

3 Particle Image Velocimetry

This chapter discusses the Particle Image Velocimetry (PIV) technique. A brief overview of PIV and its working principles has been provided. The significance of its various components in the measurement of velocity has been discussed. The various parameters influencing its performance are also discussed.

3.1 Working principle of PIV

PIV is a non-invasive optical method for measuring instantaneous fields of velocity [66,67]. A typical setup for 2-D PIV recording in a plane within the flow field is shown schematically in figure 3.1. Small tracers or seeding particles are introduced into the flow where velocity measurement is required (area of interest). A laser light sheet pulse is used to illuminate the area of interest within the flow field two times at a known time interval. The flow velocity and imaging magnification must be considered when selecting the interval between laser pulses. A CCD or CMOS camera positioned at a right angle to the laser light sheet are used to record the light scattered by the seeding particles. The image is captured in two separate frames by the camera, which is attached with a lens and a high pass filter. The captured images are moved to a computer's memory for image processing. The images are divided into subareas, defined as interrogation areas (IA). Using statistical techniques such as cross-correlation from frame 1 to frame 2, the local displacement is calculated for each IA. To produce a vector map of the average particle displacement, the evaluation is repeated for each IA of the PIV image. Using calibration, the particle displacement is converted from pixels to millimeters. Now, the displacement vectors can be transformed into a map of velocity vectors by dividing the time between the two pulses. The obtained velocity vector may contain erroneous vector. Therefore, various vector validation algorithms can be used to improve the quality of the obtained velocity field.

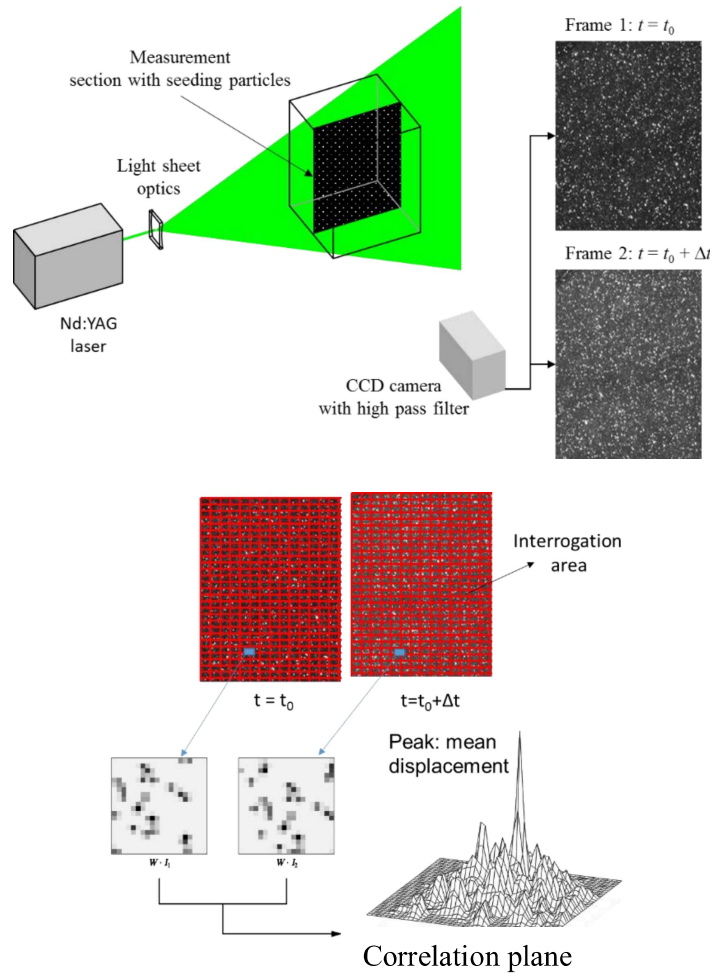


Figure 3.1: Schematic diagram representing the working principle of PIV technique
<https://docplayer.net/18824497-Introduction-of-particle-image-velocimetry.html>

The PIV system can be divided into several subsystems based on its operating principle: seeding particles, imaging, illumination, image processing. The following sections will analyze each subsystem in greater detail.

3.2 PIV subsystems

3.2.1 Seeding Particles

As was previously mentioned, a PIV system measures the displacements of the seeding particles suspended in the fluid medium over a predetermined time interval to estimate the velocity field. Therefore, seeding particles serve as a "velocity probe" in the PIV technique.

