Report of the Specialist Committee on Detailed Flow Measurement Techniques

Presented to the 27th International Towing Tank Conference, Copenhagen, Denmark

September 1, 2014

Members of the 27th ITTC Specialist Committee on Detailed Flow Measurements

- Paisan Atsavapranee, *NSWCCD* (USA), Chair
- Mario Felli, *CNR INSEAN* (Italy), Secretary
- Inwon Lee, *Pusan National University* (Korea)
- Chittiappa Muthanna, *Marintek* (Norway)
- Shigeki Nagaya, *IHI* (Japan)
- Feng Zhao, *CSSRC* (China)

Meetings

- CSSRC, China, March 2012
- NSWCCD, USA, November 2012
- Marintek, Norway, July 2013
- Pusan National University, Korea, February 2014

Term of Reference for the Committee

- Survey and report on the existing detailed flow visualization, measurement techniques and data analysis methods
- 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
- Develop a guideline for PIV/SPIV uncertainty analysis
- Collaborate with the Specialist Committee on CFD to develop methods for the validation of CFD codes using detailed flow measurements

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

Roles of Detailed Flow Measurements

- 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 phenomena, such as flow separation, cavitation, vortex-induced vibrations, etc

Outline

- State-of-the-art review
  - Ship propulsion
  - Ship hydrodynamics (maneuvering, seakeeping, etc)
  - Ocean engineering and free-surface flows
- 7.5-02-01-04: Guideline on Best Practices for the Application of PIV/SPIV in Towing Tanks and Cavitation Tunnels
- 7.5-01-03-04: Benchmark for PIV (2C) and SPIV (3C) Setups
- 7.5-01-03-03: Guideline on the Uncertainty Analysis for Particle Image Velocimetry
- Discussions on the validation of CFD codes using detailed flow measurements
- Recommendations and conclusions

State-of-the-art Review

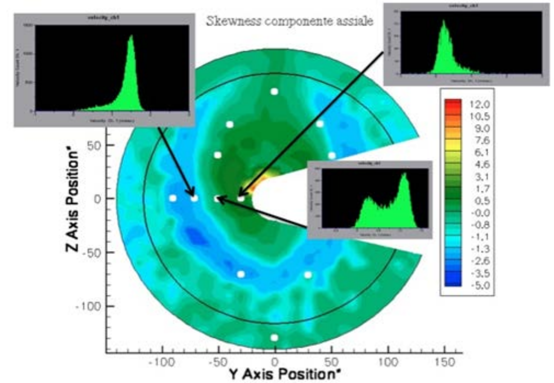
Applications of DFM in Ship Propulsion

- Since the 26th ITTC conference, there have been many good examples of detailed flow measurements in ship propulsion, primarily dealing with wake flow surveys around isolated and installed propellers, waterjets and propeller-rudder configurations.

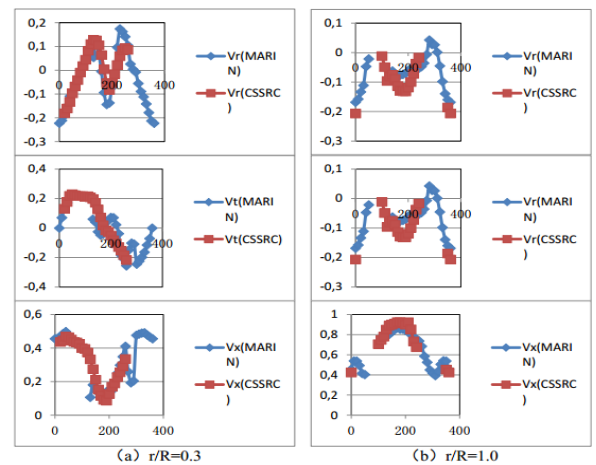
- Detailed flow measurements are still important in this area to:
  - improve the understanding on the mechanisms underlying the hydrodynamic performance of marine propulsors in off-design conditions (e.g. maneuvering operations, captive sea conditions)
  - support the diagnostics of acoustic problems
  - support validation and verification of CFD computations

Examples of Applications of DFM in the propulsion field: propeller flow

- DFM of the propeller flow have been routinely used in many ITTC organizations in various flow facilities:
  - Pecoraro *et al.* (2013) presented a detailed study of the propeller inflow characteristics based upon the analysis of the Probability Density Function and the skewness distributions.
  - Paik *et al.* (2011) investigated the trailing wake characteristics underlying the propeller singing mechanism by PIV.
  - Dang *et al.* (2012) and Bugalski & Reda (2013) documented some examples of towing tank and cavitation tunnel surveys of the flow around installed propellers by underwater stereo PIV.



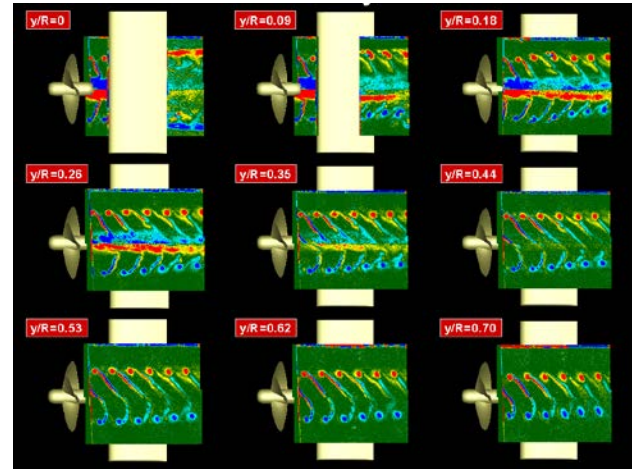
Pecoraro *et al.*, 3rd SMP, 2013



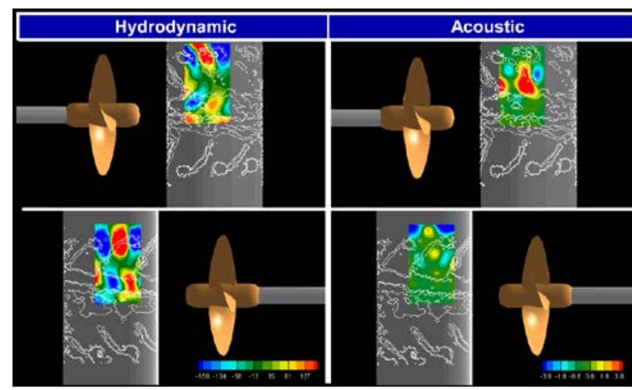
Bugalski & Reda., 3rd AMT, 2013

Examples of Applications of DFM in the propulsion field: propeller-rudder interaction (I)

- Detailed measurements of the wake flow around propeller-rudder systems have shed light into the mechanisms of perturbations in a rudder operating behind a propeller:
  - Felli *et al.* (2011) presented a comprehensive study of the propeller wake/rudder interaction mechanisms by detailed PIV and LDV measurements.
  - Felli *et al.* (2014) correlated the phase locked distribution of the vorticity field to the topologies of pseudo-sound pressure fluctuations and acoustic radiation over the rudder surface.



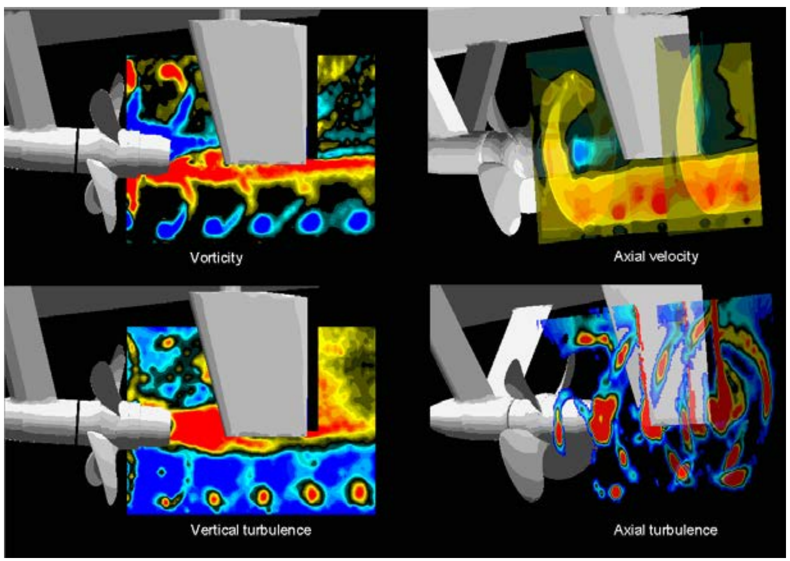
Felli *et al*., Experiments in Fluids, 2011



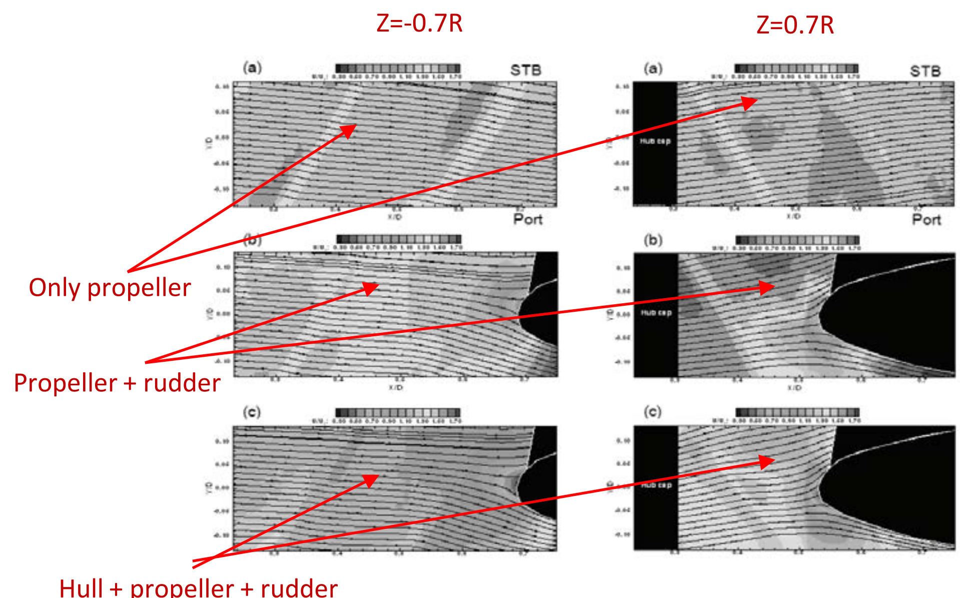
Felli *et al*., Experiments in Fluids, 2014

Examples of Applications of DFM in the propulsion field: propeller-rudder interaction (II)

- Muscari *et al.* (2011) performed detailed phase locked LDV measurements of the wake flow around an installed propeller-rudder system.
- Paik *et al.* (2011) analyzed the wake flow in front of a semi-spade rudder operating in the wake of a propeller by PIV measurements.



