ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Guideline on Best Practices for the Applications of PIV/SPIV in Towing Tanks and Cavitation Tunnels

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-01	General
7.5-02-01-04	Guideline on Best Practices for the Applications of PIV/SPIV in Towing Tanks and Cavitation Tunnels

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GUIDELINE ON BEST PRACTICES FOR THE APPLICATION OF PIV/SPIV IN TOWING TANKS AND CAVITATION TUNNELS

1. PURPOSE OF GUIDELINE

The primary purpose of this guideline is to compile a set of recommendations and "best practices" on the application of Particle Image Velocimetry (i.e. PIV) in hydrodynamic facilities within the ITTC community. The guideline targets a range of practitioners, especially those still developing their expertise, in support of the design and implementation of PIV experiments. Toward this goal, the guideline places strong emphasis on rules of thumb and examples and resorts to formulas and theoretical explanations only as necessary.

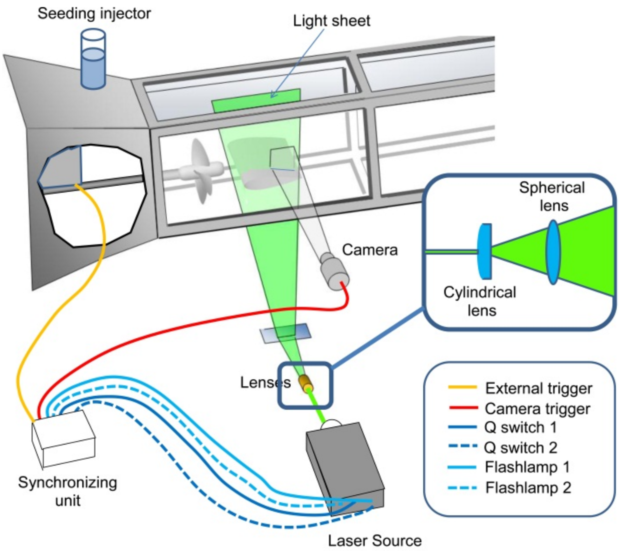


Figure 2. Overview of a PIV set up

2. BACKGROUND

The experimental setup of a PIV or Stereo-PIV (SPIV) measurement involves the use of one or two digital cameras, a light source (typically a dual-cavity pulsed laser), light-sheet optics (a set of cylindrical and spherical lenses), and a synchronizing unit (Figure 1). The flow is seeded with tracer particles, which are illuminated in the plane of measurement, at least twice successively within a short time interval. Additional devices, such as Scheimpflug adapters or water filled prisms, are also necessary when the measurement plane is not perpendicular to the camera optical axis or the PIV setup is complicated by the presence of sharp fluid interfaces, as in water-borne applications. Similar to other optical measurement techniques, PIV measures the flow velocity indirectly by the tracking the displacement of tracer particles within the flow.

Figure 2 illustrates a flow chart that describes the entire process involved in a flow-field measurement using PIV. Specifically, the process consists of the following major steps:

1. *Setup*. The equipment needed for the PIV measurement is assembled in the desired optical configuration and verified to be in working order. Light sheet is aligned to the measurement plane, and cameras and Scheimpflug adapters are aligned and the lens focused to obtain good quality images.

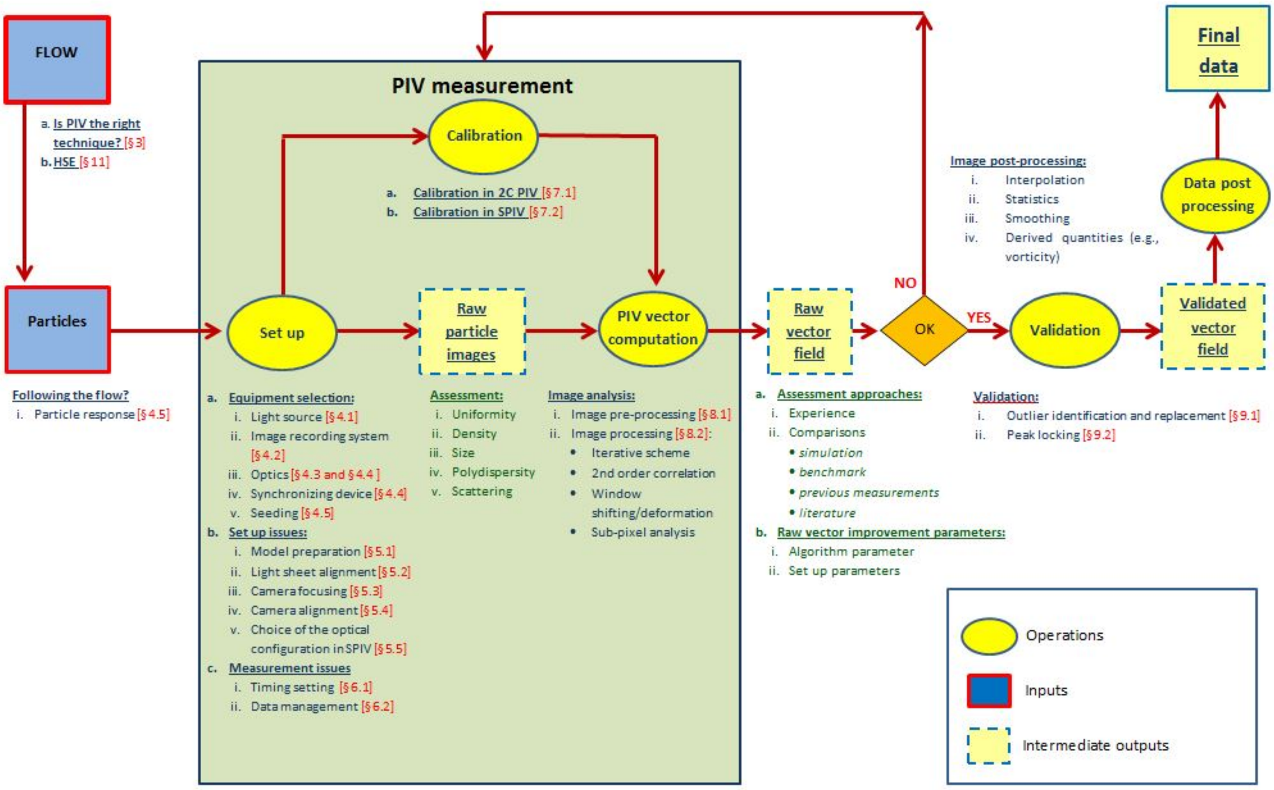


Figure 2. Flow chart of a PIV measurement

PIV or SPIV calibration is performed as appropriate.

2. *Acquisition*. The digital cameras record the light scattered by tracer particles seeded within the fluid. This flow is illuminated with at least a pair of laser pulses which are recorded onto a pair of camera frames within a very short time interval. Any acquired image is sampled onto an array of small image elements, i.e. pixels, and its intensity evaluated at discrete levels. The process of converting a continuous image intensity field onto a two-dimensional array of pixels is called pixelization. The subsequent digitalization of the signal amplitude is called quantization.

3. *Interrogation*. Recorded frames are subdivided into a number of interrogation areas for which signal correlation techniques are used to calculate a displacement vector map. Particle displacement is then converted into velocity using the time between exposures and the mapping function from the image to the physical space obtained through the calibration process. The resulting velocity map is then evaluated and any outlying vectors removed and replaced in a process called validation. And finally, post processing is performed before the final data is produced.

3. WHEN TO USE PIV

An important consideration when selecting a measurement technique for an experimental campaign is that the best methodology will largely depend on the specific problem being addressed. For example, single-point measurement techniques, such as Laser Doppler Velocimetry (LDV) or Hot Wire Anemometry (HWA), are usually the proper choice when flow statistics need to be accurately determined. On the other hand, a "multi-point" technique, such as PIV, is necessary for the measurement of instantaneous distribution of vorticity, in order to capture the dynamics of eddy structures in turbulent flows. However, when limited optical access makes the use of PIV impractical or laborious (e.g. propeller inter-blade flow, rudder-propeller interaction), LDV may be better suited to measure steady and periodic flows. Other parameters influencing the choice of technique for a given application are the velocity dynamic range, the spatial resolution, and the frequency response as well as more practical issues such as the amount of data to be managed, the facility occupancy and the processing time. The experimentalist should carefully consider the pros and cons of each measurement technique, both from the point of view of its ability to analyze the phenomenon and measure the flow quantities of interest and from the point of view of the overall complexity and cost of implementation. Often, the result of this analysis is a trade-off between conflicting requirements and constraints, which might involve both technical and practical issues. A thorough discussion into these aspects is beyond the scope of the present document, and the reader is invited to refer to a large body of literature dealing with these topics.

Similarly, once it is determined that a "multi-point" technique is desirable and PIV is the method of choice, the question of which variant of the PIV technique will best suit the needs of the experimental study needs to be considered next. Figure 3 is a pictorial representation of the capability of various types of laser velocimetry techniques to interrogate different components of flow velocities in multiple dimensions of space and time.

