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Benchmark testing for PIV (2 component) and Stereo PIV (3 component) setups

1. PURPOSE OF PROCEDURE

The purpose of this procedure is to continue the establishment of a benchmarking test for PIV/SPIV setups that was initially proposed in the 26th ITTC. Specifically, this procedure will define a set of criteria that a benchmark test must adhere to and propose two test cases; one for 2C PIV and one for 3C PIV.

2. SCOPE

One area that is critical towards facilitating the adoption of detailed flow measurements is the availability of benchmark data for the purpose of verifying the quality of the measurement setup. The primary purpose of using these benchmark cases is to ensure that the measurement system and the configuration of the cameras and light sheet meet specifications and also to give an indication to the new user of the PIV technique of how successful the measurement technique has been implemented. Further, the availability of benchmark data provides the new user with the ability to evaluate and compare their measurement setup with other established institutions.

Thus the situations in which a benchmark test may be advantageous to an institution/organization are:

- 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.

3. BENCHMARK OBJECTIVES FOR THE VERIFICATION OF PIV/SPIV SETUP

The main objectives of a benchmark test are:

- 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 hour.
- 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.

Recognizing again that potential applications for PIV are wide ranging and would concern practitioners of various levels of knowledge and experience, the committee is proposing two distinct benchmark cases. The first benchmark case utilizes a two-component PIV system on a simple 2D geometry. The second benchmark test uses an SPIV system on a more complex 3D flow field that has been established by the European Network of Excellence Hydro Testing Alliance (HTA).

One of the key aspects of establishing a benchmark test is the ability to disseminate the data from various institutions and organizations from the tests. This implies that all relevant aspects of the test must be made available to any member organization partaking in the benchmark tests. Of specific interest are the PIV images obtained during the tests, as well as processed results, such that participants can not only compare their own images, but also their PIV processing algorithms on other image sets. Thus, a repository for the benchmark data has to be established.

Due to the inherent differences between a 2C and an SPIV (3C) setup, two different benchmark tests are proposed.

4. PIV BENCHMARK SETUP

4.1 2C PIV Setup Benchmark

A simple 2D benchmark case, based on the experiment performed by Hudy and Naguib (2003), is proposed for the purpose of the verification of the setup of 2D PIV systems.

A good benchmark case should include typical flow features found in marine hydrodynamics such as flow separation and vortex generation. At the same time, it should be easy to set up and should not be very sensitive to changes in flow conditions such as small change in Reynolds number or small manufacturing imperfection of the model. For these reasons, a separating-reattaching flow around a splitter plate with a fence is chosen as a candidate.

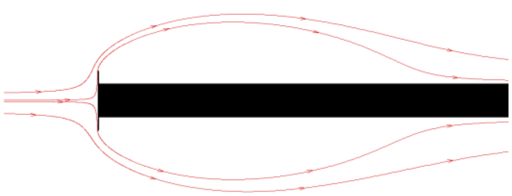

Figure 1 Flow around splitter plate with fence

Figures 1 and 2 illustrate the geometry and the flow. The fence height above the splitter plate (h_f) is 10 mm, and the total fence height ($2H$) is 40 mm. In order to assure two-dimensional flow, both ends of the plate and fence should either span the entire width of the test section or be attached to end plates of sufficient size. The influence of flow parameters and model geometry on the flow field was investigated using 2D RANS simulations with the commercial CFD code Fluent. The Reynolds number based on the fence height and the free stream velocity is 8000.

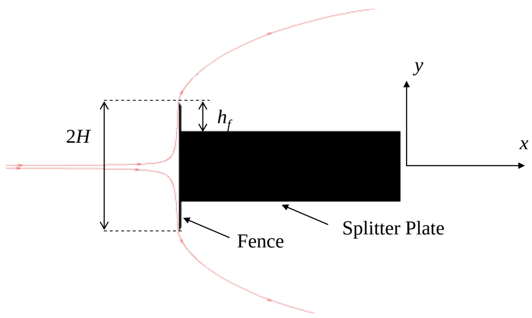

Figure 2 Geometry of the 2D benchmark

Over the course of the study, various tip geometries were examined, and the results show that the geometry illustrated in Figure 3 to be suitable.