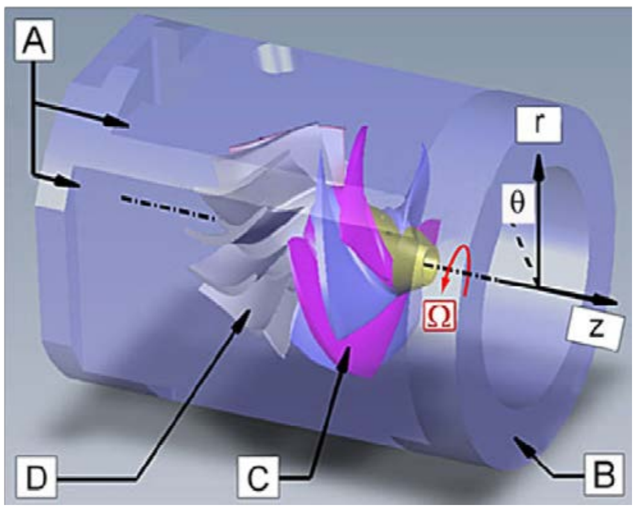
Muscari *et al.*, Journal of Fluid Engineering, 2011

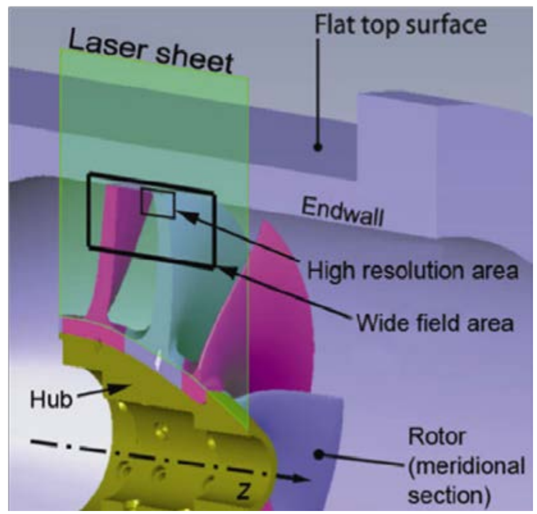


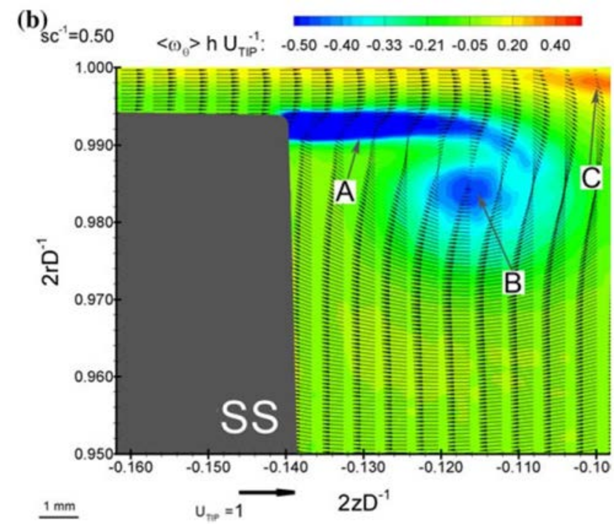
Paik *et al.*, JSNAK, 2011

Examples of Applications of DFM in the propulsion field: water jet flow

- DFM surveys of the inter-blade region of propellers and water jets were performed by matching the optical refractive index of the fluid with that of the pump blades and casing:
  - Wu *et al.* (2011) performed detailed PIV measurements in the tip region of a water-jet pump rotor at varying magnifications in a series of meridional planes that dissected the blade at different rotor phases.







Wu *et al.*, Experiments in Fluids, 2011

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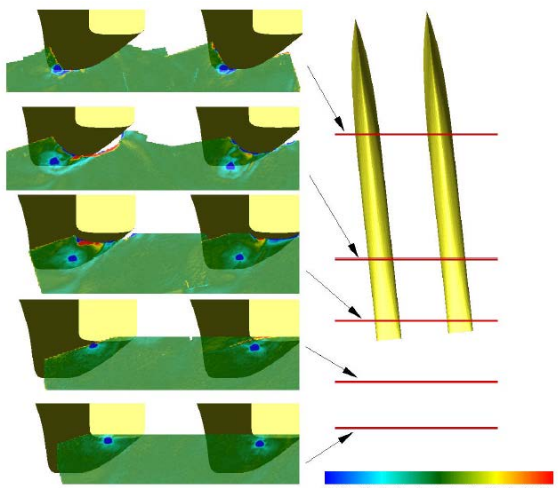
Applications of DFM in Ship Hydrodynamics

- Applications in tow tanks and maneuvering basins remain particularly challenging due to many practical issues in the implementation.
- However, demand for detailed flow measurements is increasing in this area, especially in the context of the validation of CFD computations of complex viscous hydrodynamic problems.

Examples of Applications of DFM in Ship Hydrodynamics

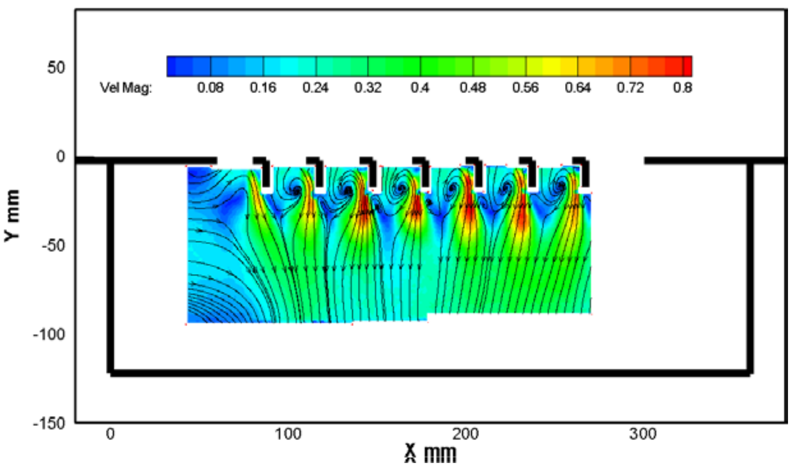
- A coordinated effort under the framework of NATO-AVT is focusing on CFD prediction of separated flows.
- One of the benchmark cases is the Delft catamaran 372 in static drift.
- Broglia *et al.* (2012) performed a comprehensive set of experiments, utilizing SPIV to measure detailed hull and wake flow.



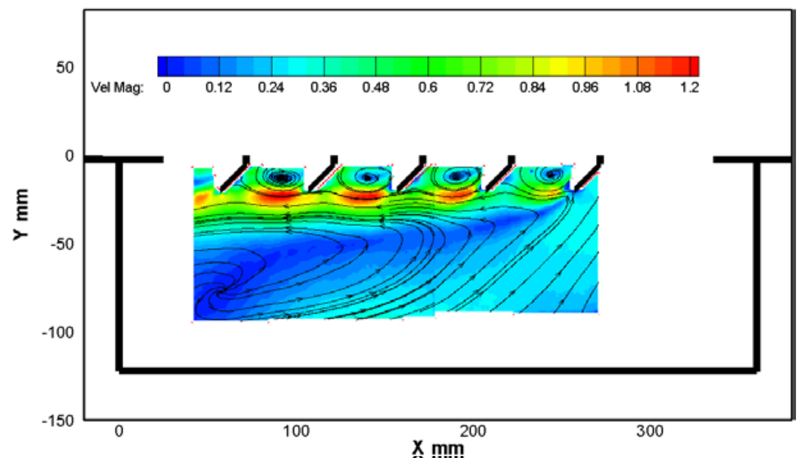
Vorticity field around the Delft catamaran 372 at Fr = 0.4 and drift angle of 6 degrees

Examples of Applications of DFM in Ship Hydrodynamics

- Novel uses of PIV on ship-related issues recently include roll damping around FPSOs, turbulent flow behind the trailing edge of a hydrofoil, flow inside a cavity with grates, and energy-saving devices (ESDs).



Flow inside a cavity with straight block (Zhang *et al*., 2013)



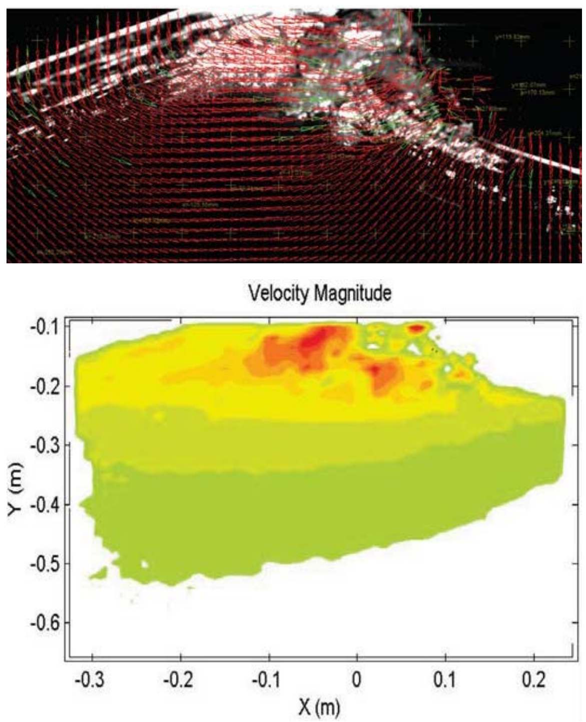
Flow inside a cavity with 45° block (Zhang *et al*., 2013)

Applications of DFM in Ocean Engineering and Free-Surface Flows

- Applications of detailed flow measurements are expanding rapidly beyond traditional areas.
- In recent years, experimental investigations using PIV/SPIV are becoming more common in ocean engineering and offshore structures.
  - VIV (Bearman, 1984; Blevin, 1990; Chaplin *et al*., 2005; Gabbai & Benaroya, 2005; Khalak & Williamson, 1996; Sarpkaya, 1978, 2004; Williamson & Govardhan, 2008; Williamson & Roshko, 1988).
  - Freely-suspended cylinders (Gao *et al*., 2013)
  - VSIV (Fernandes *et al*., 2012).

Applications of DFM in Ocean Engineering and Free-Surface Flows

- PIV measurements involving the air-water interface, especially in the presence of breaking waves, remain challenging.