Small size particles are needed to track the flow precisely. Additionally, for enough light to scatter, the particles must be large enough for cameras to identify them [68]. The particles should preferably be neutrally buoyant, i.e., their density should be close to that of the fluid.

The seeding particles are required to possess the following characteristics:

- Accurately follow the fluid flow
- Good light scattering
- Cost effective
- Non-volatile, non-reactive, non-toxic and non-corrosive

The PIV technique indirectly measures the flow velocity by tracking particle movements. Hence, the interaction between the seeding particles and the surrounding fluid needed to be investigated to obtain an accurate flow velocity. The effect of gravitational forces on the velocity of the tracer particles is a major source of error. It occurs when there is a difference in the densities of the fluid and the particles. Due to gravity, particles with densities more than the fluid start settling to the bottom with a gravitationally induced or settling velocity (u_g). From Stokes' drag law, which describes the settling of spheres in a Newtonian fluid (shown in figure 3.2), the value of u_g can be calculated as:

$$u_g = \frac{gd_p^2(\rho_p - \rho_f)}{18\mu} \quad (3.1)$$

where d_p is the diameter of the particle, μ is the dynamic viscosity, g is the acceleration caused by gravity, ρ_p and ρ_f are the densities of the particles and the fluid respectively. According to equation 3.1, for avoiding particle sedimentation, the fluid and particle densities should be identical. Such a condition results in neutrally buoyant seeding particles

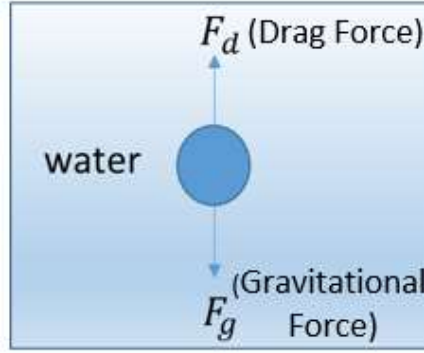


Figure 3.2: Falling sphere in a water medium (the direction of motion of fluid particle determines the drag force direction)

The tendency of the particle to reach velocity equilibrium with the fluid is measured by the particle response time (τ_p), which is given by:

$$\tau_p = \frac{d_p^2 \rho_p}{18\mu} \quad (3.2)$$

The Stokes number (Stk) of the particles must be less than 0.1 in order for the seeding particles to precisely follow the flow [66]. The definition of the particle Stk is

$$Stk = \frac{\text{Particle response time } (\tau_p)}{\text{characteristic time scale } (t_f)} \quad (3.3)$$

Here, the characteristic time scale in the flow is equal to the length scale divided by the characteristic velocity, which is generally obtained by dimensional analysis.

Based on the factors mentioned above, hollow glass spheres (HGS) made of borosilicate were used as the seeding particles in the current study as shown in figure 3.3. These spheres have a mean diameter of $10 \mu m$ and a density of $1.1 g/cm^3$.

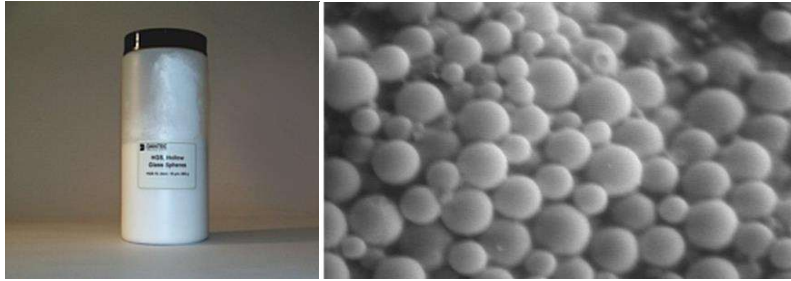


Figure 3.3: Hollow glass sphere (HGS) [69]

3.2.2 Imaging

A digital camera is used to image the seeding particles in PIV techniques shown in figure 3.4. The role of the camera is to record the location of the seeding particles within the flow field which the laser light sheet has illuminated. CCD and CMOS cameras are the two most common types used in PIV techniques. Both cameras are made up of a matrix of detectors known as pixels. The incident photons (due to light scattered by particles and illumination from the background) is converted into an electronic charge which charges every pixel. When light from the particles is captured, a high charge appears as white, and a low charge seems dark when the chip's background noise is recorded. Cameras operate in either auto-correlation or cross-correlation mode, depending on the internal design of the camera. In auto-correlation method, two successive positions of the seeding particles are captured on the same frame, whereas in cross-correlation, they are recorded on separate frames. Hence, when compared to auto-correlation, cross-correlation provides unambiguous directional velocity data. Nowadays, all PIV cameras use cross-correlation mode and have very short frames (approx. 1000 frames per second).

