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On the Technical Aspects of the Application of PIV in Turbomachinery

Abstract

The design and development of turbomachines is highly dependent on flow measurement techniques. Owed to its capabilities, particle image velocimetry (PIV) is of intense research interest for flow investigation in turbomachines. In comparison with laboratory measurements, the application of PIV in turbomachinery is more limited and requires several technical considerations. Some examples include strong light reflections from machine parts, access to flow passage, calibration of PIV setup, and highly distorted records in the case of endoscopic measurements. This paper presents several technical features and practical aspects of the application of PIV in turbomachinery, which can be helpful in designing successful PIV measurement setups.

Keywords: Endoscopic Stereoscopic Particle Image Velocimetry, Turbomachinery, Calibration, Image Distortion, Seeding, Light-Sheet Delivery

Introduction

As a non-intrusive flow measurement technique, capable of providing a planar representation of a fluid flow field, particle image velocimetry (PIV) has become a method of choice for flow investigations in turbomachines. Compared to single-point measurement techniques such as hot-wire anemometry (HWA), laser two-focus velocimetry (L2F), laser Doppler anemometry (LDA), and multi-hole aerodynamic pressure probes, PIV provides a planar two or three-component representation of an instantaneous velocity field in successive time-independent measurements (traditional PIV) as well as time-resolved measurements (high-speed PIV). The planar instantaneous representation of a velocity field reveals the flow structures and can be used to study the kinematics of the flow.

PIV setups require fine adjustments and are sensitive to the ambient effects such as vibration and are mostly used in research laboratories. The implementation of this measurement technique for flow investigation in turbomachinery requires several considerations, such as light reflection from solid boundaries, optical access to flow passage, seeding, signal distortion due to particle accumulation or droplet formation, and calibration of the measurement setup.

There has been several successful implementations of PIV in turbomachines. Voges et al. [12] and Wernet [13] used PIV for flow investigation in the diffusers of centrifugal compressors. In combination with transient pressure transducers, Wernet et al. [14] has implemented PIV to capture the compressor surge. Further applications of the PIV technique in radial machines include the study of impeller-diffuser-volute interaction in a centrifugal fan [6], flow measurement in semi-open centrifugal impeller [1], and the investigation of tongue and impeller effects on flow in a centrifugal pump [3]. The implementation of PIV in axial machines have been reported by Uzol et al. [11], Copenhaver et al. [2], Gorrell et al. [4], Kegalj et al. [5], and Yun et al. [20]. Woisetschläger et al. [19] present a review of the applications of PIV for flow investigation in turbomachinery.

In this paper, the application of PIV to internal flow measurements and turbomachinery is considered from a technical point of view. After a brief introduction to the PIV measurement technique, some technical aspects of its implementation are presented including PIV setups, seeding, calibration and distortion compensation of PIV records, light-sheet delivery, and considerations concerning the quality of PIV records.

Principle of Particle Image Velocimetry

In particle image velocimetry, a flow field is visualized by *seeding*, i.e. adding particles, and illuminating the particle stream in a visible section of a flow passage with successive instantaneous laser light-sheets. The velocity field results from analyzing the relative particle displacements in two or more successive images of the illuminated particles.

Figure 1 shows a two-component PIV setup. A particle generator seeds the flow upstream of the measurement section with solid particles or small liquid droplets. A double cavity pulsed laser is used to provide two successive light-sheets with a preset time delay. Each measurement consists of recording two successive images of the illuminated particles. The time delay between the images should be selected, so that the particle movement between the images are distinguishable, i.e. the images should be correlated. The image area is divided into smaller *interrogation windows*, within which the displacement vectors are determined by *auto-correlation* or *cross-correlation*. The size of the interrogation window is a function of the particle density or

