Particle image velocimetry experiments to measure flow around an escort tug

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PARTICLE IMAGE VELOCIMETRY EXPERIMENTS TO MEASURE FLOW AROUND AN ESCORT TUG

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SUMMARY

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PARTICLE IMAGE VELOCIMETRY EXPERIMENTS TO MEASURE FLOW AROUND AN ESCORT TUG

by

David Molyneux and Jie Xu

INTRODUCTION

Escort tugs use the combination of yaw angle and azimuthing thrusters to generate the hydrodynamic forces that are used to control a disabled tanker. The yaw angles used for escort operations are considered to be 'off-design' conditions in normal naval architecture and the resulting flow patterns at these yaw angles have not been studied in detail.

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In January 2004, Memorial University of Newfoundland purchased a PIV system for making flow measurements in a towing tank. The system was innovative since the expensive laser and CCD cameras were placed in air, above the water surface and images of the seed particles were obtained by observing the underwater flow through boroscopes. This solution removed the need for sealed underwater containers, which fix the relative distance between the cameras and make adjustments to system components difficult and time consuming. For the Memorial PIV system the primary components are separate units and so a wide range of image planes relative to the model can be obtained.

This paper describes the PIV system and presents some preliminary results of flow measurements in steady uniform flow and for the flow around an escort tug model at three different yaw angles. These experiments were the first attempt to study the flow around an escort tug over the range of operating yaw angles, and provided valuable preliminary results and experience in carrying out PIV experiments with a ship model in a towing tank. The results will be used as the basis for planning a more detailed set of flow measurements around an escort tug model.

PIV SYSTEM DESCRIPTION

General Description

For Particle Image Velocimetry (PIV), a laser light sheet is used to illuminate the fluid in the region where measurements are to be made. The flow through the measurement area is seeded with small, reflective particles, and photographs are taken at successive intervals. By timing the intervals to ensure that the same particles are in each exposure, flow vectors can be calculated, once the measurement space has been calibrated. In its simplest form, the technique is applied in two dimensions with a single camera, but by using stereo photography, it can be extended to three dimensions.

There are some optical factors to consider in the arrangement of the laser and the cameras. The optimum arrangement is for a symmetrical arrangement with one camera located on either side of the light sheet, as shown in Figure 1. This arrangement is most efficient in terms of spatial resolution because the distortion between the fields of view is the same for each camera. It is also relatively easy to maximize the overlap of the field of view for each camera to ensure the largest possible measurement space.

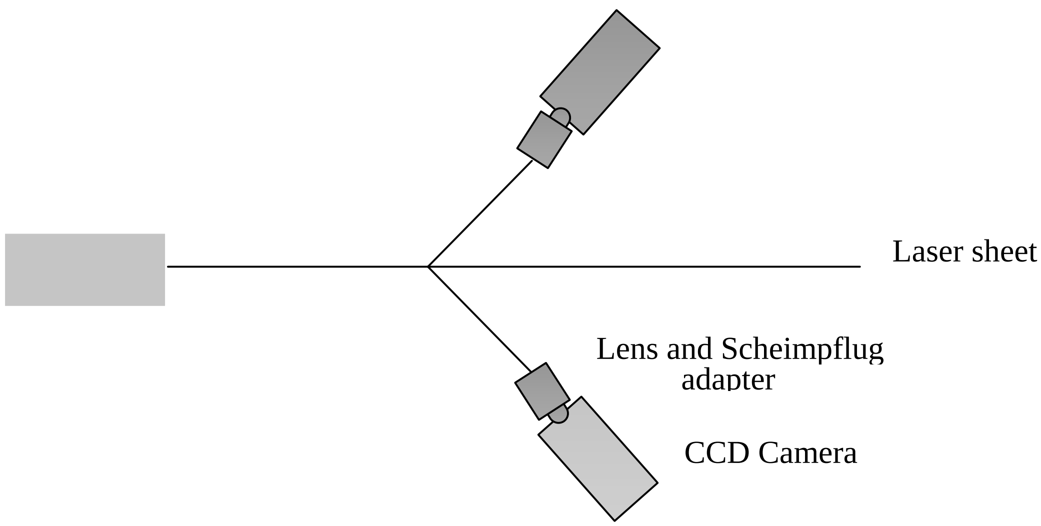

Figure 1, Primary camera and light sheet orientation.

This arrangement is not always possible in practical applications, and an alternative arrangement can be used. In this case the two cameras are located on the same side of the light sheet, as shown in Figure 2. In this case, the field of view common to both cameras can be maximized, but the distortion is no longer the same for each camera, and so spatial resolution is compromised slightly.

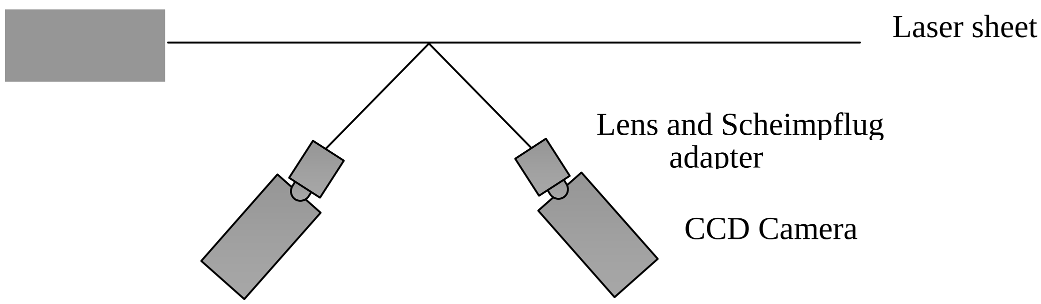

Figure 2, Secondary camera and light sheet orientation.

The ideal arrangement is for the lenses of the cameras to be normal to the laser sheet, which results in the least distortion of the collected images. If this is not possible the resolution can be improved by the use of a Scheimpflug adapter. This device creates an angle between the lens and the image collection plane, which reduces distortion in oblique views.

Either of the two arrangements can be used for measurements in one of three orthogonal planes, i.e. a vertical plane normal to the flow direction, a vertical plane along the flow direction, or a horizontal plane.

These factors were taken into consideration in the design of the PIV system purchased by Memorial University of Newfoundland from LaVision Inc. of Ypsilanti, MI, USA. The system consisted of four main elements:

- Two Charge Coupled Device (CCD) cameras
- Twin-head Nd:YAG laser and controller
- Computer for timing of laser and cameras and data acquisition

A photograph of the complete system, assembled in air, is shown in Figure 3.

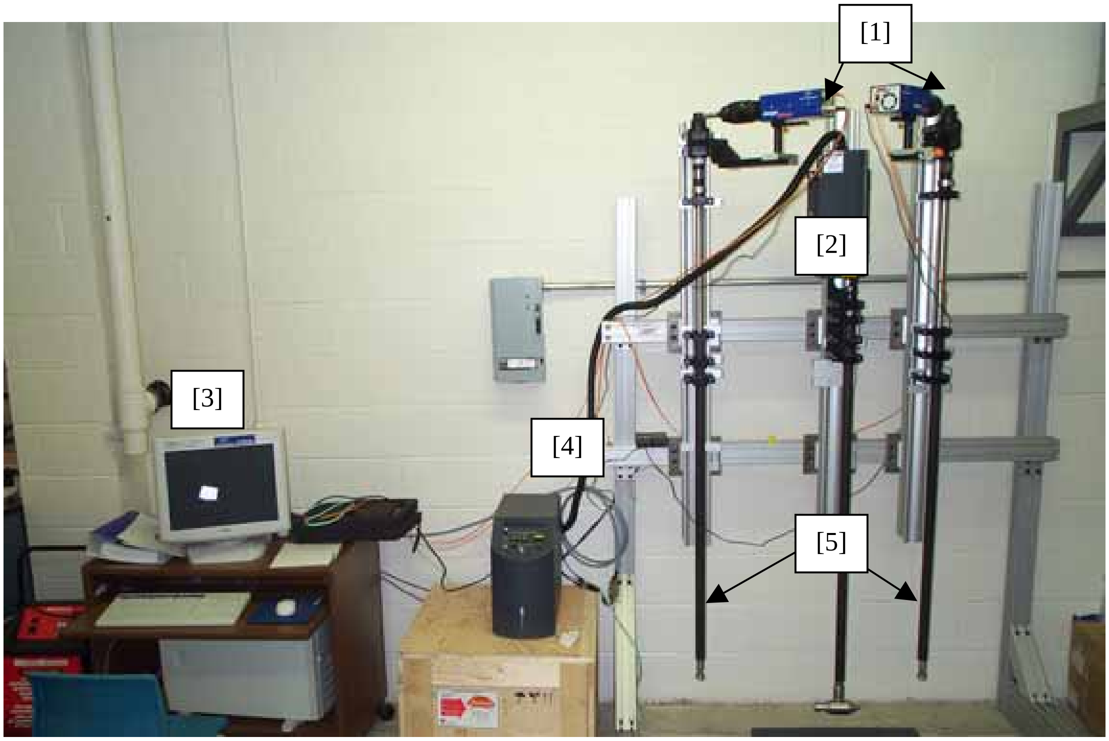

Figure 3, PIV System, view of complete system showing CCD cameras [1], laser head [2], computer [3], laser controller [4] and borescopes [5].

In addition to the components described above, which are common to all PIV systems there were two borescopes, which were unique to this particular system. The cameras were mounted in air at the top of a borescope, which provided the capability for obtaining the underwater views. The advantage of this arrangement was that delicate cameras were kept well above the water surface, removing the need for expensive watertight housings. The potential negative side of the arrangement is that the small aperture of the borescopes and the lenses inside the borescopes may result in the loss of too much laser energy, and as a result photographs of the particles are too dark. A similar arrangement was provided for the laser, but this was a plain tube, without the optics of a borescope.

Detailed descriptions of the component parts are given below (LaVision, 2002). The purchase was funded by a grant from the Canada Foundation for Innovation (CFI) and the Department of Innovation, Trade and Rural Renewal to the Canada Research Chair in Offshore and Underwater Vehicles Design.

Laser and Light Sheet Optics

The laser system used was a Solo 120 model supplied by New Wave Inc. This system consisted of a pair of Nd: YAG lasers with maximum energy output of 120 mJ/pulse and a maximum pulse repetition rate of 15 Hz. The pulsed laser beams were directed downwards through a stainless steel tube to a waterproof housing containing the light sheet optics. The light sheet optics consisted of a 45 degree mirror to turn the beam from vertical to horizontal and a fixed focal length cylindrical lens which controled the divergence angle of the light sheet (lenses for 15° and 22.5° divergence angles were available). A second 45° mirror could be used to change the direction of the laser beam. With the second mirror removed, the laser shone directly out of the stern of the optical housing. With the second mirror in place, the beam was turned normal to the housing. Rotating the complete unit changed the direction of the beam.

At the top of the tube were two telescope lenses with infinitely adjustable focal lengths (between 400 mm and 2500 mm in water). These lenses were used to adjust the diameter of the laser beam, which in turn affected the thickness of the light sheet. These lenses were adjusted with the system assembled. The downstream side of the light sheet housing and connecting tube was fitted with a faired trailing edge to minimize wake.

Charged Couple Device Camera & Boroscopes

Two identical Imager Intense™ cameras were used in the PIV system. Each camera had an adapter so that it could be used with standard Nikon C-mount or F-mount lenses. Specifications for the cameras are given in Table 1.

There was serial data transfer between the camera and the PCI-Interface-Board. A Programmable Time Unit (PTU) controlled the triggering of the camera and the synchronization with the laser. The exposure time of the camera, the laser power, and the interval between the two laser pulses were also adjusted by the PTU.

Parameter	Specification
Resolution (pixels)	1376*1040
Dynamic Range, Digitization	12 bits
Cooling	2-stage thermo electric
Quantum Efficiency	65% at 500 nm
Readout noise	4e
Readout Rate	16 MHz
Data Rate(Vector Fields/sec)	5Hz
Capture Sequence Capacity to RAM	2GB
Capture Sequence Duration to RAM	34 sec
Camera Interface	High Speed Serial, PCI bus

Table 1, Imager Intense Camera System Specification

The borescopes used in conjunction with the cameras were 1.9 m long. The collection cone angle of each borescope with no other optical devices was 35° (in air). At the lower end of each borescope was a prism, with a nominal collection angle of 20° (in air). In water the collection angle was reduced to 16° in width and 12° in height. The nominal viewing angle of each prism was normal to the boroscope body but it could be changed within +/- 15° by adjusting the angle of the prism. Each borescope was fitted with a tapered fairing to minimize wake. Rotating the borescope about its centerline set the viewing direction.

Calibration.

3D-PIV measurements require two different viewing angles of the same measurement space. The projected images of the 2-dimensional vectors on each plane are combined to give 3-dimensional vectors. It is possible to determine the viewing directions of both cameras in relation to the measurement space by using a calibration procedure. Since the arrangement of both cameras is fixed it is possible to calculate three velocity components from the two projections, by calibrating the measurement space against a matrix of points with known spacing in three dimensions.