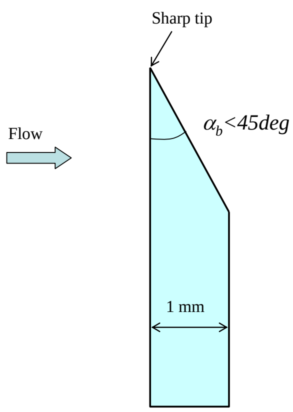

Figure 3 Detailed geometry of the fence

The front face of the fence is kept flat and perpendicular to the flow axis to create a stagnation flow before it detaches from the sharp tip.

Results show that if the backside is beveled less than 45 degrees, the flow is not sensitive to small variation in the bevel angle or the fence thickness. Velocity vectors near the fence are shown in Figure 4.

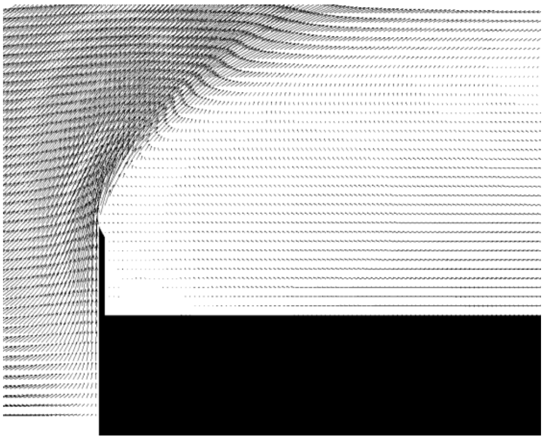

Figure 4 Velocity vectors around the fence

RANS simulations at Reynolds numbers of 16000, 8000 and 4000 were carried out and confirmed that the reattachment location does not change significantly with Reynolds number, making the flow relatively insensitive to small variation in tunnel speed and water properties.

The influence of the splitter plate length was also investigated. Because of the pressure gradient at the end of the splitter plate, the reattachment location was found to be weakly dependent on the splitter plate length. However, when the splitter plate length is more than 100 times the fence height above the splitter plate (h_f), the effect of the splitter plate length was found to be negligible.

This preliminary assessment is based on 2D steady RANS. The benchmark case has only been tested by one institution at the time of writing of this publication, CSSRC. The measurement was performed in their multi-function high speed cavitation tunnel as shown in Figure 5. The 2D benchmark test model is shown in Figure 6.

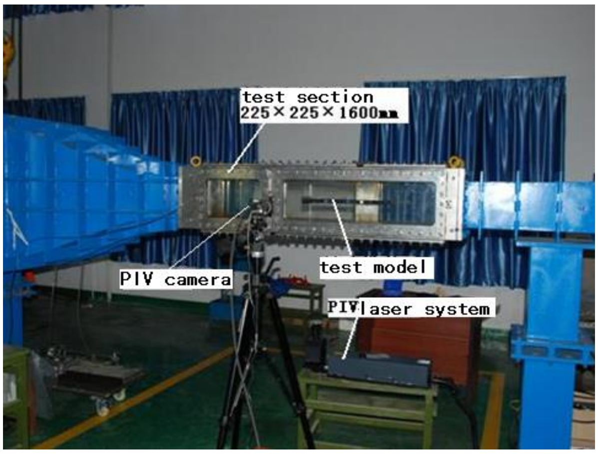

Figure 5: CSSRC multi-function high speed cavitation tunnel with PIV setup.

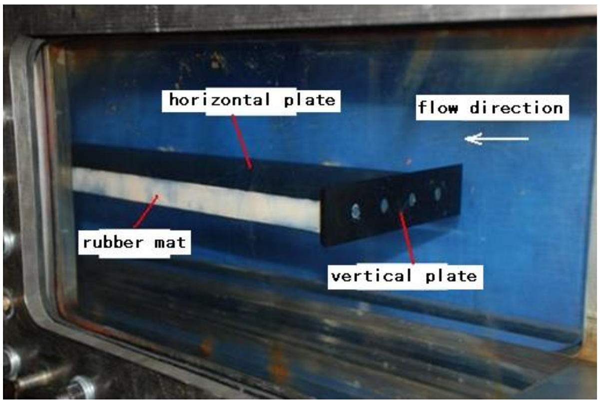

Figure 6: 2D benchmark test model fittied in the CSSRC facility shown in Figure 5.