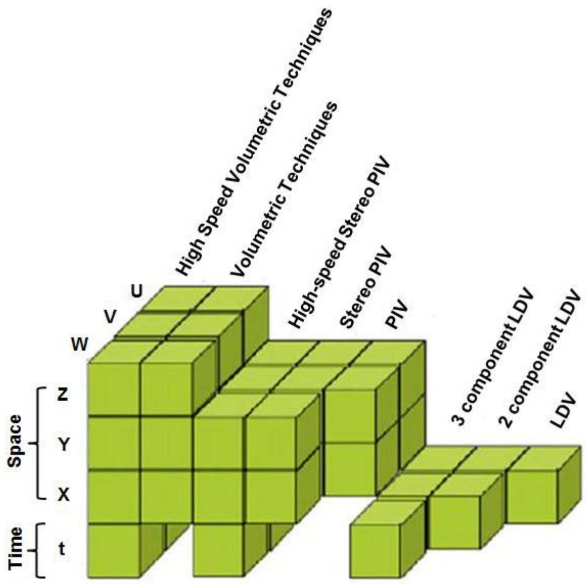


Figure 3. Measurement domain and measured components of laser velocimetry techniques, adapted from Hinsch (1995)

4. EQUIPMENT SELECTION

4.1 Light source

PIV requires the use of a high energy laser to illuminate small tracer particles within the fluid. The light source should exhibit two desirable characteristics:

1. High intensity of illumination: resulting in adequate amount light scattered by the tracer particles;
2. Short pulse duration: effectively "freezing" the motion of the particles without blurring

the particle images. The ratio of the pulse duration to the time delay between pulses, $\delta t/\Delta t$, determines the degree to which the motion of the seeding particles is frozen.

Continuous light sources such as incandescent lamps or continuous-wave lasers can be used in combination with mechanical or electro-optical shutters to provide short pulses of light. However, the use of a pulsed illumination source is strongly preferred in most situations. In particular, a pulsed laser emits energy in collimated beams of coherent light which can be efficiently formed into a light sheet. This characteristic makes the use of a pulsed laser superior to other pulsed illumination sources, such as spark discharges or flash lamps.

The most commonly-used laser system for PIV applications is a dual-cavity pulsed Nd-Yag laser, currently available in a wide range of pulse energy from 100 to 800 mJ, and with a repetition rate up to around 30 Hz. PIV applications in water require an energy density estimated in the range from 5 x 10^{-4} to 1 x 10^{-3} mJ/mm^2, assuming a light sheet thickness on the order of 1 mm with the use of 10 μm hollow glass particles. The required energy of the laser depends on the size of the region to be investigated. For instance, in most towing tank and hydrodynamic applications, a 200 mJ laser is normally adequate to investigate areas in the range of 100mm x 100mm to 500mm x 500mm.

The repetition rate of the laser pulses should match the camera frame rate or its multiples, in order to maximize the image acquisition rate (number of image pairs per second) and minimize the period of facility occupancy. For this reason, the use of lasers which can handle a reasonable range of variable repetition rates is recommended.

Weight and compactness of the laser and the ancillary systems is also an important consideration in equipment handling during the setup stage. This issue is particularly relevant for towing carriage installations.

4.2 Image recording system

PIV image recording is typically performed using specialized digital CCD or CMOS cameras, designed to capture two consecutive frames within a time interval of a few hundred *nanoseconds*. This mode of operation, known as frame-straddling mode, is fundamental to the PIV technique due to the fact that a short inter-frame delay is needed to ensure that the seed particles remain within the same interrogation region in the first and second frames. After a pair of images is captured, it must be transferred to the image-acquisition computer before the sensor is ready to acquire a new pair of images. The overall throughput of the camera is limited by the image-readout time, which determines the maximum frame rate at which a given camera can operate.

In addition, other key characteristics that need to be considered in the choice of a PIV camera are:

1. the spatial resolution of the sensor, which determines the level of detail that the continuous light intensity field is discretized onto the sensor array;
2. the sensitivity of the sensor, which determines the minimum light intensity that can be registered as measurable signal (above background noise level); and
3. the dynamic range, which refers to the recordable range between the brightest and the faintest signal within an image. The magnitude of the dynamic range is a measure of the signal-to-noise ratio and

the ability of the camera to capture faint signal without saturating the sensor in bright regions (overexposure).

Resolution and frame rate are related by an inverse behavior (i.e. higher resolution cameras typically have lower frame rate), and a trade-off usually has to be made to find the right balance between the two parameters. This trade-off should take into account the following issues:

- the type of fluid flow under investigation, and in particular, the required accuracy with which detailed flow features have to be resolved; and
- constraint on the facility time, as in the case of towing tank applications where limited facility availability usually influences the overall scope of the test.

A nominal value for suitable spatial resolution in a PIV measurement ranges between 5 and 20 pixel /mm^2.

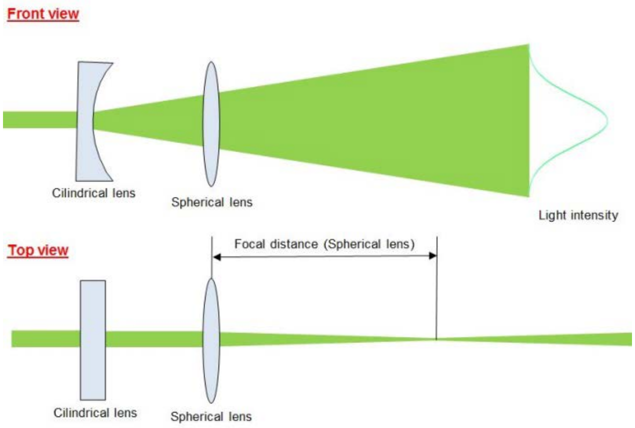


Figure 4. Light sheet generation

4.3 Lens for light sheet generation

An essential element for the generation of a light sheet, as illustrated in Figure 4, is a cylindrical lens. When used alone, a cylindrical lens only allows light to expand into a sheet in one direction without controlling the thickness of the light sheet. The focal length of the lens determines the aperture angle of the light sheet. A shorter focal length corresponds to a wider aperture angle, and vice versa.

Typically, beam divergence along the beam path results in the laser beam diameter that can be quite a bit larger than the desired light sheet thickness. In such a situation, one method is to use a long focal-length spherical lens to focus the light into a thinner sheet in the measurement domain. The cylindrical lens expands the laser into a plane in one direction, while the spherical lens compresses the plane into a thin sheet in the other direction.

An important rule, when a spherical lens and cylindrical lens combination is used, is to place the diverging lens in front of the converging lens in order to avoid focal points or focal lines. This lens arrangement protects the lens from damage due to air ionization or dust particle burning in the "hot spots," an issue particularly acute for a high-power pulsed laser with nanosecond-range pulse duration.

4.4 Tools for image focusing in SPIV: Sheimpflug adapters.

In PIV techniques, it is essential that the measurement plane falls within the focal depth of the camera in order to ensure sharp images of the seed particles. To this aim, the lens aperture is normally closed down (which increases the depth of field) until the whole image is well within focus while still maintaining adequate particle brightness. However, in practice, the effectiveness of this approach is limited to those situations in which the image plane is parallel to the object plane or slightly misaligned by a small angle. For larger misalignment, as typical in an SPIV setup, the lens and the camera body need to be tilted until the object plane, the lens plane and the image plane intersect along a common line (Figure 5), a condition known as the Scheimpflug condition. In practice, the adjustment of the camera focus is undertaken through the use of a dedicated mount, known as the Scheimpflug adapter, which allows adjustments over a range of camera translation and rotation so that the Scheimpflug condition can be satisfied.

	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

Table 1. Seed particles commonly used for liquids

4.5 Synchronizing device

The synchronizer is a master control unit which provides external triggers for both the camera(s) and the laser. Controlled by a computer, the synchronizer dictates the timing of the camera frame sequence in conjunction with the firing of the laser, with a time precision on the order of 1 ns.

In practice, the adjustment of the camera focus is undertaken through the use of a dedicated mount, known as the Scheimpflug adapter, which allows adjustments over a range of camera translation and rotation so that the Scheimpflug condition can be satisfied.

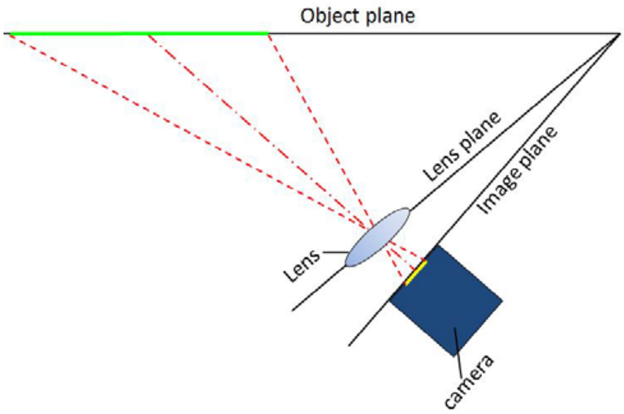


Figure 5. The Scheimpflug condition

4.6 Synchronizing device

The synchronizer is a master control unit which provides external triggers for both the camera(s) and the laser. Controlled by a computer, the synchronizer dictates the timing of the camera frame sequence in conjunction with the firing of the laser, with a time precision on the order of 1 ns. Thus, the time between laser pulses and the firing of the laser relative to the timing of the camera exposure can be accurately controlled. An accurate measure of this timing is critical as it is used to determine the velocity of the fluid in the PIV analysis. Stand-alone electronic synchronizers, called digital-delay generators, offer variable resolution timing from as low as 250 ps to as high as several ms. With up to eight channels of synchronized timing, the digital-delay generators offer the means to control several flash lamps and Q-switches as well as multiple camera exposures.

