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TIME RESOLVED PIV SOLUTIONS
– PIV AT 4000 FRAMES PER SECOND –

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ABSTRACT

The rapid evolution of digital imagery and the fast growth of computational power over the last ten years have contributed significantly in the development and maturity of image-based diagnostic techniques for flow field characterization. Of the several techniques that have evolved, particle image velocimetry (PIV) for velocity determination has reached a good level of maturity and thus currently enjoys an increasingly level of popularity and acceptance by experimental fluid dynamicists. The current paper focuses on Time Resolved PIV (TR-PIV) presenting its methodology and implementation in terms of hardware for characterization of unsteady flow phenomena.

Key Words: particle image velocimetry (PIV), time resolved measurements, velocity determination

1. INTRODUCTION

Since the early sixties, the investigation of three-dimensional coherent structures in turbulence has been of significant interest to researchers. Time series analysis and theories based on the statistical interpretation of flow have influenced the development of instrumentation dealing with such flows, and led to the evolution of hot-wire anemometry and laser Doppler anemometry as standard tools in turbulence research. The latter came along with the introduction of the laser, and offered researchers a robust way for making non-intrusive measurements of the flow velocity at a point in space. Furthermore, while flow visualization existed prior to this time, the introduction of the laser transformed visualization to speckle photography, opening a new era of laser-based whole field metrology. It was not until the advent of digital imagery and powerful personal computing, however, that the benefits of laser-based visualization really transformed from being qualitative to quantitative.

These two technological advances, digital imagery and computational prowess, have been key for the rapid development of image-based metrology, which in the past decade has enabled researchers to expand their view of turbulent flow phenomena from single-point time series events to multi-point spatially and temporarily evolving events. Currently, image-based flow diagnostics enjoy rapid growth and maturity, as researchers seeing the benefits of non-intrusive multi-point quantification are eager to deploy such techniques in their respective applications. The present paper reviews the particle image velocimetry technique, presenting its methodology, implementation to highly unsteady flows and practicality as tool for obtaining valuable insight to fluid processes.

2. *PARTICLE IMAGE VELOCIMETRY (PIV)*

The power of PIV lies in its ability to provide two- or three-component velocity information at many points in the flow simultaneously. Thus, it can provide a list of direct or derived quantities useful for flow characterization, especially turbulence. Such information includes, mean and fluctuating component velocities, normal and Reynolds stresses, high order moments (skewness & flatness), spatial correlations of in-plane velocity components, integral scales within the plane, vorticity, strain rate, momentum and energy flux estimation, flow rate, and spatial structure information. Furthermore, the recent integration of high framing rate digital cameras and high pulsing rate Nd:YAG lasers (in the kHz range) gives the added capability of determining robustly time-dependent statistics such as multi-point spectra and time correlations.

2.1 PIV Methodology

The basic relation of displacement divided by time to yield velocity is the fundamental principle of the PIV technique. Although PIV is a non-intrusive measurement technique, it requires tracer particles to be suspended in the flow under investigation. These tracer particles can be either naturally occurring or artificially added to the flow. Hence, PIV directly estimates the displacement information of these tracer.

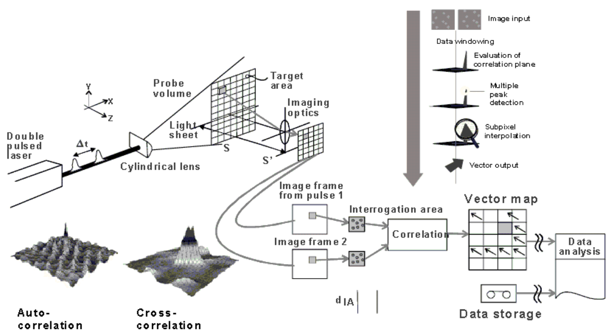

Figure 1. The PIV measurement principle

The PIV apparatus consists of an illumination source, an image capture device, synchronization and data acquisition hardware, and software for user control and data analysis. This technology behind the PIV technique is illustrated in Figure 1. Illumination of the tracer particles is done using a thin light sheet, which is pulsed to freeze the particle motion. The Mie scattering from the imaged tracer particles is recorded at two instances in time using a digital camera. The two sequential digital images are then sub-sampled at particular areas via a prescribed interrogation window, and a spatial cross-correlation is performed using fast Fourier transform (FFT) analysis, resulting in a surface function, as shown. If the two images are recorded on a single camera frame, then an auto-correlation is performed.