A low speed 2D PIV setup was used, with data obtained at a sampling frequency of 2Hz. Appropriate care was taken with the laser power to avoid the over-saturation of the images. The average flow field, evaluated from 75 instantaneous measurements, is shown in Figure 7. It shows that behind the vertical plate there are two main vortex areas, one is a small clockwise vortex, another is a large counter clockwise vortex, and the velocity amplitude in the vortex area is low, but high in the external flow field. A shear layer region is visible between the vortex region and the outer flow field region, which makes the low speed vortex area “packaged” and attached to the horizontal plane.

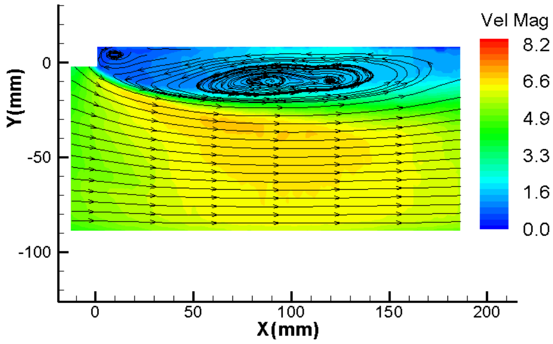

Figure 7: Experimental results from the CSSRC 2D benchmark study.

The 2C benchmark has only been performed at one institution, but participating institutions are invited to begin performing the benchmark tests, as test data from different facilities and experience gained from these experiments can be used to finalize the model tests specifications for the benchmark tests. Additionally, more detailed computations, possibly with URANS or LES are also needed to help with the benchmark model parameters.

4.2 Stereo PIV Setup Benchmark

A piercing surface flat plate operating at incidence is selected as the test case for SPIV benchmarking. This test case was devised by the European Network of Excellence Hydro Testing Alliance (HTA), and many of the HTA members have participated in its assessment. After consultations with the HTA working group, the Detailed Flow Measurement Techniques Committee has decided to recommend the HTA benchmark case as the ITTC benchmark case for SPIV configurations. In addition to the objectives stated earlier, the SPIV case:,

- 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;

Figure 8 shows a representative sketch of the piercing surface flat plate. The plate is a steel rectangular plate measuring 800 mm (L) x 500 mm (W) x 6.35 mm (H). Both leading and trailing edges of the plate have a round edge of 3.175 mm radius. The plate experiences some deformation when operating at incidence. It is therefore important to assure the plate deformation be repeatable in all the benchmarking exercises. In this regard, the benchmark case also specifies the geometry of the anchoring system, which consists of aluminum blocks held together by screws, as detailed in Figure 9.

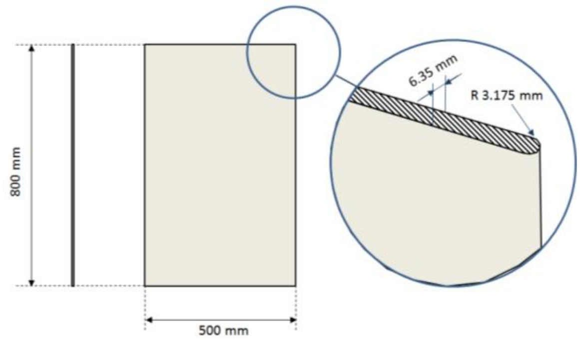

Figure 8 Flat plate geometry

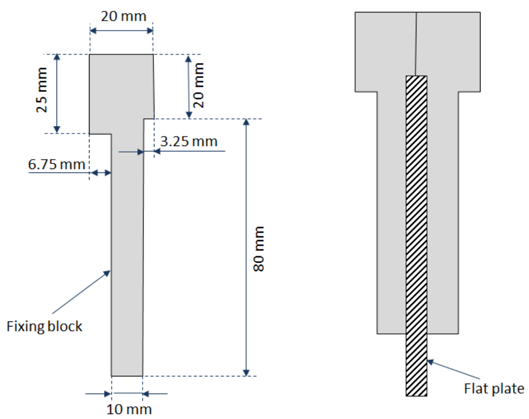

Figure 9 Flat plate fixing blocks

The flat plate model has been built by INSEAN, and the model was shipped to various