Calibration of the LaVision system was carried out using a special calibration plate and the DaVis software, supplied by LaVision. The stepped calibration plate was a black background with white equidistant dots (Figure 4). To obtain a calibration, the plate was put into the fluid at the location where velocities were to be measured and was exactly aligned with the location of the laser light sheet, although the calibration was made using visible light. The calibration plate image was recorded by the two cameras and evaluated by the software in order to calculate the mapping function between the two images of the plate. Parameters, such as the type of calibration plate, distance between marks in the xy plane, displacement in the z plane (dz) and the size of dots (in pixels) were entered into the software during the calibration.

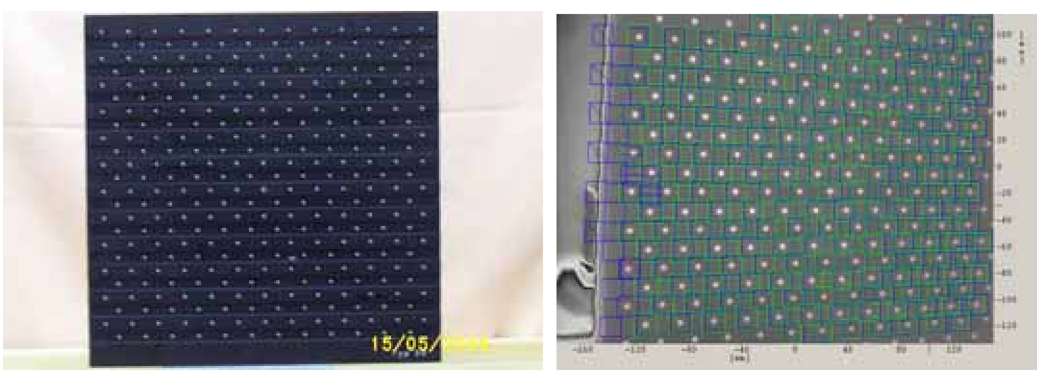

Figure 4, Calibration plate (left) and calculated mapping function (right)

Seeding Particles

The seeding particles used for all the experiments were hollow, silver coated spheres (SH400S33) supplied by Potters Industries of Valley Forge PA, USA. Preliminary experiments on different types of seeding powder (Molyneux & Xu, 2005) indicated, that although these are the most expensive in terms of unit price, the image quality and the ability of the particles to stay suspended for the longest time make them the most viable technical solution. The particle specifications are given in Table 2 (Potters Industries, 2005).

Particle composition	Silver coated glass
Shape	Spherical
%Ag metal	33
Ten percentile, particle diameter, microns	8
Ninety percentile, particle diameter, microns	20
Mean particle diameter, microns	14
True density, g/cc	1.7

Table 2, Seeding particle specifications

No formal method for ensuring constant seeding concentration was developed for these experiments. The holding tank was filled to approximately the same level each time and seeding particles were added by scoops with a small spoon. Visually, the mixture was opaque and cloudy grey in colour.

Data Collection and Image Processing

Data collection and image processing was carried out with DaVis 6.2.3 software, supplied by LaVision Inc. This is a comprehensive software package that allows the user to manage all the optical aspects of carrying out a PIV experiment and analyzing the results.

Camera exposure times, the time between laser pulses and the number of frames used by the cameras were all set by the user, depending on the nature of the experiment. All of the experiments described in this report were carried out using stereo images, which required four exposures to process the results. The four views were one from each camera at time t and one from each camera at $t=\delta t$. A series of frames were taken, which depended on the nature of the experiment. For simple flows, twenty exposures were used, but for more complex flows, fifty exposures were used.

Analysis of the images to produce flow vectors over the measurement area can take place immediately after the experiment. DaVis 6.2.3 has an interactive method for analysis of a single set of exposures, which allows the user to adjust the size of the interrogation window, the amount of overlap between interrogation windows and the number of iterations used to come to a solution.

The preliminary analysis will usually include spurious vectors, often caused by an insufficient number of particles in a particular area of the image. The vector field can be re-analyzed, with iterative methods for filtering and smoothing the data to remove these irregularities.

Once the most suitable analysis procedure has been developed for a particular experiment, based on a single frame using interactive methods, the image processing and vector analysis can then be carried out for all frames in a sequence using batch processing. For steady flows, sets of vectors can be combined to provide an average vector map over a period of time.

Results can be visualized in a variety of ways. Particle images and calculated vectors can be viewed as movies, so that particle movement and calculated vectors can be inspected. Vector maps of the flow can be plotted, and summary statistics of the images (particles or vectors) can be calculated.

Installation on OERC Towing Carriage

The support frame for fixing the PIV components to the carriage was assembled using pre-fabricated components manufactured by 80/20 Inc. of Columbia City, IN, USA and donated to Memorial University of Newfoundland by Oceanic Consulting Corporation. The system consisted of extruded aluminium sections (square or rectangular), corner braces, right angle brackets and locking screws. In order to provide a rigid connection between the support frame and the carriage, two extruded aluminium bars (6 inches by 3 inches) were placed across the carriage test frame and clamped in place. Upright square sections (3 inches by 3 inches) were fixed to the horizontal bars, with corner braces, and horizontal bars to provide bracing for the structure were fixed to the upright beams with right angle brackets.

The structure to support the PIV system components was provided by LaVision Inc. These parts were extruded circular aluminium sections with four lugs in an X configuration. Mounting brackets for the PIV components clamped to the x-section, and the x-section was clamped to the support frame using brackets fabricated at Memorial University. Moving the support frame provided coarse adjustment, and moving the x-sections along the frame provided fine horizontal adjustment. Moving the PIV components on the x-section provided fine vertical adjustment.

MEASUREMENTS IN UNIFORM FLOW

Proto-type Seeding Delivery System

Seeding the flow is an essential element of PIV measurements. If the PIV system is stationary and the fluid is stationary, then it is only necessary to seed the volume of fluid close to the laser sheet. This option would be feasible for a stationary PIV system in a towing tank, where the ship model passes through the measurement volume. The movement of the model ship through the seeded fluid will cause a disturbance and the movement of the seed particles can be observed. The disadvantage of this system is that very little data is obtained at a specific location on the hull, since only one set of frames is obtained for each run down the tank.

If the fluid is moving relative to the PIV system then one option is for the complete volume of the fluid to be seeded. This option may be feasible for a circulating water tunnel but is not practical in a towing tank, which has a very large volume of fluid, requiring a large number of particles. Eventually almost all of the seed particles will either sink to the bottom or float to the top. This means that the fluid must be re-seeded after a certain period of time, further increasing the amount of particles consumed.

A practical alternative is to introduce seed particles to the flow so that seeding is present only in the measurement volume for the duration of the measurements. This should allow for a controlled use of the seeding particles, and should provide high quality PIV images, since the seeding density is correct for the volume of fluid being studied, and the parts of the flow that are of no interest to the study are ignored. The disadvantage of this approach is that the seeding delivery system may affect the momentum of the seeding particles, which will influence the results. This was the option chosen for the MUN PIV system in the OERC towing tank.

Since we had limited experience with seeding systems, it was decided to make the initial system as cheaply as possible, so that it would be a small expense if it had to be scrapped completely. A sketch of the initial concept is shown in Figure 5.

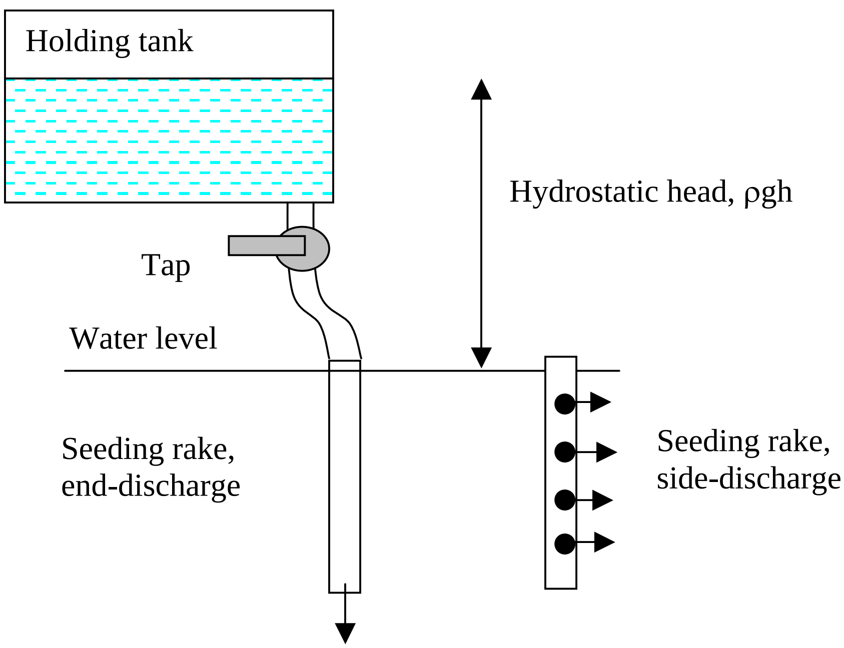

Figure 5, Concept sketch for seeding delivery systems

The prototype system was constructed from readily available plumbing parts and included:

- Holding tank and drain (plastic laundry tub)
- Dishwasher connectors and pipes
- Tap to control flow rate
- Seeding rake made from 22.2 mm ($^{7}/_{8}$ inches) diameter copper pipe and plumbing connectors

The system used hydrostatic pressure to deliver the seeded flow from the holding tank to the measurement volume. Adjusting the height of the holding tank, relative to the water level, controlled the static head and a tap was used to control flow rate. The seeding particles were mixed into clean water in the holding tank. The mixture was stirred prior to carrying out an experiment, to keep the seeding evenly distributed.

The end-discharge system was intended to seed the flow upstream and above the area of interest for the flow measurements. Since the rake was nominally above the measurement area, the disturbance to the flow caused by the rake over the measurement area was minimized. The disadvantage of this system was that the particle distribution was not uniform, and clusters of particles would appear periodically, influenced by vortices formed by the interaction of the seeded flow with the stationary water in the towing tank.

The side-discharge system was also placed upstream of the required measurement area but the seeded fluid was discharged from the downstream side of the pipe. The advantage of this system was that the seeding particles were more evenly distributed, but the disadvantage was that the rake was close to the path of fluid entering the measurement area, and the wake of the seeding rake can effect the measurements. In practice, it was found that provided the distance upstream was at least 1 metre, this effect was very small.

Two versions of the side-discharge seeding rake were made. The first version had holes 6.35 mm ($^{1}/_{4}$ inches) diameter drilled at 41.3 mm ($1^{5}/_{8}$ inches) spacing and the second version had holes 1.58 mm ($^{1}/_{16}$ inches) diameter drilled at 19.1 mm ($^{3}/_{4}$ inches) spacing. The version with small holes worked well at zero velocity, but did not deliver sufficient seeding particles at the forward speeds required for ship model work (0.1m/s and above).

Installation of Laser and Cameras on OERC Towing Carriage

The first set of experiments was an attempt to measure steady flow in a plane across the undisturbed flow (Molyneux & Xu, 2005). The location of the cameras and the laser for this orientation are shown in Figure 6. The laser is in the centre and the two cameras are on either side. This arrangement was picked since it was the one recommended by LaVision for most ship model flow experiments. These experiments were not successful but the system supplier later notified us that there might have been a fault with the laser. The laser was returned to the manufacturer and checked prior to the start of the second round of experiments.

Figure 6, Primary light sheet and camera arrangement for vertical plane across the direction of flow.

It was also desirable to check the secondary camera and light sheet arrangement, so for the second set of experiments (described in this report), the laser was set up to provide a measurement plane in the direction of carriage motion. This orientation provided the maximum dimension of the laser sheet in the strongest direction of flow. This arrangement is shown on the OERC towing tank in Figure 7. The laser is seen at the left hand side of the picture and the two cameras are seen at the right hand side. During flow measurements the carriage motion was from left to right, so the laser was on the downstream side of the measurement plane.

Figure 7, Secondary light sheet and camera arrangement for vertical plane within the direction of flow.

Data Collection and Analysis of Results

Data was collected and analyzed using DaVis 6.2.3. Measurements of flow vectors for carriage speeds of 0.10, 0.30, 0.50, 0.75 and 1.00 m/s were made using the PIV system. Some experiments were carried out with particles introduced to the flow using the seeding systems described above and some were carried out using only particles left in the fluid from previous runs. When the seeding system was used, it was located upstream of the measurement area, just out of the field of view for the cameras. For the side discharge version, the rake extended across the depth of the field of view. For the end discharge version, the bottom of the rake was ahead and above the field of view.

A summary of the experiment conditions presented in this report is given in Table 3.