PIV measurement of near-surface velocity field in breaking wave. Upper: Velocity vectors superimposed on video snapshot. Lower: Contour plot of velocity magnitude. Model Scale 1:125 (Stansberg *et al.*, 2012)

Guideline on Best Practices for the Application of PIV/SPIV in Towing Tanks and Cavitation Tunnels (7.5-02-01-04)

Scope

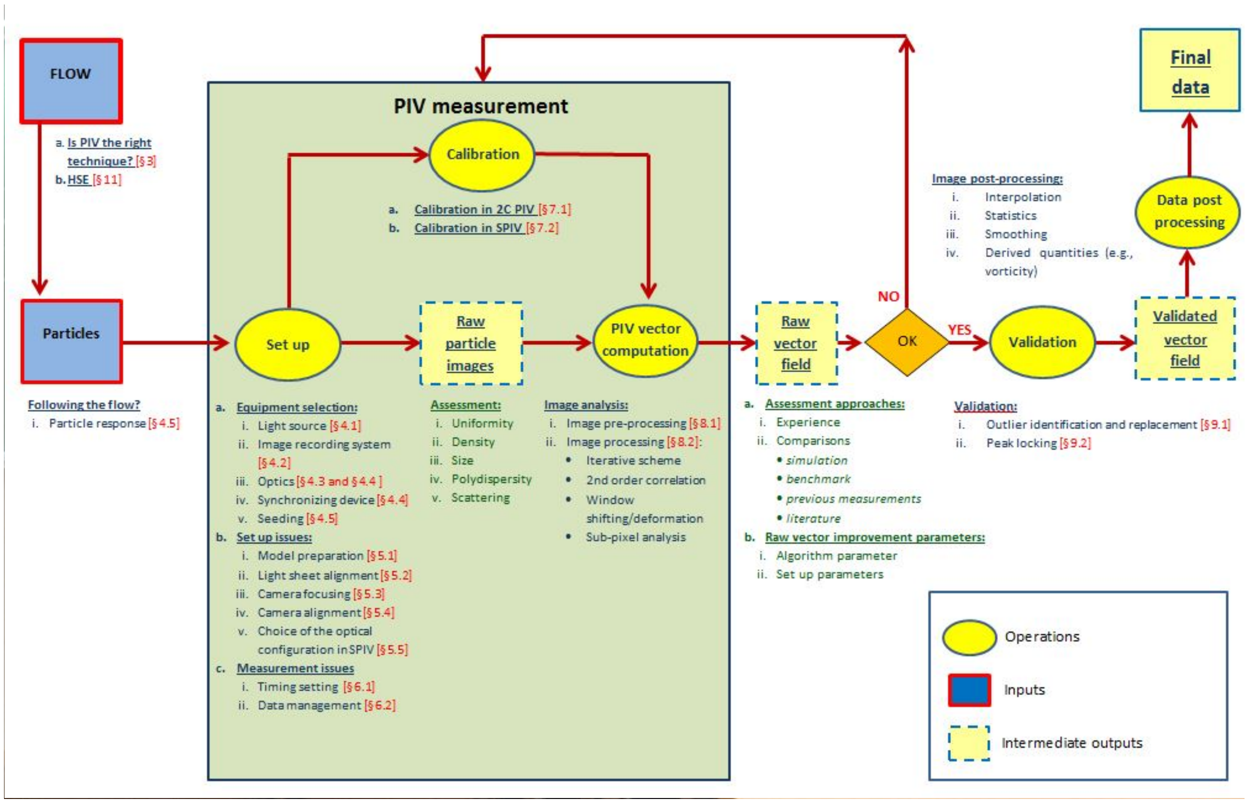
- Proper applications of PIV/SPIV in large-scale hydrodynamic facilities remain non-trivial.
- Success generally requires experience, training and, in some cases, advice from experts.
- Dedicated literature (i.e. books, papers) is often too theoretical, lacking in practical advice and, in many cases, ineffective in dealing with practical issues.

Objectives

- Provide recommendations and “best practices” to support the design and conduct of a PIV/SPIV experiment
- Targets a range of practitioners, especially those still developing their expertise
- Help users avoid “beginner’s errors” and obtain good quality results when employing PIV/SPIV techniques
- Places strong emphasis on rules of thumb and examples and resorts to formulas and theoretical explanations only as necessary

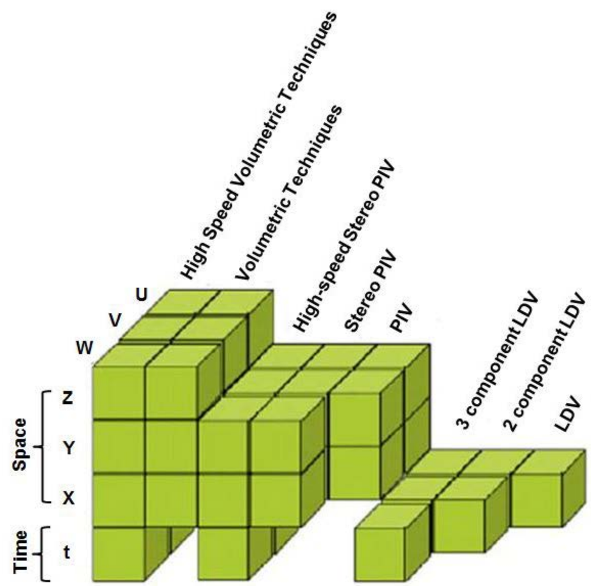
Background

- Numerous steps in performing a PIV/SPIV measurement are described.



Method Selection

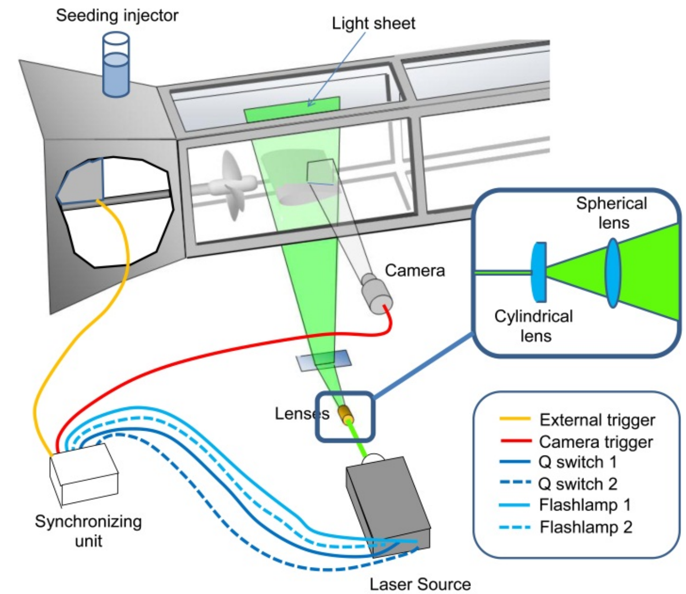
- PIV/SPIV is not always the most appropriate technique to use. The guideline provides a discussion on how to select the right flow-measurement technique for a given application.

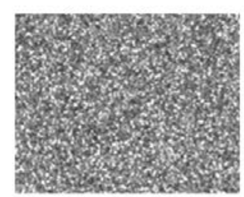


Measurement matrix for various flow measurement techniques (Hinsch, 1995)

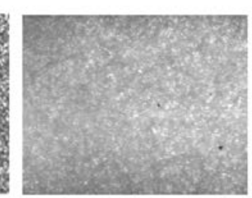
Best-Practice Guideline Organization (I)

- Measurement method selection
- Equipment selection
  - lasers, cameras, optics, etc
- Setup issues
  - Model preparation
  - Light sheet adjustment
  - Camera alignment and focusing
  - Choice of SPIV configuration
  - Seeding

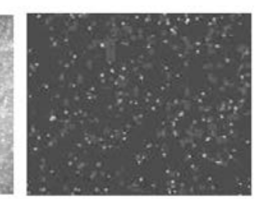




Optimum



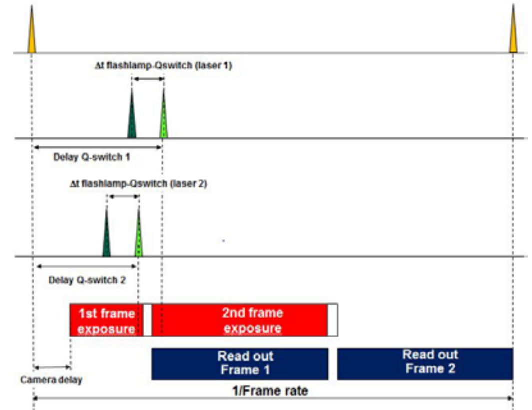
Out-of-focus



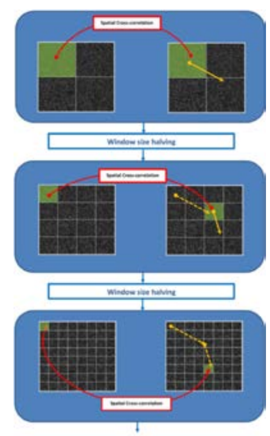
Low density

Best-Practice Guideline Organization (II)

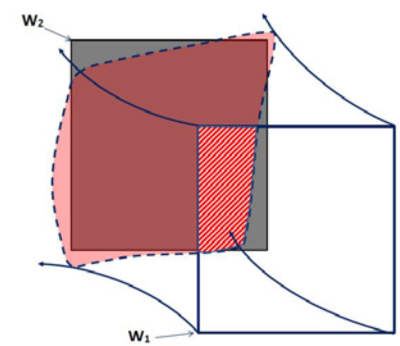
- Measurement issues
  - Timing setting
  - Data management
- Calibration
  - 2C PIV
  - 3C SPIV
- Image analysis
  - Image pre-processing
  - Image processing



A typical PIV timing diagram



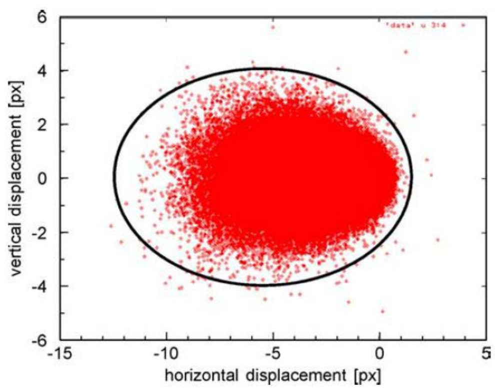
Iterative window offset correlation

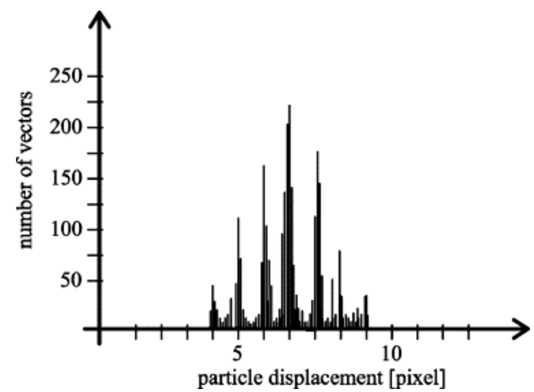


Iterative window deformation

Best-Practice Guideline Organization (III)

- Vector validation
  - Outlier identification/replacement
  - Peak locking





- Specific problems for different facilities
- Safety issues

Experimental Benchmarks for PIV (2C) and SPIV(3C) Setups (7.5-01-03-04)

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Scope

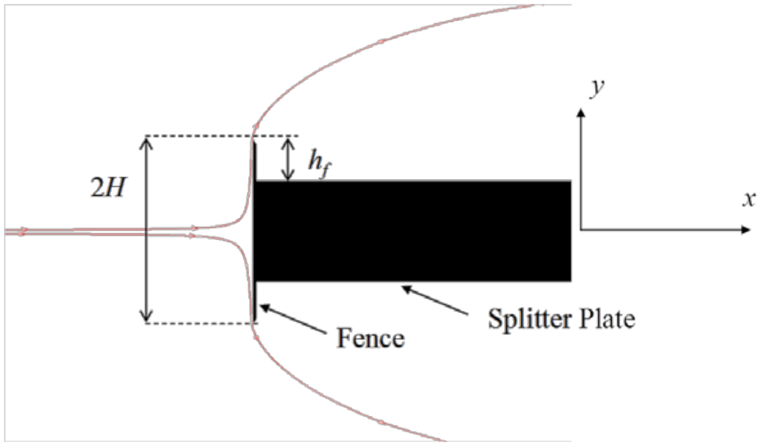
- An organization may be acquiring a PIV system and would like to evaluate it on a simple known flow.
- An organization has acquired a PIV system and is in the process of learning the system or need to train test personnel in using the system.
- An organization needs to evaluate the performance of an existing PIV system to ensure that it meets industry standard and customer performance criteria.

