Report of the Specialist Committee on Detailed Flow Measurements

Presented to the 26th International Towing Tank Conference,

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Members The 26th ITTC Specialist Committee on Detailed Flow Measurements

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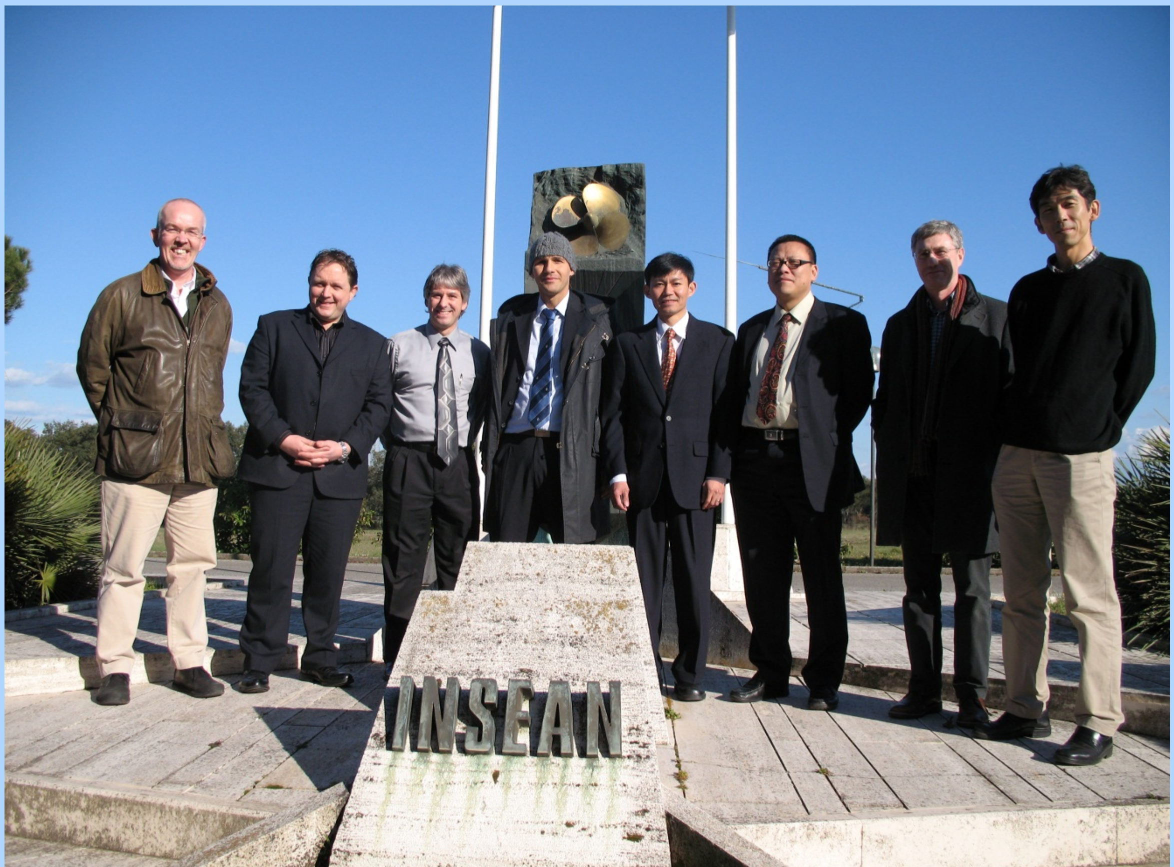
Members The 26th ITTC Specialist Committee on Detailed Flow Measurements



Meetings

- **INSEAN, Italy, February 2009**
- **Ecole Centrale de Nantes, France, September 2009**
- **University of Tokyo, Japan, March 2010**
- **University of Newcastle Upon Tyne, UK, April 2011**

Overall Scope of Work for the Committee

- **To review up-to-date systems and techniques for the measurement of flow field and wave field in ship hydrodynamics or ocean engineering applications**
- **Describe applications of Particle-Image Velocimetry (PIV), stereoscopic PIV (SPIV), Laser-Doppler Velocimetry (LDV), etc, for hull flow, separation, wake, vortex strength, etc.**
- **Additional committee considerations**
  - **Practical issues associated with applications in large-scale facilities**
  - **Need for experimental benchmark for the assessment of PIV/SPIV setup**
  - **Current state-of-the-art on PIV/SPIV uncertainty analysis**
  - **Need for technical standards and certification requirements**
  - **The usage of detailed flow data for the validation of CFD**

Outline

- **Overview**
- **Review of conventional flow-field measurement techniques**
- **Applications in different marine hydrodynamic areas**
  - **Ship propulsion**
  - **Maneuvering**
  - **Seakeeping and free-surface flows**
- **Review of emerging flow-field measurement techniques**
- **Review of conventional and emerging wave-field measurement techniques**
- **Additional considerations and recommendations**
- **Conclusions**

Overview

Why the Interest in Detailed Flow Measurements

- **Enhance understanding of complex physics**
- **Play an important role in the evaluation of hydrodynamic performance of marine vessels and offshore structures**
- **Provide valuable information for the validation of CFD and the development of physics-based models**

How Detailed Flow Measurements Play a Role

- **Tightly integrated into certain disciplines of marine hydrodynamics such as propeller evaluation and analysis**
- **Finding expanding use in other fields, such as maneuvering and seakeeping, which are benefiting significantly from ongoing advancement in computational tools and techniques**
- **Central to fundamental advancement in complex viscous phenomenon, such as flow separation, cavitation, vortex-induced vibrations, etc**

Conventional Flow-Field Measurement Techniques

Evolution of Flow-Field Measurement Techniques

Intrusive point measurement: single / multi-hole Pitot tubes, ADV

Qualitative Flow Visualisation: paints / dyes tufts

↓

Non-Intrusive optical point measurement: **LDV / LDA**

↓

Non-Intrusive two component optical measurement in 2D plane: **PIV/PTV**

↓

Non-Intrusive three component optical measurement: of 3D flow in 2D plane: **SPIV**

↓

Non-Intrusive three component optical measurement: of 3D flow in volume: **DDPIV, Tomography**

Laser Doppler Velocimetry (LDV)

- **LDV is a well-established technique for detailed flow measurements and is routinely used in many research organizations throughout the world**
- **LDV can accurately measure all three velocity components even in highly turbulent flows and in flows with recirculation zones, at high temporal and spatial resolution.**
- **LDV is fundamentally a point measurement technique: the time evolution of velocity can be measured with great accuracy at a point, but if a map of an area of the flow is to be obtained, it must be built up point by point.**

Laser Doppler Velocimetry (LDV)

- LDV is most suitable for flows that are either steady or highly repeatable; spatial characterization of unsteady large-scale coherent structures is challenging
- Extended periods of facility operation are typically required if a large area has to be investigated at an adequate spatial resolution.
- Particularly critical to applications in tow tanks, where the limited length can heavily impact the productivity of the measurement and consequently on the operational cost.