File	δt (μs)	Seeding	Laser power	Carriage speed
Test_05	5000	Rake, side holes	50%	0.1 m/s
Test_06	3000	Rake, side holes	50%	0.3 m/s
Test_07	2000	Rake, side holes	50%	0.5 m/s
Test_08	3000	Rake, side holes	50%	0.5 m/s
Test_09	1000	Rake, side holes	50%	0.75 m/s
Test_10	1000	Rake, side holes	50%	1.00 m/s
Test_23	300	Rake, end hole	50%	0.75 m/s
Test_24	300	Residual	50%	0.75 m/s

Table 3, Summary of experiments carried out in steady flow, with no model

The measurement area was calibrated using a 300 by 300 mm plate. The resulting measurement area after calibration was 200 mm in the x direction by 145 mm in the y direction. The orientation of the plate was for positive x-axis along the centreline of the carriage, in the direction of carriage motion. The positive y-axis was vertical, and the positive z-axis was from left to right when looking in the direction of the positive x axis.

The general procedure for carrying out the experiments was to start the PIV system in 'grab' mode, which allowed the camera images to be seen on the computer screen. The carriage was then accelerated to the required speed and the seeding system (if it was used) was turned on. The flow rate was adjusted until suitable images were obtained, then the PIV system was set to 'acquire' and a series of twenty frames was collected for each experiment. Processing of single image sets (four frames) to obtain preliminary results was carried out immediately on completion of the experiment. Detailed processing of sequences of images to obtain final results was completed after all experiments were finished.

Particle images were analyzed using interrogation windows of 64x64 pixels, with 50% overlap of each window. The resulting vector field was further processed to remove spurious vectors and the vector field smoothed. Each sequence of calculated vector fields was examined to make sure that flow was approximately steady, and then the flow vectors were averaged for each point over the twenty frames were calculated. The calculated mean speeds over the complete vector field are given in Table 4.

File	Carriage Speed, m/s	Mean value calculated from PIV, m/s				
	Vc	Vx	Vy	Vz	**|V|**	Rms (**V**)
Test_05	-0.1	-0.114	0.010	0.008	0.122	0.031
Test_06	-0.3	-0.148	0.013	0.037	0.174	0.056
Test_07	-0.5	-0.244	0.015	0.064	0.299	0.010
Test_08	-0.5	-0.198	0.020	0.062	0.278	0.166
Test_09	-0.75	-0.349	0.019	0.107	0.416	0.135
Test_10	-1.0	-0.753	-0.008	0.664	1.194	0.471
Test_23	-0.75	-0.532	0.054	-0.046	0.563	0.082
Test_24	-0.75	-0.750	0.031	-0.223	0.840	0.184

Table 4, Summary of PIV flow measurements

An effective wake for the seeding system was defined as (Vc-Vx)/Vc, and calculated values for each experiment are given in Table 5.

	Vc, m/s	Vx, m/s	Wake fraction
Test_05	-0.1	-0.114	-0.140
Test_06	-0.3	-0.148	0.507
Test_07	-0.5	-0.244	0.512
Test_08	-0.5	-0.198	0.604
Test_09	-0.75	-0.349	0.535
Test_10	-1	-0.753	0.247
Test_23	-0.75	-0.532	0.291
Test_24	-0.75	-0.75	0.000

Table 5, Estimated wake due to seeding system

These results show that the best speed measurement was for Run_24, which was made with the residual seeding left in the tank from previous runs. This case shows very good agreement between the flow speed and the carriage speed. In all other cases, the flow was affected by the presence of the seeding system. For the side seeding system, at the lowest speed (Test_05), the calculated velocity is within 14% of the free stream speed, but in all other cases the effective wake fraction, defined as (V-Vx)/V is between 25% and 50%. These values are given in Table 5. There is a significant improvement between the side discharge version (Test_09) and the end discharge version (Test_23), but even the end discharge version has a significant effect on the flow.

Examples of the flow velocity distribution are given in Figures 8 to 10, which show contours of Vx and in-plane velocity vectors for three cases at speeds of 0.75 m/s. Flow is moving from right to left. The expected result was to have a constant velocity in the negative x direction with the same magnitude as the carriage speed and zero velocity components in the y and z direction.

The side discharge rake results in lower velocities close to the rake, and increasing velocities downstream from the rake. The flow vectors are all almost parallel to the x-axis, but the gradient in the flow speed was unacceptable.

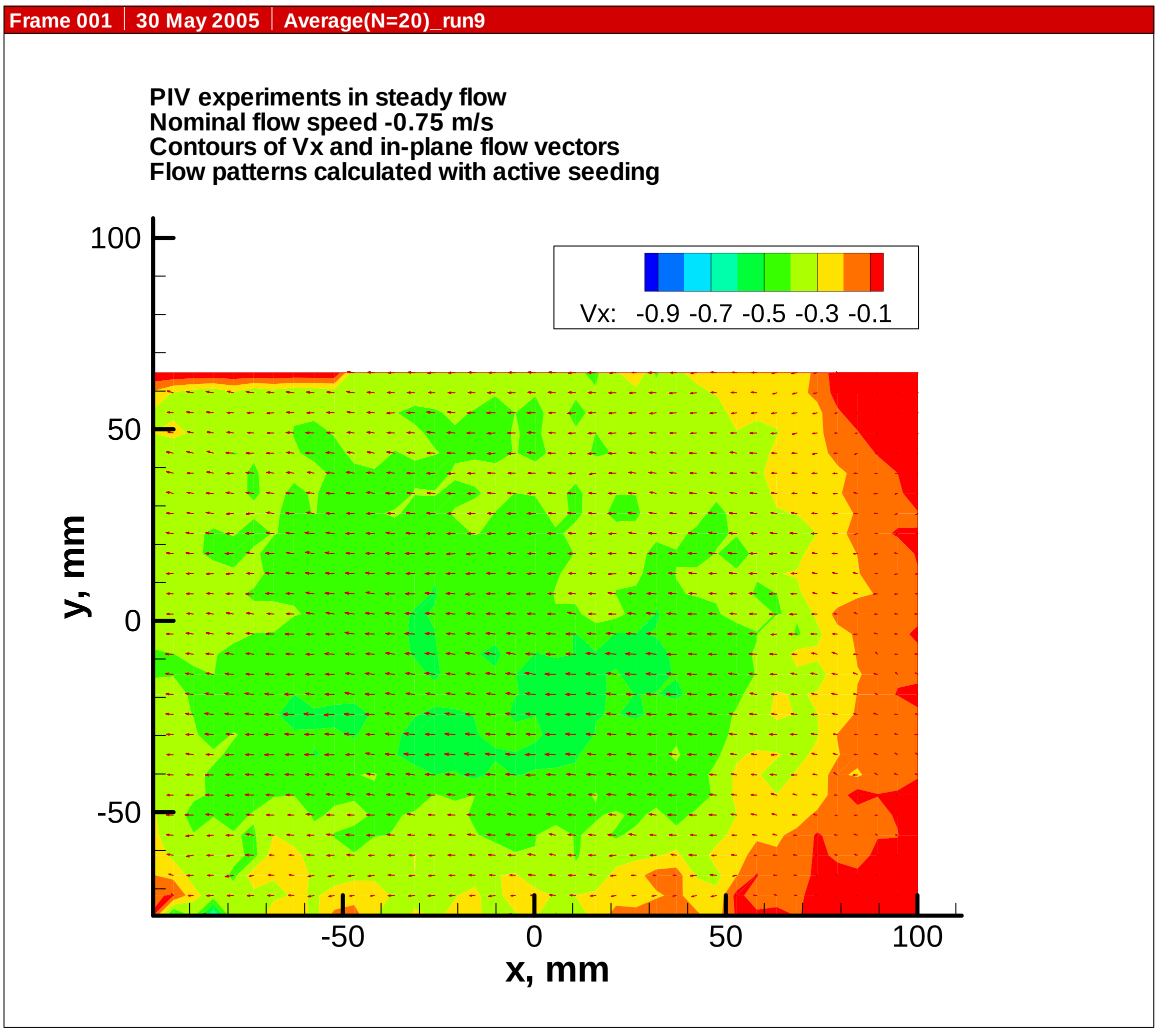

Figure 8, Steady flow at 0.75 m/s, side discharge seeding system, rake just upstream of field of view.

The end discharge system, with the discharge just upstream and above the field of view, resulted in a more uniform velocity distribution, that was closer to the carriage speed, but the average velocity was approximately 30% lower than the carriage speed. The flow vectors were parallel to the x-axis.

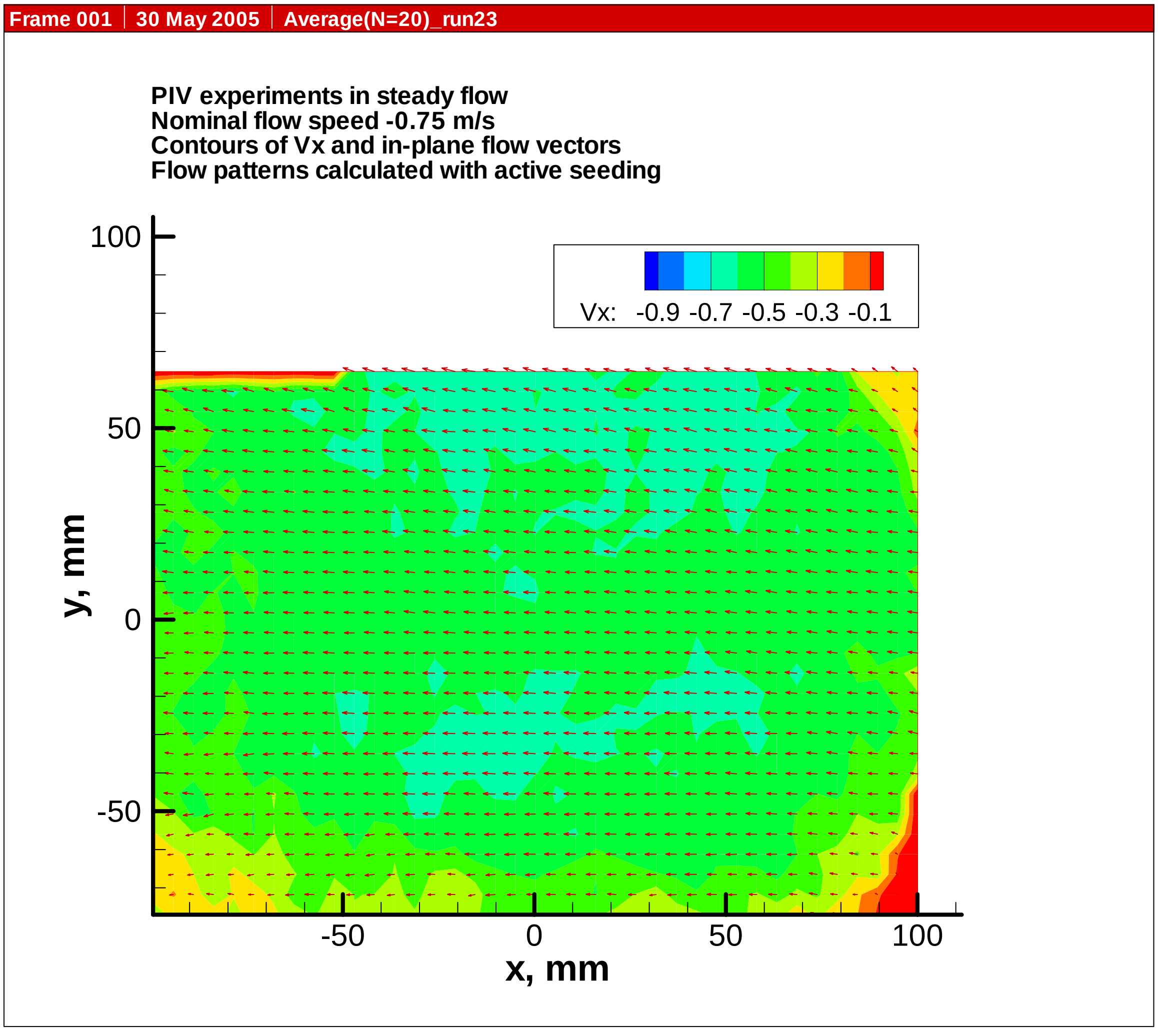

Figure 9, Steady flow at 0.75 m/s, end discharge seeding system

After a few experiments had been completed, there was sufficient seeding left in the tank to be able to process the images without an active seeding system. In this case, very good results were obtained, as shown in Figure 10. This figure shows an almost constant vector field, with flow vectors parallel to the x-axis and of the correct magnitude.