One of the most vital factors in choosing a camera is its resolution. The number of pixels in rows and columns determines the resolution of a camera. PIV resolution, on the other hand, refers to the number of vectors (N_{vector}) in a velocity field.

The value of N_{vector} depends on the camera resolution ($m \times n$ pixels) and is calculated as

$$N_{vector} = \left[\frac{m}{(1 - O_{row}) \cdot M} \times \frac{n}{(1 - O_{column}) \cdot N} \right] \quad (3.4)$$

Here, $M \times N$ is the interrogation area size, O_{row} and O_{column} are interrogation area overlap used in rows and column respectively for the evaluation of PIV data. The N_{vector} should be as large as possible to get the best insight into flow physics. It is obvious from equation 3.4 that the number of vectors depend on the size of the camera resolution.

The seeding particles image size or particle image diameter (d_{image}) also plays a significant role in assessing PIV performance. This parameter is affected by a number of factors, including camera magnification (M), f-number ($f_{\#}$), light source wavelength (λ), and seeding particle size (d_p). It is calculated as

$$d_{image} = \left[(Md_p)^2 + (2.44(1 + M)f_{\#}\lambda)^2 \right]^{\frac{1}{2}} \quad (3.5)$$

The measurement would be biased when the particle image diameter is less than 2 pixels. It is due to the pixel locking effect in which measurements are biased towards integer pixel values[70]. To avoid this, the value calculated from equation 3.5 must always be greater than 2 pixels [66].

Camera calibration is required to change the displacement vector coordinates from pixel to millimeter. For this, a calibration plate with multiple small, evenly spaced holes that are precisely drilled is typically used as shown in figure 3.5. The calibration plate was kept in the area where measurements are required. The camera was focused in the measurement area using the holes of the calibration plate. Based on the camera magnification at imaging, a relation between spatial coordinate and the pixels of the image is obtained. A Flow Sense EO 4M CCD camera was employed in the current study to image the seeding particles. It has a $7.4\mu m$ pixel size and a resolution of 2048 x 2048 pixels.



Figure 3.4: Flow sense EO CCD camera (<https://pdf.directindustry.com/pdf/dantec-dynamics-s/flowsense-eo/15753-696991.html>)

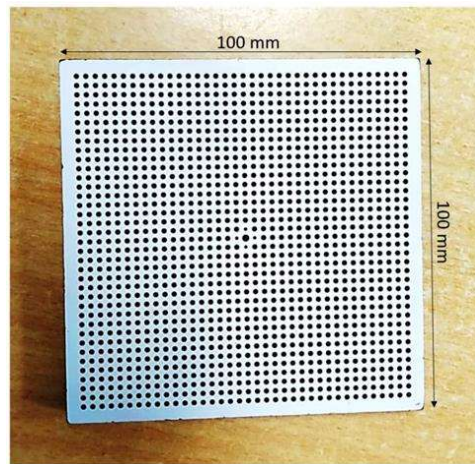


Figure 3.5: Calibration plate

3.2.3 Illumination

A light source is required to illuminate the measurement plane. For this purpose, lasers are frequently used in PIV. It is due to their ability to create monochromatic light with a high energy density that can be readily bundled into thin light sheets. Neodymium- Yttrium Aluminum Garnet (Nd: YAG) are the most important solid-state laser for PIV application having excellent mechanical and thermal characteristics as well as high amplification. In this laser, neodymium doped YAG crystal are used to generate the beam. Figure 3.6 shows a schematic of the Nd: YAG laser, which includes an elliptical cavity, a flash lamp, a YAG

crystal, and reflecting mirrors. The position of these parts is intended to maximize energy transfer from the flash lamp to the crystal. The laser cavities are operated in Q-switch mode to deliver intense energy over a short time required for illumination.