Particle-Image Velocimetry (PIV)

- **PIV overcomes many of the limitations of LDV.**
- **PIV measures flow velocities over a 2D plane allowing characterization of unsteady large scale vortical structures.**
- **Hence reduced time required to obtain a statistical set of data has brought a significant savings in the testing costs.**
- **"Traditional" PIV measures in-plane components of velocity only**
- **Significant practical issues remain before a wider adoption among the ITTC community is possible.**

Stereoscopic Particle-Image Velocimetry (SPIV)

- Stereoscopic PIV is an extension of planar-PIV to applications in which the presence of strong three-dimensional coherent structures and velocity gradients requires all velocity components to be measured.
- The technique is based on the principle of stereoscopic imaging. Two cameras are arranged to image the illuminated flow particles from different perspectives. The combination of both camera projections allows the reconstruction of the three-dimensional particle displacement inside the measurement volume and the evaluation of all three velocity components.
- SPIV alleviates the problem of cross-plane velocity bias of two-component PIV, but is more complex to implement.

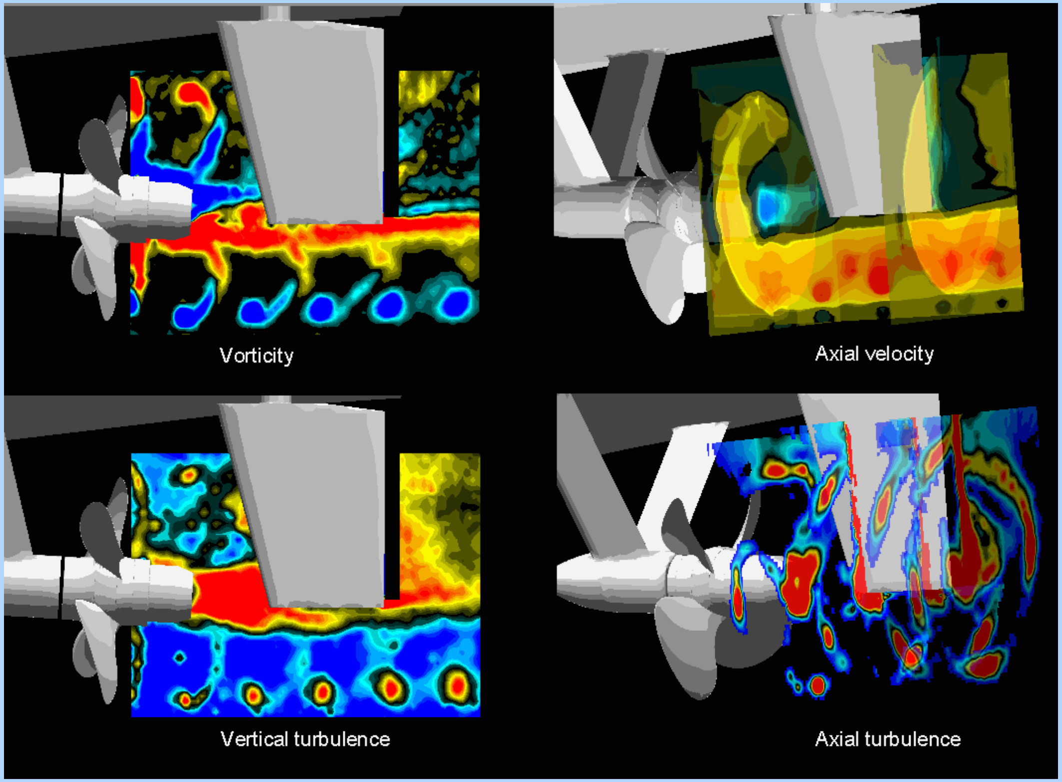
Detailed Flow Measurements in Ship Propulsion

Applications of Flow Measurements in Ship Propulsion

- Quantification of complex flow details such as non-uniform inflow into the propeller and vortical structures in the near wake is critical to modern marine propulsion analysis and performance evaluation.
- Marine propulsion field pioneered the early adoption LDV, a non-intrusive laser-based flow measurement technique (Min, 1978), which is a significant improvement over intrusive pitot probes.
- The combined use of LDV and phase-sampling techniques has allowed an efficient and robust reconstruction of the flow field along cross sections of the propeller wake and made possible the analysis of the turbulent flow around a propeller.

Applications of Flow Measurements in Ship Propulsion

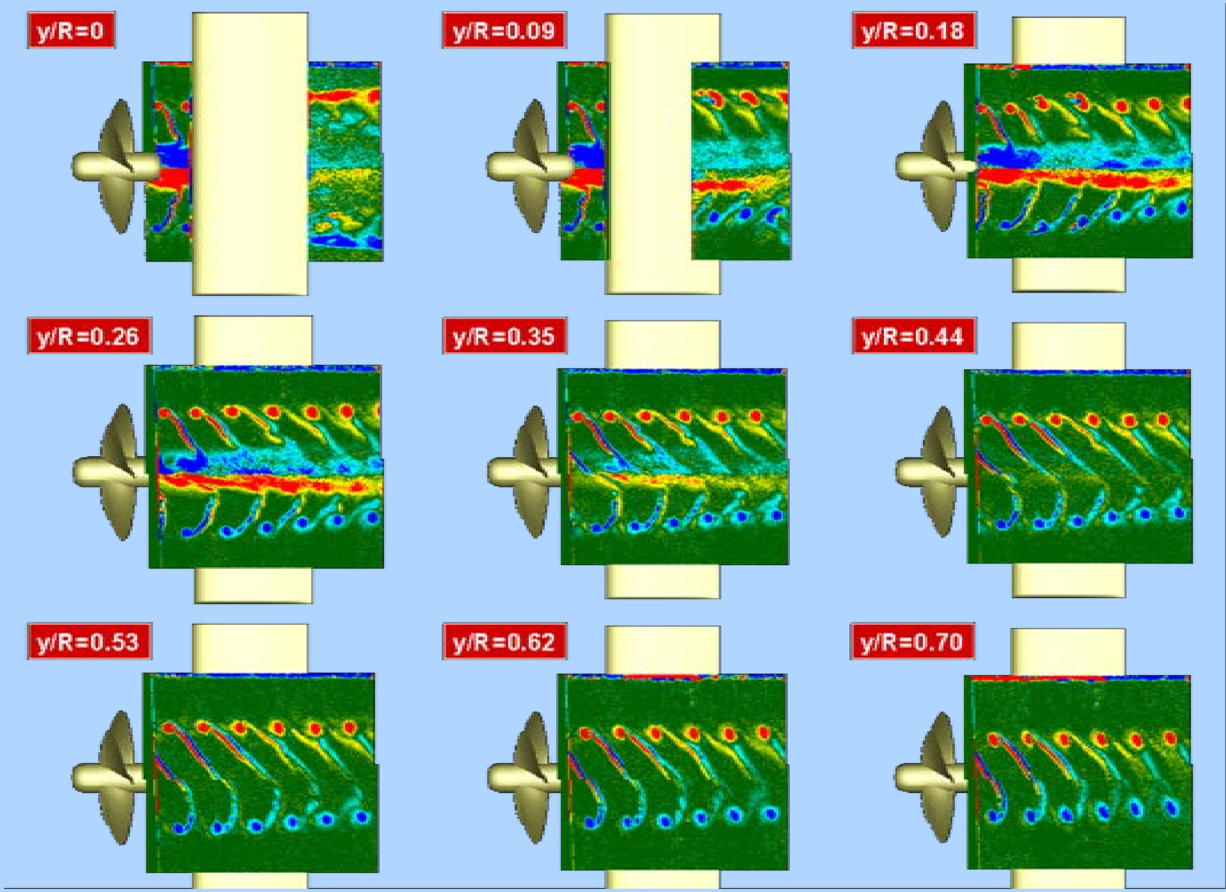
Measurement of complex details such as blade boundary layer, blade wake and tip vortices have today become widely practiced.