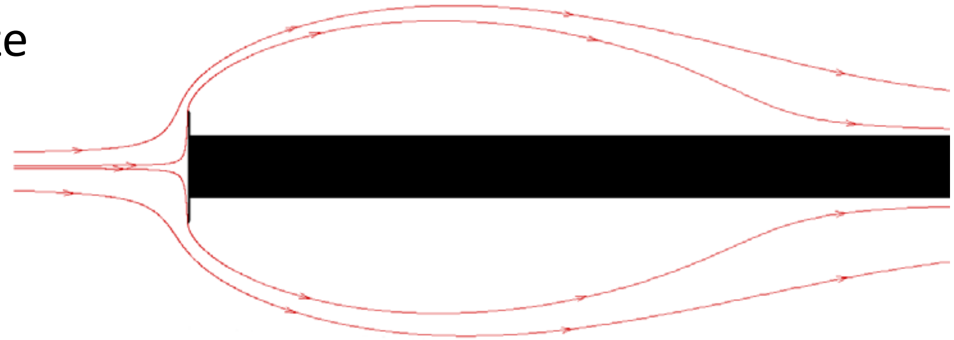
Objectives

- Simple and cheap experimental setup to be used during any test campaign in the facility
- Detailed specifications to assure a high repeatability test among the partners
- Minimize the time for the test setup would incorporate into a scheduled measurement program. Test setup would require approximately an extra 2 hours.
- Measurements performed in 1 or 2 repetitions
- Test case representative of typical PIV setup and the issues associated with these setups
- The possibility to exchange and compare images and velocity data

2C PIV Benchmark Tests

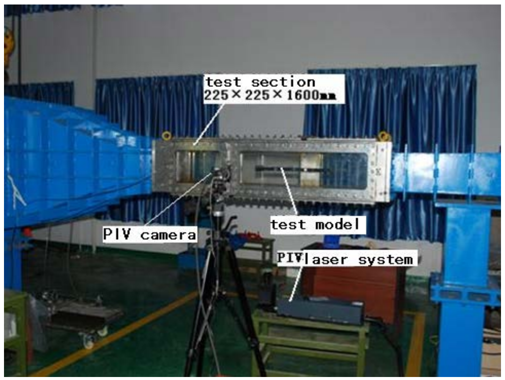
- Splitter Plate: separating-reattaching flow around a splitter plate with a fence
  - Flow separation regions
  - Vortical flow structures
  - Relatively insensitive to small Re # changes or manufacturing imperfections
  - Simple geometry
  - Studied numerically to optimize the design



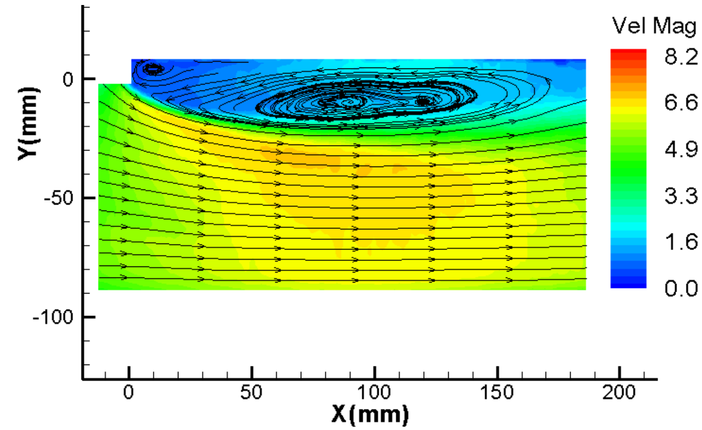


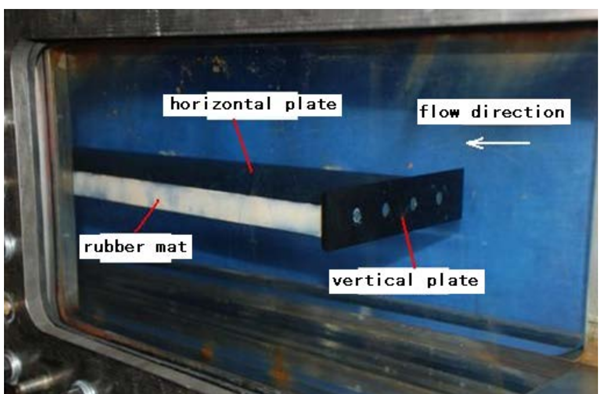
2C PIV Benchmark Results

- Experiments performed at CSSRC

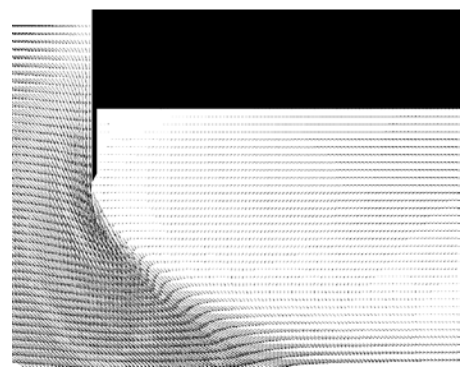


PIV Results





CFD Results

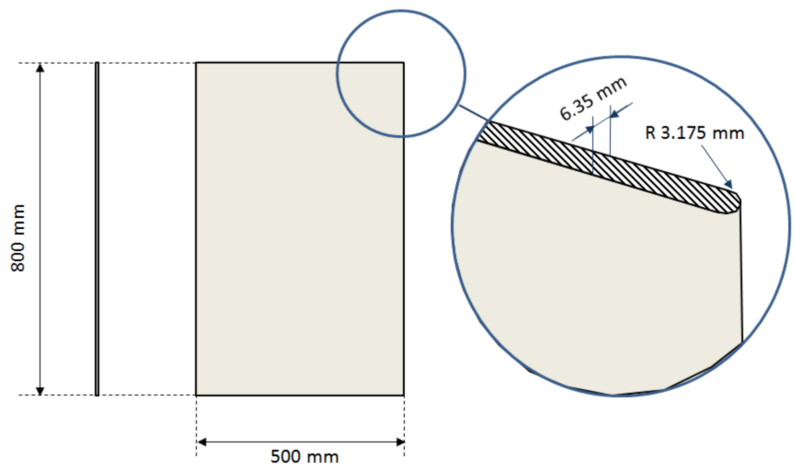


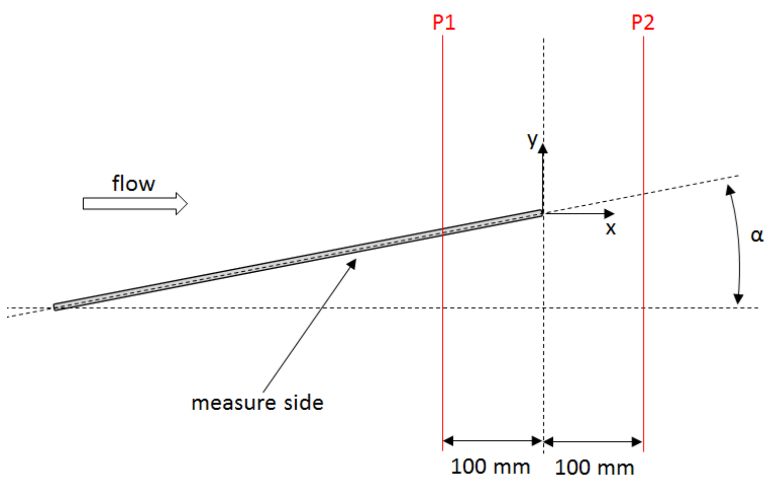
3C SPIV Benchmark Tests

- Piercing surface flat plate operating at incidence: devised by the European Network of Excellence Hydro Testing Alliance (HTA)
  - should be representative of the major critical issues of SPIV measurements in towing tanks or circulating water channels, such as high velocity gradients, surface effects, presence of air bubbles and reflections
  - should represent a simple and cheap experimental setup that can be adapted to the multitude of facilities

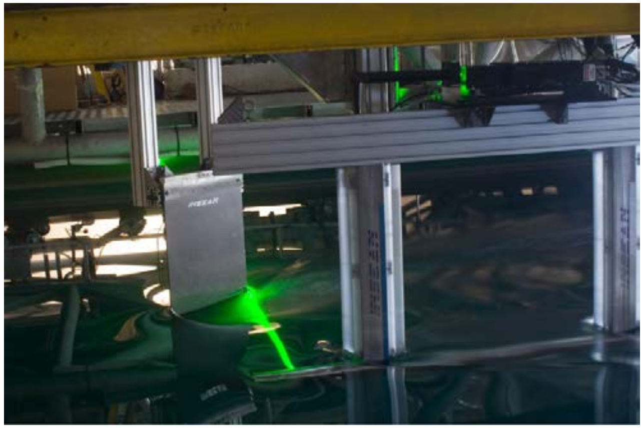
3C SPIV Benchmark Geometry

- Piercing Flat Plate
  - Steel rectangular plate 500x800x6.35 mm
  - 3.175mm radius rounded leading and trailing edges
  - 2 measurement planes