A dual cavity flash-pumped Nd: YAG laser with a maximum pulse energy of 135 mJ and a wavelength of 532 nm was used in the current study. Using laser optics, the collimated beam was transformed into a laser sheet of approximately 1 mm thickness. The laser pulses were timed with the camera frame rate using a synchronizer.

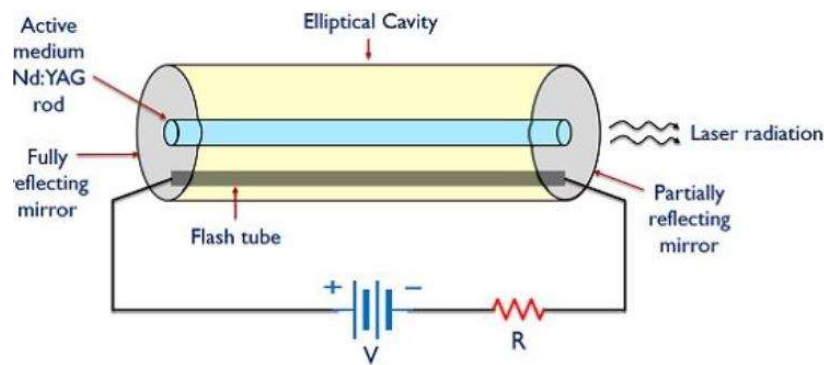


Figure 3.6: Schematic diagram of Nd: YAG laser (<https://circuitglobe.com/ndyag-laser.html>)

3.2.4 Image processing

The analysis of PIV images used to determine the particle displacement can be divided into three parts: - 1) pre-processing (identification of the wall, reduction of the background noise, improving contrast), 2) evaluation methods like adaptive correlation and 3) post-processing (vector validation). These analysis processes should be chosen in a proper way to get accurate measurements of the velocity by PIV. Image quality is enhanced in the pre-processing stage before applying any correlation algorithm. For instance, any reflection from objects in the image should be minimized to obtain an accurate velocity vector. The

second step is to evaluate the velocity field from the pre-processed PIV images. The evaluation process for obtaining a vector map is illustrated in Figure 3.7.

Images 1 and 2 show the spatial position of the seeding particles at times ' t_0 ' and ' $t_0 + \Delta t$ ' respectively. These pictures are subsampled in $m \times n$ pixels (where m represent number of row and n represent number of column). The intensity of light within IA is described by the functions $f(m, n)$ and $g(m, n)$ at ' t_0 ' and ' $t_0 + \Delta t$ ', respectively. FFT (Fast Fourier Transform) converts these functions into the frequency domain as $F(u, v)$, and $G(u, v)$. Then, the two functions, F and G , are correlated using any algorithm like auto, cross, adaptive, or ensemble correlation. An adaptive correlation is the most advanced algorithm that uses particle image data pairs to calculate velocity vectors. This technique allows for the iterative adjustment of the individual IA dimensions, shapes, and locations in order to accommodate varying local seeding densities, flow velocities, and gradients in a flow field. When an instantaneous velocity vector is required, adaptive PIV methods provide reliable data. However, ensemble correlation is preferred for a steady laminar flow, where an average velocity vector is needed. The correlation function of each interrogation area is averaged at each location for all the images in "average or ensemble correlation" as shown in figure 3.8. After using the correlation algorithm, an inverse FFT is used to transform a frequency domain function into a spatial domain function. Now, the displacement vector is transformed into the velocity vector following the peak detection of the correlation plane by dividing time between two subsequent images. If any incorrect or bad vectors are present, further processing or post processing of the obtained vector map is necessary to remove or replace them. Incorrect vectors can be accomplished by filters such as the moving average method, the universal outlier detector etc.