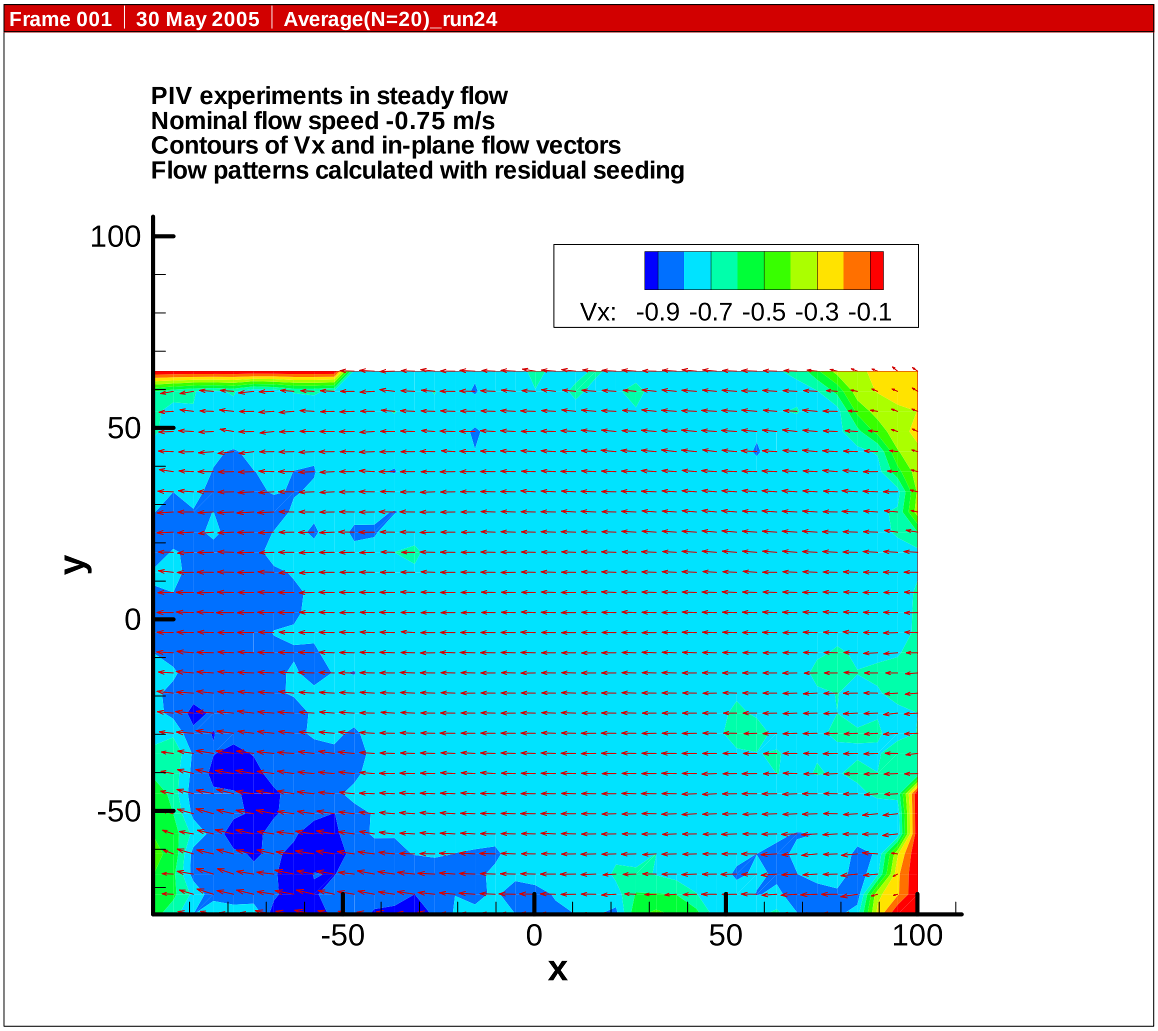

Figure 10, Steady flow at 0.75 m/s, residual seeding only

These results highlight the challenges to designing an effective seeding system, even for very simple flow conditions. Neither of the systems used gave even particle distributions across the complete field of view. The side discharge system resulted in periodic waves of particles across the field of view, shown in Figure 11, whereas the end discharge system resulted in periodic clouds of particles, shown in Figure 12. The periodic waves are possibly caused by vortices shed off the rake, whereas the periodic clouds are probably caused by the mixing of the jet from the rake with the undisturbed flow. The end discharge system also resulted in air bubbles appearing in the field of view, which can be seen at the top of Figure 12.

A revised rake design should be prepared before further testing is carried out. Factors to consider will be a smaller diameter, fairing the downstream side of the rake, minimizing air bubbles in the discharge fluid/particle mix and moving the rake as far upstream as possible to minimize the disturbance to the fluid caused by the rake. CFD might be a useful tool to study alternative rake designs before committing to production.

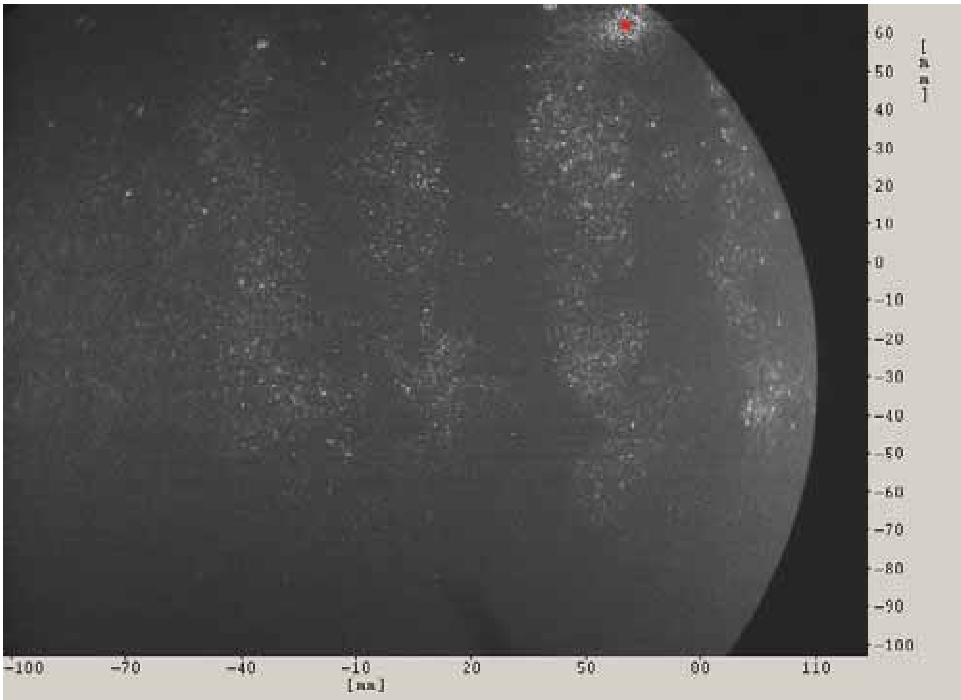

Figure 11, Seeding particles from side discharge rake at 0.75 m/s, showing periodic waves of particles

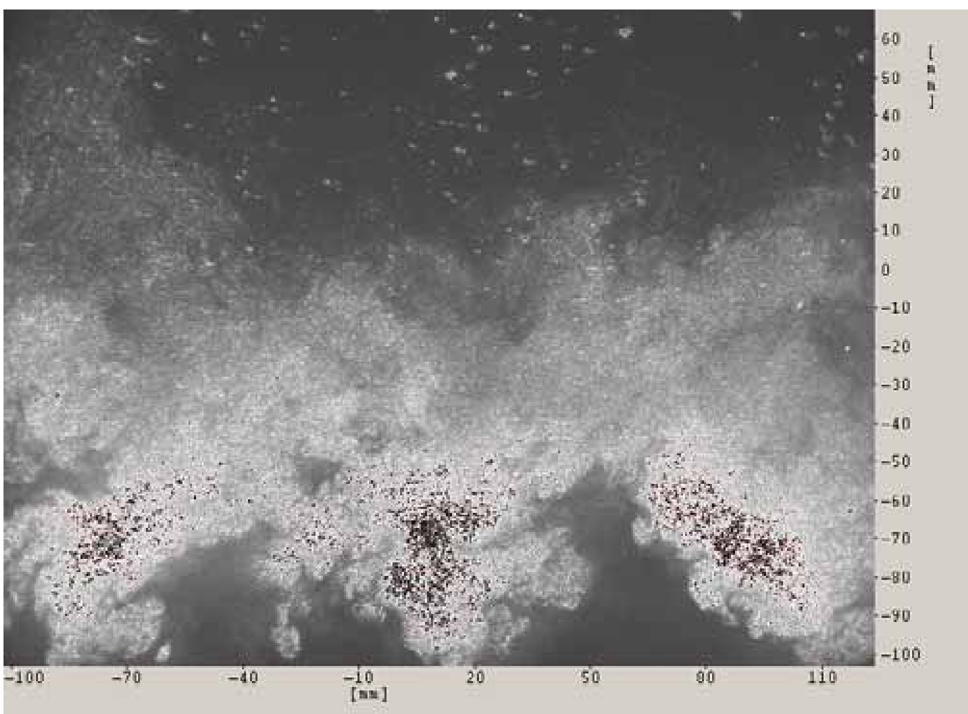

Figure 12, Seeding particles from end discharge rake at 0.75 m/s, showing periodic clouds of particles

FLOW MEASUREMENTS AROUND AN ESCORT TUG

Ship Model Preparation and Installation

The hull chosen for the flow measurements represented a 1:18 scale model of a z-drive tractor tug concept developed by Robert Allan Ltd. of Vancouver, B. C (Allan & Molyneux, 2004). The model was fitted with a fin and a grounding plate. The model was originally manufactured and tested at the NRC Institute for Ocean Technology (IOT), where measurements were made of the lift and drag forces for the hull over a range of speeds from 4 to 12 knots for the ship (with model speeds based on Froude scaling), for yaw angles between zero and 105 degrees (Molyneux, 2003). For these experiments the hull was free to heel, sink and trim. The body plan for the tug is shown in Figure 13 and the profile is shown in Figure 14. For the experiments in the OERC towing tank, no bulwarks or deckhouses were fitted, although they are shown in the figure.

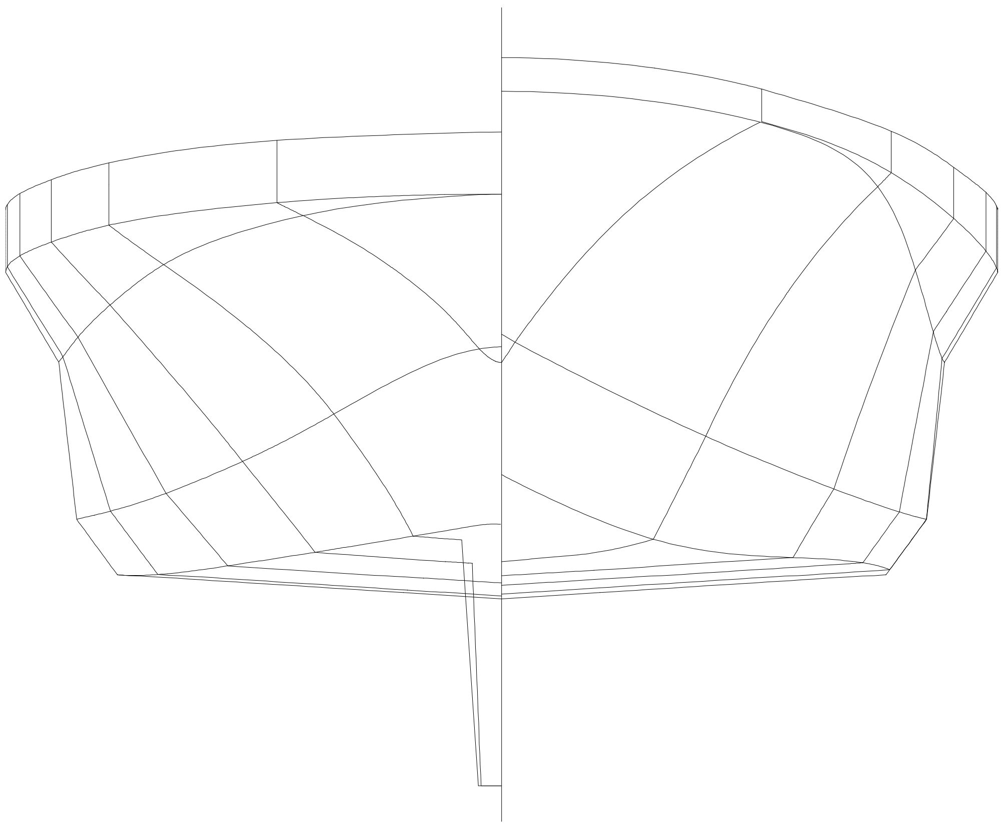

Figure 13, Body plan for tug model, used in PIV experiments.

A summary of the tug geometry is given in Table 6 and the speeds are given in Table 7. For this series of experiments the model was always moving with the cage for protecting the propellers going forwards and the fin in the stern.