Seed particles

Tracer (seed) particles are a critical component in a PIV system that requires serious consideration. Desirable properties for good tracer particles are: 1) the ability to form visible images under a given illumination. (visibility), 2) the ability to accurately follow the fluid motion without influencing the flow (particle inertia), and 3) the ability to tag enough points in space to effectively resolve the flow spatially (concentration).

Good particle visibility is considered to be exposure levels that are at least 30-50% of the saturation level of the image recording medium. For a given particle refractive index, the exposure level increases much more efficiently with larger particle diameter than with higher laser energy. In practice, it has been observed that light scattering can be increased by a factor of 10-100 by a relatively modest increase in the particle diameter or the refractive index, whereas achieving a similar increase through additional laser energy can be cost prohibitive.

The ability of a particle to follow the flow motion depends on various parameters related to the properties of the fluid, the flow and the particles themselves. Specifically, these parameters are:

- the fluid density and viscosity;
- the flow mean and maximum acceleration; and
- the particle diameter and density.

Achieving better light scattering through increasing particle size must be balanced against the need to ensure high-fidelity tracking of the fluid velocity. In this regard, the estimation of the relaxing time is commonly used as a measure of the tendency of tracer particles to attain a velocity equilibrium with the fluid.

Considering spherical particles of very low Reynolds number, their ability to follow the flow or respond to the flow motion is inversely proportional to the square of their diameter and to the difference between the particle and the fluid density. On the other hand, the scattered light is directly proportional to the square of the particle diameter. Thus, the particles should be small enough to exhibit a good response time while still large enough to scatter adequate amount of laser light.

In hydrodynamic applications, particle size is usually not a critical issue when the particle specific gravity is close to unity. In such a situation, the velocity lag is negligible even for particles as large as 100 μm. The choice of particle size is, therefore, primarily dictated by the available laser energy. Normally, about 10^{-3} mJ/mm^2 of laser energy is needed when 10 μm hollow glass particles are used. For lower energy levels, either larger particles or highly reflective particles (such as silver coated hollow glass particles) have to be used.

In bubbly or cavitating flows, the risk of damage to the camera sensor, due to intense light scattering from bubbles or cavitation, requires the use of fluorescent particles, which absorb the laser energy and reemit the incident light at a different wavelength. The use of a dedicated narrow band-pass optical filter placed in front of the camera lens allows only the fluorescent light to pass through, while filtering out the reflected light from bubbles and cavitating regions (see e.g. Gopalan and Katz 2000; Foeth et al., 2006).

Table 1 lists different types of particles that are commonly used in hydrodynamic applications.

Figure 6. Use of Perspex in order to avoid light reflection (Felli et al., 2011)

5. SETUP ISSUES

5.1 Model preparation

An important issue to consider in the preparation of a physical model is the possibility of glare or surface reflection where the laser sheet hits the model surface. Surface reflections can modify the grey levels of the PIV images, mask the seed particles, and negatively impact the quality of the measurement. There are no image-processing algorithms that can fully reverse such an effect, and the best approach is to avoid or minimize surface reflections from the beginning.

A common approach to minimize surface reflections is to paint the region where the laser sheet hits the model an opaque black. Opaque black paint has a surface reflectivity of about 10%. An alternative approach, which reduces surface reflection even further, is to manufacture part of the model with transparent materials. Surface reflectivity of uncoated Perspex or Plexiglass is only about 4% (see e.g. Felli et al., 2011 and Figure 6). Another solution is to apply a fluorescent paint (see e.g. Visscher et al., 2009) on the model in order to change the wavelength of the reflected light. This approach requires the use of a narrow band filter that allows light scattered by the particles to pass through while filtering out the fluorescent light from the model. It is important to note that the application of the fluorescent paint can result in a thick coat and may not be suitable for applications where detailed geometry, such as propeller blade tips, is important.

The use of a black cover to mask any background object in the field of view of the PIV camera is also strongly recommended to minimize any indirect illumination.

5.2 Light sheet adjustment

Light sheet adjustment is a critical step in the PIV/SPIV setup which concerns both accuracy and safety issues. The light sheet defines the measurement plane; therefore, it needs to be carefully aligned to the flow coordinate system in order to avoid velocity bias errors which could result from any misalignment.

Some general recommendations for light sheet alignment are given below:

- Laser beam and sheet alignment should be performed with the laser energy set as low as possible. The light sheet should be adequately visible under low ambient light condition (to ensure general safety). A recommended approach is to start with the laser energy at minimum and increase it to a safe, usable level.
- If possible the use of a calibration target is recommended. It is easier and safer to align the target first, and then use the target as reference to align the light sheet.
- Initial alignment can be performed first in air (especially for cavitation tunnels or flow channels). Final alignment should be performed *in situ* or as close as possible to the manner in which the PIV measurement will take place. The procedure may require iteratively making adjustments in air and checking alignment in water. A convenient approach for tow tank applications is to perform the alignment in a dry dock, which can be easily drained or flooded in a short period of time.
- The visibility of the light sheet in air can be enhanced using a water spray nozzle. In water, the light sheet visibility can be increased by injecting a high concentration mixture of water and seed particles over the light sheet (i.e. about one-two teaspoons in a liter of water).
- For submerged PIV systems, performing the alignment in calm-water inherently assumes that the PIV support structure does not significantly bend under hydrodynamic loads when the system is in operating condition. Therefore, the support system should be designed to be adequately stiff for this assumption to hold true.
- Plumb line, level arm, meter, targets, reference lines or model geometries may be helpful tools for the alignment.

Light sheet thickness is an additional important parameter in the adjustment of the light sheet. Usually, the light sheet thickness is controlled by the selection of a spherical lens with a proper focal length. For 2D-PIV and Stereo-PIV, the light sheet thickness is chosen to allow only a small fraction of the seed particles to enter or leave the light sheet between the two exposures in order to minimize the loss of pairs between the first and second frame. Given typical in-plane and out-of-plane displacements of 5-10 pixel, the light sheet should be at least 10-20 pixel thick so that the number of unmatched particles does not exceed 50%. For cross-flow measurements with high out-of-plane motions, the light sheet thickness can be much larger, especially if small in-plane fluctuations need to be measured with sufficient dynamic range. Thicker sheets reduce the in-plane spatial resolution of the vector field.

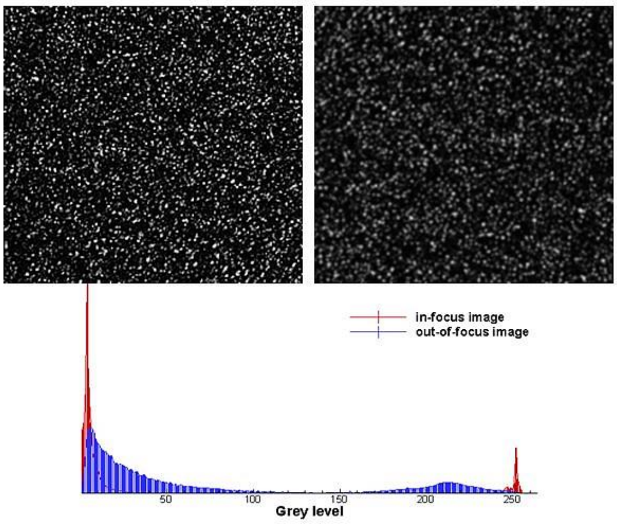


Figure 7. Adjustment of the camera/particle focusing by the examination of the grey level distribution

5.3 Camera focusing

In PIV measurements, image sharpness strongly influences the accuracy of the cross-correlation and the overall fidelity of the results. Image quality is optimal when particles are in focus and well exposed (appearing small and bright), and the contrast level is high (with low background level as to appear nearly black). However, it is also important to ensure that the particle images are not saturated, as it will lead to weak correlations and loss of accuracy.

A convenient way to optimize the focus is to work with a magnified view of the image, with the lens set at a large aperture (i.e. low f-number). Once good focus is achieved all across the imaged region, the lens aperture can be closed down (increase the f-number), while still maintaining good particle visibility. Closing down the lens increases the depth of field, which leads to improved image focus, especially around the edges of the image where lens aberrations are highest.

An alternative approach, which is not based on the subjective examination of the user, consists of the analysis of the grey level distribution in the image. Specifically:

For an image which is at an optimum focus, the gray level exhibits a bi-modal distribution with well-defined peaks at the extremities of the histogram (red distribution in Figure 7). The peak on the right are due to the well-focused and bright particle images, and the peak on the left represents the dark background.

- For an image which is slightly out of focus, the two peaks within the histogram tend to broaden (blue distribution in Figure 7), with peak intensity values shifting towards the middle. This behavior is a result of a degradation of the image contrast. The intensity value for the right peak is reduced, as the particle images are blurred, and the intensity value for the left peak is increased, as background noise level is magnified.

5.4 Camera alignment

Camera alignment is another significant issue that can drastically affect the accuracy of the measurement. In a two-dimensional, two-component (2D2C) PIV experiment, the camera is required to be set with the optical axis perpendicular to the light sheet. In fact, any misalignment between the camera and the light sheet results in a bias in the velocity measurement, whereby the measured particle displacements would apparently be equal to the projection of the real displacements onto the image plane.