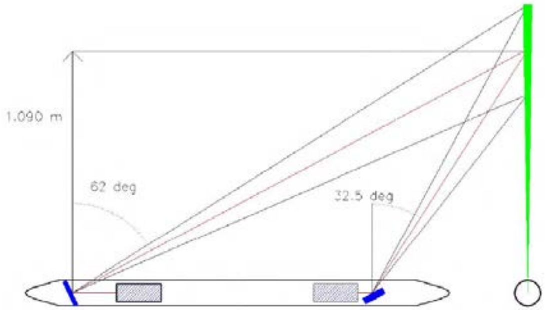




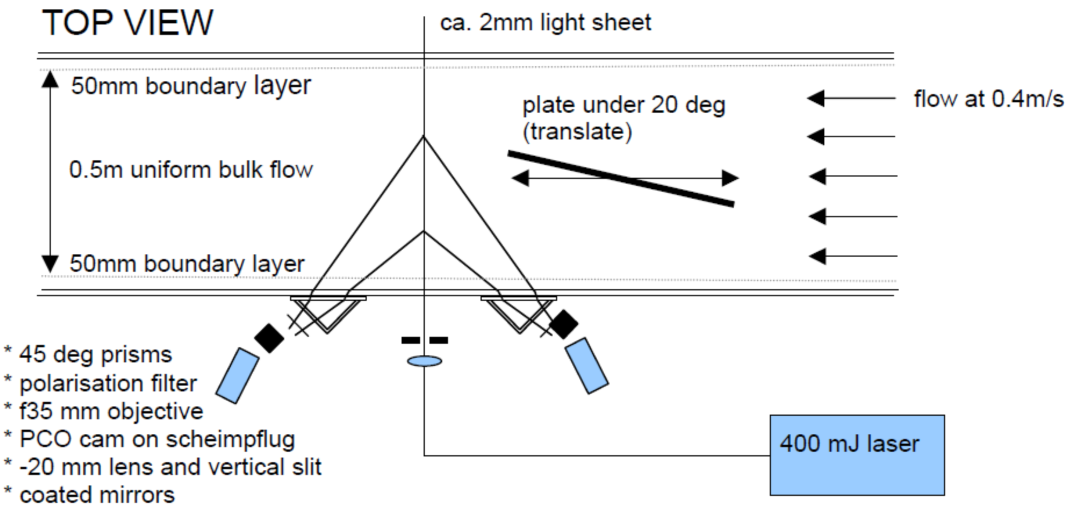
SPIV configurations



INSEAN Towing Tank

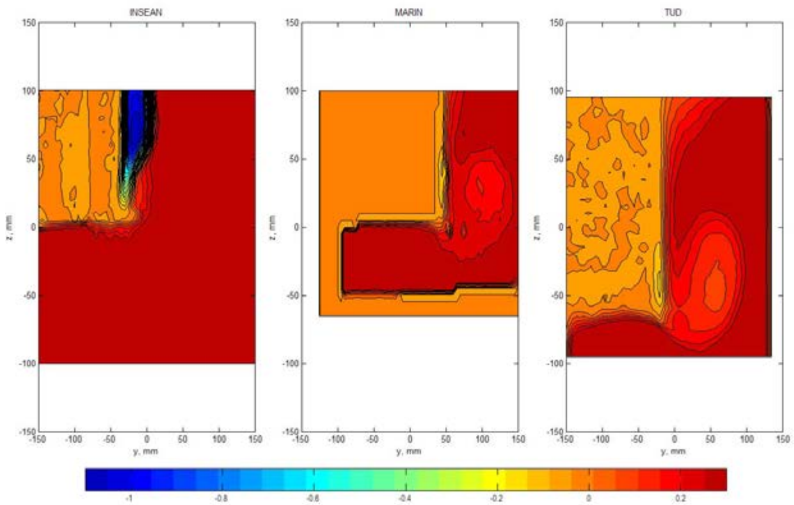


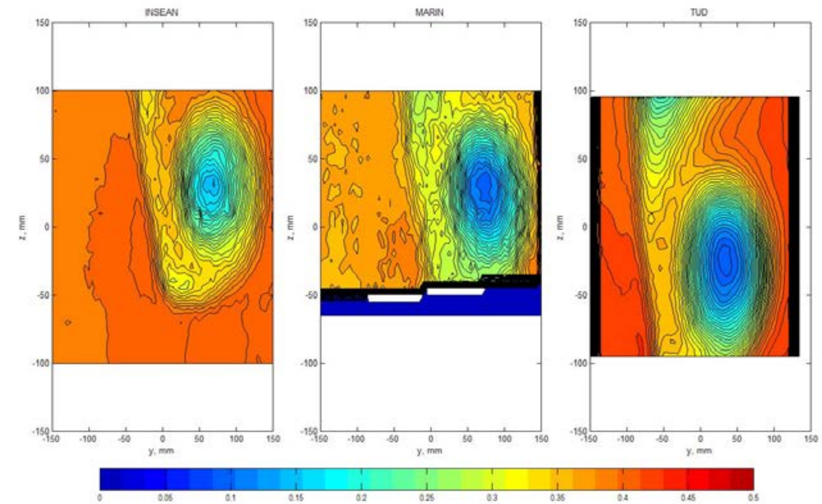
MARIN Towing Tank



Circulating Water Tunnels or Cavititation Tunnels. Figure is from TUDelft

3C SPIV Benchmark Results





U velocity contours at the P1 plane.

U velocity contours at the P2 plane.

The order of images (from left to right) is INSEAN, MARIN and TUDelft.

Benchmark Organization

- It is recommended that an ITTC member organization or organizations coordinate as the organizer of the benchmark test
- Organizer should provide clear instructions for performing the benchmark. This includes details such as the models to be used, measurement conditions, measurement parameters, final data delivery.
- Organizer should disseminate information pertaining to the benchmark tests to member organizations and organizing their participation.
- Organizer should collect, quality control, and store all benchmark data from participating organizations in a single repository that is accessible to all member organizations. Ideally, one organization would be tasked with hosting the benchmark data from participants.

Guideline on the Uncertainty Analysis for Particle Image Velocimetry (7.5-01-03-03)

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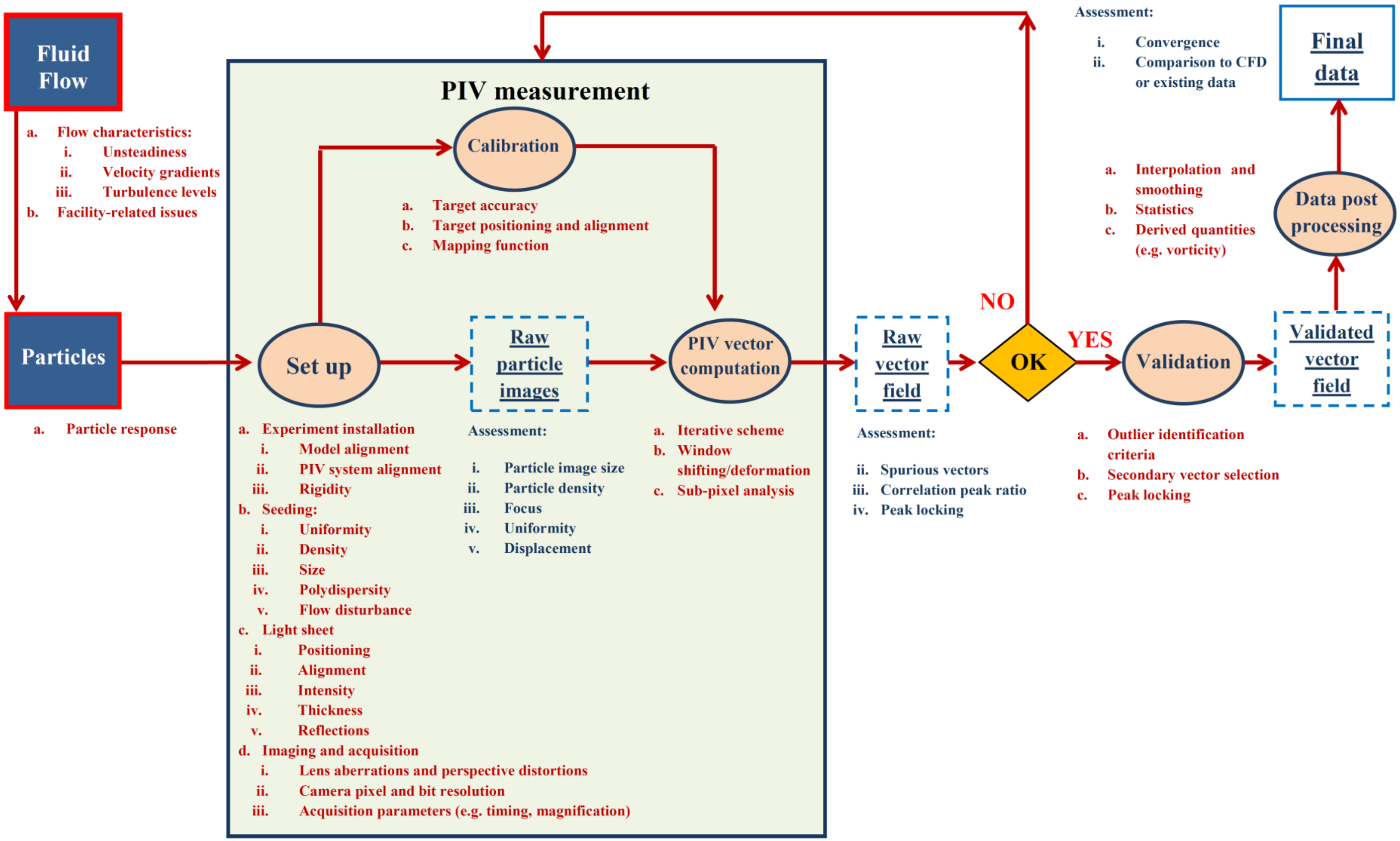
Scope

- Measurement uncertainty analyses have been
  - mostly isolated to the improvement of algorithms
  - scarcely involved in an actual PIV setup in a large facility
- Evaluation of the overall system performance and uncertainty level of an entire PIV system …
  - … may indeed appear daunting.
  - Even a few error sources require a fair level of effort.
  - How to capture the system uncertainty in a realistic way ?

Objectives

- To outline a method of analysis of the measurement uncertainty for particle image velocimetry (PIV) and stereo PIV (SPIV) for a realistic setup
- Error sources involved:
  - error sources inherent to the PIV technique itself
  - error sources due to practical issues:
    - suboptimal seeding
    - improper light sheet overlap
    - large velocity gradients in the interrogation regions
    - in-plane and out-of-plane loss of particles between the image pairs

PIV Uncertainty Sources



Approaches for PIV uncertainty analysis (I)

- Goal of experiment → appropriate level of UA
  - Qualitative phenomenology vs. Absolute quantification
- Levels of error sources:
  - Level 0 : sources inherent to PIV technique
  - Level 1 : error sources inherent to the particular setup (suboptimal seeding, improper light sheet overlap, etc.)
  - Level 2 : error sources inherent to the flow of interest (large velocity gradients, in-/out-of-plane loss of particles)

Approaches for PIV uncertainty analysis (II)

- Three categories of UA methodology:
  - #1. Component error estimation approach
  - #2. System-level approach using a simulated PIV setup and synthetic images
    - possible to analyse flow-based errors and image-based errors
  - #3. System-level approach using the actual physical PIV setup
    - limited to simple flows, such as uniform flow
    - Ex) the PIV system can be towed through quiescent fluid (without test model) and results compared with an assumed uniform flow.

Approaches for PIV uncertainty analysis (III)

- #1. Component error estimation approach
  - General data reduction equation & related uncertainty

$$r = r(X_1, X_2, \dots, X_j),\ U_r^2 = \left(\frac{\partial r}{\partial X_1}\right)^2 U_{X_1}^2 + \left(\frac{\partial r}{\partial X_2}\right)^2 U_{X_2}^2 + \cdots + \left(\frac{\partial r}{\partial X_j}\right)^2 U_{X_j}^2$$

  - Typical data reduction equation for PIV

$$u = M(\Delta X/\Delta t) + \delta u$$

    - ΔX represents the displacement of the particle (cross-correlation)
    - Δt is the time interval between successive images
    - M is the magnification factor
    - δu is additional errors due to particle lag and the projection procedure from the 3-D physical space to the 2-D image plane

Approaches for PIV uncertainty analysis (IV)

- #1. Component error estimation approach
  - Error sources which could be effectively analysed:
    - Particle lag in the presence of flow acceleration
    - Timing error from the delay generator and laser
    - Experimental installation and other facility-related Issues:
      - misalignment of the model (causing a different flow than the desired one)
      - precision of speed control (leading to error in the reference velocity)
      - blockage effect or other facility bias (affecting the flow of interest)

Approaches for PIV uncertainty analysis (V)

- #2. Using a Simulated PIV Setup and Synthetic Image
  - Typical procedures in the previous researchers
    - The first image is a random distribution of particles.
    - With a known flow field, the second image is generated by advecting the particles from the first image.
    - The synthetic image pair is used as an input to the PIV algorithm, and the vector field is calculated and compared to the known solution.
    - Either simplified PIV setup and simple canonical flows (uniform flow, shear flow, rotational flow, isotropic turbulent flow, etc) can be used.
    - The goal is to reach general conclusions on the effects of the parameters of interest and not to evaluate the uncertainty level of a realistic setup.