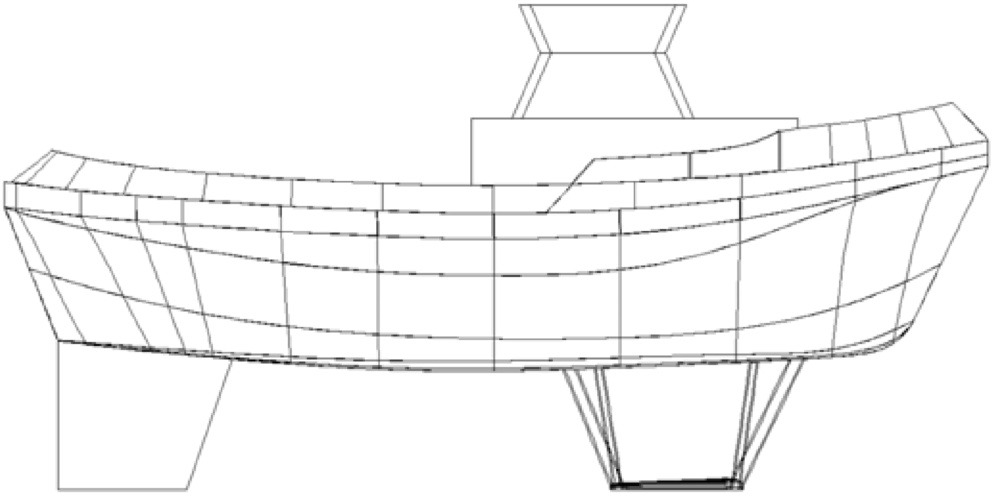

Figure 14, Profile view of tug model used in PIV experiments

Length, waterline, m	2.122
Beam, waterline, m	0.789
Draft, hull, m	0.211
Daft, maximum, m	0.471
Displacement, kg	213.3
Nominal scale	1:18

Table 6, Summary of model particulars

Condition	Model speed, m/s
90 degree yaw	0.1, 0.25, 0.5*
25 degree yaw	0.1, 0.25, 0.5*
45 degree yaw	0.1, 0.25, 0.5*

Table 7, Summary of speeds tested

* Only results for carriage speeds of 0.5 m/s are presented in this report.

To minimize the corruption of recorded images by reflected laser light, the hull was painted matt black. For the PIV experiments, a rigid connection between the model and the towing carriage ensured that the measurement plane was always in the same location relative to the hull. The model was fixed at the design draft and a roll angle of zero. The model was connected to the carriage by two vertical, cylindrical poles and a yaw table, originally developed for experiments on the C-SCOUT AUV. This yaw table enabled yaw angle to be adjusted from zero to ninety degrees, in five-degree increments.

A photograph of the model at ninety degrees of yaw is shown in Figure 15.

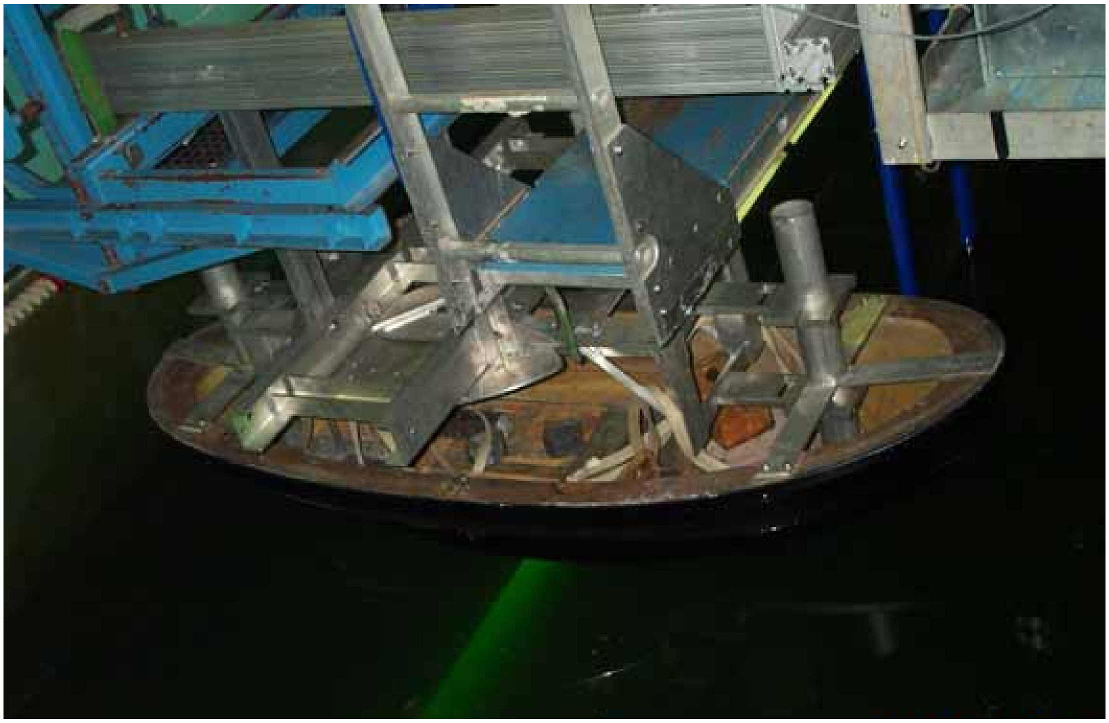

Figure 15, Model tug at 90 degree yaw angle, showing yaw table, connection method and borescopes on the downstream side.

YAW ANGLE 90 DEGREES
MEASUREMENT PLANE PARALLEL TO UNDISTURBED FLOW

The intention of testing at this yaw angle was to approximate two-dimensional flow over the midsection of the tug. Preliminary CFD predictions for two-dimensional flow (Molyneux, 2005) had suggested that there would be a region of circulating flow on the downstream side of the hull, between the waterline and the bottom of the hull. This was most easily investigated with the tug at 90 degrees of yaw angle, relative to the direction of carriage motion and the laser plane pointing in the direction of carriage motion. This was the laser orientation used for the undisturbed flow experiments, and so it was chosen as the starting point for experiments with the tug. The approximate measurement area is shown in Figure 16, together with different locations for the seeding rake. The plane intersected the hull at a point 80mm from midships towards the protective cage.

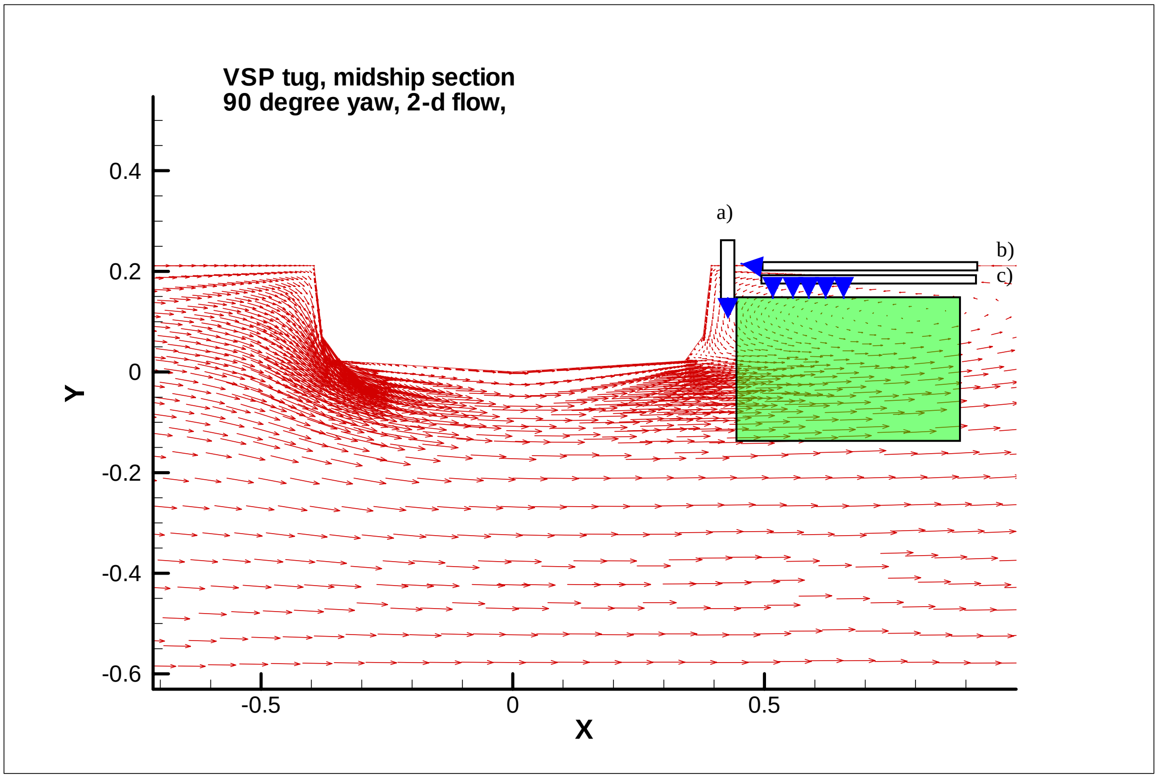

Figure 16, CFD predictions for two-dimensional flow around escort tug midsection, together with approximate measurement plane and seeding methods

(a) End discharge, vertical
(b) End discharge, horizontal
(c) Side discharge, horizontal

Several problems were encountered in carrying out these experiments. Initial attempts to seed directly into the downstream side of the hull proved to be unsuccessful. The seeding rake was too close to the measurement area, and momentum from the seeded flow entering the flow around the hull seemed to alter the flow patterns significantly, resulting in very unsteady measurements. For seeding, the end discharge rake was used in the vertical orientation (shown in Figure 16) and horizontal orientation (with the centreline of the rake parallel to the waterline), but no successful measurements of flow on the downstream side of the hull, close to the hull were carried out.

Some successful measurements of flow under the hull were carried out when seeding was introduced to the flow from the upstream side of the model using the side-discharge rake. The measured vector magnitudes were very close to the speed of the undisturbed flow. In this case the rake was far enough upstream for the effect on the flow to be diffused by the time it reached the measurement area. This technique could not be applied to the downstream region close to the hull because seed particles introduced on the upstream side did not flow into the measurement area. This was observed by watching some of the experiments through the underwater windows in the OERC towing tank.

YAW ANGLE 25 DEGREES
MEASUREMENT PLANE PARALLEL TO UNDISTURBED FLOW

After the attempts to measure flow patterns at 90-degree yaw, some experiments were carried out with the model at a yaw angle of 25 degrees. This represented a low to moderate yaw angle for an escort tug in its operating condition. For this yaw angle, the flow on the downstream side of the hull was much less disturbed than for the 90 degree yaw angle, and this provided easier flow conditions in which to develop seeding techniques.

The laser plane intersected the tug at midships and was oriented parallel to the direction of motion of the carriage. The measurement area was calibrated using the calibration plate supplied by LaVision (300mm by 300mm). The calibration was carried out prior to the first experiments. The resulting measurement area was 220mm by 165 mm. The orientation of the plate was for positive x-axis along the centreline of the carriage, in the direction of carriage motion. The positive y-axis was vertical, and the positive z-axis was from left to right when looking in the direction of the positive x-axis.

For these experiments, the total measurement area of interest was larger than a single frame of view. To cover the complete, region several frames had to be combined. Two vertical levels were used, with the upper level being as high as the borescopes could be and still be sufficiently under the water to avoid ventilation from the surface affecting the view. The lower level was 150mm below the upper level. The longitudinal position was changed in 100mm increments, until the model just entered into the field of view for the upper region. This approach was used to avoid the time consuming process of calibration for each measurement space. A total of eight measurement areas were used. The approximate measurement location, relative to the model is shown in Figure 17.