A recommended procedure to optimize the alignment of the light sheet to the camera is described below:

1. verify the light sheet is aligned to the coordinate system of the experiment;

2. seed the field of view region of the camera and keep the flow at zero speed;
3. set the camera at the maximum aperture;
4. magnify the image and adjust the focus at the center of the imaged region;
5. check if particles are in focus on both left and right sides simultaneously;
6. if particles are not in focus on the left and/or right sides of the field of view:

   a) if particles are out of focus both on the left and right sides and well in focus at the center of the imaged region, try to close the aperture 1 or 2 stops and then check again, repeating from step 5. When a small focal length lens is used, the large curvature might cause particles to be out of focus in the border region of the imaged area. This effect can be easily compensated by reducing the camera aperture;
   b) if particles continue to be out of focus after step 6.1 or if particles are not in focus at least on one side of the image, try to slightly rotate the camera around the vertical axis (in azimuth) to correct for any misalignment of the camera, and then check again, repeating from step 5;

3. check if particles are in focus on both top and bottom sides simultaneously;

4. if particles are not in focus on the top and/or bottom sides of the field of view:

   a) if particles are out of focus both on the top and bottom sides and well in focus at the center of the imaged region, try to close the aperture 1 or 2 stops and then check again, repeating step 5 and from step 7;

c) if particles continue to be out of focus after step 8.1 or if particles are not in focus at least on one side of the image, try to slightly rotate the camera around the horizontal axis (in elevation) to correct for any misalignment of the camera, and then check again repeating step 5 and from step 7;

5. close the camera aperture as much as possible to increase depth of field while ensuring that particles remain well exposed.

5.5 Choice of the optical configuration in SPIV

Naval flows are strongly three-dimensional and the adoption of a stereo setup may be required. A large body of literature exists on the accuracy of SPIV, and the pros and cons of different optical configurations (Raffel et al., 2007; Adrian and Westerweel, 2011).

The configuration with the cameras placed symmetrically on both sides of the light sheet with the region of interest being viewed in forward scatter [Figure 8(a)] is, in general, the most accurate. However, this configuration is often impractical because of the limited optical access in the wake of ship models. Therefore the optical setup with both cameras on the same side of the light sheet is typically used.

The configurations in Figures 8(c) and (d) are typically used in dry arrangements of the PIV system (e.g. cavitation tunnels and channels). The arrangement in Figure 8(c) is preferred due to the fact that both cameras have the same light scattering angle (90°) and thus receive the same exposure. The arrangement in Figure 8(d) is not as desirable because the two cameras observe the tracer particles in opposite scattering directions, resulting in unequal exposure with the forward-scatter camera being much brighter than the back-scatter camera.

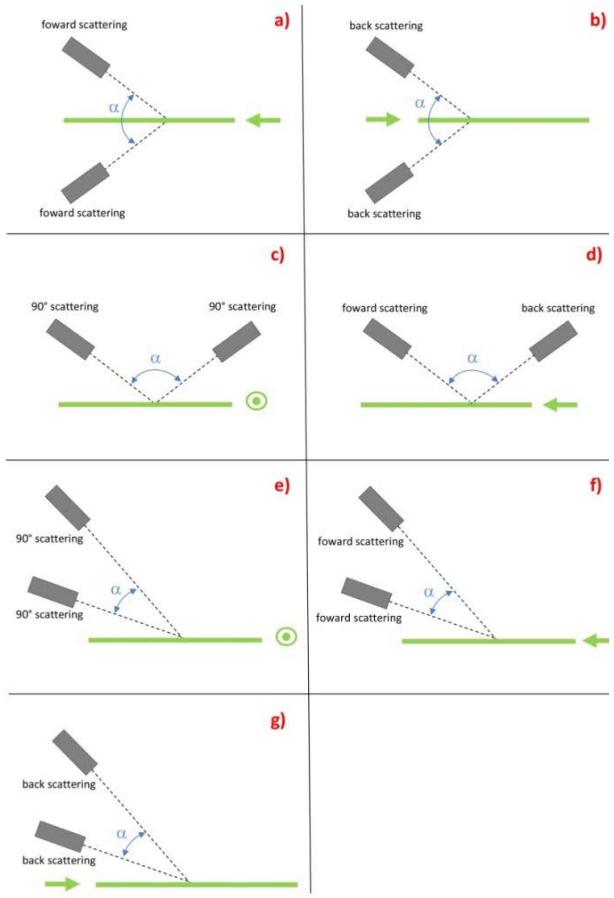


Figure 8. Typical optical configurations in Stereo PIV. The arrow indicates the direction in which light propagates.

The configurations in Figure 8(b) and (g) are the standard optical configurations for SPIV underwater probes. The light sheet and the two cameras reside on the same side, with the region of interest being observed in back scatter mode. Even though back scattering results in less observable light than forward scattering [Figures 8(a) and (f)], optical configurations with back scattering has the advantage in terms of practicality and optical access.

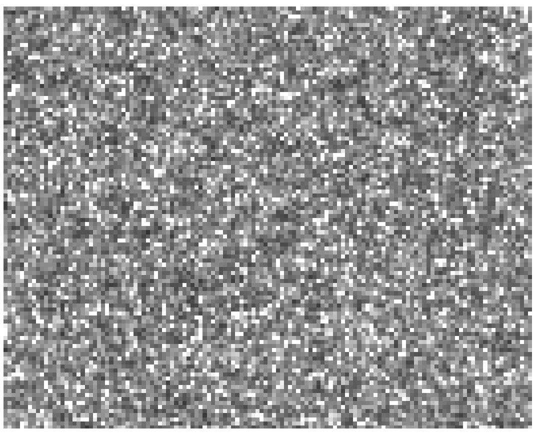
Whatever configuration is ultimately chosen, it is recommended that the angle between the cameras be greater than 20° in order to ensure accurate stereo reconstruction.

5.6 Seeding

The mechanics of seeding the flow can play a significant role in determining the overall quality of the PIV measurement. In particular, four characteristics of flow seeding need to be carefully considered:

- the level of particle polydispersity;
- the homogeneity of particle distribution;
- the concentration of particles in the flow;
- the perturbation associated with the momentum injection when seeding.

The size specified by the vendor of PIV particles is usually a measure of the mean or the mode size of a batch of particles. In actuality, normal manufacturing process would result in an inherent level of polydispersity, or non-uniform distribution over a certain size range. The effect of a polydisperse particle population is to degrade the image quality, as fine particles contribute to a murky background and overly large particles lag the flow and distort the image interrogation process. The degree of polydispersity needs to be reduced as much as possible, either by selecting particles with a narrow size range or by processing out undesirable particles from a given batch (for example, by sieving).



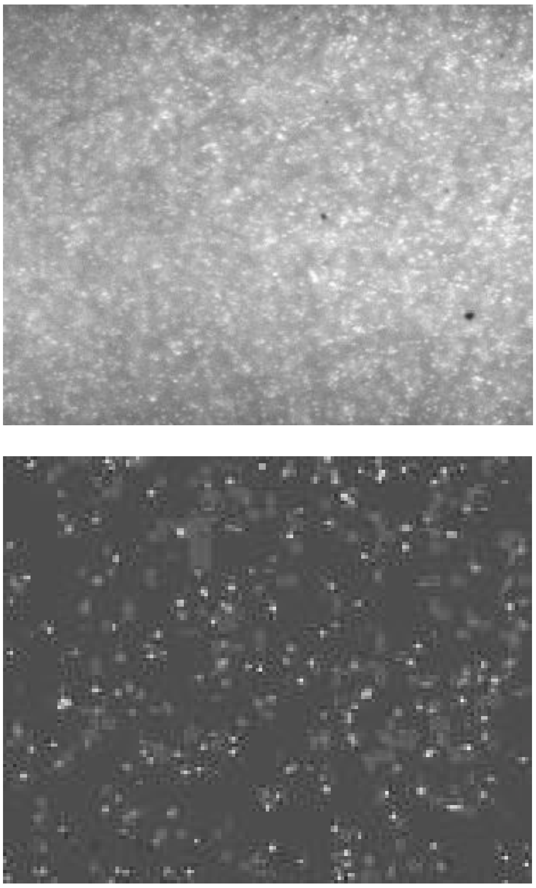


Figure 9. Example of a seeding distributions: suitable seeding distribution (top), defocused seeding distribution (mid), low seeding concentration (bottom)

The distribution of tracer particles within the flow should be as homogenous as possible (Figure 9, top), in order to achieve a high quality PIV measurement. In some cases, particle distribution can be complicated by the local characteristics of the flow. For instance, a strong vortex, such as a tip vortex from a highly loaded propeller, has a tendency to deplete its core of particles through inertial effects (Figure 10). In such a situation, a bias error may result, as data are acquired only when the local vorticity is lower than a given threshold.A general guidance is to seed the flow gradually until adequate particle concentration is reached (at least 10 particles per interrogation area). Low particle concentration results in reduced probability of a valid displacement detection and increase the overall measurement uncertainty. On the other hand, excessive particle concentration may lead to degraded image contrast (as the water becomes turbid) and increase the overall cost and cleanup time.