Wake evolution by phase-locked LDV measurements (Muscari *et al*., 2010)

Applications of Flow Measurements in Ship Propulsion

Adoption of whole-field flow measurement techniques such Particle-Image Velocimetry (PIV) has provide a more robust way of measuring time-varying three-dimensional flow.

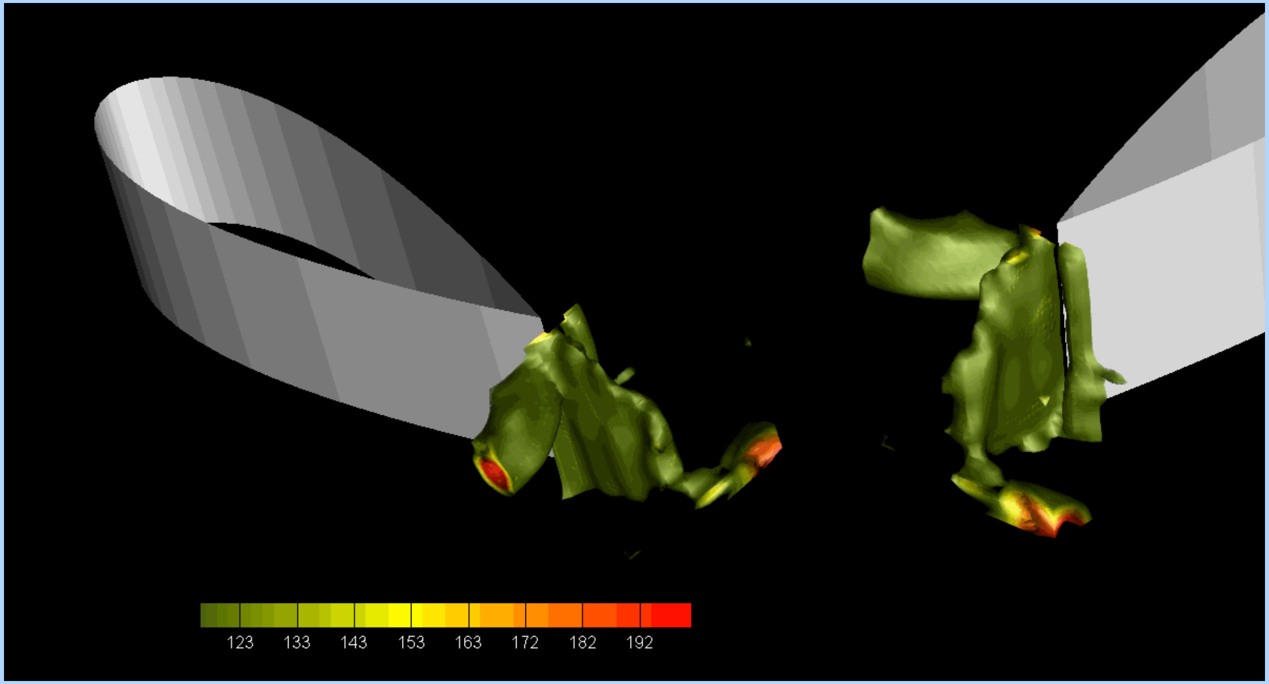


Out of plane vorticity from a comprehensive study using PIV, LDV, and rudder-surface-pressure measurements

(Felli *et al*., 2010)

Applications of Flow Measurements in Ship Propulsion

Nevertheless, LDV continues to be used in a routine fashion even in a highly complex flow.



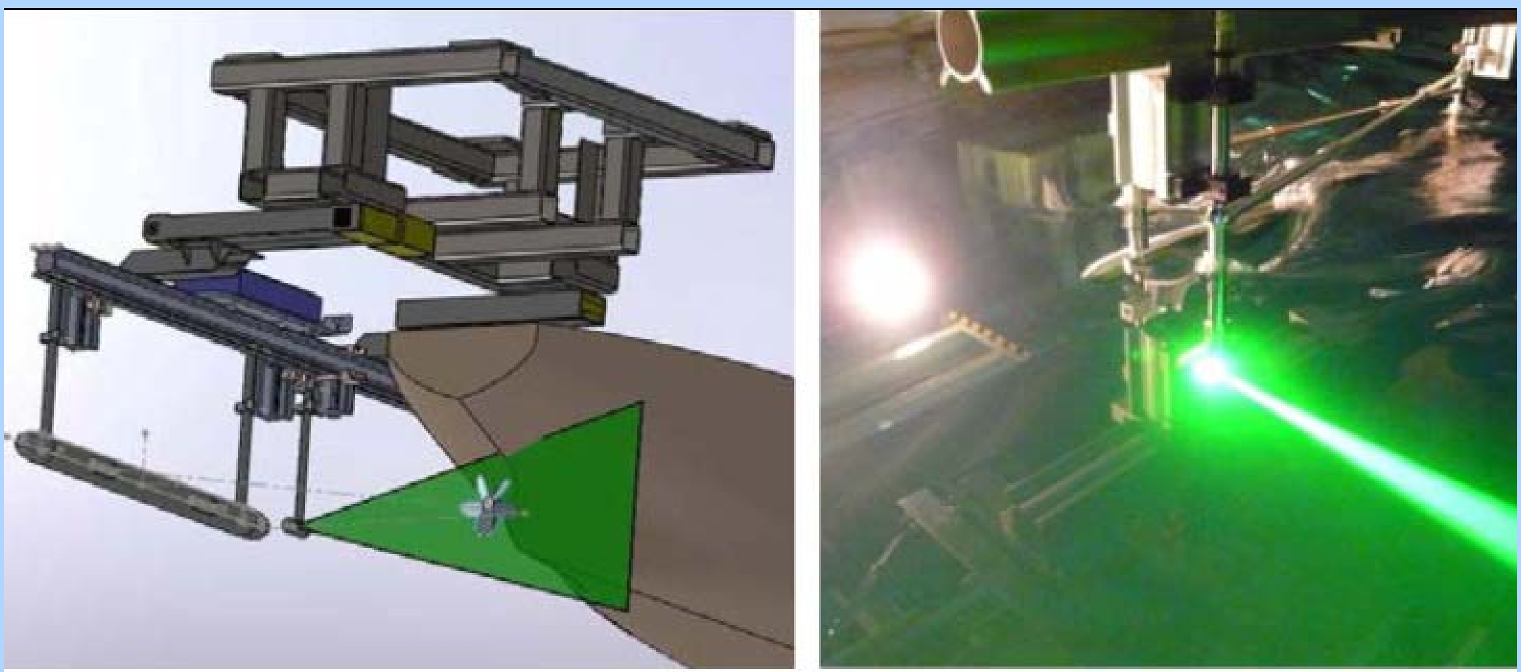
Volumetric LDV measurements about the tip vortex rejoining downstream of a rudder (Felli *et al*., 2009)