Approaches for PIV uncertainty analysis (VI)

- #2. Using a Simulated PIV Setup and Synthetic Image
  - Modelling of a realistic PIV setup
    1. Selection of a known flow: from canonical flows (for Level 1 errors) to the flow of interest itself (for Level 2 errors) using the CFD solution
    2. Particle field: a uniformly distributed field with a certain size range
    3. Illumination field: modelled using varying degrees of realism
    4. Particle image intensity distribution: modelled using a Gaussian intensity profile
    5. 2D imaging system: modelled as $(x, y) = M * (X, Y)$,
       SPIV imaging system: Scheimpflug mechanism and index of refraction step changes in underwater PIV (Appendix A)
    6. Image recording: pixelization of a continuous distribution of imaged light onto a discrete light-sensitive sensor array
  - Comparison between the synthetic images with the actual images obtained by the physical setup

Approaches for PIV uncertainty analysis (VII)

- #3. Using the actual physical PIV setup
  - In a tow tank, the PIV system can be towed at a known velocity in quiescent fluid to generate a uniform flow.
  - The cavitation tunnel can be operated at a steady speed with no model present.
  - This technique represents a good way to baseline the performance of the system in an idealized situation but cannot capture error sources such as those arising from a complex flows and practical issues such as non-optimal seeding.

Assessment of the Overall Uncertainty

1. Perform component error estimation for components such as particle lag and timing error
2. Perform Monte Carlo simulations to evaluate the uncertainty of the system using the simulated PIV setup
3. Repeat step (2) with a simplified flow reliably duplicated with the physical PIV setup
4. Perform a physical measurement of the simplified flow to determine the baseline uncertainty level of the physical system
5. Difference between (3) and (4) provides a good estimate for the modelling error of the simulated setup
6. Propagate the different sources of uncertainties from (1), (2), and (5) into the overall uncertainty of the system

Summary

Conclusions

- The committee has compiled a set of recommendations and "best practices" into a guideline for the design and implementation of PIV experiments in large-scale hydrodynamic facilities.
- The committee has proposed two experimental benchmark cases (2C and 3C) for the purpose of verifying the quality of the measurement setup.
- The committee has outlined a method of analysis of the measurement uncertainty for particle image velocimetry (PIV) and stereo PIV (SPIV).
- Much work remains in the development of process and procedures in using detailed flow measurements for the validation of CFD codes.

Recommendations to the Conference

- Adopt the best practice guideline (7.5-02-01-04)
- Adopt the benchmark guideline (7.5-01-03-04)
- Adopt the uncertainty analysis guideline (7.5-01-03-03)

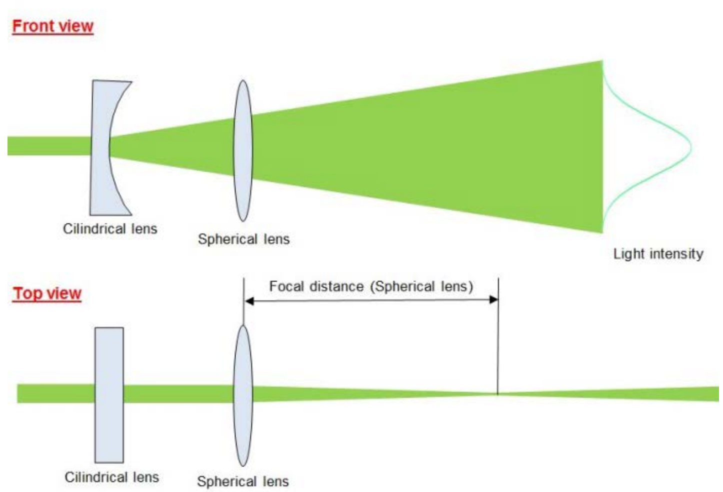
Future Work

- Perform a detailed evaluation and implementation of the best-practice, the benchmark, and the uncertainty analysis guidelines:
  - develop a questionnaire to collect feedback and inputs from the general ITTC community on how to refine and update the best-practice guideline
  - organize an electronic repository of information and data on the benchmarks cases
  - implement and evaluate the proposed uncertainty analysis approach in details

Extra Slides

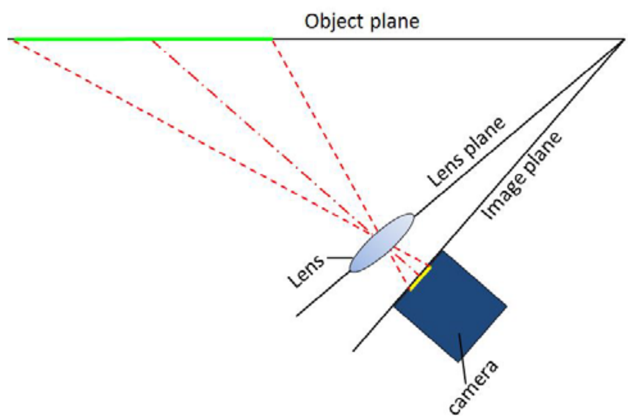
Equipment Selection

- The selection of the lasers, cameras, light-sheet optics, Scheimpflug mechanism, timing device, and seed particles are discussed, and guidance provided when possible (laser power, camera resolution and sensitivity, and seed particle size and density).



A typical light-sheet optics arrangement

Equipment Selection



The Scheimpflug condition

	Nominal mean diameter [μm]	Size range [μm]	Density [g/cm³]	Shape
hollow glass spheres	9	<7 (10%), <25(97%)	1.10± 0.05	Spherical
Silver coated solid glass spheres	9	4-12	2.5	Spherical
Silver coated hollow glass spheres	14	<7 (10%), <21(90%)	1.4	Spherical
Polyamide seeding particles	5 20 50	1-10 5-35 30-70	1.03	Non-spherical but round
Fluorescent polymer particles	10 30	1-20 20-50	1.19	Spherical

Seed particle selection

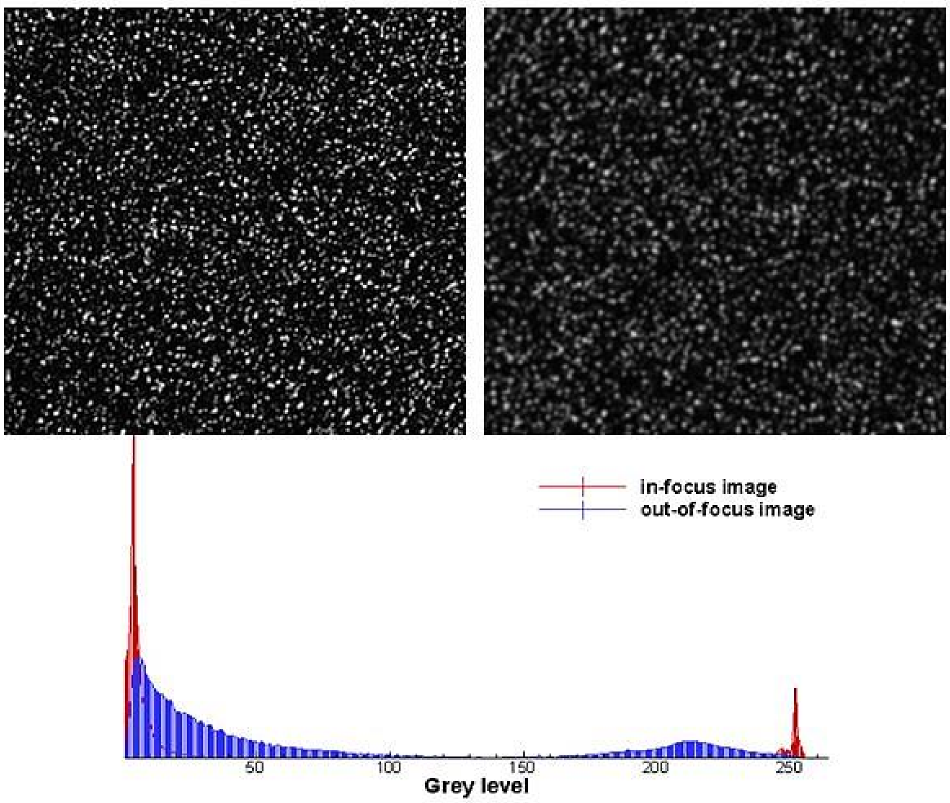
Setup Issues

- Important considerations in setting up a good PIV/SPIV experiment are discussed in details.
  - Model preparation
  - Light sheet adjustment
  - Camera alignment and focusing
  - Choice of SPIV configuration
  - Seeding

Setup Issues

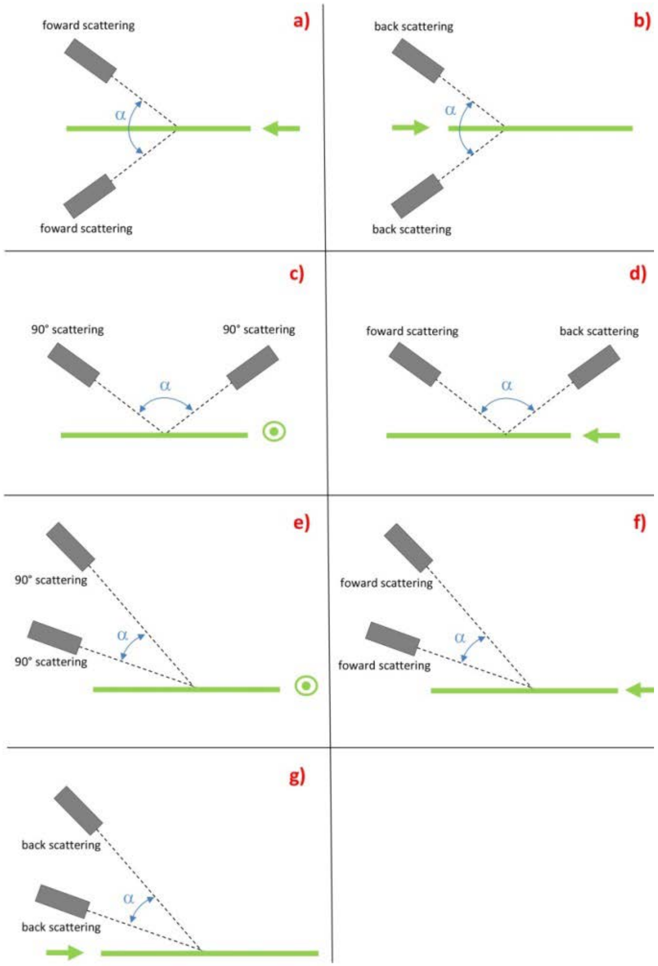
Use of Perspex in order to avoid light reflection