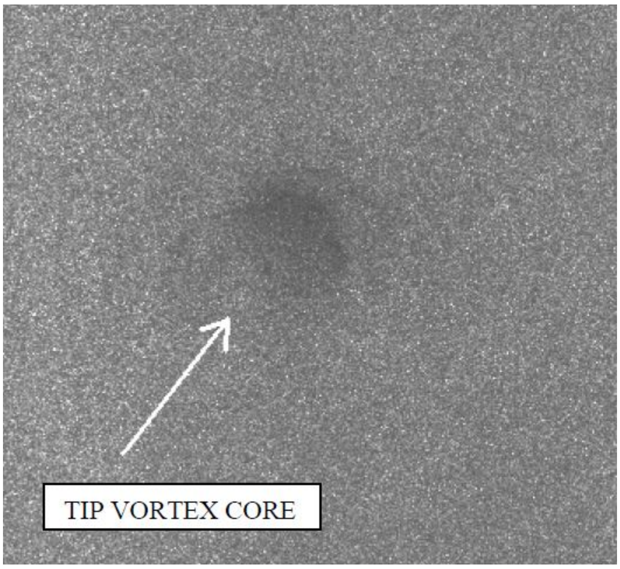


Figure 10. Example of tip vortex centrifugal effect on the seed particles

Finally, it is important to achieve uniform seeding of a suitable concentration without overly disturbing the flow. Seeding is usually performed by dedicated devices, placed upstream of the measurement region to avoid any local flow disturbance. The rate of momentum injected when seeding should be negligible compared to the flow being investigated, especially in cavitation tunnels where the water moves past a fixed plane of measurement. In towing tanks, the rake can be placed downstream of the measurement area and the flow seeded during the return run of the carriage.

6. MEASUREMENT ISSUES

6.1 Timing setting

A PIV setup consists of a complex set of components, including a laser with flash-lamps/Q-switches and digital cameras, that all need to be precisely timed and synchronized with a specific event in the experiment. A typical timing diagram is illustrated in Figure 11. The timing sequence is initiated by a reference signal, which typically comes from an external trigger associated with the experiment (e.g. the passage of a propeller blade, the starting of a maneuvering operation etc.). The synchronizing device provides trigger pulses which fire the flashlamps and Q-switches and control the exposure of the cameras in a specific order.

The timing sequence starts with the exposure of the first frame of the image pair. In order to fire the first laser, the synchronizing device triggers the flashlamp, which pumps energy into the laser rod; and a short time later triggers the Q-switch, effectively releasing the energy absorbed by the laser rod in a short burst of light. The time delay between the flashlamp and the Q-switch is usually set to a fixed value, corresponding to the maximum light emission. This optimal time delay is specific to each laser system and is usually recorded by the laser manufacturer in the user manual.

After the first frame is exposed, the process is repeated for the second frame after a short time delay. For dual-frame cameras, the exposure time of the first frame is much shorter than that of the second, the latter being constrained by the image read-out time. While the first frame is being transferred to the frame grabber, the second frame remains exposed, making it much more sensitive to the effect of background light. Turning off lights, covering windows, doors, and any background object in the field of view with dark fabrics, and using a narrowband camera filter at the laser wavelength, are some recommended steps to control the background light during a PIV experiment .

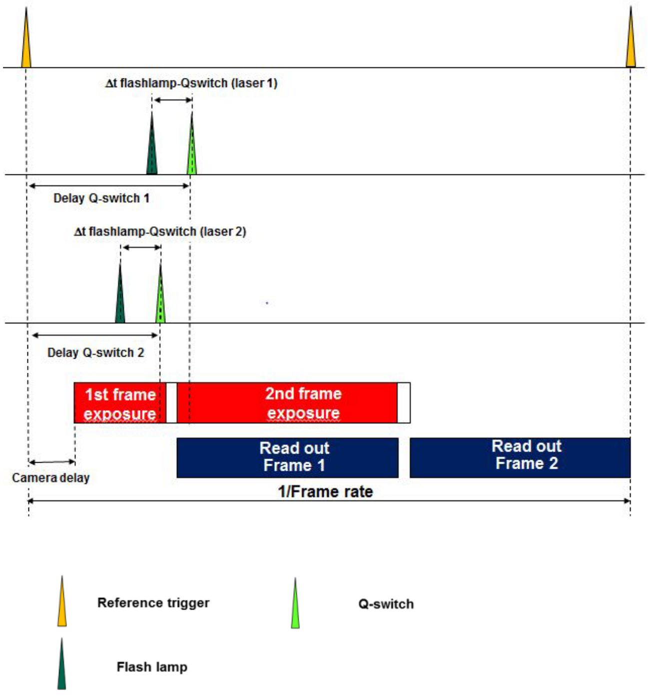


Figure 11. Timing diagram

In general, the timing of the two laser pulses should result in an in-plane particle displacement of at least 5 pixel, in order to obtain an optimal signal-to-noise ratio. However, when the desired flow features are best observed in a plane orthogonal to the free stream, such as in many cases of highly three-dimensional flows, the selection of the appropriate time delay requires additional considerations. This so-called "cross-flow PIV" is characterized by large out-of-plane motions, which could result in loss of particle pairs between the first and second frames. It has been demonstrated (see Keane and Adrian, 1993) that the amplitude of the displacement correlation peak decreases in proportion to the out-of-plane particle displacement. However, this effect is negligible when the out-of-plane displacement is less than 1/4 of the light sheet thickness. For cross-flow PIV, a thicker light sheet is recommended in order to obtain adequate in-plane particle displacement, while keeping out-of-plane loss of particles to an acceptable level.

6.2 Data management

A typical PIV experiment can result in a large number of PIV images, making data management a concern. Requirements for data storage should be determined prior to the experiment. The memory space S (in MB) of an instantaneous 2C-PIV/S-PIV acquisition (i.e. one image pair/two image pairs), acquired by one/two camera/cameras having P megapixel resolution and saved in a Q bit quantization format is given by:

$$S = N \cdot [P \cdot (Q/8)] \quad \text{MB} \tag{1}$$

where N=2 for 2C-PIV and N=4 for S-PIV. The required storage for the whole test campaign is obtained by multiplying the result of (1) by the number of instantaneous acquisitions.

For example, the size of an instantaneous PIV acquisition, obtained by a 4 MP camera and saved in a 16 bit format, is S=2·[4·(16/8)]=16 MB. In a typical 2C-PIV/S-PIV campaign, it is not uncommon for hundreds of gigabytes of images to be acquired. In some cases, the amount of data gets doubled if images are pre-processed. In this regard, a rough rule of thumb is that data acquired in one day of a towing tank test require at least 5 days for processing, using currently available computer technology (3 GHz multi-core- multiprocessor PC) and state-of-the-art PIV algorithms.

7. CALIBRATION

The subject of calibration is fundamental to the accuracy and reliability of any PIV measurement. As with all measurement systems, the accuracy of the calibration process needs to reflect the level of accuracy required for the measurements. A simple rule of thumb should be that the uncertainty associated with the calibration process should be at least an order of magnitude lower than the overall uncertainty threshold for the measurements, as numerous other sources of uncertainty exist.

7.1 Calibration in 2C-PIV

In PIV, image displacements are measured in the image plane and, therefore, represent a scaled measure of real particle displacements. The PIV calibration process determines the mapping function by which the image plane is mapped onto the object plane. For conventional PIV, the variation of the mapping function over the field of view is usually negligible if the image plane is parallel to the object plane. It follows that the mapping function is a constant function, usually referred to as the magnification factor, whose value is determined by imaging a reference object with known length l_{ph} at plane of focus of the camera.

Even though any object of known dimension can be used as reference for the determination of the mapping function, the use of a calibration target is recommended. The magnification factor M is given by l_{ph}/l_{im}, where l_{im} represents the reference length in the image plane measured in pixels. The uncertainty in the magnification factor can be minimized by using a reference object with accurate and identifiable reference marks and ensuring that the reference object is accurately positioned in the camera plane of focus.

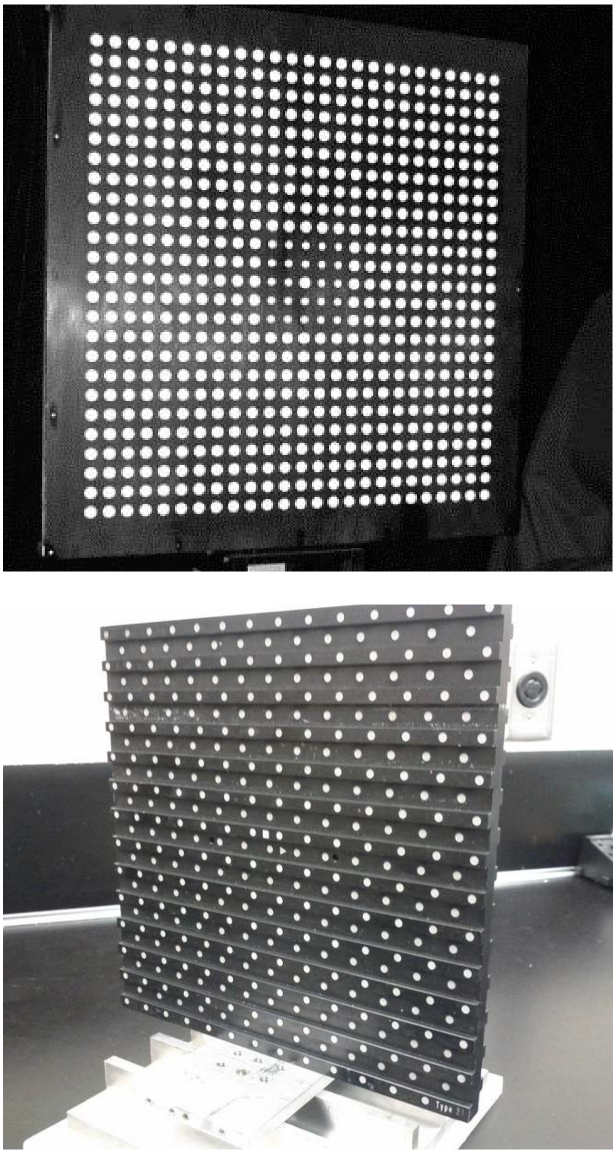


Figure 12. Calibration target for Stereo PIV: single-plane-double-side type (top), double-plane-double-side type (bottom)

7.2 Calibration in SPIV

Stereoscopic PIV employs a calibration process that combines two 2D vector fields onto a 3D vector field (Soloff, 1997). The calibration returns a set of polynomial equations through which a camera pixel (X, Y) location in the image plane is mapped onto a physical (x, y, z) location in the object plane.