Recent Advancements in Flow Measurements in Ship Propulsion

- **Application of whole-field flow measurement techniques such Particle-Image Velocimetry (PIV) has allowed more detailed investigation of marine propulsion hydrodynamics.**
- **Di Felice *et al*. (2004) demonstrated the capability for PIV to identify the dynamics of dominant flow structures in the near wake of a propeller operating at different loading conditions.**
- **Felli *et al*. (2006) used PIV and a rake of hydrophones to measure the phase-locked correlations between velocity and in-flow pressure fluctuations downstream of a marine propeller operating different advance ratios.**
- **Jessup *et al*. (2006) utilized SPIV to measure the unsteady flow of a ducted propeller in crashback operation.**

Recent Advancements in Flow Measurements in Ship Propulsion

Most recently, PIV/SPIV have been applied to tow-tank applications to capture detailed flow of fully-configured ship models.



SPIV probe used in Nagaya *et al*. (2011)

Recent Advancements in Flow Measurements in Ship Propulsion

- **Applications of tools such as LDV and PIV/SPIV in tow-tank applications are highly attractive but remain challenging due to a number of practical issues (complexity of experimental setup, low data rate per pass, etc.)**

Detailed Flow Measurements in Ship Maneuvering

Applications of Detailed Flow Measurements in Ship Maneuvering

- While use of advanced flow measurement techniques such as LDV starts in the late 70s in the ship propulsion community, such usage in the ship maneuvering community did not start until the mid 90s.
- The development of complex hull force models that take into account effects such as nonlinear yaw-roll coupling and cross-flow drag still relied heavily on results from captive model tests of varying degree of sophistication (build-up tests, segmented model, etc).
- Contributing to this history is the fact that the application of measurement techniques such as LDV and PIV/SPIV in tow-tank environment still remains a challenge today.

Applications of Detailed Flow Measurements in Ship Maneuvering

- **From the early 90s, interest in maneuvering became more focused on the flow physics in addition to the quantification of the integral quantities (forces and moments).**
- **Advanced numerical tools such as potential flow codes with physics-based models and RANS were being applied to maneuvering problems.**
- **DFM provides direct measurement to develop understanding and validate numerical codes.**

Applications of Detailed Flow Measurements in Ship Maneuvering

- **Nonaka *et al*. (1995) performed an experimental investigation on three VLCC ship models with different shaped sterns in oblique towing motions. Measurements included the overall forces and moments on the hull, flow field in the stern region using 5-hole pitot probes, and visualization of separation regions by tufts.**
- **Ando *et al*. (1997) and Nakatake *et al*. (1998) developed a surface panel method and presented results comparing numerical solutions with the experimental results by Nonaka *et al*. (1995).**
- **Kijima *et al*. (1995, 1996) also used the same experimental results in comparison to their estimation method of hull forces and moments using a cross flow drag term based on a vortex shedding model and separation line from captive model experiments.**

Applications of Detailed Flow Measurements in Ship Maneuvering

- **Longo and Stern (1996) applied 5-hole pitot probes to measure the time mean velocities around a series 60 CB=0.60 ship model at angles of drift, along several longitudinal stations. Wave profiles and local and global elevations using capacitance and servo probes were also measured to assess the nature of the interaction between ship-induced wavemaking with the boundary layer and wake.**
- **This extensive dataset were heavily used for the purposes of CFD validation by various researchers.**
- **Di Felice and Mauro (1999) performed a series of experiments on the same hull form in a double-model configuration at a very large drift angle of 35 degrees and measured the mean cross-flow velocities using LDV.**

Applications of Detailed Flow Measurements in Ship Maneuvering

- **Starting in the mid 90's, many experimental activities involving PIV/SPIV on submerged vessels in the towing tanks has been documented. In 1994, Liu *et al*. demonstrated the use of PIV to measure flow structures around a submarine model in the Rotating Arm Basin at NSWCCD.**
- **With a much more advanced system, Fu *et al*. (2002) measured the flow in a cross-plane around the submarine model, ONR Body-1, in rotation using a submersible PIV system fixed to the basin.**
- **Atsavapranee *et al*. (2004) performed SPIV, force and moment, and pressure distribution measurements around the same model towed in a straight course at angles of drift.**

Development of PIV/SPIV Measurements in Ship Maneuvering

SPIV measurement setup in a straight-line basin from Atsavapranee *et al*. (2004)

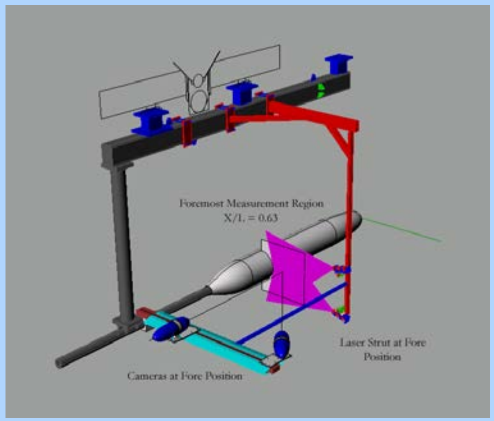
- **Component-level developments contributing to practical use**
- **Availability of sensitive high-resolution cameras**
- **Fiber-coupled high-power lasers**
- **More reliable and compact submersible housings and optics**
- **Robust and easily deployable mounting platforms**

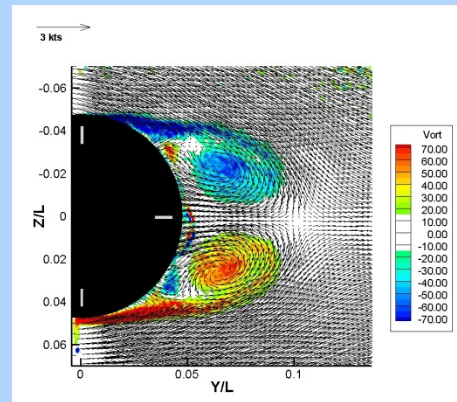
Practical Issues Related to Optical Flow Measurements in Ship Maneuvering

- Two-component PIV suffers from a velocity bias when the measurement plane has a large out-of-plane component.
- A basin-fixed system or a system mounted outside of a cavitation tunnel usually stays fixed, but the model angle of drift changes often in a maneuvering test.
- A carriage-fixed towed SPIV system that rotate with the model drift angle is a desirable solution.
- A towed SPIV system is complex. Existing facilities were usually not designed with this type of systems in mind.