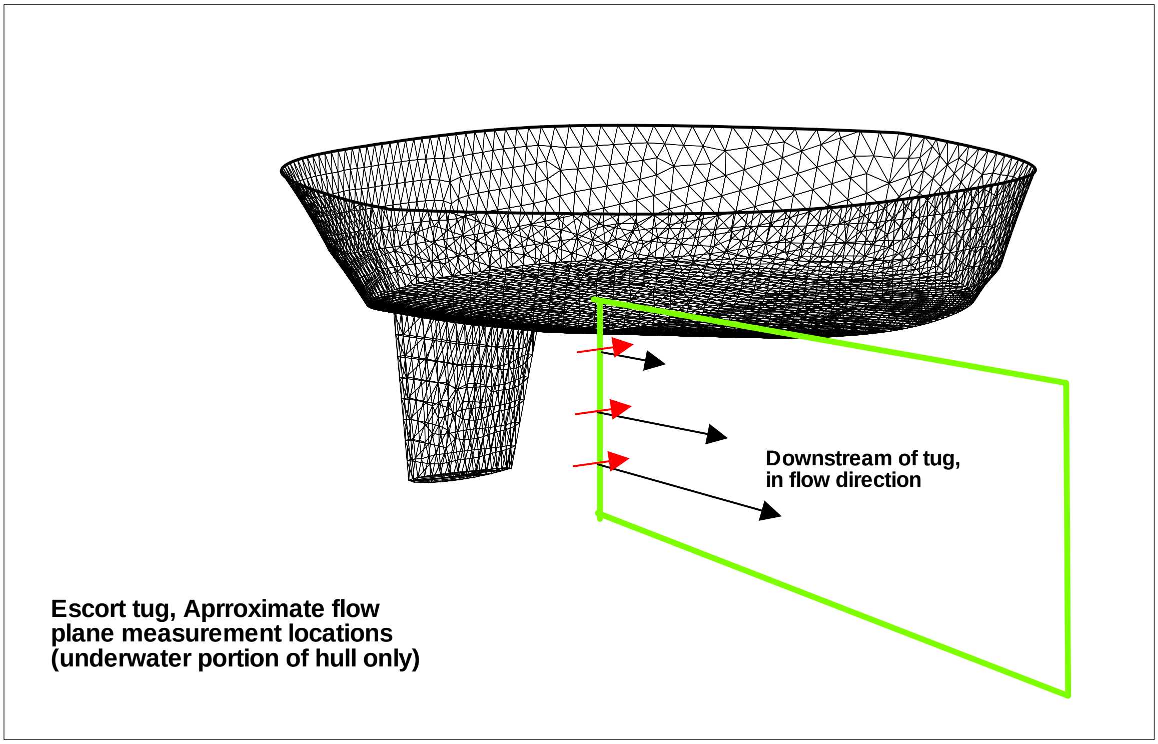

Figure 17, Escort tug model at 25 degrees of yaw, approximate location of measurement plane (In-plane flow direction shown in black, through plane flow direction shown in red).

Seeding for these experiments was carried out using the side-discharge rake, located in the laser plane, on the upstream side of the model. This method provided seeding particles with sufficient density (when averaged over fifty frames) over the complete measurement region, except for the bottom of the two areas furthest down stream from the hull.

Each measurement area was analyzed using a similar procedure to that discussed above for the steady flow experiments. The general procedure for carrying out the experiments was to start the PIV system in ‘grab’ mode, which allowed the camera images to be seen on the computer screen. The carriage was then accelerated to the required speed and the seeding system was turned on. The flow rate was adjusted until suitable images were obtained, then the PIV system was set to ‘acquire’ and a series of fifty frames was collected for each experiment. Processing of single image sets (four frames) to obtain preliminary results was carried out immediately on completion of the experiment. Detailed processing of sequences of images to obtain final results was completed after all experiments were finished.

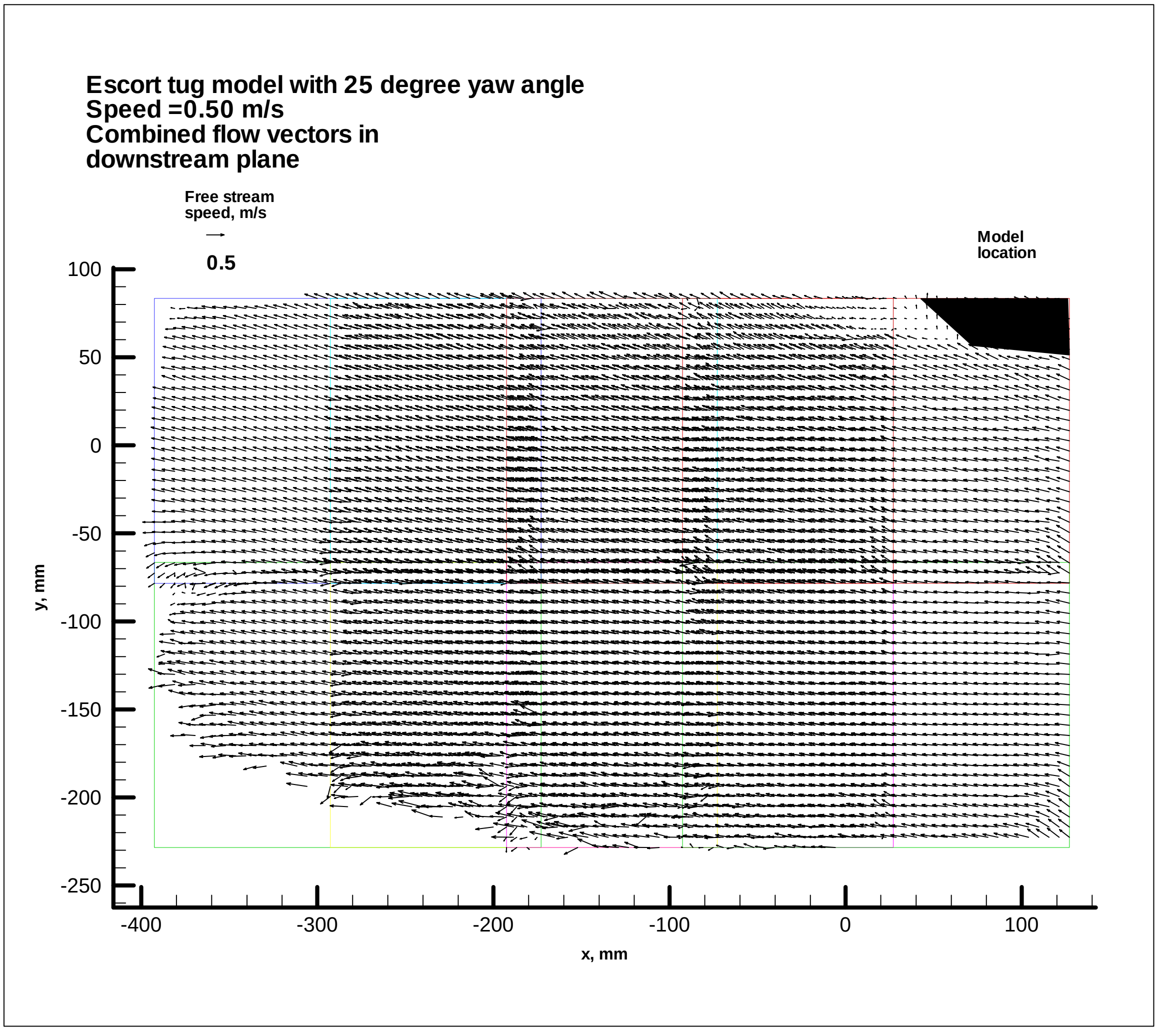

Figure 18, Vectors of in-plane flow on down-stream side of escort tug model, 25 degree yaw angle, measurement plane parallel to tank centreline

Particle images were analyzed using interrogation windows of 64x64 pixels, with 50% overlap of each window. The resulting vector field was further processed to remove spurious vectors and the vector field smoothed. Each sequence of calculated vector fields was examined to make sure that flow was approximately steady, and then the flow vectors were averaged for each grid point over the fifty frames. The average flow vectors were presented on a common measurement grid using the data graphing and display program 'Tecplot'.

Figure 18 shows the combined vector field for the flow measurements with the measurement plane parallel to the direction of motion, including the overlap for the eight measurement regions. The model location is shown in the top right hand corner. The part of the model seen was the lower corner of the downstream bilge. The results show that far below the model, the flow vectors are moving almost horizontally, with a magnitude equal to the free stream flow. Nearer the surface, the flow has an upward component. Close to the model, the flow is moving very slowly.

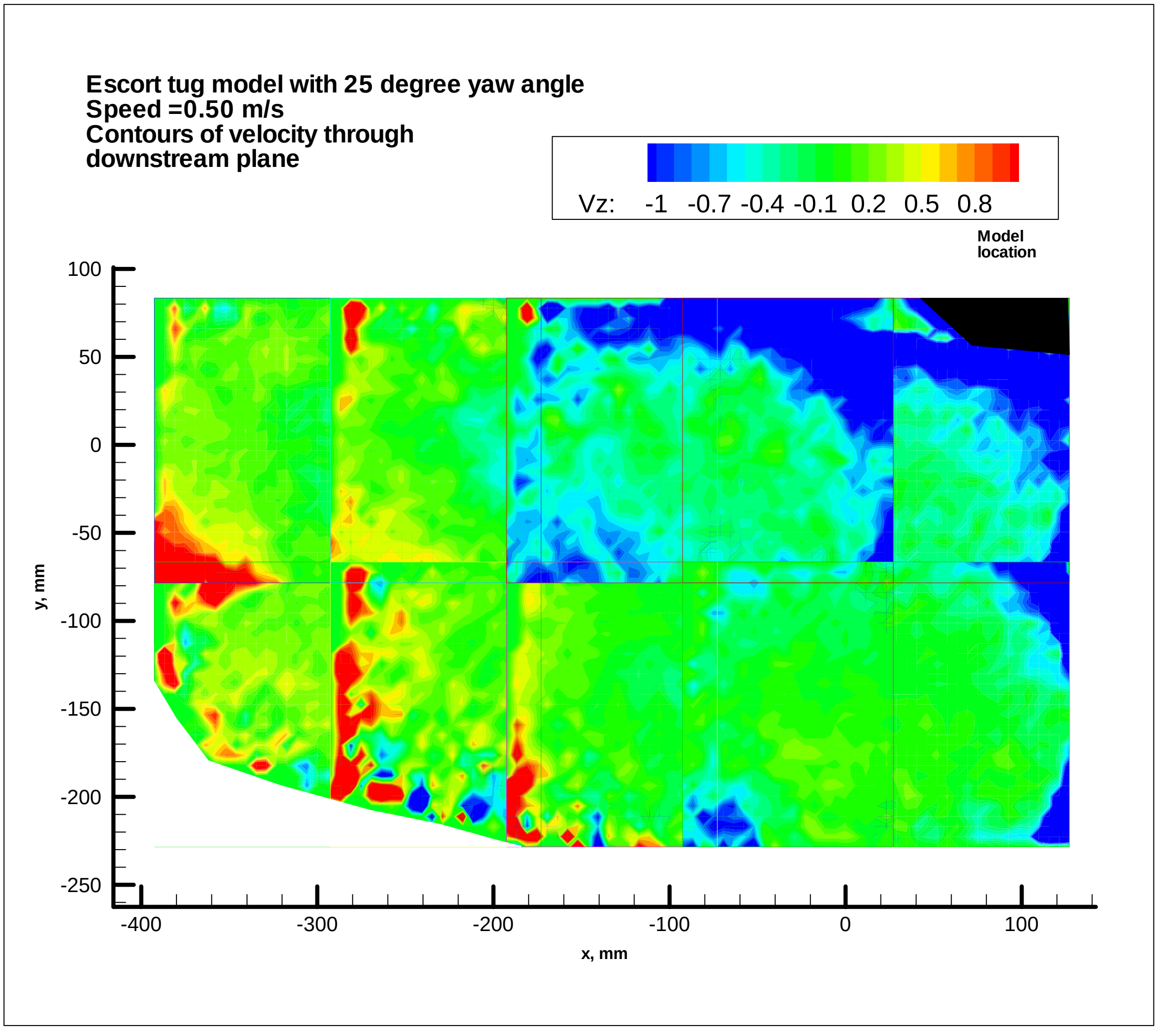

Figure 19, Contours of through-plane flow velocity on down-stream side of escort tug model, 25 degree yaw angle, measurement plane parallel to tank centreline

Contours of the through plane flow are shown in Figure 19. From this figure it can be seen that the through-plane flow is almost zero over most of the measurement space, but a few areas do not have this expected result. Close to the model, strong through-plane velocity components were calculated. Also, at the edges of the field of view, strong through plane velocities were calculated. The optical quality of results at the edges of the field of view is reduced due to distortion in the optical system. This is contributing to the poorer quality in these regions. In addition, when measurements were made close to the hull there is still some reflection due to the model, and this affects the quality of the analysis. Figure 20 shows an image taken including the model and the band of reflected light is clearly seen in the picture.

The flow patterns calculated for the same measurement area, but calculated from different images, show very similar flow patterns, although the area of overlap should have been larger, especially in the vertical arrangement. The amount moved (150 mm) was based on half of the calibration area, but this failed to take into account that the full area was not observed when the field of view from both cameras was taken into account.

Unfortunately in the initial set-up, the viewing angle from the bottom of the borescopes was below horizontal, and this prevented the measurement of flow patterns closer to the water surface, since if the borescopes were raised, the bottom of the borescopes would have been out of the water.