The calibration procedure uses a calibration target which consists of a grid of markers placed in, or near the light sheet. Commercially available three-dimensional targets (bottom of Figure 12) allow a simpler calibration procedure and are typically preferred.

A two dimensional target (top of Figure 12), displaced over several positions along the out-of-plane direction by means of an accurate traverse system, is an alternative approach. In both cases, the accurate positioning of the target is the major critical issue for a high-quality calibration.

After PIV calibration is performed, another critical step is the alignment of the light sheet to the plane of the target. Most commercially available SPIV software allows the evaluation and correction of any misalignment, using images of the particle field taken in calm water. The correction is based on the fact that the cameras each observe the same particles (Wieneke, 2005) and performs well for misalignment of around 1 degree or less. For larger misalignments, the use of a mirror placed behind a slit and attached to the side of the target is a helpful solution. When the light sheet is centered on the slit and the light reflects back on the laser, the light sheet is aligned.

In order to verify the quality of the PIV calibration, a verification test in which a known uniform flow is measured (such as by towing the PIV system through calm water or operating the cavitation tunnel with no model) is highly recommended. A good calibration results in a deviation between true and measured velocities that is less than 2% over 95% of the image area, usually with the largest errors occurring in the corners of the measurement area.

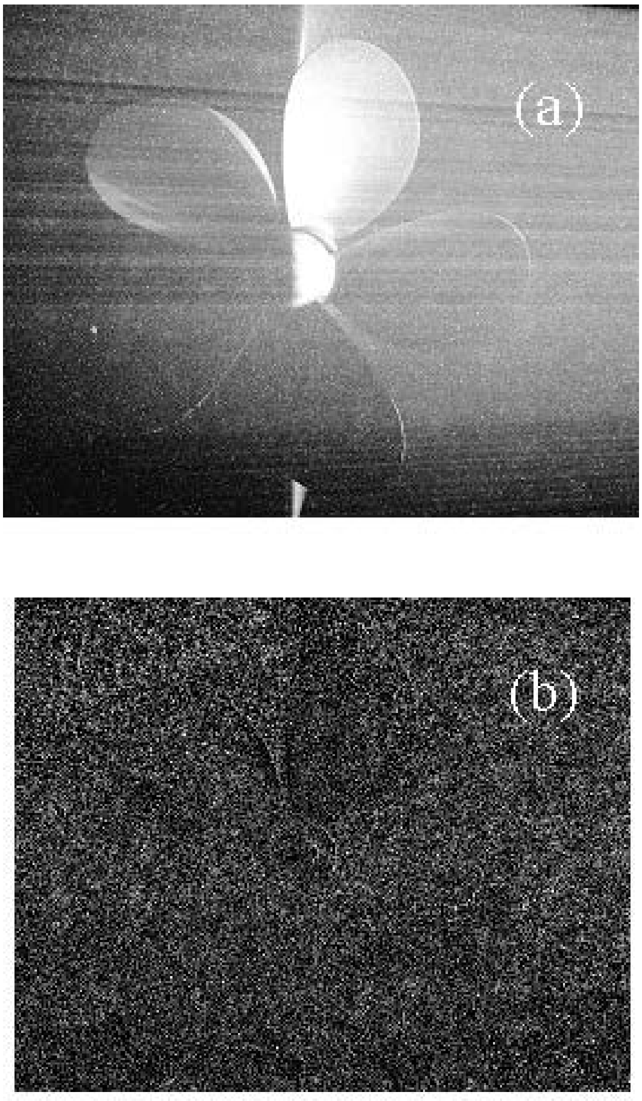


Figure 13. Image preprocessing: a) original image, b) pre-processed image by background removal (Felli et al., 2002)

8. IMAGE ANALYSIS

8.1 Image pre-processing

Processing of PIV images can be greatly enhanced by employing suitable pre-processing schemes to improve the visibility of the seed particles. The accuracy of the PIV measurement is largely determined by the quality of the images. A variety of practical issues associated with the application of PIV in industrial hydrodynamic facilities often result in non-homogeneous illumination, poor contrast, bright background, moving objects, etc, and pre-processing of the original images is often necessary after acquisition (Raffel et al. 2007).

A common issue that can severely degrade the quality of the PIV images is the light contamination by laser flares, reflections from the model or any object in the background (facility walls, windows), as well as those from the free surface. A corrective pre-processing operation consists of removing the background from recorded images, in order to enhance the visibility of the seed particles. A reference background image is computed by taking an average over a sufficient large number of images (at least 20-50) with no tracer particles. Digital subtraction of the reference background image from each recording is then performed to remove the background (Figure 13). A more laborious but also more effective solution can be obtained by a pixel-by-pixel normalization of each image with the local time averaged mean intensity, paying attention to set all the zero grey values to ‘1’ to avoid a division-by-zero error.

The use of masks to zero out the grey levels of the pixels that either fall outside the flow domain or contain substantial wall effects is also an effective practice. If left untreated, these effects can severely degrade the quality of the correlation and lead to significant velocity bias issues.

Other less common preprocessing operations can be employed to further improve the quality of the correlation. However, it is recommended that the effectiveness of these routines is first established on a sample image, in order to avoid waste of computer processing time.A review of the multitude of preprocessing operations is beyond the scope of the present document. Two examples of useful preprocessing tools are reported below:

- image low-pass digital spatial filtering followed by subtraction from the original image to remove unwanted random objects, such as large particles, bubbles or droplets;
- narrow-band low pass spatial filtering to remove high frequency noise such as those due to pixel anomalies, camera shot noise, digitalization artifacts, etc.

8.2 Image processing

This section addresses the relevant issues associated with PIV digital image processing, with the primary purpose being to provide beginners with some guidance through a general discussion on the choice of image processing methodologies and parameters. A full account of the multitude of digital image processing techniques used in PIV is beyond the scope of the present document, and the reader is instead referred to numerous excellent sources of information in the literature (e.g. Raffel et al., 1998; Adrian and Westerweel, 2011; Scarano, 2000; Stanislas et al., 2003, Stanislas et al., 2005; Stanislas et al., 2008). Furthermore, this discussion is mainly focused on the case of single-exposure, double-frame recording of densely seeded flow, being the most relevant in the typical practice of ITTC members.

The standard statistical analysis in high image density PIV is based on the spatial correlation between corresponding subdomains of the first and second exposures (Figure 14). In each subdomain, the result of the spatial correlation determines the local in-plane displacement vector and ultimately the associated velocity vector (through division by the time delay between laser pulses).

The spatial correlation analysis of PIV images consists of two primary steps:

- **Selection.** Images in the first and second exposures are split into subdomains (namely interrogation windows), whose size defines the spatial resolution of the measurement. All the seed particles belonging to the same subdomain are assumed to move with the same local velocity. Accuracy of the spatial correlation analysis is directly proportional to the magnitude of the displacement-correlation peak and adversely correlated with the correlation fluctuations. Optimal condition is accomplished when the following requirements are met:
    - each subdomain needs to contain at least 10 particle images, on average, in order to distinguish the displacement correlation peak unambiguously from the random correlation peaks (i.e. measurement noise);
    - the in-plane displacement should be limited to ¼ of the subdomain size. The amplitude of the displacement correlation peak decreases with increasing in-plane displacement. However, this effect is negligible when the in-plane displacement is less than ¼ of the size of the interrogation domain;
    - the displacement differences between neighboring subdomains should be less than 3-5% of the size of the interrogation region. Spatial gradients of the displacement field increases the width of the displacement-correlation peak and decrease its amplitude, leading to poor correlation.

The above requirements thus partially determine the minimum size of the interrogation region, once the laser pulse separation time has been fixed. In practice, a favorable dimension for the interrogation window lies somewhere between 16 and 64 pixel units.

