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Comprehensive Study on Various Types of Particle Image Velocimetry with Explicit Instrumentation

Vishvendra Singh Tomar [a,*], Sahib Chawla [a], Vipul Sangwan [a], Raj Kumar Singh [a], Arun Dhyani [b]

[a] Department of Mechanical Engineering, Delhi Technological University, New Delhi, India
[b] Department of Electronics and Communication Engineering , Delhi Technological University, New Delhi, India

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Abstract

This paper reviews the recent advancements in Particle Image Velocimetry (PIV) along with the specific Instrumentation required. The conventional PIV systems often faced with various problems like longer time lag between pulses, object's shadow problem, opacity of the Test section, PIV errors, restricted Velocity range etc. To curb down these, various PIV systems have been proposed and still PIV is in development phase. Some of the recent developments discussed in this paper include Double-Wavelength Digital PIV, Ultrasonic or Echo PIV and PIV with three color pulsed lamps. To validate these systems, an efficient design and architecture for Real Time PIV based on FPGA technology has been discussed.

1. Introduction

Particle Image Velocimetry (PIV) has been a subject of exhaustive research and development since last three decades due to its ability to provide simultaneous data of the velocity distribution instead of a single point data, when compared with other measuring techniques. It is a whole field, non-intrusive instantaneous flow field measurement technique based on the direct determination of the two fundamental dimensions of the velocity: displacement and time.

In 1991, C. E. Willert set up a new PIV system in which, he substituted the analog camera with a CCD camera, enhancing the accuracy level of measurements. The new PIV system was termed as Digital Particle Image Velocimetry (DPIV). The basic principle of the PIV (Fig. 1.) is that a laser light sheet is used to illuminate the flow field which is seeded with small particles to visualize a flow to be measured. A double pulse YAG laser and a double shutter camera are synchronized to record two particle images with very short time separation. The observed tracer patterns at two subsequent instances are considered as the input and output of the system, and the velocity field is inferred from the analysis of the input and output signals. Cross-correlation algorithm is used to get the displacement of same particles in two images and the velocity of any point in the flow field is analyzed by the time interval between two images and movement of particles. Time interval of the two images should be as short as possible to improve the superior limit of measurable Velocimetry of DPIV system [1, 2].

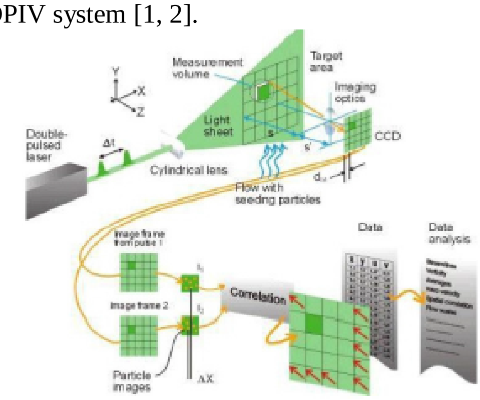

Fig: 1. Experimental Set-Up of DPIV

Corresponding Author,
E-mail address:vst.dtu@gmail.com

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The notable features of PIV includes: (a) Non-intrusive velocity measurement, (b) Indirect velocity measurement by measuring the velocity of tracer particles within the flow, (c) Whole field technique-allowing to record images of large parts of flow fields in a variety of applications in gaseous and liquid media, (d) Velocity lag between seeding particles and fluid flow, (e) Illumination-Using a high power light source for illumination of the tiny tracer particles in order to well expose the photographic film or the video sensor by scattered light, (f) Duration of illumination pulse-short enough to “freeze” the motion of the particles in order to avoid image blurring, (g) Time delay between illumination pulses-long enough to determine the displacement between the images and short enough to avoid particles with an out-of-plane velocity component leaving the light sheet between subsequent illuminations, (h) Distribution of tracer particles in the flow, (i) Density of tracer particle images, (j) Number of illuminations per recording, (k) Number of components of the velocity vector, (l) Extension of the observation volume, (m) Temporal resolution, (n) Spatial resolution and (o) Repeatability of evaluation. Therefore the PIV system must be designed and calibrated keeping in view the above mentioned features [3, 4].

2. Double-Wavelength PIV

These days, ‘Frame Straddling’ is the most extensively used technique for velocity measurement in DPIV, especially at high speeds. In Frame straddling (Fig. 2.), the first laser pulse is produced at the end of first exposure period of camera and the second one is produced at the beginning of the second exposure period by controlling time sequence between the pulsed laser and the special high speed cameras. These cameras can hold two images recorded in rapid succession by transferring the first image recorded by each pixel to on-chip storage well and then recording a second image which is quite expensive. Another restriction to its use is due to its limitation imposed by the frame rate of the cameras and laser pulses controlling.