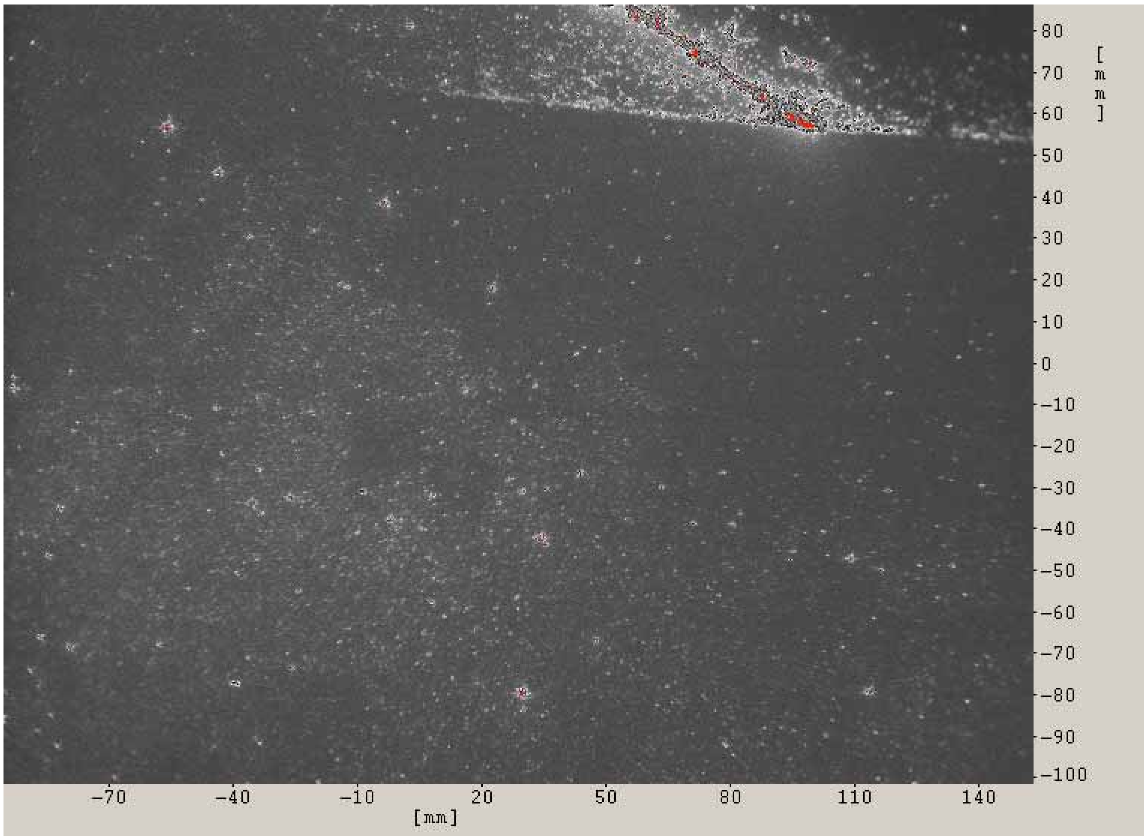

Figure 20, Field of view close to model, 25 degree yaw angle, showing reflections due to the hull.

YAW ANGLE 45 DEGREES

A yaw angle of 45 degrees represents a typical average operating condition for an escort tug. In this condition, the flow patterns are much more disturbed than the 20 degree yaw angle, but still not as extreme as the 90 degree yaw angle. In this condition, two measurement orientations were used. The first experiments carried out were in the measurement plane parallel to the undisturbed flow. Since this experiment only required a change to the model orientation, the calibration used was the same as for the 25-degree yaw angle experiments. The second set of results was for the plane across the undisturbed flow (normal to the carriage centreline). Since the previous calibration did not allow measurements close to the water surface, the viewing angle of the prism was changed, and the measurement area was re-calibrated. In each case, the total measurement area was reduced relative to the experiments at 25-degree yaw angle, so that the only adjustment was 150 mm vertically, but both cases included the region very close to the model. Data collection and analysis procedures were the same as those for the 25-degree yaw angle, but the seeding techniques were slightly different. The approximate measurement plane locations are shown in Figure 21.

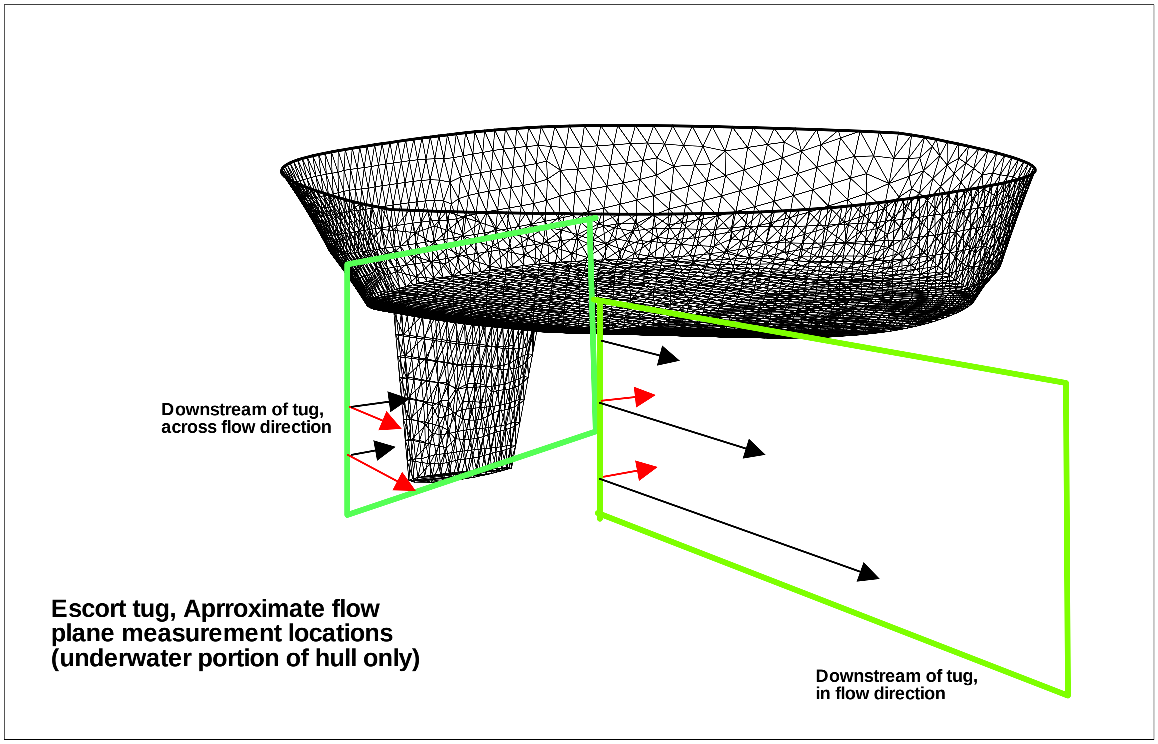

Figure 21, Escort tug model at 25 degrees of yaw, approximate location of measurement plane (In-flow direction is shown in black, through plane flow direction is shown in red).

MEASUREMENT PLANE PARALLEL TO UNDISTURBED FLOW

For this measurement location, seeding from the upstream side of the hull worked well, similar to the results obtained from the 25-degree yaw angle. The combined results for this orientation are shown in Figure 22.

These results show similar patterns to the 25 degree case, in that far below the model, the flow vectors are parallel to the x axis, with a magnitude the same as the carriage velocity. The flow takes on an upward component on the downstream side of the model, but in this case it was smaller. The through plane velocities, shown in Figure 23, are close to zero except close to the model, and at the edges of the field of view.

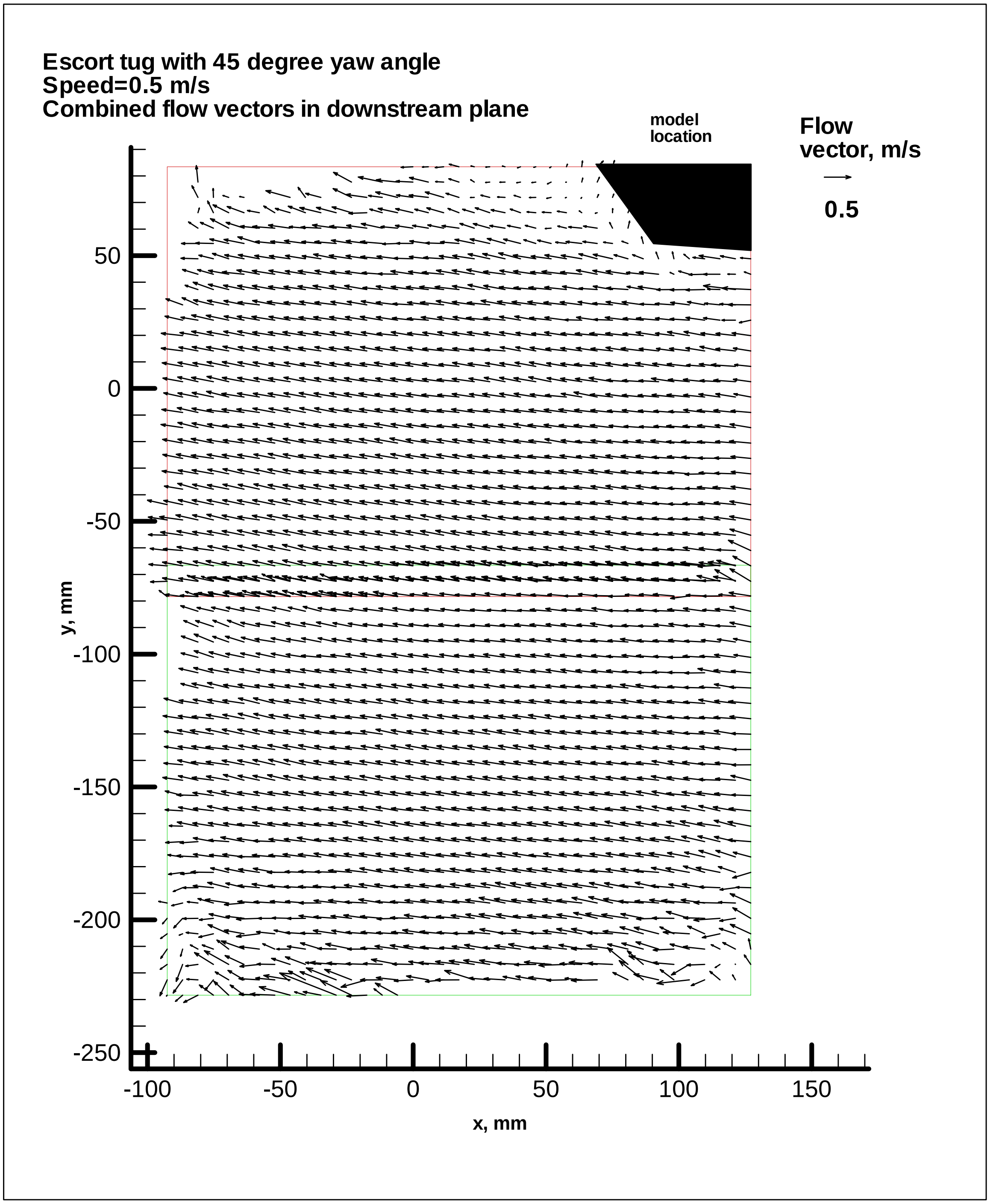

Figure 22, In-plane flow vectors for plane parallel to direction of carriage motion, yaw angle 45 degrees, carriage speed=0.5 m/s