2.2 Implementation of PIV

The layout of a typical PIV system is shown in figure 2. Synchronization is a critical part of the system, since laser pulses and camera acquisition need to come together within nanoseconds, especially for high relative (with regards to the image plane) velocity events. In addition, the system needs to control camera shutters to limit background light exposure (such as in combustion), as well as, to be responsive to external trigger events for phase-locked acquisition. Ambient conditions may vary during testing, and thus, acquisition of external transducers simultaneous with PIV data is also important. The end result of acquisition following a simple field-of-view calibration is a planar field of velocity vectors, which may be further reduced to other quantities characterizing the underlying fluid mechanics, as described earlier.

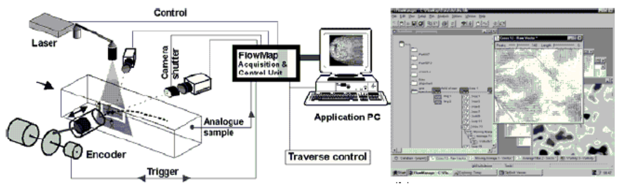

Figure 2. (a) Typical configuration of a commercial PIV system; (b) PIV data analysis

2.3 Time Resolved PIV

The layout of a Time Resolved PIV system is shown in figureFigure **3**. At first glance there is not much difference to a conventional PIV system. It consists of a high repetition rate laser with 50 W or 2 x 12.5 mJ at 2 kHz, a high frame rate CMOS camera that is able to record frames with 30 Hz to 4,000 Hz in the standard version (an upgrade to

10,000 Hz is available). The chip has a size of 1k pixel x 1.3k pixel. Further on, you will find a standard PC equipped with a frame grabber card and a timer card. The PC also controls the hardware and takes over the PIV processing of the particle images.

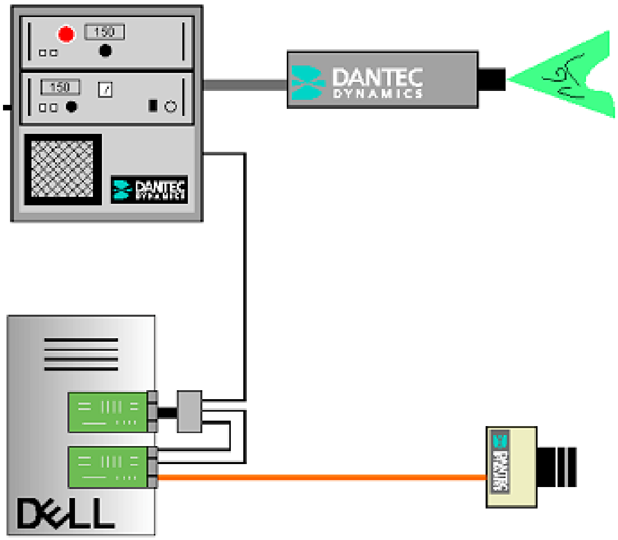

Figure 3. Time Resolved PIV system in single laser configuration

2.4 Lasers for TR-PIV

Lasers for Time Resolved PIV are available either as Nd:YAG lasers @ 532 nm or as Nd:YLF lasers @ 527 nm. Thus both types work within the green range of the visible light. In both cases lasers operate either with a single or a double cavity. Nd:YLF lasers can operate down to small Δt (time between pulses) while their energy output decreases rapidly at frequencies higher than 1 kHz (see Figure 4). On the other hand Nd:YAG lasers with a single cavity have a limit of approx. Δt=40 μs for the time between pulses while they provide twice the energy at higher repetition rates. When smaller times between pulses are needed, double cavity lasers have to be chosen. Independently of Δt the energy only depends on the repetition rate (see Figure 6).