HTA members to test at their respective facilities, be it towing tanks, circulating water tunnels, or cavitation tunnels. The choice of facility is not prescribed as it is assumed that unique requirements of each facility may dictate some differences in procedures and test setup. Since the actual physical model is the same, each organization would be free to approach the test case in its own way, for example reflections can be minimized using special paints, using fluorescent seeding particles or special filters.

Two experimental configurations have been proposed to fit the standard characteristics of towing tanks and circulating water channels, as documented in Table 1. However, due to limitations in facilities, it may be inevitable that the parameters for towing tanks might have to be used in a circulating facility and vice versa.

	Towing tank	Circulating water channel
Plate dimensions (L x W x H) (mm)	500 x 800 x 6.25	500 x 800 x 6.25
Speed (m/s)	0.4	2
Angle of incidence (deg)	20	5
Tip-free surface distance (mm)	300	300

Table 1 Configurations for towing tank and circulating water tunnel

Two cross planes in the near tip region of the flat plate (Figure 10), located 100 mm in front (plane P1) and behind (plane P2) of the trailing edge, have been identified for the benchmarking exercise. Plane P1 would be subject to laser light reflections from the model, while P2 would have no model reflections present, but a very strong vortical structure. An upstream cross plane far enough from the leading edge also has been considered to survey the undisturbed velocity field. The field of view is rectangular (at least 200 mm high by 300 mm wide) and is situated on the suction side of the incident plate.

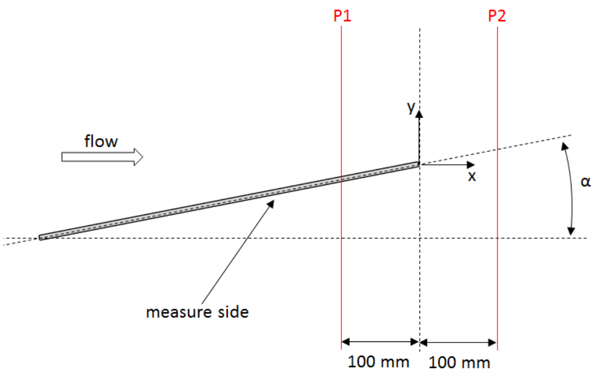

Figure 10 Measurement planes

The dataset should consist of at least 128 instantaneous three dimensional velocity fields. For the sake of maintaining a homogeneous data format among participants, mean velocity fields should be provided according to the following order: X (mm), Y (mm), Z (mm), U (m/s), V (m/s), W (m/s).

The origin of the reference system has been set at the trailing edge of the plate tip, with the X axis aligned to the free-stream direction, the Z axis vertical and the Y axis horizontal and oriented from the low to the high pressure side of the plate. The partners shall provide results on a 41 x 61 grid wide exactly as the requested interest zone [Z = (-100, 100) ; Y = (-150, 150)].

Instantaneous images from the left and right cameras in tiff or bmp format, instantaneous velocity fields from the left and right camera and after the stereo reconstruction, calibration images, datasheet with the mean velocity fields as previously specified, testing and processing information (e.g., left and right camera arrangement, set up specifics, processing and stereo reconstruction techniques and parameters) are requested to be supplied by each of the participants.

The detailed specifications of the benchmarking program are available on the website of HTA Network of Excellence (www.hta-noe.eu) on the page 'Research/JRP1'. Results from a sample of tests carried out by HTA member facilities has also been presented by Muthanna et al. (2010) and are presented in the next section.

4.3 Benchmark test results

The following section presents some results from HTA member facilities that have performed the stereo PIV benchmark tests. The work has been presented by Muthanna et al. (2010) and is summarized here.

