. Due to the tick mark labels it is possible to then set the scale of the image using label associated with each tick

mark and entering in into ProAnalyst. After the scaling is set, place the cursor on the image in line with the free surface and click "set origin" and set the Y axis so that positive is up.

B.8 Establishing Tracking Lines

ProAnalyst has two options for tracking features in a frame, one dimensional tracking, and two dimensional tracking. For the purposes of this experiment, only the one dimensional feature is used.

First, click on the 1-D tab and enable one dimensional tracking. Next lines of tracking need to be set. To add a line, click the + button and a new tracking line will be added to the list. Use the adjust line feature to set the coordinates of the line. When adding lines it is important that all of the lines have the same Y-coordinates. This will allow direct comparison between lines and make plotting the surface possible. Further details on how to program the lines is available in the ProAnalyst Manual. A sufficient number of lines to cover a distance equal to one chord length away from the foil will need to be set. Save your work as ProAnalyst becomes unstable if too many lines are created, thirty lines should be considered the maximum number of lines to maintain stability.

Once all the lines are set, click on the wrench icon on the first line. Set the tracking feature to highest intensity. This will have the program search for the pixels along the tracking line with the highest intensity and record that position. Set the line width to 3 pixels. This will provide an initial filter. Check the box 'apply to all lines' so that each line is programmed identically.

Now that all lines are set and programmed, click on the 'play' button on the bottom of the screen. ProAnalyst will now run through each frame and calculate

the location of the free surface. Once the program has run completely, export the data as a "Blank Excel Spreadsheet".

B.9 Processing the Elevation Data from ProAnalyst

Once all the data has been exported from ProAnalyst, it can be placed into a folder in the Matlab path. Make sure that the following files are also in this folder:

- generate_elevation_matrix.m
- importfile.m
- naca4gen.m
- plotlist.m
- nacagen.m
- supitle.m
- ElevationScript.m

Below is the sequence that these files should be run as well as a brief explanation of what they do. Each file has notes embedded to assist the user. It is to adjust certain parameters if a new data set is used. If adjustments need to be made they are called out below.

generate_elevation_matrix.m This file combined with 'importfile.m' takes the excel spreadsheet from ProAnalyst and imports the data into Matlab .mat format. It is important to open this file and alter the distance parameter and numlin variable so suit the data being imported. More details are in the file.

ElevationScript.m This program sets the axis for the data as well as adjust the data for the frame rate. It is important to read this script to ensure that the appropriate dimensions are being applied based on frame rate and free surface location. The data is also filtered to smooth out any noise in the data.

plotlist.m This final script is used to create plots for data. The script is self explanatory and has very few parameters to be adjusted.

Other Scripts The other scripts located in this file support those explained above. 'nacagen.m' creates a naca profile with in the plot. 'suptitle.m' creates a superior title at the top of a multi frame plot.

APPENDIX C

Transverse Slicing Set Up and Experiment Execution

C.1 Setting up the Tank

In order to set up the tank do the following:

1. Clean and fill tank with fresh water to the desired level.
2. Install Foil to load cell.
3. Home all axis of the tank drive system using the homing routine on the control computer.
4. Seed the tank with particles, for this experiment $50nm$ particles were used.

C.2 Setting up the PIV system

1. Phantom Cameras should be placed at the end opposite the tank filter equipment such that they are pointed down the length of the tank. They should be close to the wall and at a slight angle toward the center of the room.
2. The trolley with the laser head should be positioned as close to the cameras as the track will allow.
3. The trigger switch that is mounted to the side of the tank should be positioned such that it is triggered prior to the foil crossing the laser sheet. Take care to measure the distance between the laser sheet and when the trigger is activated. This is critical to establishing when the foil crosses the laser plane during processing.
4. Connect the PIV cameras, Laser head, timing controller, and PIV computer as instructed by the LaVision manual.

5. Mount the calibration plate so that the laser sheet is in plane with the front of the plate and the the plate is located in the same location as where the foil will cross the plane of the laser sheet.
6. Start DaVis 8.0 and choose the record setting, enable both cameras and then choose "live mode".
7. Use the calibration plate to adjust the cameras so that they are imagine the same area. Do not move the calibration plate, it is important for the next part of the set up.

C.3 Setting up the GoPro

1. Prior to setting up the camera, download and install the GoPro app onto a smart phone. This will allow you to view the camera image prior to the testing as well as trigger the camera during testing. The GoPro website www.gopro.com has full instructions and information on how to download, install, and connect the camera to a smart phone.
2. The GoPro will be mounted on the side of the tank closest to the wall. Use a suction cup mount to stick the flexible arm to the glass.
3. Prior to setting up the camera ensure that the following settings are chosen in the camera: (use the manual to set them if you are not familiar with the camera)
 - Invert the image
 - Use the narrow field of view
 - Set the frame rate to 240 hz
 - Choose the highest resolution available at 240hz.