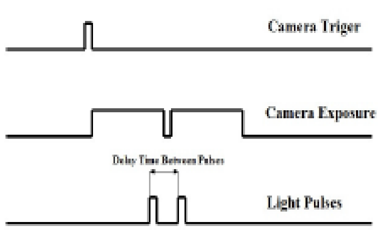

Fig: 2. Basic idea behind Frame-Straddling.

To enhance the superior limit of measurable Velocimetry of DPIV system, DPIV is supplemented with Double-Wavelength system (Fig. 3.). The basic idea behind this is, the light with different wavelengths propagates independently and thus, the two laser pulses can be separated by themselves which allows the use of several laser pulses with different wavelengths to illuminate flow field at different moments. Particle images are captured by different CCDs, each being sensitive to one certain wavelength. In this, the time interval between different particle images in multi-wavelength DPIV just depends on the pulse interval time of different wavelengths, and is independent of the frame rate of the camera leading to a shorter time interval [2-5].

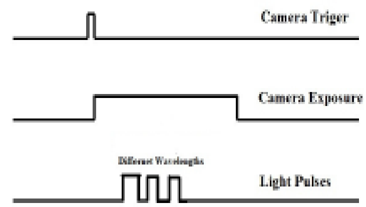

Fig: 3. Basic Idea behind Mullti-Wavelength DPIV.

Chunxiao et al [5] used two different wavelengths 650 nm and 532 nm pulsed lasers for experimental set up behaving as Double-Wavelength DPIV system (Fig. 4.).

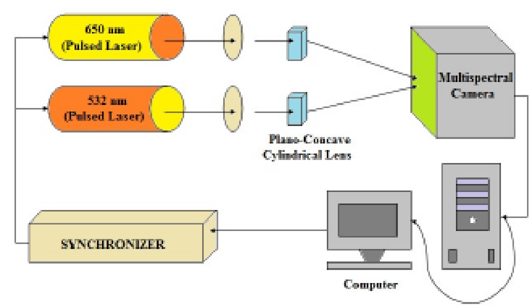

Fig: 4. Experimental Set-Up of Double-Wavelength DPIV.

It consisted of a color camera (RGB CCD), a synchronizer and a computer with frame grabber. A synchronize controls time sequence of the camera exposure and laser pulses. The computer sends a start signal to the synchronizer through the image grabber then synchronizer controls the camera to open the shutter which controls the lasers to generate laser pulses at different moments in one exposure time to illumine the flow field. Light entering the camera through the lens and is separated by a diachronic prism. For selective selection of wavebands, optional narrowband filters were placed in front of the CCD arrays. The red CCD is only sensitive to 650nm light and the green one is only sensitive to 532nm light. Pixel data from each of the CCD arrays was digitized and processed by the Digital Signal Processing module separately. The cross-correlation method was incorporated to statistically determine the most probable displacement of a group of particles in a sampled area.

3. Ultrasonic or Echo PIV

An Ultrasound based Particle Image Velocimetry (Echo PIV) technique for opaque flow analysis consists of identifying and tracking a flow tracer (ultrasound contrast Micro-bubbles) within a flow field, and computing local velocity vectors. In Echo PIV, ultrasound imaging is achieved by sweeping a focused ultrasonic beam generated by ultrasound transducer through the desired field of view of the fluid. The Micro-Bubbles of gas seeded into the fluid flow scatter the ultrasonic beam and due to the huge acoustic impedance mismatch on the interface of bubble and fluid, the bubbles scatter strongly and shine acoustically in ultrasound field. This results in a clear brightness mode image of the particle positions with excellent signal to noise ratio. Following this, two sequential images are then subjected to image processing and data manipulation (Fig. 5.).

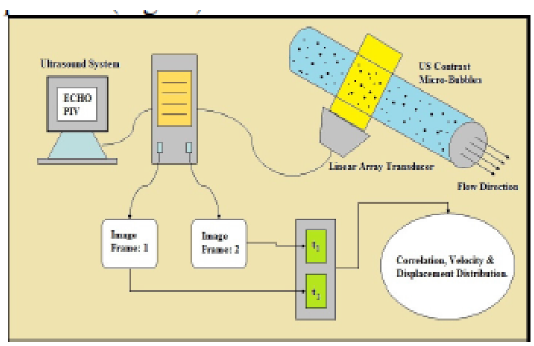

Fig: 5. Experimental Set-Up of Ultrasonic or Echo DPIV.

Using a Cross-Correlation algorithm between the two images, the displacement of the particles, velocity vector field can be evaluated depending on the time difference between the two images. Velocity fields from various flow patterns ranging from rotating flow, transient jet vortex to the flow around carotid plaques can be obtained with good spatial accuracy and dynamic velocity range using Echo PIV. One of the limitation faced by Echo PIV is, the ultrasound contrast micro-bubbles seeded in fluids usually decay with time because their instability in fluids and effect of ultrasonic force. But still, for opaque flow measurement this technique is one of the best, providing a very high degree of precision and accuracy. Moreover, controlled time-sensitive micro-bubble concentration can be varied, depending on the level of measurement required [6, 7].