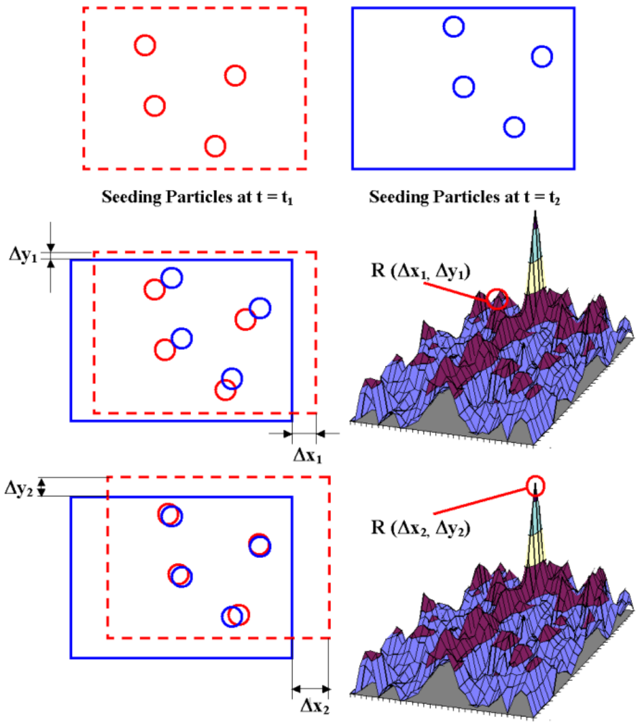


Figure 14. Spatial correlation analysis

- **Spatial correlation analysis.** The displacement vector for each interrogation domain is calculated through the spatial cross correlation analysis on the corresponding grey levels of the first and second exposures (see Figure 14). The calculation of the spatial correlation is a computationally intensive operation, typically performed using Fast Fourier Transform (FFT) for its efficiency compared to direct correlation (direct correlation requires $O[N^2]$ operations, while FFT reduces it to $O[N^2/\log N]$, N being the size of the interrogation window).

In most commercial PIV software, special methodologies and interrogation strategies are implemented, in order to improve the spatial cross correlation analysis. These methodologies are discussed below:

- *Non square interrogation windows.* This option can be advantageous for strongly unidirectional flows and involves the use of interrogation windows with a dimension that is larger in the flow direction.
- *Window weight functions*. Non uniform weight functions, such as Gaussian, Parzen or Hanning, can be applied to avoid or minimizing edge effects due to clipping of particle images near the edges of the interrogation windows. Clipping of particle images is associated with increased noise in the spatial correlation analysis. The number of clipped images increases with: i) increasing image density, ii) decreasing interrogation area and, iii) increasing particle image diameter. For example, assuming a 32x32 interrogation window, a number of seed particles equal to 10, and a particle image diameter of 2 pixel, the fraction of clipped particles is given by the ratio between the number of pixels in the 2-pixel wide perimeter (2x32x4=256) and the total number of pixel (32x32=1024), roughly about 25%. This implies that four clipped particle images, i.e. 10·0.25=4, will occur on average. This number increases to 5 for a 16x16 interrogation window and reduces to 1.25 for a 64x64 interrogation window.
- *Window offset correlation*. The accuracy of the PIV processing can be significantly improved by using a window offset equal to the local displacement obtained in the previous pass (Figure 15) of an iterative multi-pass operation. This operation employs a hierarchical approach in which the size of the interrogation windows is contextually reduced, allowing a progressive refinement of the sampling grid. The implementation of the offset correlation improves the peak detectability by minimizing the in-plane loss of

correlation, allowing a smaller final interrogation area and better spatial resolution of the interrogation analysis. In order to optimize the parameters of the window offset correlation, an empirical approach is recommended. Specifically, this consists of considering a reference image-pair and processing it with a different combination of parameters (i.e. initial and final size of the interrogation windows, number of passes) until the best trade off in terms of accuracy (i.e. number of spurious vectors) and processing time is found.

In this regard, a reasonable approach is recommended as follows:

1. *Determination of the initial size of the interrogation windows $\Delta W_{initial}$.* A possible approach consists of estimating a representative displacement in the highest velocity regions (says Δs_{high} pixel, e.g. 15 pixel), multiplying it by four (i.e. $\Delta s_{high} \cdot 4$ pixel, e.g. 20·4=80 pixel) and round up to the next power of 2 (i.e. $\Delta W_{initial}$ =128).
2. *Determination of the final size of the interrogation windows ΔW_{final}.* Analogously to the previous point, a possible approach consists of estimating a representative displacement in the low velocity regions (says Δs_{low} pixel, e.g. 4 pixel), multiplying it by four (i.e. $\Delta s \cdot 4$ pixel, e.g. 4·4=16 pixel) and round up to the next power of 2 (i.e. ΔW_{final}=32 pixel).
3. *Determination of the iteration number N_{steps}.* The number of iterations can be set equal to:

$$N_{steps} = \log_2\left(W_{initial} / W_{final}\right) + 1$$

(e.g. with reference to the example made in points 1 and 2: $N_{steps} = \log_2(128/32) + 1$=3).

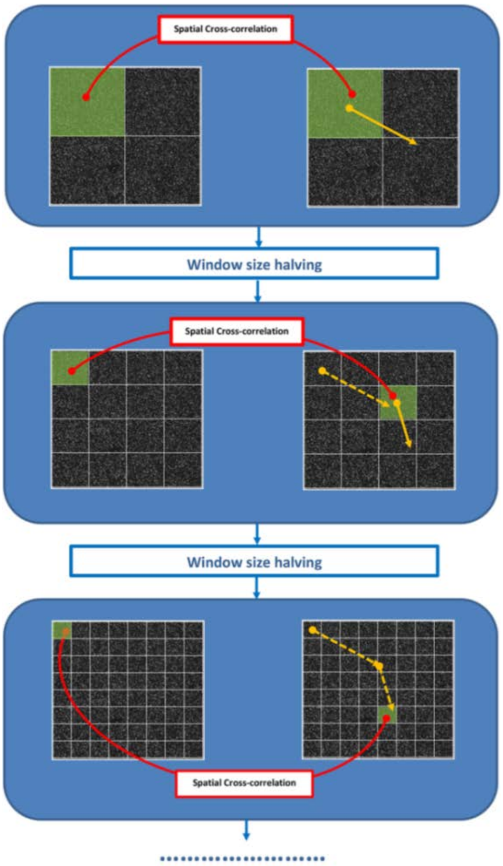


Figure 15. Spatial correlation analysis: iterative window offset correlation

In most commercially available commercial software, it is also possible to use window sizes that are not equal to powers of 2. This implementation is particularly useful to define the size of the final interrogation window in a manner that optimizes the resolution of the measurement. In the above example, for instance, the final size of 32x32 pixel might be too conservative and an equivalent correlation might be obtained at 24x24, improving the resolution by a factor 0.5625 (i.e. vector to vector distance).

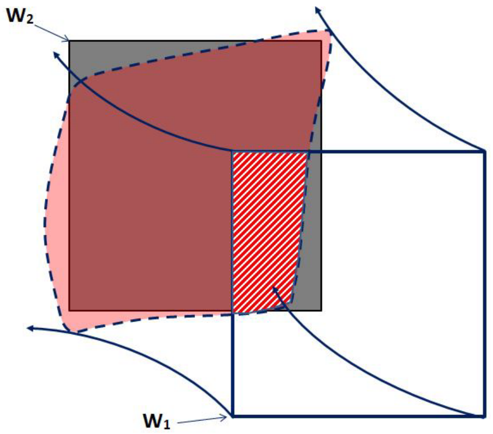


Figure 16. Iterative window deformation

- *Iterative window deformation*. Window deformation is used to minimize the degradation of the correlation peak signal in flow regions with large velocity gradients (Huang at al., 1993; Scarano, 2002). It consists of a flow-adaptive local window refinement scheme that deforms the shape of the interrogation window according to the local curvature of the velocity components to minimize the loss of particle pairs in the correlation analysis. Figure 16 illustrates the technique: particles imaged at time t1 in window W1 are advected by the local flow in the time duration between the two laser pulses. At time t2, only a fraction of the particle images remain within W1 (red and white lines). An offset interrogation window W2 can capture a large fraction, but not all, of the displaced particle (Adrian and Westerweel, 2011). The iterative window deformation technique, on the other hand, calculates the optimal window (deformed dashed region) that can maximize the quality of the correlation peak computation.

Although iterative window deformation can result in an improvement in peak detection and a reduction in the measurement error, its application may significantly increase processing time. It is recommended that the use be limited to the following conditions:

a) Flow dominated by large in-plane displacement gradients with a typical length scale on the order of the dimension of the interrogation window or larger;
d) Flows with a non-significant variation of the displacement at scales below the dimension of the interrogation domain;
e) Measurement setups with a light sheet thickness Δz smaller than the in-plane dimension of the interrogation domain.

If the above conditions are met, the effectiveness of the algorithm and its impact on the processing time should be evaluated on a reference image-pair before the option is applied to the entire experiment data set.

- *Window overlap*. The spatial correlation process is typically repeated at discrete intervals equal to a number of pixels that may be less than the interrogation window size. This overlap among neighboring interrogation windows improves the spatial sampling of the measurement and allows small flow structures to be better resolved. An overlap of 75% is usually recommended, at least in the final passes of the iterative processing (if applied), at the cost of increased processing time. For example using 50% overlap (a vector spaced every half of an interrogation window size) will be about 8 times faster than 75% overlap (a vector spaced every quarter of an interrogation window size).

9. VECTOR VALIDATION

9.1 Outlier identification and replacement

Spatial correlation analysis is likely to return a number of "spurious" vectors whose occurrence is inevitable even in carefully designed experiments. These vectors deviate in magnitude and direction from nearby valid vectors and largely arise due to insufficient number of particle image pairs.