Examples of Towed SPIV Applications in Ship Maneuvering

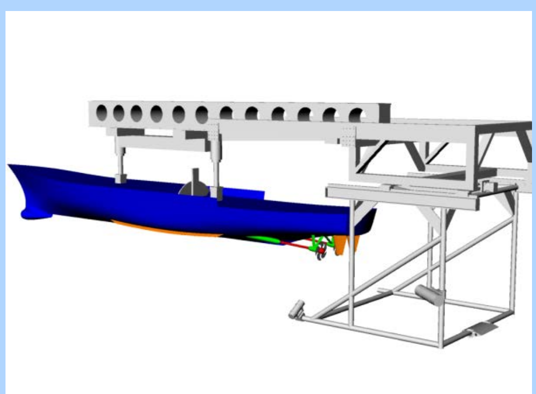
SPIV on SUBOFF model, Etebari *et al*. (2008)

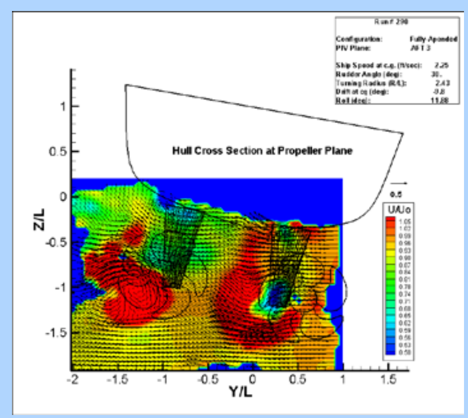




Results

SPIV on SUBOFF model, Atsavapranee *et al*. (2010)





Results

Detailed Flow Measurements in Seakeeping And Free-Surface Flows

Applications of Detailed Flow Measurements in Seakeeping And Free-Surface Flows

- **Increasingly complex nonlinear viscous phenomena such as wave breaking, bow slamming, green water, or roll damping are challenging current analysis tools.**
- **The rapid development of CFD since the mid 90's, coupled with parallel advancement in measurement techniques has lead to increased understanding of the flow phenomena**
- **In addition, the wider application of detailed flow measurement has contributed to high-quality benchmark experimental data for the validation of CFD tools.**

Detailed Flow Measurements On Series 60

- Toda *et al*. (1992) applied 5-hole pitot probes to measure the time mean velocities around a series 60 ship model at several longitudinal stations. Wave profiles were also measured to assess the nature of the interaction between ship-induced wavemaking with the boundary layer and wake.
- Longo and Stern (1996) performed similar measurements for the same model at different angles of drift.

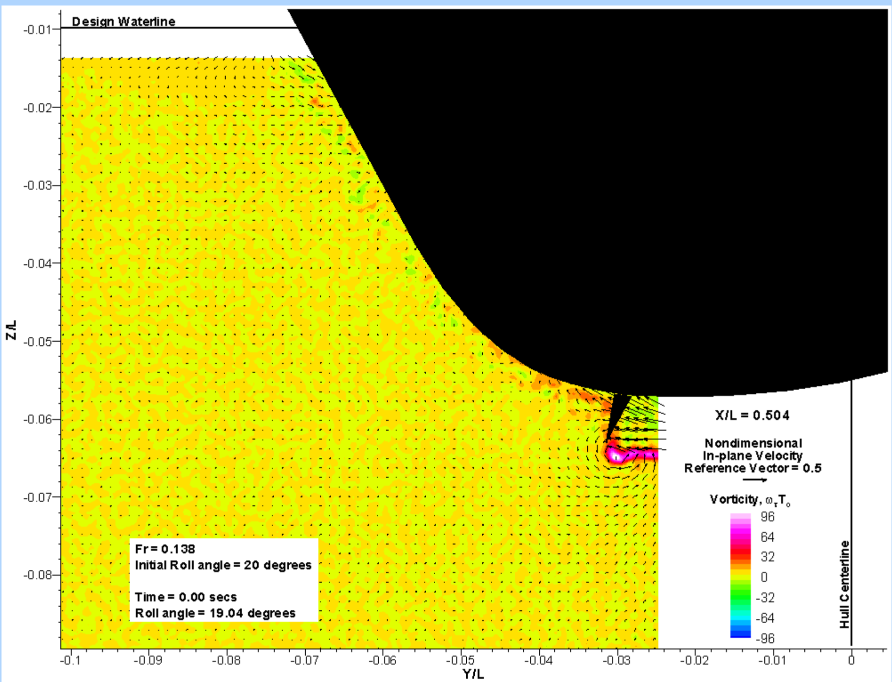
Detailed Flow Measurements on DTMB 5415

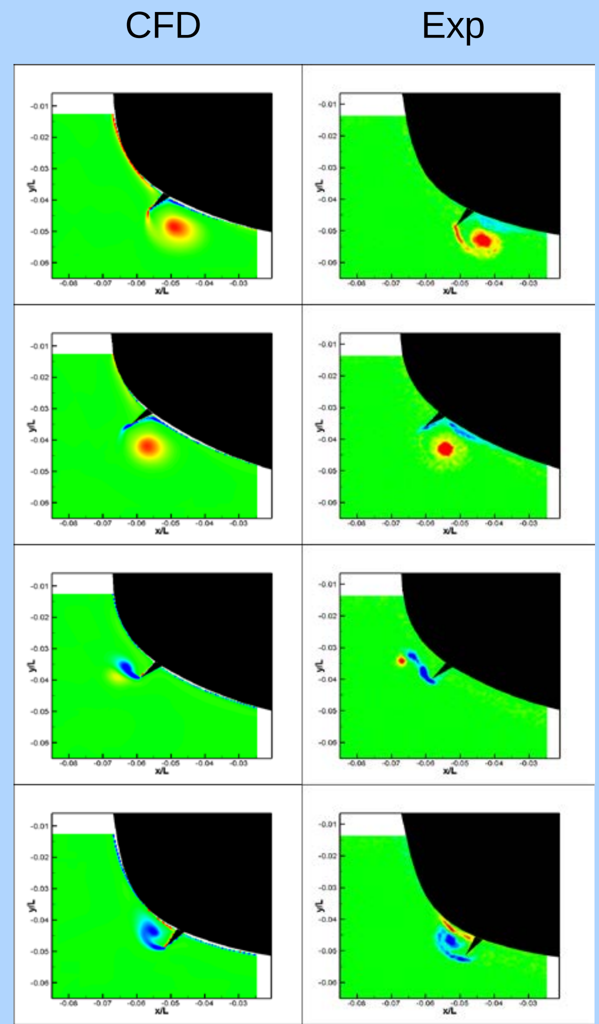
- **The combatant hull form as represented by DTMB model 5415 has been used widely in various hydrodynamic studies.**
- **Trilateral international collaboration with overlapping tow tank tests between three institutes (IIHR, INSEAN, and NSWCCD) measuring resistance, sinkage and trim, wave profile and elevation, and nominal wake using pitot probes were performed using the same hull geometry at different scales (DTMB model 5512, DTMB model 5415, and INSEAN model 2340A).**

Detailed Flow Measurements on DTMB 5415

- **Further cooperation by the same consortium (IIHR , INSEAN, and NSWCCD) collaborated further on a complex viscous hydrodynamic problem of a surface vessel in roll using the same DTMB 5415 hull form with bilge keels and other appendages.**
- **Single-degree-of-freedom roll decay tests were performed at various forward speeds, with comprehensive measurements including two-component LDV measurements along eight transversal planes at INSEAN (Felli *et al*. 2004), wave-field and PIV measurement at IIHR (Irvine *et al*. 2004), and PIV and force and moment measurements at NSWCCD (Bishop *et al*., 2004).**