4. position the GoPro such that it can image the back of the calibration plate which should still be located in plane with the laser sheet. The camera can be flipped upside down to get the best viewing azimuth.
5. Ensure that at least one quarter of the calibration plate is visible in the camera image. The more the better.
6. Once the camera is mounted, record a series of images of the calibration plate to use for calibration. DO NOT MOVE THE CAMERA after these are taken, or you will have to re-take the images.

C.4 Calibration

Once the cameras are set up, focused, and ready to record images, run a few test runs to ensure that the trigger, camera angle, and frame rate are suitable. Once you are satisfied with the image quality and field of view, use DaVis to calibrate the PIV cameras in accordance with the DaVis Manual and Wizard.

The calibration for the GoPro video will be done separately as part of the processing to determine the elevation of the free surface.

C.5 Experiment Execution

Once the system is calibrated, use the control computer and Matlab to control the foil movement.

1. First, set DaVis to "record on TTL input"
2. Open Matlab
3. Open 'JJ Test' folder on the desktop or external hard drive.
4. Open 'tankloop.m' and 'experimentalsetdefinition.m'

5. 'experimentalsetdefinition.m' contains the motion profiles for the foil. choose the appropriate profile (the experiments done for this thesis were conducted using set 1).
6. Set 'Foil y distance' parameter to $-5.0cm$.
7. Set 'speed' to $0.31m/s$.
8. Save 'experimentalsetdefinition.m'
9. Run 'tankloop.m'

This will start the controller and run the system through one experiment. It is necessary to use the GoPro smart phone application to trigger the go pro. Trigger the GoPro early as extra frames may be deleted during processing. After the experiment has run, ensure that the data is complete and download all images from PIV cameras.

Downloading GoPro Data Images from the GoPro may be downloaded via WiFi as follows:

1. Ensure GoPro WiFi is turned on.
2. Connect the PIV computer to the "DahlGoPro" WiFi network, the password for the network is the same as the control computer.
3. Use Chrome to access <http://10.5.5.9:8080> this will allow a backdoor into the gopro file system.
4. Navigate to "dcim" folder and the various videos stored on the GoPro will be visible

5. Right click on the file to be downloaded and choose "save destination file as", select where you want to save it, and click ok.
6. the file should now download.

APPENDIX D

Transverse Slice Elevation Processing Procedures

D.1 Introduction

In order to take the raw mp4 video from the GoPro and calculate the elevations, the video must be processed. During the processing the images in the video will be calibrated, the free surface tracked, and then plotted.

D.2 Creating Frames from Video Files

Each mp4 file downloaded from the GoPro should be placed into a folder within the Matlab path. A copy of 'splitmp4.m' should be placed on the same level as the video files. In Matlab run 'splitmp4.m' to create separate folders with the video files split into individual frames. This is also a good time to trip any unnecessary frames from the files, this will conserve computing and processing time.

D.3 Import Video to DaVis

The folders created in the last section need to be imported back to DaVis. DaVis has an "import" function which will allow the importation of folders of image frames. Follow the DaVis Manual to import the images, including the calibration images.

D.4 Calibration

Once imported, use the calibration wizard to establish the calibration curve for the images. Instead of capturing images, use the folder button on the image acquisition page of the wizard to locate the calibration frames imported in the last step. When prompted for the type of calibration algorithm, choose the "pinhole camera" option. Once the calibration is complete click "OK".

D.5 Correction

Once the images are calibrated, click on the processing tab at the top of the screen in DaVis. By right clicking and choosing "hyperloop" it is possible to batch process many experiments at once. Once the appropriate folders have been chosen, click on the "Parameter" button at the bottom of the page.

On the parameter page select the first processing step and choose,

This will apply the calibration function to each image. This is also a good time to mask any parts of the image that are not necessary to the calculation of the free surface. Using the various masking tools, exclude all of the image with the exception of the high intensity line which will be tracked in future steps. Leave adequate room above and below the line such that any deflections will be retained after masking.

D.6 Export from DaVis to ProAnalyst

Once the frames are corrected and masked, use the hyperloop tool to export the frames as .avi videos. Export all of the frames and ensure that your naming convention is still intact. Once exported, the .avi files can be directly imported to ProAnalyst using the "add file" option on the toolbar.

D.7 Establishing Scale and Origin

Once a file is open in ProAnalyst, the first task is to establish the scale and origin of the image.

Set the first point as one of the tick marks on the Y axis of the image. Set the second point as the tick mark above or below. Due to the tick mark labels it is possible to then set the scale of the image using label associated with each tick mark and entering in into ProAnalyst. After the scaling is set, place the cursor on the image in line with the free surface and click "set origin" and set the Y axis so

that positive is up.