Setup Issues



Adjustment of the camera focus by the examination of the grey level distribution

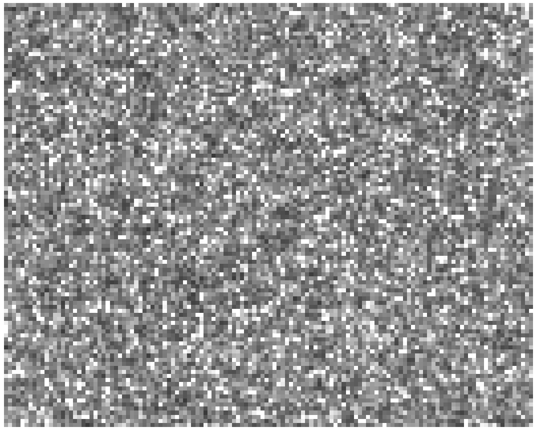
Setup Issues



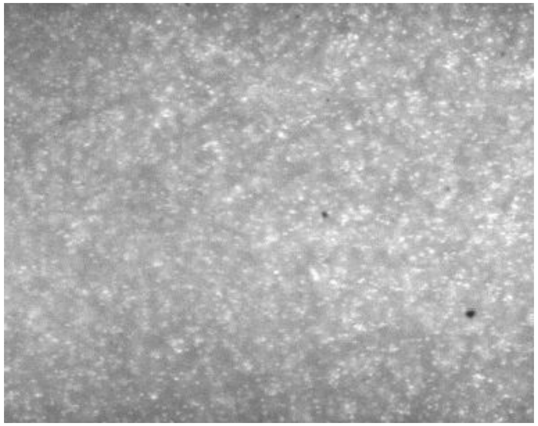
Choice of SPIV configuration

Setup Issues

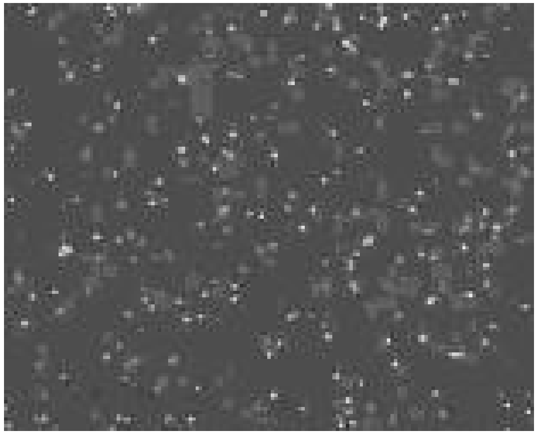
- Examples of particle images are provided.



Optimum

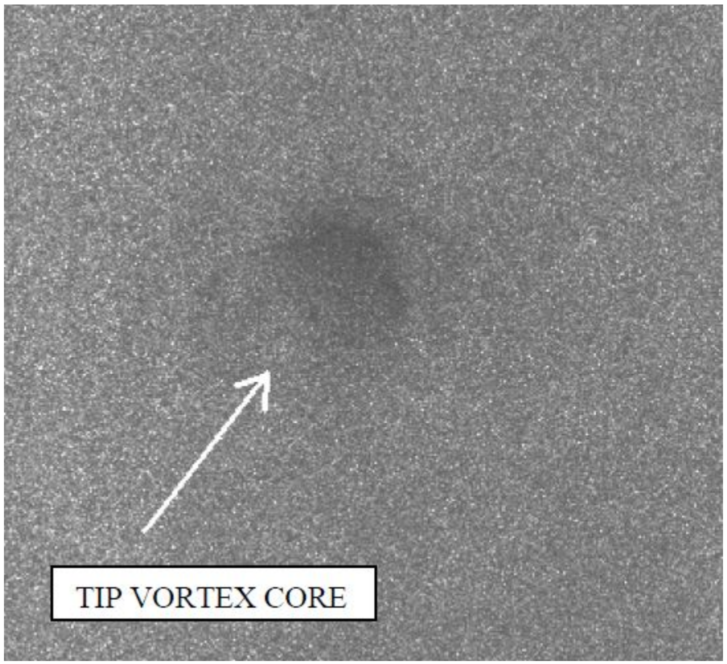


Out-of-focus



Low density

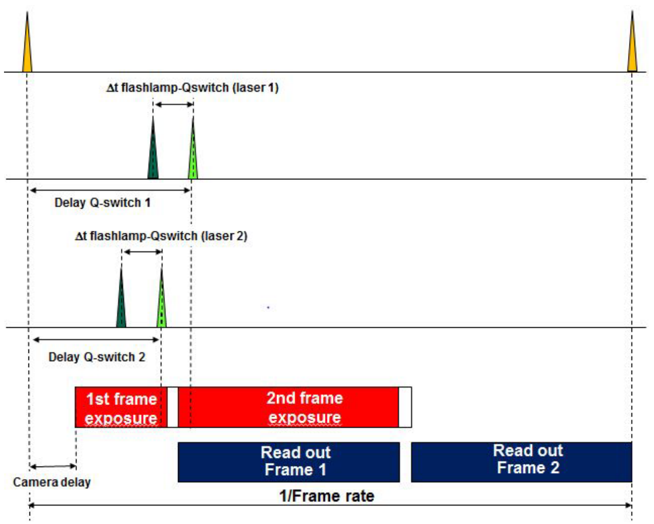
Setup Issues



Example of an otherwise optimal seeding which is negatively affected by the high shear region inside a vortex core

Measurement Issues

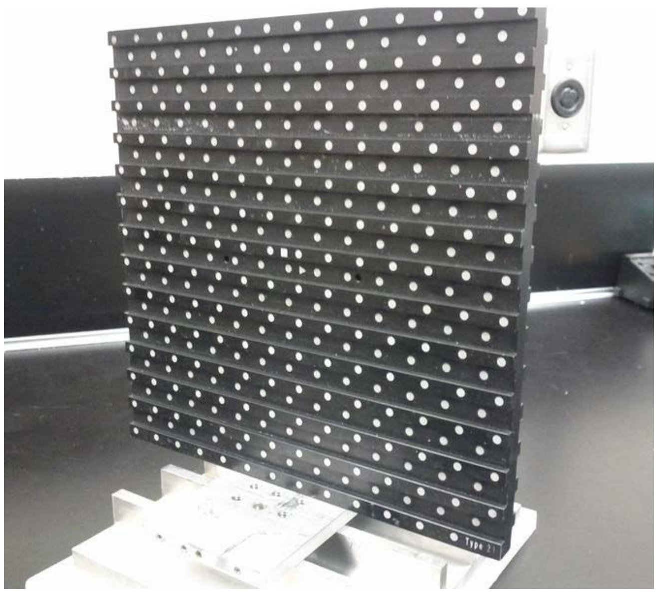
- Measurement issues such as the selection of an appropriate dt to maximize in-plane signal-to-noise ratio while keeping out-of-plane loss of particles to an acceptable level are discussed.



A typical PIV timing diagram

Calibration

- Calibration for 2C PIV and 3C SPIV and important issues in regards to alignment of target and laser sheet are discussed.

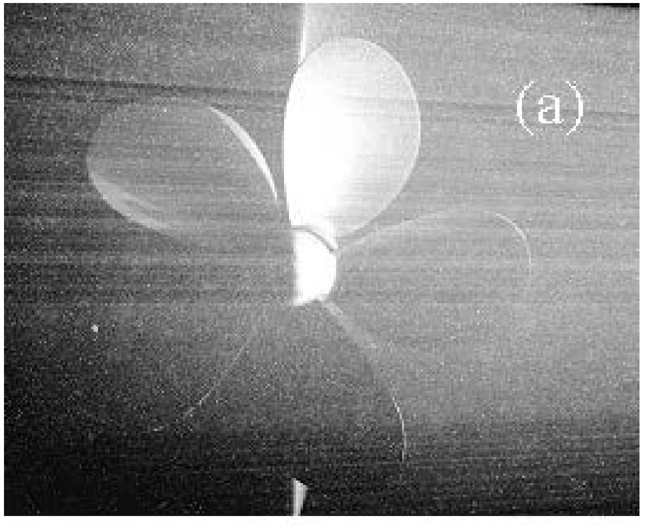


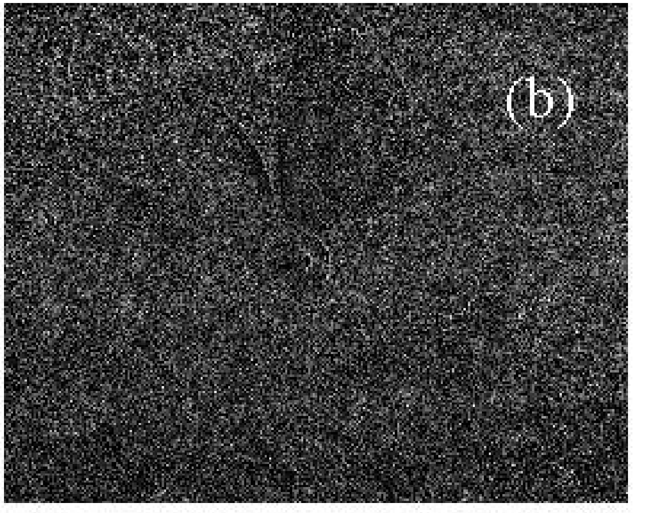
A double-plane-double-side type SPIV calibration target

Image Analysis

- Important considerations in performing high-quality PIV/SPIV image analysis are discussed in details.
  - Image preprocessing
  - Image processing
    - Selection
    - Spatial correlation analysis
      - Non-square interrogation window
      - Window weight function
      - Window offset correlation
      - Iterative window deformation
      - Window overlap

Image Pre-processing





a) original image

b) pre-processed image by background removal

(Felli et al., 2002)

Image Processing

- The selection of the interrogation domain should be performed such that:
  - Each sub-domain contains at least 10 particle images on average .
  - The in-plane displacement is limited to about ¼ of the sub-domain size.
  - The displacement differences between neighboring sub-domains is less than 3-5% of the size of the interrogation region.

Image Processing

- Spatial correlation analysis calculates the displacement vector by Fast Fourier Transform (FFT) to obtain the correlation peak between the sub-domains from the first and second image.