Detailed Flow Measurements on DTMB 5415



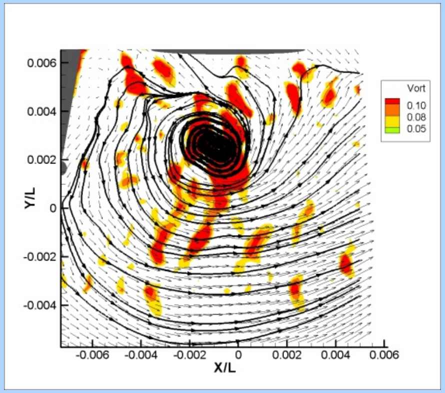


Comparison of Roll Decay Flow Field Results Between Experiments (Bishop, *et al.*, 2004) and CFD (Miller, *et al.*, 2008)

Phase II of IIHR/INSEAN/NSWCCD Collaboration

- During a follow-on phase of this collaborative effort, a calm-water roll-decay trial was performed on the Italian vessel, *Nave Bettica*, (Atsavapranee *et al*., 2008). Viscous flow field around the port bilge keel of the *Bettica* was measured using PIV, along with the lateral force on the bilge keel using surface-mounted strain gages.
- This study represents the first application of the PIV technique on a full-scale vessel.

PIV setup on the Italian vessel, *Nave Bettica*, from Atsavapranee *et al*. (2008)



Full-Scale PIV Results

Detailed Flow Measurements on Bow Waves

- **A number of investigations recently focused on the breaking waves around a surface vessel. Waniewski *et al*. (2002) characterized the bow wave of a stationary deflecting plate in recirculating water channel and a wedge model in a tow tank, using contact line measurement with capacitance probes and wave profile measurements using a resistive wave gage.**
- **Karion *et al*. (2003) used a laser-sheet technique called *QVIZ* to profile the breaking bow waves on large 20-degree and 40-degree wedge models.**
- **Fu *et al.* (2005) and Fu *et al.* (2006) conducted detailed measurements to characterize the wave field around the DTMB model 5365, a model of the *R/V Athena I*, and also on the full-scale ship itself.**

Emerging Flow-Field Measurement Techniques

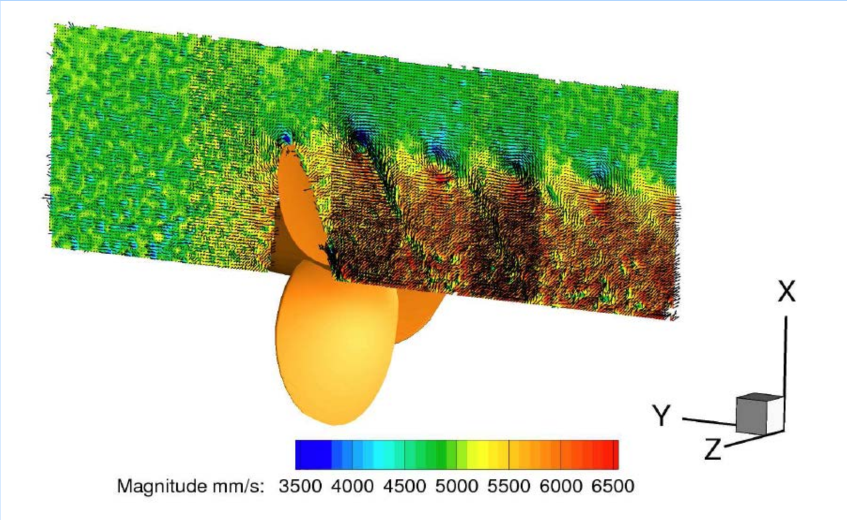
Why Do We Need Frontier Flow Measurement Techniques?

- **For the most challenging naval hydrodynamics problems, even standard and stereoscopic PIV provide only a partial view of the complex three-dimensional unsteady problem.**
- **As organizations continued to adopt maturing flow measurement techniques, maintaining awareness and a level of involvement in frontier measurement techniques is important.**
- **The interaction between researchers from tow-tank organizations and academic institutions in this area helps foster technology development and insertion, mentoring of students, and eventually the adoption of maturing frontier measurement techniques.**

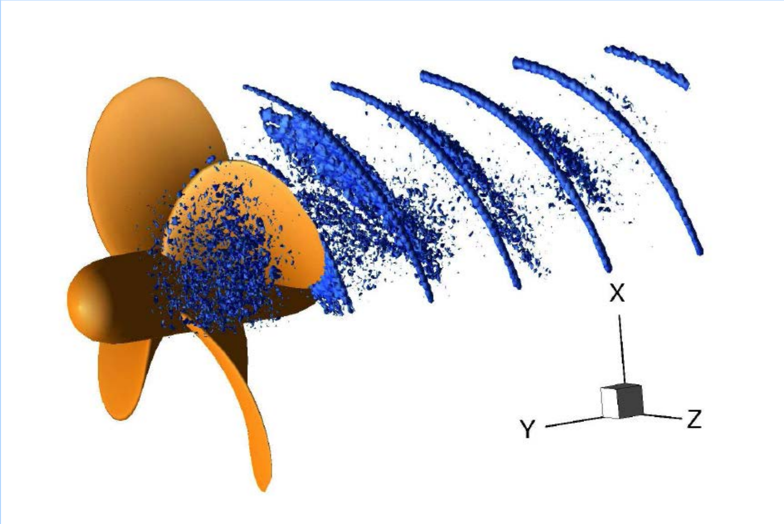
3-dimensional and 3-component Flow Measurements

- **3D-particle tracking velocimetry (Maas *et al*. 1993)**
- **Holographic PIV (Pu and Meng, 2000; Hinsch, 2002)**
- **Tomographic PIV (Elsinga *et al*., 2006)**
- **Defocusing PIV (Willert, 1992)**

Sample Results Using Defocusing PIV



Sample velocity field measurement using the DDPIV technique (Pereira, 2011)



Sample void fraction measurement using the DDPIV technique (Pereira, 2011)

Other Frontier Flow Measurement Techniques

- **Particle Shadow Velocimetry (PSV, Goss *et al*., 2007a)**
- **MicroPIV (Santiago *et al*. 1998)**
- **Forward Scatter PIV (fsPIV, Ovryn *et al*., 2000)**
- **Surface Stress Sensitive Film (S3F) (Crafton *et al*., 2008)**

Conventional Wave-Field Measurement Techniques

Evolution of Wave-Field Measurement Techniques

Intrusive point measurement:
Resistance & Capacitance probes

Advanced semi-intrusive techniques:
servo probes etc.