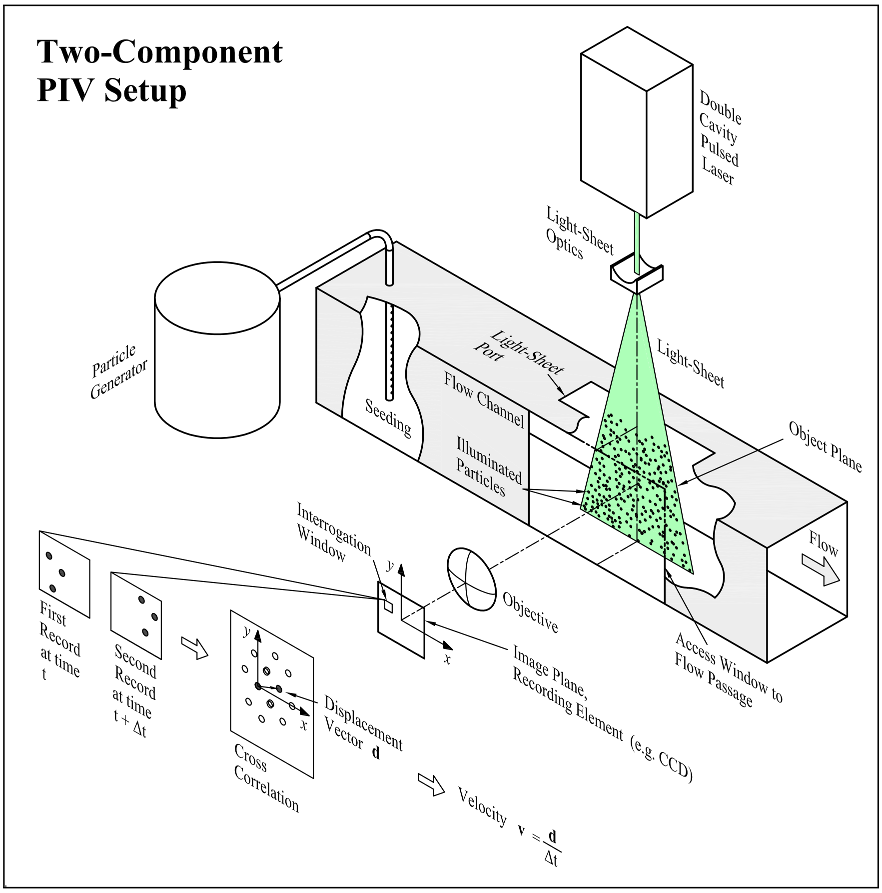


Figure 1: Two-component PIV setup

the number of particles per unit volume, the size of the particle images, the resolution of the recording element, and the displacement of the particles between the image pairs. The projection of the velocity field on the light-sheet which reveals two components of the velocity vectors, results from the division of the displacement vectors by the time difference between the images.

In order to capture all components of a velocity field, an stereoscopic PIV setup, fig. 2, with a minimum of two cameras is required. In an stereoscopic configuration, each camera captures a projection of the velocity vectors. The complete velocity field in the light-sheet results from these projections. A detailed account of the PIV measurement technique can be found in [8], [16], and [10].

Application of PIV in Turbomachinery

PIV measurement in turbomachinery is a very demanding task. The feasibility of a measurement is dependent on several factors. In the following, some of the practical aspects and considerations regarding the application of PIV in turbomachinery are presented.

Table 1: Common PIV setups

	Recorder				Light-Sheet Delivery		
Velocity Components	No. of Cameras	Camera Objective	Camera Endoscope	Scheimpflug Adapter	Light-Sheet Optics	Light-Sheet Endoscope	References
2	1	Yes	-	-	Yes	-	[1, 3]
2	1	Yes	-	-	-	Yes	[12, 14]
2	1	Yes	Yes	-	-	Yes	[5]
3	2	Yes	-	Yes	-	Yes	[15, 20]
3	2	Yes	Yes	Yes	-	Yes	[7]

Common PIV Setups

A summary of common PIV setups is provided in table 1. If applicable, a two-component measurement setup, fig. 1, favors considerable simplicity in comparison with a three-component stereoscopic setup, fig. 2. Considering the sizes of cameras, objectives, and light-sheet optics, the geometrical dimensions of a machine may limit the application of an stereoscopic setup. In such cases, endoscopic PIV provides more flexibility. A two-component PIV setup with a camera objective and a light-sheet endoscope is illustrated in fig. 3 for flow measurement downstream of the rotor blades of an axial turbine. The light-sheet is in the plane of the figure and at 90° with respect to its endoscope axis. The access of the camera to the flow passage is provided by a window in the turbine casing, which is marked as the ``visible range'' in the figure. The light-sheet endoscope can be moved along the height of the flow channel for flow measurement at different blade sections. Direct light reflections are limited to the regions, where the light-sheet meets the blade boundaries, and have limited effect on the rest of the illuminated region.