The three data sets that are compared here are from

- INSEAN (Italian Ship Model Basin)
- Laboratory for Aero & Hydrodynamics at the Delft University of Technology (TUD)
- Maritime Research Institute Netherlands (MARIN) (cooperation MARIN-SIREHNA)

Among the results discussed here, INSEAN and MARIN performed the benchmark tests in their respective towing tanks, and TUD performed the tests in their circulating water tunnel. INSEAN have used their PIV system developed in collaboration with TSI. MARIN has used a PIV system developed by Dantec Dynamics, and operated by SIREHNA. TUD has used a custom PIV solution using the DAVIS analysis software. Thus, it can be expected that there will be some differences in the results obtained. The INSEAN configuration was an asymmetrical 3-Component PIV setup as shown in Figure 11. MARIN also used an asymmetric setup in the towing tank as shown in Figure 12. A sketch of the configuration in the water tunnel at Delft is shown in Figure 13.

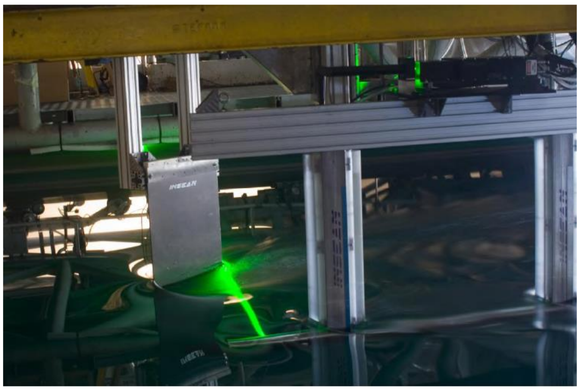

Figure 11: Benchmark model in the INSEAN towing tank.

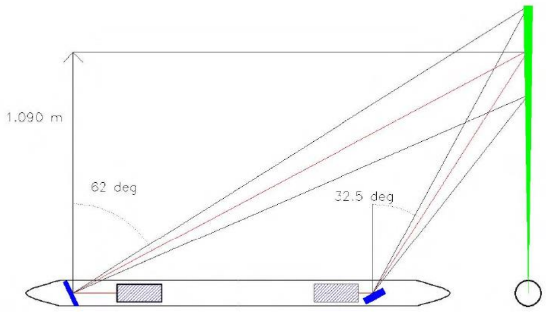

Figure 12: Sketch of MARIN's stereo PIV setup

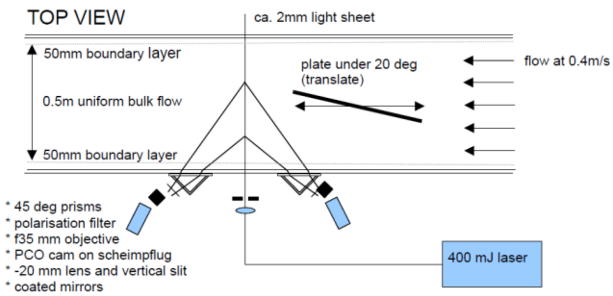

Figure 13: Sketch of TUD's stereo PIV setup in a circulating water tunnel.

The velocity data was delivered in ASCII format giving the measurement grid in X, Y, Z, and the three velocity components U, V, and W. The data sets being compared here are the average velocity maps as computed by each individual institution's averaging algorithms. The data is presented on the interpolated grid as specified, and again, the interpolation routines were chosen by each institution.

Shown in Figures 14, 15, and 16 are the mean velocity contours of the *U*, *V*, and *W* components respectively for the P1 measurement plane. This plane would be most affected by the presence of the flat plate, due to reflections from the plate surface, and thus impact the overall image quality of the PIV measurement.

The out-of-plane (i.e. streamwise) component of the velocity, U, is shown in Figure 14. This measurement result is the most sensitive to the setup of the Stereo PIV hardware in terms of making an accurate measurement. While the MARIN data sets show the presence of a large region of velocity deficit near the flat plate, the INSEAN data does not. This same region is visible in the TUD data, but it should be noted that the position of the flat plate in the TUD data set seems to be considerably different from that in the two towing tanks (likely relating to coordinate system definition).