D.8 Establishing Tracking Lines

ProAnalyst has two options for tracking features in a frame, one dimensional tracking, and two dimensional tracking. For the purposes of this experiment, only the one dimensional feature is used.

First, click on the 1-D tab and enable one dimensional tracking. Next lines of tracking need to be set. To add a line, click the + button and a new tracking line will be added to the list. Use the adjust line feature to set the coordinates of the line. When adding lines it is important that all of the lines have the same Y-coordinates. This will allow direct comparison between lines and make plotting the surface possible. Further details on how to program the lines is available in the ProAnalyst Manual. A sufficient number of lines to cover a distance equal to one chord length away from the foil will need to be set. Save your work as ProAnalyst becomes unstable if too many lines are created, thirty lines should be considered the maximum number of lines to maintain stability.

Once all the lines are set, click on the wrench icon on the first line. Set the tracking feature to highest intensity. This will have the program search for the pixels along the tracking line with the highest intensity and record that position. Set the line width to 3 pixels. This will provide an initial filter. Check the box 'apply to all lines' so that each line is programmed identically.

Now that all lines are set and programmed, click on the 'play' button on the bottom of the screen. ProAnalyst will now run through each frame and calculate the location of the free surface. Once the program has run completely, export the data as a "Blank Excel Spreadsheet".

D.9 Processing the Elevation Data from ProAnalyst

Once all the data has been exported from ProAnalyst, it can be placed into a folder in the Matlab path. Make sure that the following files are also in this folder:

- generate_elevation_matrix.m
- importfile.m
- naca4gen.m
- plotlist.m
- nacagen.m
- supitle.m
- ElevationScript.m

Below is the sequence that these files should be run as well as a brief explanation of what they do. Each file has notes embedded to assist the user. It is necessary to adjust certain parameters if a new data set is used. If adjustments need to be made they are called out below.

generate_elevation_matrix.m This file combined with 'importfile.m' takes the excel spreadsheet from ProAnalyst and imports the data into Matlab .mat format. It is important to open this file and alter the distance parameter and numlin variable so suit the data being imported. More details are in the file.

ElevationScript.m This program sets the axis for the data as well as adjust the data for the frame rate. It is important to read this script to ensure that the appropriate dimensions are being applied based on frame rate and free surface location. The data is also filtered to smooth out any noise in the data.

plotlist.m This final script is used to create plots for data. The script is self explanatory and has very few parameters to be adjusted.

Other Scripts The other scripts located in this file support those explained above. 'nacagen.m' creates a naca profile with in the plot. 'suptitle.m' creates a superior title at the top of a multi frame plot.

APPENDIX E

Comparison of Methods Procedure

E.1 Introduction

In order to compare the two methods Dynamic Mode Decomposition as explained by (Schmidt, 2010) is used. This method

E.2 Matlab Script and Function Descriptions

E.2.1 `matrixweave.m`

The function assembles the three component velocities (U,V,W) into a matrix such that each column of the matrix represents a single snapshot of the flow. U, V, W are arranged vertically in the column. Details on how to utilize this function, input and output are found in the function itself.

E.2.2 `DMD_FlowField.m`

This function is the actual Dynamic Mode Decomposition. It uses the mathematical principles described in (Schmidt, 2010) to break the flow into individual modes. The input to this function is the output from `matrixweave.m`.

E.2.3 `axisscales.m`

This script contains the axis scale values for all plots. This allows the axis limits and increments to be changed in one locations. It is used in both `DMDLong.m` and `DMDTransverse.m`.

E.2.4 `DMDLong.m`

This script carries out data processing and DMD on the longitudinally sliced data. It contains all of the above functions, plus some data manipulation in order to plot the most significant mode present in the data.

E.2.5 DMDTransverse.m

This script carries out the data processing and DMD on the transversely sliced data. It contains the functions above in addition to data manipulation required to plot the most significant mode present in the data.

E.3 Operational Procedures

1. Place the final data sets for the method to be analyzed into the Matlab directory.
2. Open the DMDTransverse.m or DMDLong.m which applies to the data present.
3. Update the name of the file to be loaded on line 7.
4. Update the chord length of the foil used.
5. Run the script.
6. Open the Ui variable which represents the imaginary portion of the complex mode shape. Make note of the columns which present at all zeros. These are the most significant modes.
7. Place the column numbers into the array on line 74 as values of q.
8. Run the script again. A figure should print to the screen for each number you placed into array q. Each plot is one of the significant mode shapes. Choose the one that best represents the original data.
9. Delete the values in q that do not best represent the data. The remaining plot will be of the most significant mode shape.

A full description of how DMD works can be found in (Schmidt, 2010). Each script and function contains notes within the individual file to describe what is occurring within the script.

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