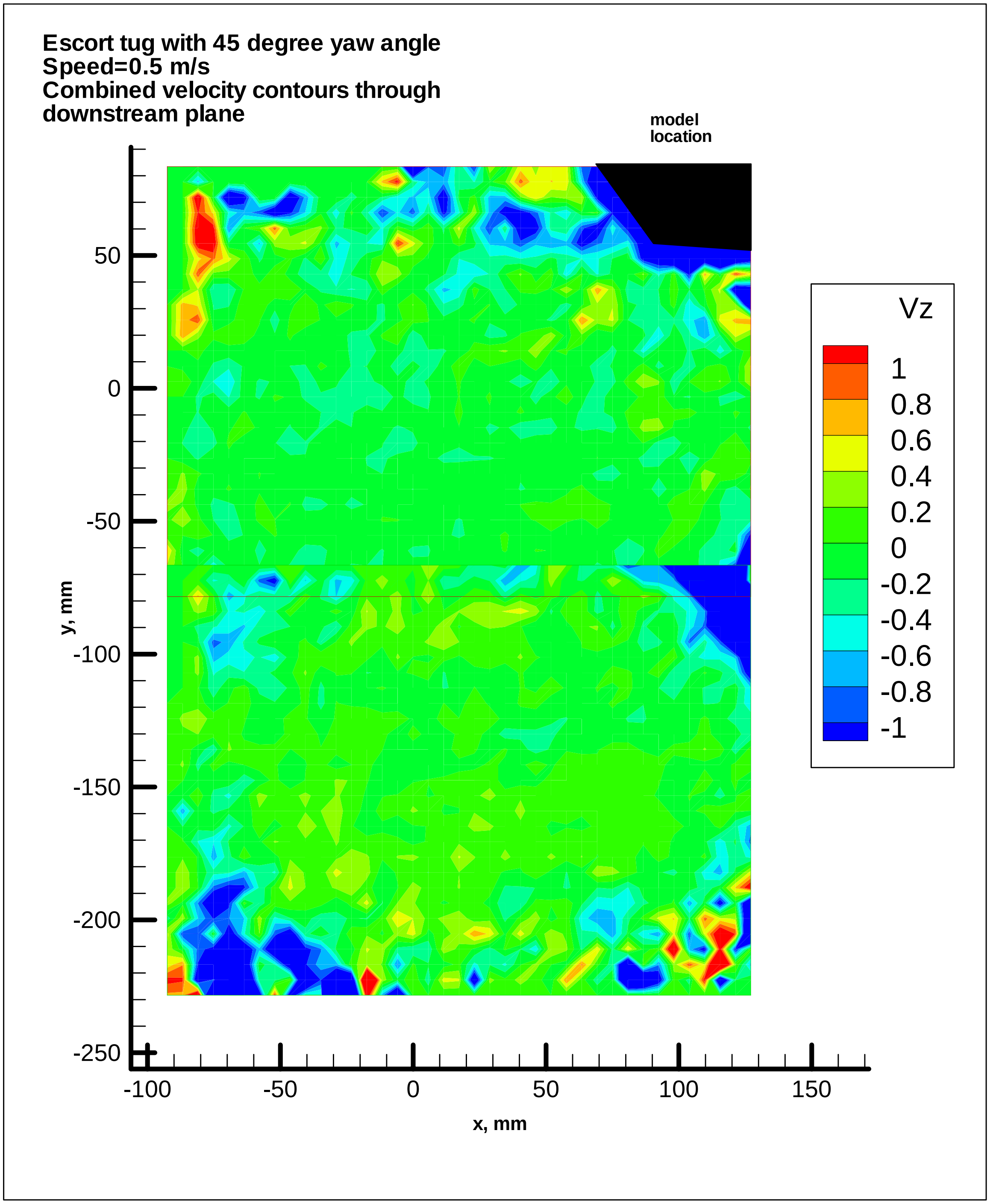

Figure 23, Through-plane velocity contours for plane parallel to direction of carriage motion, yaw angle 45 degrees, carriage speed=0.5 m/s

MEASUREMENT PLANE NORMAL TO UNDISTURBED FLOW

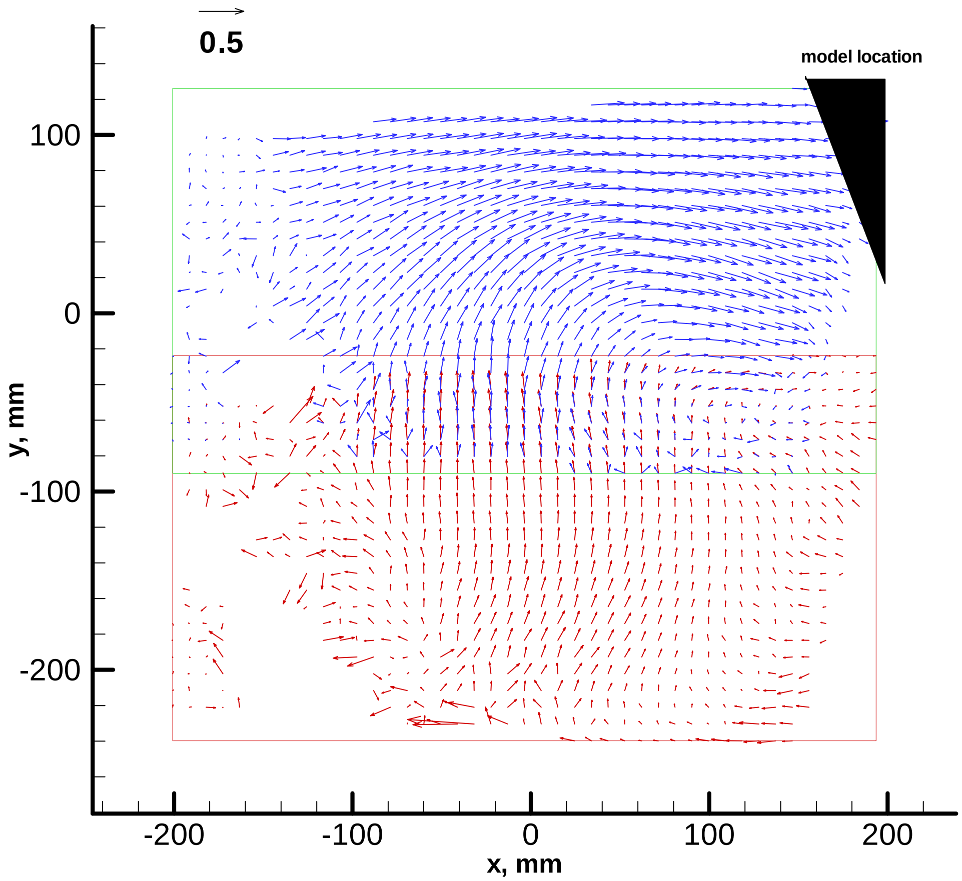

Figure 24, In-plane flow vectors for plane normal to direction of carriage motion, yaw angle 45 degrees, carriage speed=0.5 m/s

Preliminary CFD predictions for the flow around an escort tug at operational yaw angles had indicated that there should be a vortex in the flow on the downstream side of the hull when viewed in the cross-flow measurement plane.

For this measurement it was necessary to obtain a field of view very close to the hull and the water surface. Prior to carrying out these experiments, the viewing angle of the prism was changed and the system was recalibrated for the cross-flow plane orientation. In this orientation, the positive x was pointing to the upstream side of the model, positive y was vertically upwards, and positive z was in the direction of motion of the carriage.

For this measurement orientation, it was found that two seeding locations were necessary. For the lower region the side-discharge rake, located on the upstream side of the model worked sufficiently well, although seeding was not distributed over the complete viewing area. For the upper region, the seeding system had to be relocated to the downstream side of the hull, with the rake just upstream of the laser plane. For these experiments the seeding system was held in place by hand, and not fixed to the model.

The combined results are shown in Figure 24. This result shows the presence of a vortex in the expected location. The through-plane velocity contours are shown in Figure 25. The calculated through plane velocity far from the model is very close to the speed of the carriage. This is very encouraging, given the problems with measurements described in the first round of experiments (Molyneux & Xu, 200).

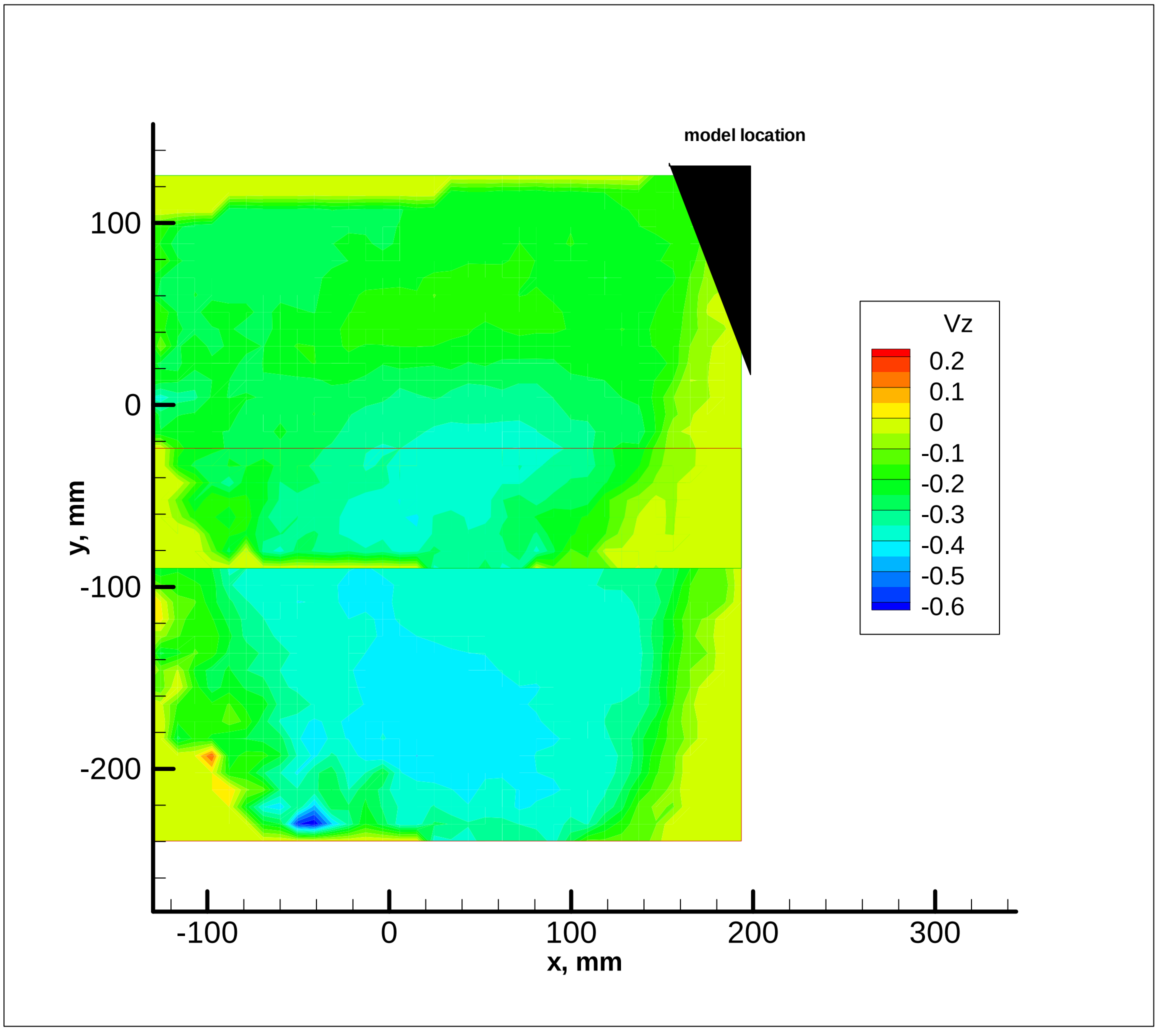

Figure 25**,** Through-plane velocity contours for plane normal to direction of carriage motion, yaw angle 45 degrees, carriage speed=0.5 m/s

Seeding for the plane across the flow direction still needs to be improved. The seeding did not extend across the whole field of view, as can be seen from the region where vectors were calculated, relative to the total area.

OVERALL DISCUSSION ON THE RESULTS & RECOMMENDATIONS FOR FURTHER IMPROVEMENTS

The results from this phase of testing are much more encouraging than the earlier experiments carried out with the PIV system (Molyneux& Xu, 2005). Flow patterns and velocity magnitudes appear to be much more consistent and realistic than the earlier experiments, and it seems as though there may have been a problem with the laser system, as indicated by the supplier.

These experiments have been a very useful step in the development of experiment techniques for making PIV measurements in a towing tank. Some areas still need to be developed, and these should be carried out prior to the next round of testing.

a) Seeding System

The seeding system needs to be refined. The simple method described in this report appears to work reasonably well if the seed is introduced to the flow sufficiently far upstream of the measurement area that any additional momentum caused by the injection process has damped out. Based on the experiments carried out here, a practical minimum distance is of the order of 0.75 metres. The simple system works well for relatively unobstructed flow, but does not work well for areas of low speed flow, close to the model. Severe problems were encountered trying to measure flow on the downstream side of the hull at 90-degree yaw angle, and the same problem was apparent at 45 degrees of yaw. For 45 degrees of yaw, there was sufficient flow along the side of the model that flow could be introduced on the downstream side of the hull. For future experiments, a new seeding system must be developed which has a very low jet speed and minimum disturbance to the flow due to wake.

b) Frame Overlap

The amount of overlap was estimated based on 50% of the calibration plate. It failed to take into account that the final calibrated area was smaller than the total area available. As a result there was only a small amount of overlap for frames in the vertical direction. For future experiments, the amount of overlap should be determined on the actual area, not the nominal area.

c) PIV Calibration and relationship to model geometry

Accurate location of the measurement plane relative to the model geometry was weak in this set of experiments. A better procedure is required for calibrating the measurement space, and relating the calibrated space to the measurement area. An improved ‘global’ reference system will most likely require a common reference frame, based on carriage geometry for both the model and the PIV system combined with more effective targets on the model itself. A method of providing a ‘hard’ location between the model and the actual field of view will also ensure that the measurement location is in the correct location relative to the hull model. This will most likely be in the form of some calibrated targets that can be fixed to the model, and located within the field of view.

For the escort tug model, preliminary CFD predictions have shown that the wake of the fin on the underside of the model is likely to be an important flow feature. This will require locating calibrated measurement planes under the model, which was not done for the experiments described in this report.

The model being used presents some special challenges, since the waterline is narrower than the maximum beam. As a result it is difficult to work with the model close to the hull.

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