Non-Intrusive point measurement:
Ultrasonic Probes

Optical point measurement
Laser profilometry

Optical line measurement
Laser wave cut measurements

Optical measurement of 2D wavy surface:
Multi-point / stereo photogrammetry / grid distortion techniques

Intrusive Wave Measurement Systems

- **Intrusive wave probes are widely used and well established**
  - **Resistance probes**
  - **Capacitance probes**
  - **Servo-mechanical (finger) probes**
- **Issues**
  - **Meniscus reversal**
  - **Scattering of waves around the wires**
  - **Vibration affecting separation of the wires (in large waves)**
  - **Ventilation in non-zero mean flow speed can occur**
  - **Non-linear response in very shallow water**
  - **Fouling and contamination**

Ultrasonic Wave Measurement Systems

- **Ultrasonic wave probes are widely used and well established**
  - **Non-intrusive**
  - **Good data rate**
  - **Ease of handling**
- **Issues**
  - **Key performance parameters such as spot size and data rate vary with beam angle and working distance**
  - **Dynamic effects due to spatial averaging at wave peaks and troughs related to the finite size of the acoustic footprint**
  - **Signal drop outs for steep waves**
  - **Unsuitable for densely populated point measurements**

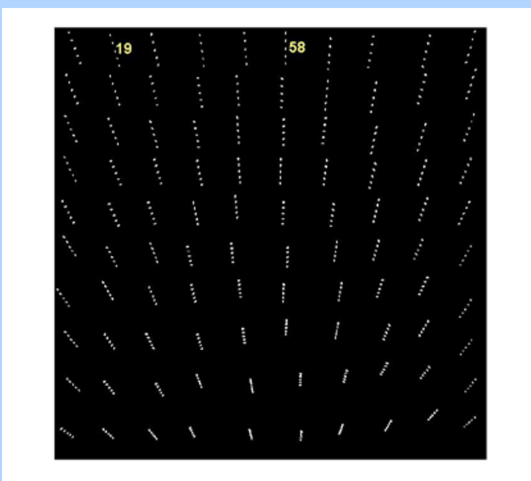
Emerging Wave-Field Measurement Techniques

Optical-Based Pointwise Wave Measurement Systems

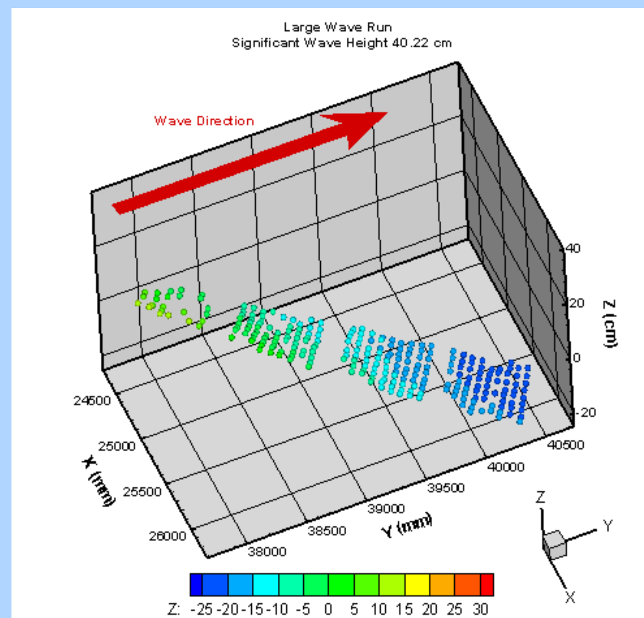
- **Generally uses one more multiple laser beams and use evaluation techniques such as triangulation.**
- **Richon *et al.* (2009) describe the development of a single point measurement system based on the principle of a laser rangefinder, using a high-power laser pointing vertically downwards at the water surface with a CCD camera.**
- **Payne *et al.* (2009) and Day *et al.* (2011) describe the development of a system using a moderate power laser and video cameras.**

Optical-Based Pointwise Wave Measurement Systems

- Atsavapranee *et al.* (2005) and Carneal *et al.* (2005) describe the development of a system described as Global Laser Rangefinder Profilometry (GLRP) which uses a large array of low-power (3.5-15mW) lasers to measure wave elevation at discrete points on the water surface.



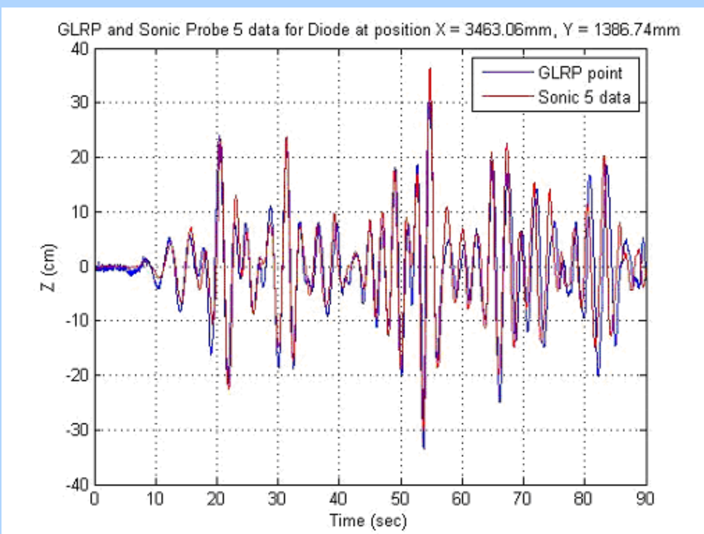
Superposition of five GLRP calibration images taken in calm water at five water elevations



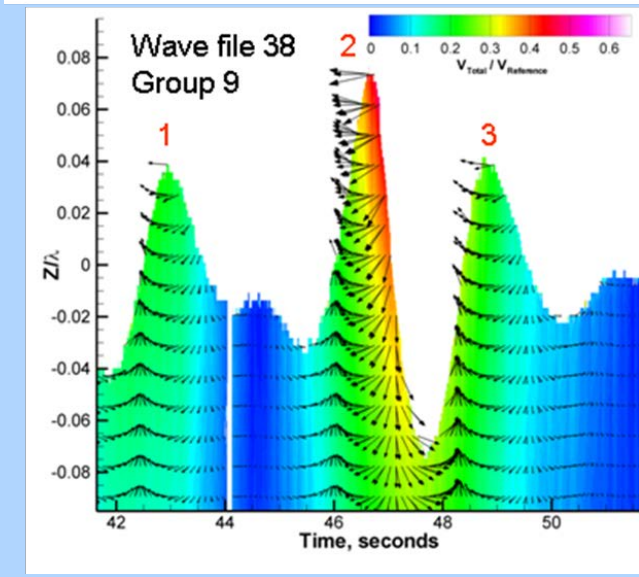
Sample GLRP Results

Optical-Based Pointwise Wave Measurement Systems

- **Recently, the GLRP technique has been used to quantify the three-dimensional wave field in an investigation of various means to generate large-amplitude wave groups and single extreme waves (Bassler *et al*., 2008, Minnick *et al*., 2011).**



Comparison between GLRP and sonic probe in the measurement of a large-amplitude wave group (Bassler *et al*., 2008)



Wave height and kinematics of a large-amplitude wave group (Minnick et al., 2011)

Light Sheet Wave Measurement Systems

- **Furey and Fu (2002) describe an early implementation of the QViz (Quantitative Visualisation) system which used a high-power laser to create a light sheet normal to the water surface and a digital camera to record images of the intersection of the light sheet with the water surface.**
- **Developments and subsequent applications of the QViz system are described in Rice *et al.* (2004), Fu *et al.* (2005) and Fu *et al.* (2009). Field application of the system to measure the bow and stern waves of a full-scale ship at sea is described in Fu *et al.* (2006).**