For TR-PIV Nd:YAG lasers are cw-diode pumped, Q-switched and frequency doubled, suitable for generation of short pulses at high repetition rates. Traditional PIV lasers are pumped by pulsed flashlamps, which emit white light over a broad spectral range. Only a small part of the pump energy is effective in pumping the Nd:YAG rod, the bulk of the lamp energy converted to heat, which must be removed by a water cooling circuit. The thermal loading of the laser rod and the need for cooling the flash lamp limit this type of laser to repetition rates below 100Hz. In contrast, cw-pumping by laser diodes with emission wavelength well matched to the absorption band of the Nd:YAG results in high pumping efficiency and thus less heat to be removed by cooling. This results in lasers with high average power and high overall efficiency, and combined with a Q-switch, allows for high pulse repetition rates.

Although these lasers have much higher average power (50 W–100 W) than flashlamp pumped Nd:YAG lasers, the high pulse repetition rate limits the individual pulse energy to levels less than for traditional PIV lasers.

Sinlge cavity Nd:YAG lasers have been designed for double-pulse operation. Because the diodes need some time to pump the laser rod between pulses, very short time pulse intervals (< 40 μS) are not possible in standard versions. The laser has a finite energy output, meaning that the higher the repetition rate, the less energy in each pulse is possible.

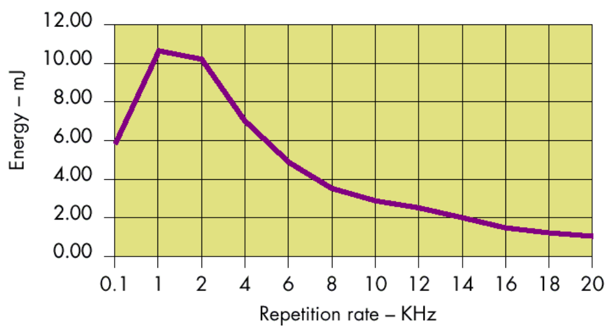

Figure 4. Energy output for a typical ND:YLF laser

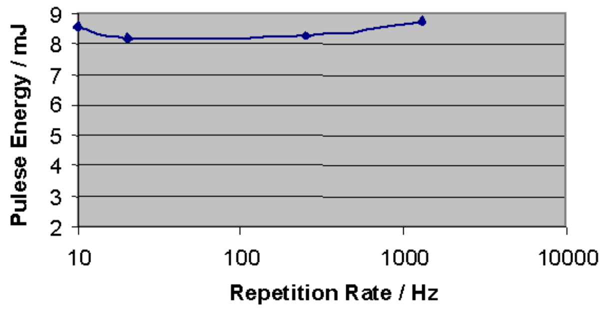

Figure 5. Energy output for a single cavity Nd:YAG laser at a Δt of 200 µs

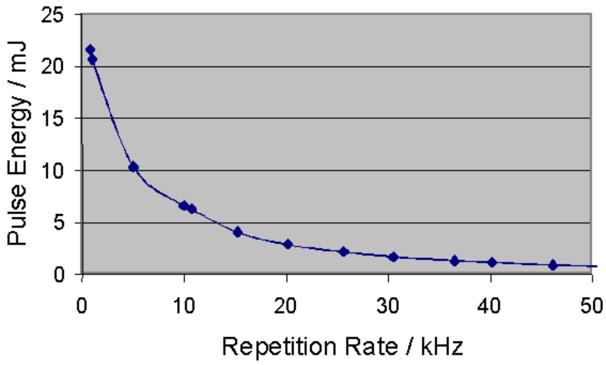

Figure 6. Energy output for a double cavity Nd:YAG laser; energy is independent of Δt

2.5 Cameras for TR-PIV

Cameras for TR-PIV combine an advanced high-speed megapixel resolution CMOS sensor with the features necessary for high-speed analysis of flow phenomena. They are designed to record image data directly into a PC utilising several GB of image memory. The cameras usually are controlled by a control and image acquisition software, and offer flexible triggering options for camera and laser synchronisation. Most cameras can record up to several thousand frames/second. In double-frame mode used for PIV operation the inter-frame closing capability is down to 3 µs–5 µs, meaning this is the minimum Δt which can be realised. Today´s cameras are able to record full resolution images at approx. 1280 pixels x 1024 pixels at frame rates up to a few hundred Hz. Higher frame rates are available with partial readout of the image sensor area. The maximum frame rate depends on the selected image area size. TableTable **1** below gives the dependency between image area and frame rate for a typical TR-PIV camera.