4. PIV System Based on Three COLOUR Pulsed Lamps

The classical PIV with Laser [8] as illumination source is faced with so many challenges like expensive cost of experimental set-up (mainly due to Laser), its limits on the velocity range that can be measured simultaneously with adequate accuracy and the difficulty in using relatively thick light sheets. As a substitute of it, a simple PIV acquisition system with three colored halogen lamps as pulsed-light sources can be employed. The basic principle behind this is to us three light pulses which provides images of slow particles being well separated, in the long time interval, and images of fast particles being well resolved and maintained on the same image in the short time interval. This gives notably different populations of moving particles depending on their velocity. With such high velocity gradients, the classical correlation analysis can be applied to the whole field by widening the interrogation cell and reducing the velocity field resolution, or more complex evolutions of the correlation technique need to be used. The three flashes provide for two different time intervals between pulses which help in resolving of the low velocities with the same spatial resolution as for the high velocities. Among three lamps, there can be three time intervals available as: Δt_{RG},Δt_{RB} andΔt_{GB} = Δt_{RB} -Δt_{RG}. Hence, now three different velocities can be correlated, which is very helpful for in-cell validation of measurements (Fig. 6.).

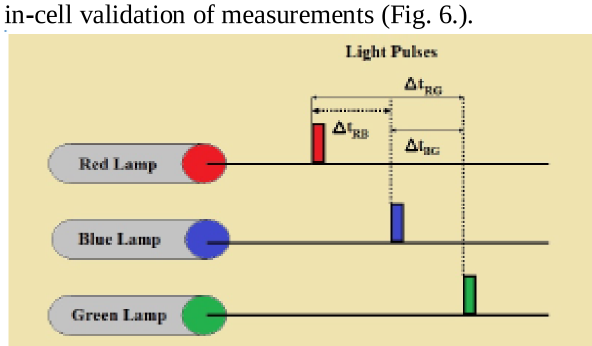

Fig: 6. Three time intervals generated by three lamps.

In the presence of large turbulent structures, the velocity component normal to the light sheet can be significant and the number of particles that remain in the measurement sheet for several elementary measurement times depends on the thickness of the sheet. Due to the mono illumination source, part of the flow around an obstacle may be placed in a shadow region where the measurement is not possible. Using three colored lamps, problems due to shadows can be tackled.

5. PIV Based on FPGA

The PIV algorithms require the region captured on video frames to be divided into small rectangles called interrogation windows. During processing one velocity vector is associated to each rectangle. Subsequently, a uniform grid of results is provided as a practical set of data for post-computations. A smaller piece of one image, called particle image pattern A (PIPA), is extracted from one of those images and the second image is named AREAB. PIPA is compared to all possible sample-shift patterns of AREAB through a correlation formula (RAB) that is computed for each sample-shift [9].

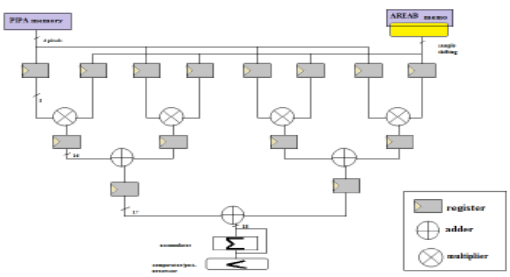

Fig: 7. Fundamental Processor (FP).

Thus, the sample-shift patterns of AREAB are sized like PIPA. Therefore, the peak position of the correlation map is used to search the displacement of particles between both images in the interrogation window. By assuming n = k. We also can define the side size of AREAB as m, with m >n. The architecture implemented in this work is shown in Fig. 7. and named as fundamental processor (FP). The number of multipliers per FP is set by FPGA resources characteristics. Each FP module has a post-processing unit that computes the position of the correlation maximum and may retain useful local data of the RAB map for the sub-pixel computation of the peak position. The critical FSM is named as process controller (PC).

6. Conclusions

The various types of PIV have been conferred, having certain advantages over conventional PIV. The problems like longer time lag between pulses, object's shadow problem, opacity of the Test section, PIV errors, restricted Velocity range etc are sorted out using explicit optical and electronics instrumentation as in Double-Wavelength PIV, Echo PIV and PIV system based on three color pulsed lamps. PIV, one of the best non-intrusive techniques, has got so much potential to generate more accurate and precise results. Further, the instrumentation described above provides it too much flexibility. PIV based on FPGA is described at last.

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