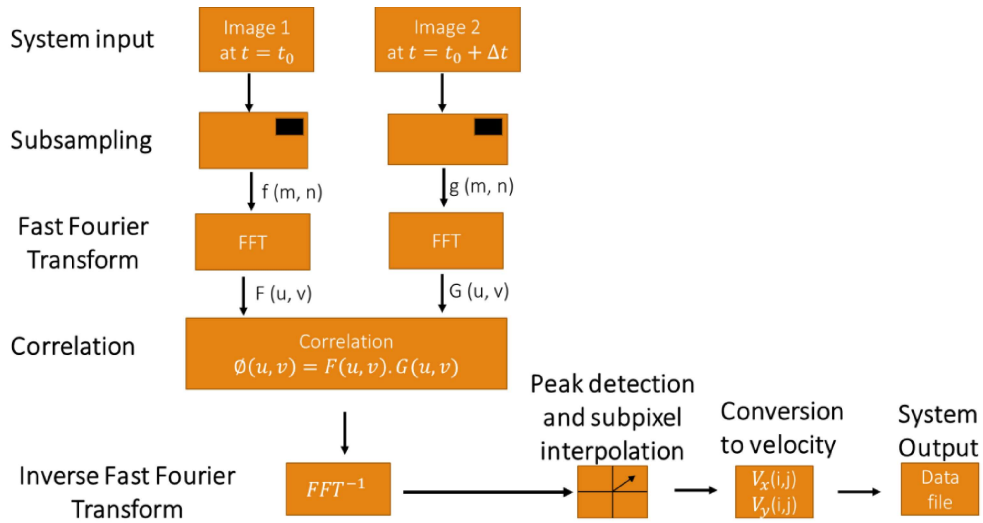


Figure 3.7: PIV Image processing flow chart

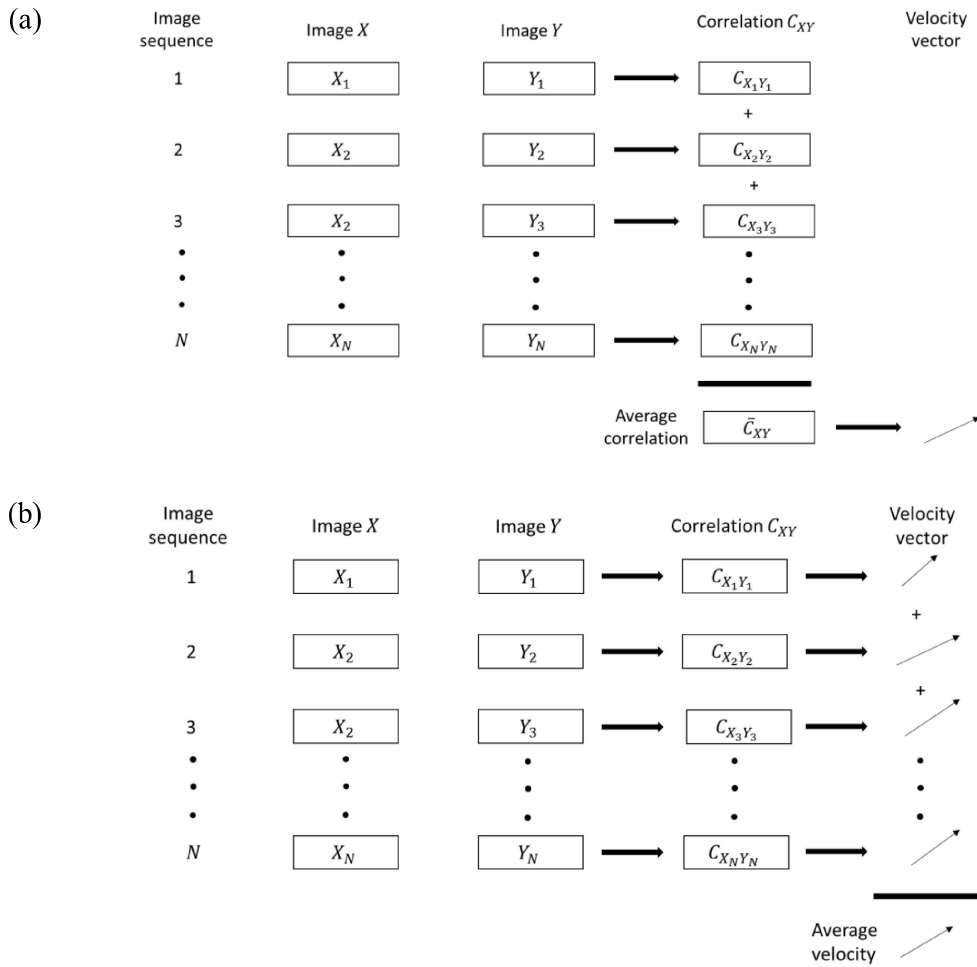


Figure 3.8: Comparison of algorithms used to obtain average velocity with (a) ensemble correlation and (b) adaptive correlation