Scheimpflug criterion [9] should be satisfied in three-component stereoscopic setups by special adapters, which allow the rotation of camera with respect to its objective. This criterion is illustrated in fig. 2, where the planes of the light-sheet, the objective, and the recording element of each camera intersect each other at a common line. Fig. 4 shows a full endoscopic stereoscopic PIV setup for flow investigation between the inlet guide vanes (IGVs) and the impeller of a centrifugal compressor [7]. The setup consists of two cameras at about 90° with respect to each other and a light-sheet in between. Each camera has a Scheimpflug adapter, an objective, and an endoscope. The light-sheet is delivered via a light-sheet endoscope, which is in the plane of the camera endoscopes. The plane of the light-sheet is perpendicular to the plane of the camera endoscopes and passes through the machine axis. Fig. 7 shows a PIV record of this setup.

The quality of endoscopic PIV records are considerably lower than that of traditional PIV. Due to higher signal-to-noise ratio and lower image distortion, imaging with camera objectives is preferred to imaging with camera endoscopes. The light-sheet provided by light-sheet optics has more intensity than the light-sheet delivered by a light-sheet endoscope. However, light-sheet endoscopes can effectively be used in PIV measurements. Therefore, a PIV setup which uses camera objective and is equipped with light-sheet delivery either with light-sheet optics or light-sheet endoscope is preferred to a setup, in which camera endoscope is used.

Seeding

Seeding plays an important role in PIV measurements. The particles are added upstream of the measurement section, so that the particle distribution in the test section be homogeneous and

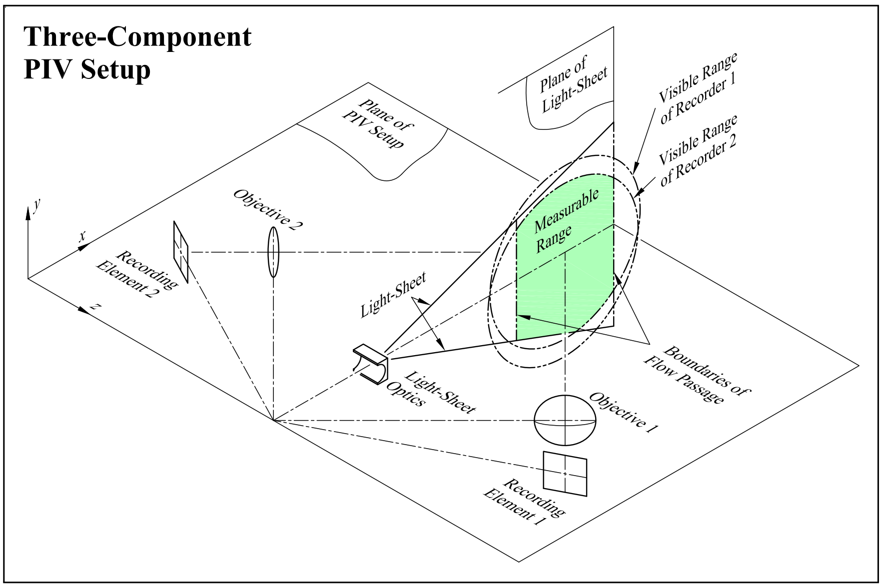
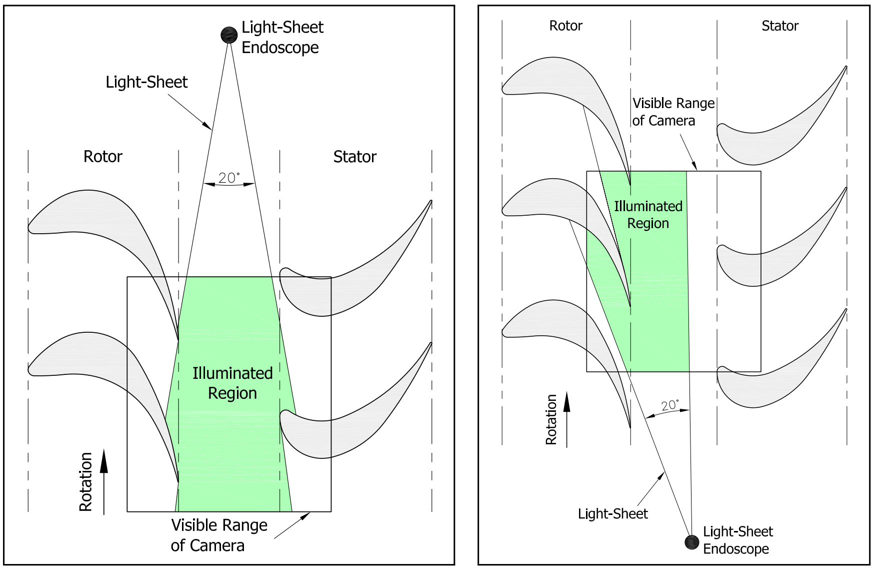