Table 1. Available combinations of frame rate and resolution

Resolution		Frame rate					
Hor	Ver	0.5k	1k	2k	4k	8k	16k
1280	1024						
1280	512						
640	512						
1280	256						
640	256						
320	256						
640	128						
320	128						
160	128						
640	64						
320	64						
80	64						
320	32						
160	32						

3. *APPLICATION EXAMPLES*

Two examples shall give an impression of what is possible with TR-PIV systems. Figure 7 shows some images of a time series that has been recorded in only two seconds. The data that has been recorded comes up to 2000 PIV vector maps or 1 Gbyte of PIV images. One can see the unsteady separated flow behind a wing in stall. It is possible to identify the center of vortices and follow their way downstream. For better visibility the average velocity has been subtracted.

The second example shows the time-space correlation illustrated by a short series of vorticity maps derived. The entire series contained 500 maps and had a duration of 2 seconds, showing the continuous shearing of a Ø25 mm water jet. The average flow is superimposed on the plot.

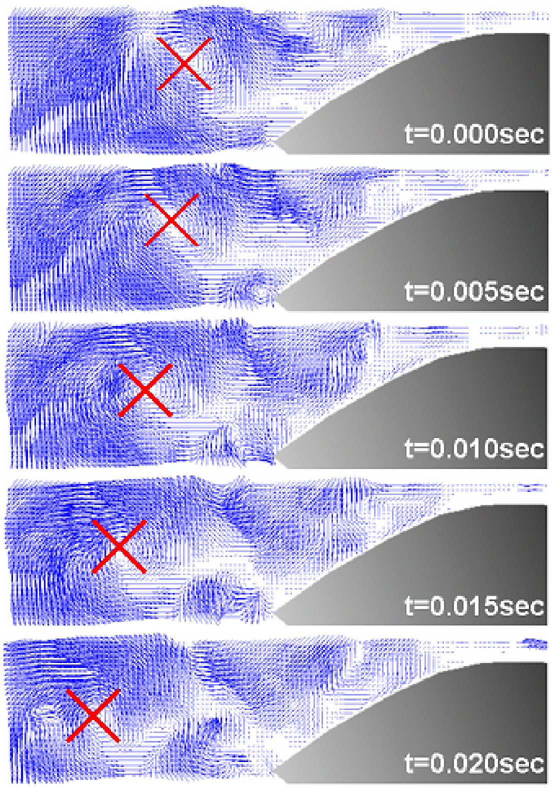

Figure 7. Some images of 2000 PIV vector maps or 1 Gbyte of PIV images in 2 seconds

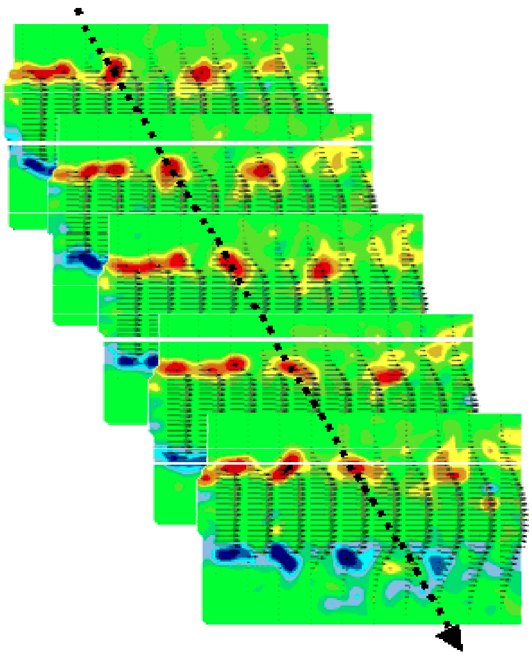

Figure 8. Time-space correlation illustrated by a short series of vorticity maps derived

4. SUMMARY

The typical layout of a TR-PIV system and its components have been described. All the components have to be carefully integrated into a complete system that allows users to study complex unsteady phenomena.

A few examples give an impression of the new possibilities that TR-PIV offers to the fluid mechanics community.