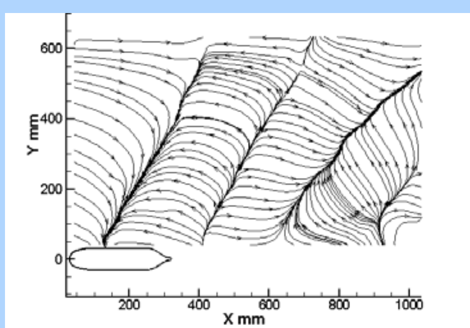
2D Optical Wave Measurement Systems

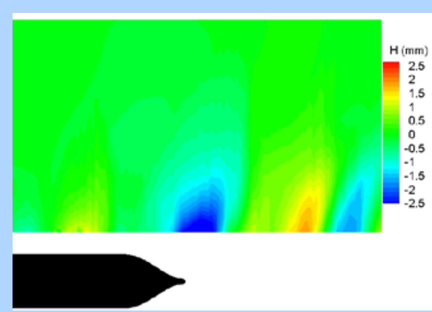
- **A variety of techniques have been explored to measure waves over an area rather than along a line or at a discrete point.**
- **A stereo–photogrammetry technique described as the *Automated Trinocular Stereo Imaging System (ATSIS)* is described by Wanek and Wu (2005), with the main challenge being stereo image matching for images with low contrast.**

2D Optical Wave Measurement Systems

- **Kanai (1985) describes a technique based on the measurement of the deformation of a grid pattern projected onto the water surface from above.**
- **Sanada *et al*. (2008) measure the instantaneous 2D wave field around a ship model by projecting a colour-coded line pattern onto the water surface**
- **An optical refraction technique and PIV were used to measure the flow field and surface waves induced by internal waves generated by an underwater moving body in CSSRC's stratified fluids tank.**

Streamtrace of flow field





Surface waves induced by internal waves

Additional Committee Considerations, Recommendations and Conclusions

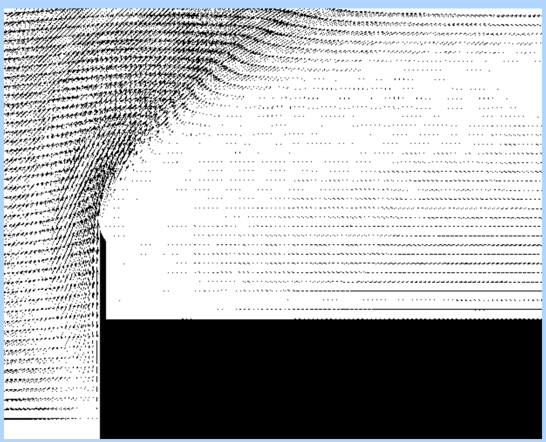
Practical Issues with Applications of Detailed Flow Measurements in Large-Scale Facilities

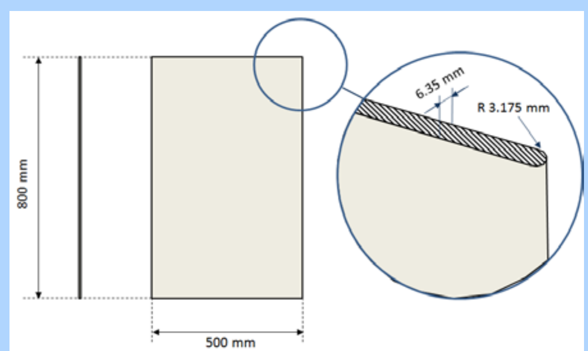
- **A practical guideline is needed in order to facilitate the adoption and application of PIV and SPIV in the ITTC.**
- **The development of such a guideline is complicated by the fact that potential applications for PIV/SPIV are so wide ranging and would concern practitioners of various levels of knowledge and experience working in different facilities.**
- **Issues to cover include:**
  - **Hardware selection**
  - **Experimental design (optical arrangement, mounting hardware, support structure interference, etc)**
  - **Post-processing algorithm**
  - **Seeding**
  - **Glares and reflection…..Etc.**

Experimental Benchmark for the Assessment of PIV/SPIV Setup

- **Widely accepted experimental benchmarks can be extremely helpful assessment the "goodness" of a PIV/SPIV setup.**
- **Two benchmarks, one for two-component PIV and one for SPIV are being considered.**
- **HTA had developed an SPIV benchmark which is extremely attractive.**

Preliminary CFD of a potential PIV benchmark





Geometry of HTA SPIV benchmark

PIV/SPIV Uncertainty Analysis

- **The 25th Specialist Committee on Uncertainty Analysis published procedure 7.5-01-03-03 on the uncertainty assessment of PIV that is both up-to-date and compliant with industry standards in regards to uncertainty analysis methodologies.**
- **Although the current procedure is very comprehensive in its coverage of error sources due to the PIV measurement system itself, sources of bias and random uncertainties due to the particulars of the flow (velocity gradients within the flow, out-of-plane particle motion across the laser sheet) and test-specific issues (such as seeding density and non-uniformities, particle image size, and laser glares on model) were not addressed.**
- **Uncertainty analysis procedure for SPIV is needed.**

The Use of Detailed Flow Data for The Validation of CFD

- **As numerical simulations are required to solve more complex problems, the requirements for experimental measurements become significantly more demanding, with ever-increasing focus on unsteady nonlinear phenomena—Are the currently available experimental database adequate for the current needs?**

- **The specific ways that experimental database are used to “validate” CFD varies widely, often times being mostly qualitative in nature—Do we need to develop a rigorous definition of “CFD validation” and come up with an internationally accepted standard procedures (or is that even possible)?**

Recommendations to the 26th ITTC

- Develop a best-practice guideline for the applications of PIV/SPIV in tow tanks and cavitation tunnels
- Develop experimental benchmarks for the verification of PIV/SPIV setup
- Collaborate with the Specialist Committee on Uncertainty Analysis to assess PIV error sources beyond those considered in existing procedure 7.5-01-03-03 and develop Recommended Procedures and Guidelines on stereo-PIV uncertainty analysis
- Collaborates with the Specialist Committee on CFD in Marine Hydrodynamics to review existing data sets suitable for benchmarking and validating CFD codes and advance the process and procedure for such use.

Conclusions

- **Continued rapid advancement in non-intrusive measurement technologies in the last 15 years has allowed researchers across many ship hydrodynamic disciplines to investigate complex viscous phenomena including separated flow and unsteady vortical structures.**
- **This development has occurred in parallel and in conjunction with increasing usage and improvement in state-of-the-art numerical tools such as unsteady RANS and inviscid flow codes with advanced physics-based models.**
- **In certain areas, numerical tools are not mature or sophisticated enough, and experiments are heavily relied upon.**
- **Many challenges and practical issues remain before such tools can find routine everyday use within the towing tank community.**

Conclusions

- **Given the recent trend, it is expected that these technologies will continue to mature, leading to increased utility and wider adoption by the ITTC organizations.**
- **Therefore, it is of critical importance that the ITTC addresses these practical issues and challenges in a systematic manner in order to facilitate the adoption of detailed flow measurement techniques within its member organizations.**