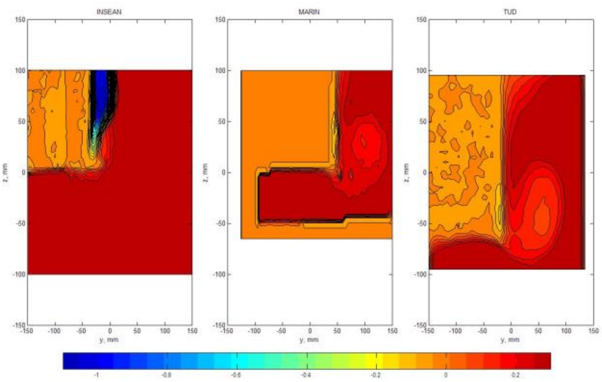

Figure 14: U velocity contours at the P1 plane. The order of images (from left to right) is INSEAN, MARIN and TUD.

However, when comparing the in-plane velocity measurement, *V* (spanwise, or parallel to the free surface, Figure 15), the three data sets are very similar, showing similar values for the measured velocities, as well as the same flow structures with the exception of the INSEAN data, whose results seem to be affected more than the others at this measurement location. However, the general trend of the INSEAN data indicates a similar flow structure as that seen in the other two data sets.

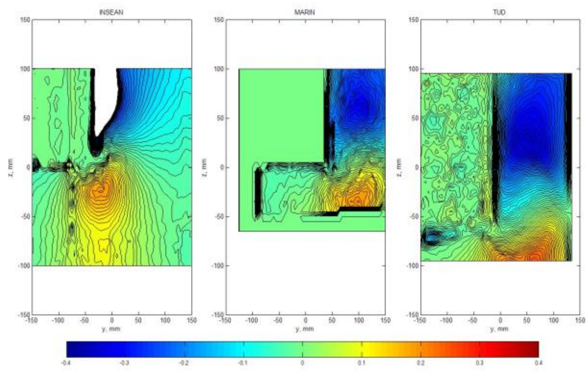

Figure 15: V velocity contours at the P1 plane. The order of images (from left to right) is INSEAN, MARIN and TUD.

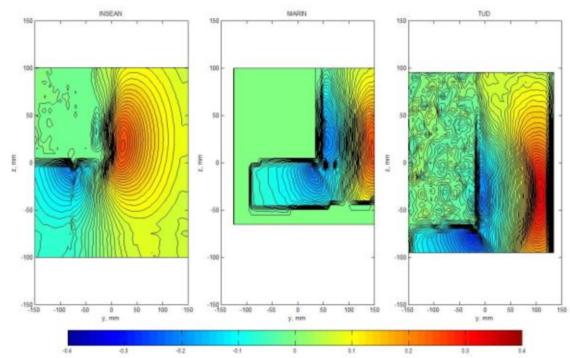

Figure 16: W velocity contours at the P1 plane. The order of images (from left to right) is INSEAN, MARIN and TUD.

The second in-plane velocity measurement, *W* (normal to the free surface, Figure 13), also shows a similar consistency in values measured in the three data sets, but here there is a difference in the overall flow structure. Again, the INSEAN data seems to be affected the most, and does indicate a slightly different flow structure near the flat plat region.

The mean velocity fields, *U*, *V*, and *W* at the P2 measurement plane are shown in Figures 17, 18, and 19 respectively. The results show that at least qualitatively, the results are similar between all the different measurements. The figures all show the presence of the tip vortex in the *U* velocity contours. The *V*, and *W* velocity contours are very similar in their distribution and values between the three measurements.