The challenge in data validation is to strike a good balance between over-detection (unintended removal of valid data) and under-detection (inadequate rejection of spurious vectors). The current discussion is limited to the most widespread validation criteria implemented in many commercial software, and the reader is referred to a large body of literature for a more complete review of the multitude of vector validation techniques:

- *Local median-filtering criterion*. This procedure identifies displacement vectors which deviate from the nearest neighboring vectors by a prescribed amount in magnitude or direction (Westerweel, 1994; Westerweel and Scarano, 2005).
- *Cross-correlation signal-to-noise ratio validation criterion*. This procedure uses the intensity ratio between the first and second highest correlation peaks as a selective criterion to identify outliers. Vectors are considered spurious if such a ratio drops under a defined threshold (Keane & Adrian 1992).
- *Displacement range validation criterion*. All vectors outside a defined displacement range are considered as outliers. A representative value of the displacement range is the mean value plus/minus three standard deviations calculated over the whole field of view.
- *Geometric validation criterion*. All vectors falling within a defined region are rejected.

The optimization of the validation parameters is another example where empirical testing is the most practical approach. Different choices of parameters are tested on a reference image until an acceptable result is found. In this regard, it is worth noting that several validation criteria are non-linear, so the order in which they are applied is important and somewhat data dependent. A simple starting procedure is suggested in Adrian and Westerweel (2011) and consists of the following steps:

- Determine the mean and standard deviation over the whole field of view;
- At each grid point remove the vector if its magnitude differs from the global mean by more than three standard deviations. This eliminates the worst invalid vectors;
- At each grid point, calculate a representative value of the neighboring vectors and discard all the vectors that fall too far away from the median. Typically, the median value of the eight nearest neighboring grid points is used and the comparison based on magnitude and directions;
- Look at the second and third tallest correlation peaks to check if one of them agrees with the neighborhood mean better than the first and use this value;
- Use post-validation histogram to detect any remaining outlier and spurious data (Figure 17);
- Interpolate over holes in the data that cannot be filled by the preceding steps;
- Repeat the procedure until it converges.

Once an optimal routine is identified, it can be automatically applied to the entire PIV image set. The percentage of outliers should typically be less than 5%. Above this value, adjustment to the image quality and preprocessing and processing parameters should be considered.

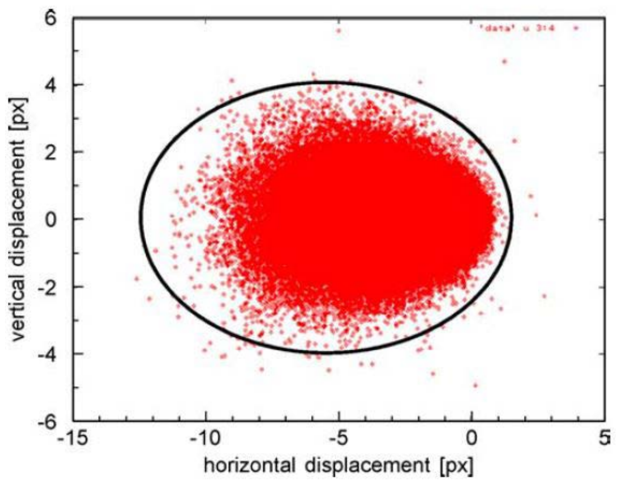


Figure 17. Example of post-validation histogram: all data outside the ellipse are considered to be outliers (Stanislas et al., 2005)

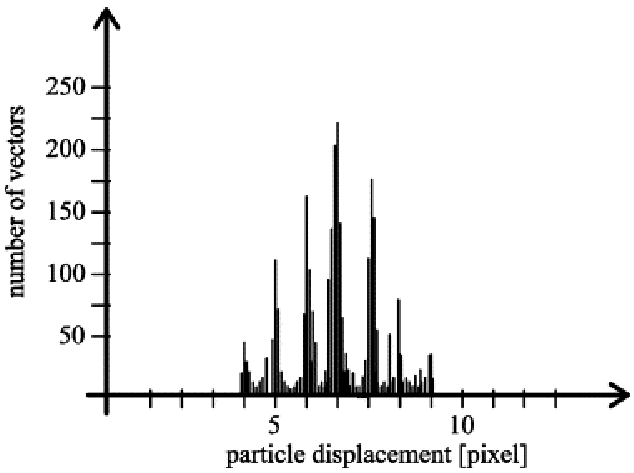


Figure 18. Illustration of peak locking effect associated with insufficient particle image size.

9.2 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. This error occurs when particle images are much smaller than the size of a pixel. A design rule that minimizes the effect of pixel locking states that the particle image diameter should be at least 3-5 pixel (Prasad et al., 1992). The occurrence of pixel locking can be diagnosed by the analysis of the histogram of the global displacement field, looking for peaks spaced at intervals corresponding to 1 pixel (see Figure 18). If pixel locking is found to affect the quality of the data significantly, improvements can be obtained by increasing the diameter of the particle image. In this regard, possible solutions are:

1. defocusing slightly or blur particle images (easiest way).
2. increase the image magnification (at the cost of the field of view)
3. reduce lens aperture (which requires a proportional increase of the laser energy).

10. SPECIFIC PROBLEMS FOR DIFFERENT FACILITIES

10.1 Application in towing tanks

Unlike LDV and other single point techniques, the application of PIV and SPIV is a suitable approach for towing tank measurements and offers the best compromise in terms of costs and accuracy. Thus within the ITTC community, the use of PIV and SPIV for towing tank applications has become more widespread.

Apart from a few cases in which a PIV/SPIV system is fixed in a static position within the facility, most applications in a towing tank involve the installation of both laser and camera on the towing carriage. In these cases, the absence of viewing windows typically necessitates the use of an underwater system. However, underwater PIV systems are time consuming to set up and require a reasonably high degree of expertise, especially if stereoscopic measurements are to be carried out. In the underwater arrangement, camera/cameras must be mounted inside waterproof case/cases, whose position relative to the experiment has to be kept fixed as much as possible. This point is particularly critical in a SPIV setup, where camera arrangement must be kept rigid under hydrodynamic loads, as any relative motion between the two cameras would invalidate the measurements. Recently, the availability of fully underwater SPIV probes with accurate camera positioning systems and remote focus mechanisms has overcome most of the aforementioned problems and allow PIV measurement to be performed in towing tanks with relative ease and reasonable cost.

10.2 Application in hydrodynamic tunnels

In cavitation or water tunnel facilities, water moves within a closed loop and the model is kept fixed. In most of these applications, camera/cameras and laser can be positioned outside of the tunnel, with optical access though the facility windows. This kind of arrangement removes the requirement of rigidly fixing all the components of the system and, thus, results in a reduced measurement uncertainty. On the other hand, the dry arrangement suffers from the problem of reflections induced by the facility windows as well as the effect of the optical aberrations when the optical axis of the camera/cameras is non-perpendicular to the air/glass/water interfaces (e.g. in a SPIV set up). In this regard, using a water-filled prism attached to the facility window, with the air/glass/water interface perpendicular to the camera axis, overcomes most of these problems. In large cavitation tunnels, camera and lasers can be also mounted inside the test section. In such a case, setup issues are similar to those for a towing tank. However, unlike most towing tank applications, the assembly of the system can be easily performed with the tunnel empty.

In a pressurized facility, however, it is likely that tunnel windows might deform and introduce errors to the calibration obtained at ambient pressure. In this case, it might be necessary to undertake calibration under pressurized conditions to avoid any implication to the accuracy of the stereo reconstruction. This operation is quite laborious and requires a more elaborated apparatus to keep the calibration target in position. Nevertheless, it is strongly recommended whenever a high fidelity measurement is required under pressurized conditions.

10.3 Application in other facilities

The use of a conventional maneuvering and seakeeping basins for PIV measurements is relatively uncommon. Basins equipped with a towing carriage operate similarly to a linear towing tank and, thus, the arrangement of a PIV setup has analogous problems, advantages, and disadvantages. Basins designed for the use of free running models only allow measurements with fixed stationary system or one mounted onboard the moving model. The use of PIV in rotating arm facilities is similar in nature to the application in towing tanks.

11. SAFETY ISSUES

All test facilities should be operated and managed with a safety culture based around safe operating procedures supported by training and agreed-upon procedures and processes. In some cases, safety routines and procedures need to be developed, particularly when operating the facility in an unusual or unorthodox manner for specific and unique experiments. The operation of PIV falls within this category.

Electrical safety shall be considered at all times, particularly when operating equipment in the vicinity of hydrodynamic facilities.

PIV experimentation and measurements involve the use of lasers and optical arrangements which pose potentially serious safety hazard for the users. Laser safety involves the safe design, operation and implementation of lasers to minimize the risk of laser accidents. The use and operation of lasers is subjected to government regulations, which should form a part of any safety case or overall risk assessment of the experiment. The operators shall be suitably trained to ensure the correct use of the facility in question. In the case of PIV operation, specialist technicians may be required to support experiments within the facilities. In addition, personal protective equipment (PPE) shall be available and used in accordance with the facility safety policies, in order to eye exposure to direct or indirect laser light. Appropriate signage shall also be displayed at all times during the operation of PIV equipment within the hydrodynamic facility, and access to the facility should be limited to essential personnel only.

The setup of PIV equipment involves significant additional cables/cabling over those normally installed in the hydrodynamic facilities, posing possible trip hazards requiring consideration over the routing and treatment of such cables.

The use of tracer particles is also a relevant issue to be taken into account. Specifically, the user needs to be aware that the handling of small particles may involve some health hazard. Many of these particles are supplied as dry powder, and they may be deposited in the lungs if inhaled. In some cases, these substances may be toxic or carcinogenic. For this reason, the user is strongly advised to use proper measures for protection, such as wearing a mask and gloves while handling these particles as well as applying proper means for disposal of these particles after use.

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