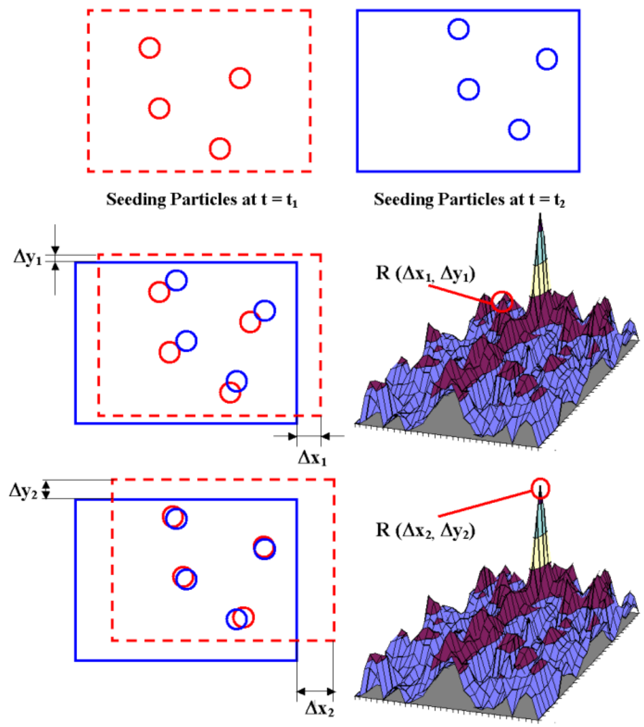
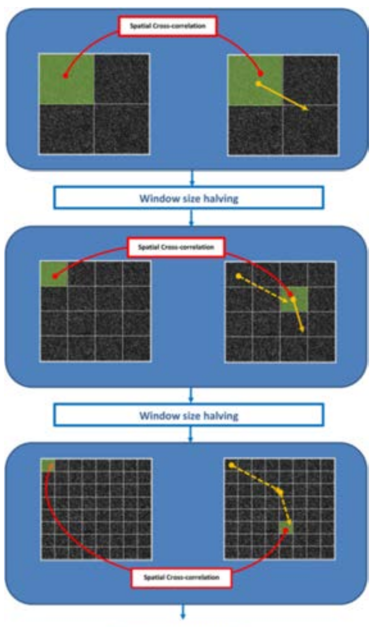
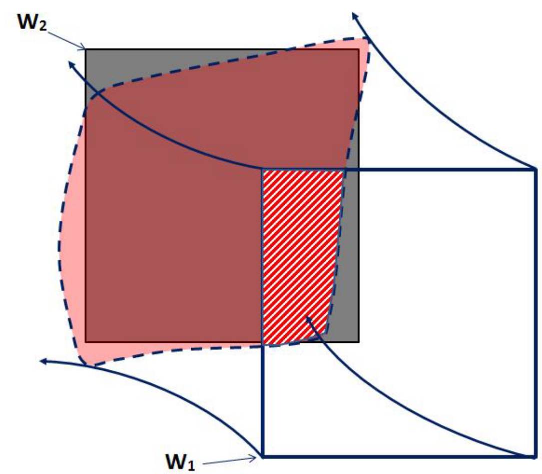


Image Processing

- Special methodologies that are now routinely used in the spatial correlation analysis include non-square interrogation window, window weight function, window offset correlation, iterative window deformation, and window overlap.



Iterative window offset correlation



Vector Validation

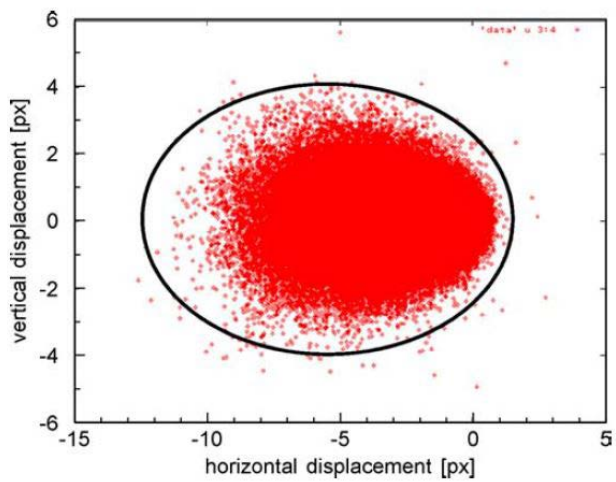
- Vector validation is the process of detecting and removing "spurious" vectors whose occurrence is inevitable even in carefully designed experiments.
- Many criteria are now routinely used in commercial software:
  - Local median-filtering criterion
  - Cross-correlation signal-to-noise ratio validation criterion
  - Displacement range validation criterion
  - Geometric validation criterion

Typical Vector Validation Process

- Determine the mean and standard deviation over the whole field.
- Remove vector if its magnitude differs from the global mean by more than three standard deviations.
- Calculate a representative value of the neighboring vectors and discard all the vectors that fall too far away from the median.
- Look at the second and third tallest correlation peaks to check if one of them agrees with the neighborhood mean better than the first
- Use post-validation histogram to detect any remaining outlier and spurious data.
- Interpolate over holes in the data that cannot be filled by the preceding steps.
- Repeat the procedure until data converges.

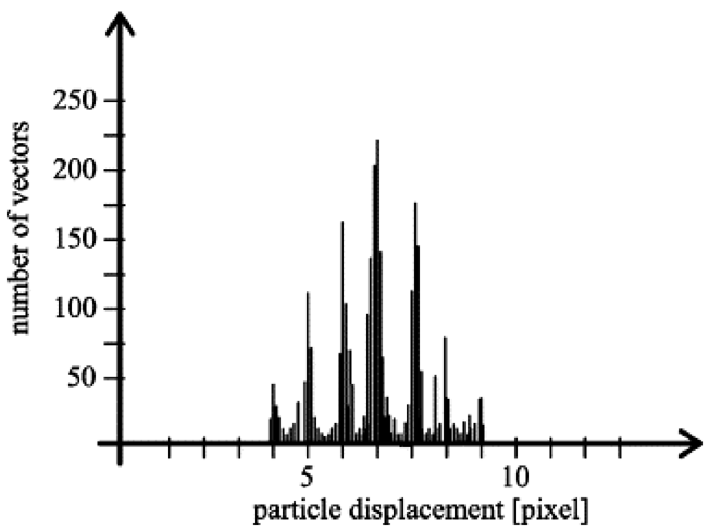
Post-Validation Histogram

- Provides a visual mean to detect outliers and spurious data.
- Rigorous criteria can be applied (such as Chauvenet's criterion)



Peak Locking

- Peak locking (or “Pixel locking”) is one of the most significant errors associated with a PIV measurement and consists of the biasing of particle displacements toward integer pixel values.
- Peak locking occurs when particle images are on the order of a pixel.
- To minimize the effect of pixel locking, the particle image diameter should be at least 3-5 pixel (Prasad et al., 1992).



Other Issues

- Practical issues associated with applications of PIV/SPIV in large-scale hydrodynamic facilities:
  - Tow tanks
  - Flow tunnels
  - Other facilities such as maneuvering and seakeeping basins or field use
- Safety issues:
  - Laser radiation
  - Electrical hazard
  - Trip hazard
  - Respiratory hazard (seed particles)

Approaches for PIV uncertainty analysis (VIII)

- #2. Using a Simulated PIV Setup and Synthetic Image
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    3. Illumination field : modelled using varying degrees of realism.
    4. Particle image intensity distribution : modelled using a Gaussian intensity profile

$$I(x,y,z) = I_o exp\left[\frac{-(x-x_o)^2-(y-y_o)^2}{(1/8)d_\tau^2}\right],\ I_o(x,y,z) = q * I_{illum}(X,Y,Z)$$

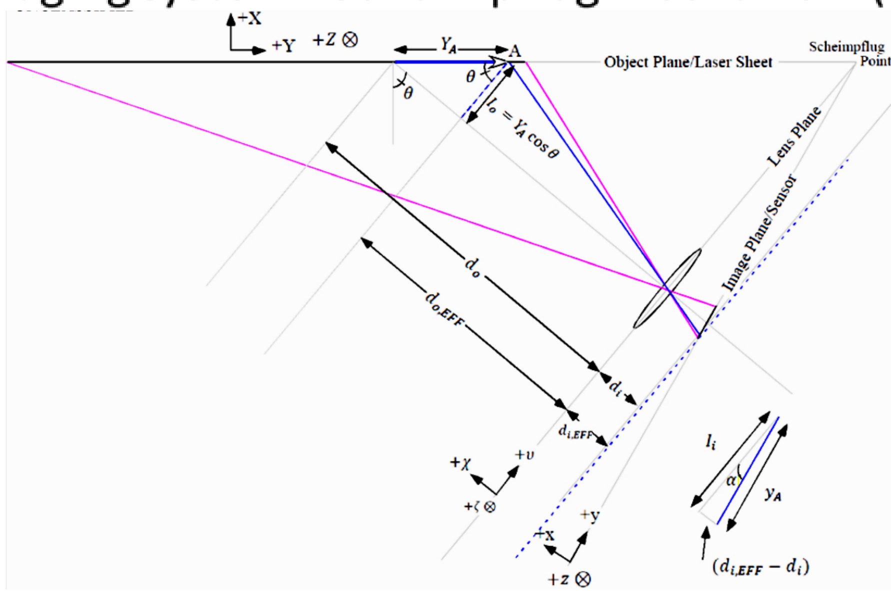
$$d_\tau = \sqrt{(Md_p)^2 + d_{diff}^2},\ \ d_{diff} = 2.44 f_{\#}(M+1)\lambda$$

Approaches for PIV uncertainty analysis (IX)

- #2. Using a Simulated PIV Setup and Synthetic Image
  - Modelling of a realistic PIV setup

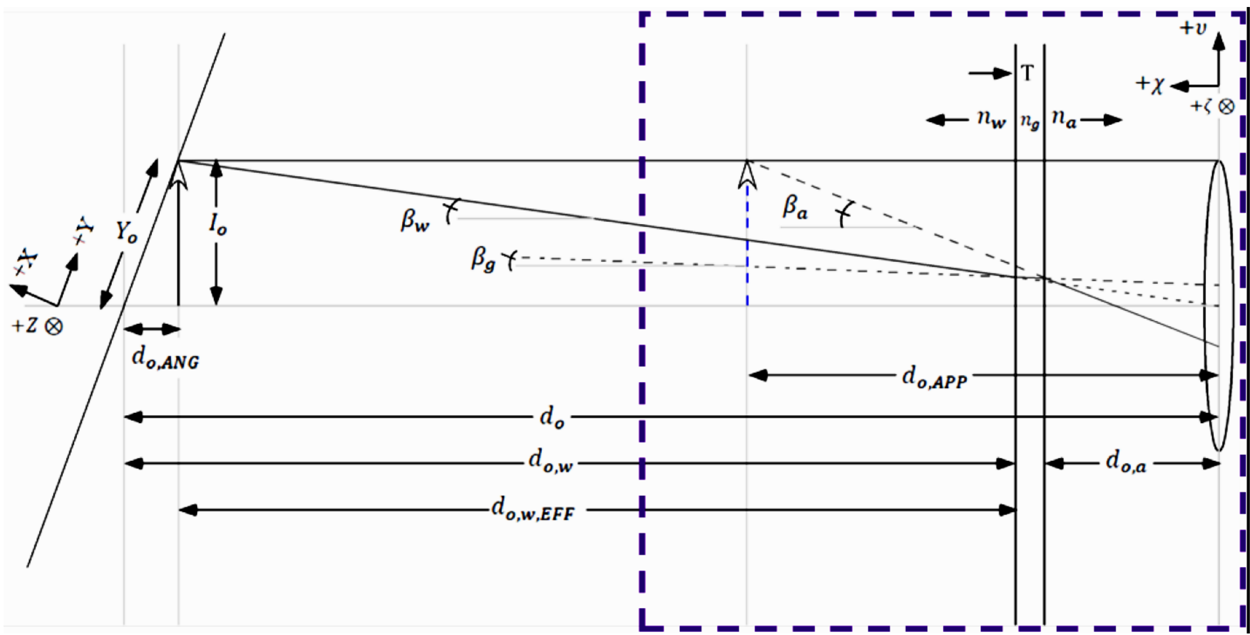
    5. 2D imaging system : modelled as $(x, y) = M * (X, Y)$,

       SPIV imaging system : Scheimpflug mechanism (Appendix A)



Approaches for PIV uncertainty analysis (X)

- #2. Using a Simulated PIV Setup and Synthetic Image
  - Modelling of a realistic PIV setup
    5. Index of refraction step changes in underwater PIV (Appendix A)



Approaches for PIV uncertainty analysis (XII)

- #2. Using a Simulated PIV Setup and Synthetic Image