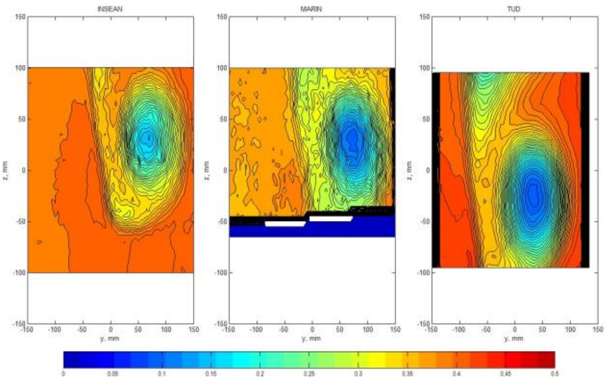

Figure 17: *U* velocity contours at the P2 plane. The order of images (from left to right) is INSEAN, MARIN and TUD.

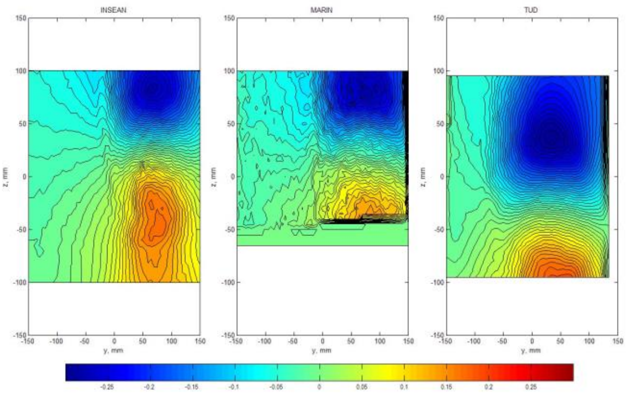

Figure 18: *V* velocity contours at the P2 plane. The order of images (from left to right) is INSEAN, MARIN and TUD.

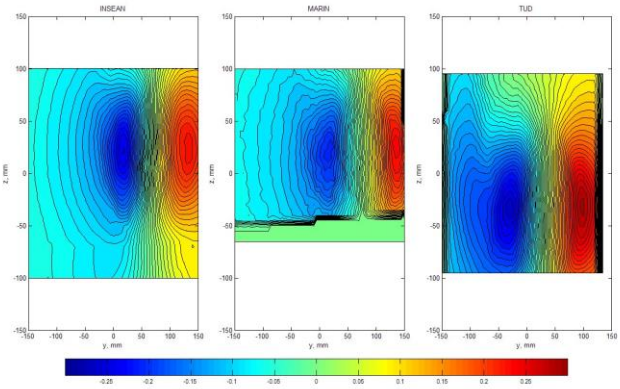

Figure 19: *W* velocity contours at the P2 plane. The order of images (from left to right) is INSEAN, MARIN and TUD.

The results of the mean flow field for the PIV data show that in general, the results obtained from a PIV measurement are consistent qualitatively. The overall flow structure is similar in all the cases, with any differences attributed to a fundamental change in the laboratory or measurement technique. However, quantitatively, there still seems to be some variations in the values being obtained.

Analysis and comparisons of the mean flow fields between three different institutions revealed that the PIV technique is fairly robust and reliable when working under ideal conditions. Despite the fact that the same model was used in three different facilities, there were some differences in the flow field, primarily with respect to the location of various flow features. Each test case had a different PIV configuration and post-processing routines, and so some differences can be expected. By having access to a database of benchmark data, institutions will thus be able to evaluate their own systems and procedures in a simple and confident manner.

5. ORGANIZATION

As stated previously, one key aspect of establishing a benchmark for PIV measurements is the organization of such a test program. Aspects that need to be established are:

- An ITTC member organization or organizations to coordinate as the organizer of the benchmark test.
- Clear instructions for performing the benchmark need to be established. This includes details such as the models to be used, measurement conditions, measurement parameters, final data delivery
- Dissemination of information pertaining to the benchmark tests to member organizations and organizing their participation.
- Collection, quality check, and storage 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.

The PIV group from the HTA has successfully organized a 3C benchmark set of tests as described in section 1.1.2. Thus the ITTC benchmark should incorporate this study as the starting point for the 3C PIV benchmark.

The 2C PIV benchmark proposed by the DFM committee has not yet been finalized. An initial measurement campaign should be established to establish the appropriateness of the proposed setup before it can be disseminated to other member ITTC organizations.

6. REFERENCES

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