Figure 2: Three-component stereoscopic PIV setup



(a) (b)

Figure 3: Two-component PIV configurations for downstream flow measurement of rotor blades in an axial turbine. Light-sheet is provided by a 90° light-sheet endoscope. Camera access is provided by a window in the casing.

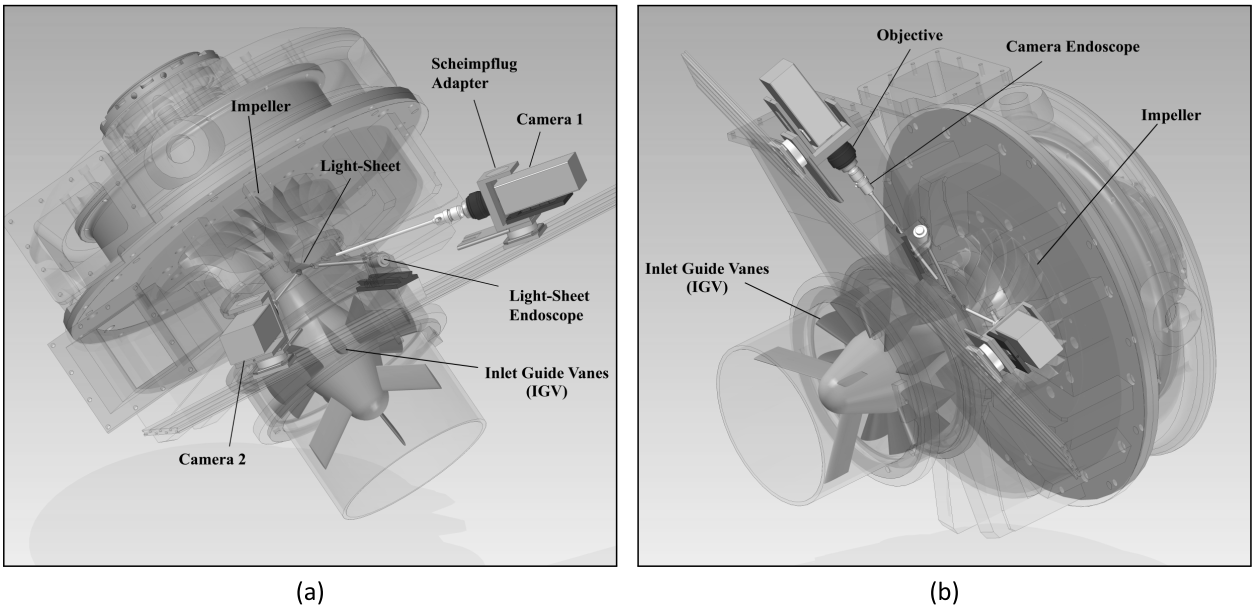


Figure 4: Three-component PIV setup for flow investigation between the IGV and impeller in a centrifugal compressor [7]

with a suitable particle density. Since only the particles, which pass through the test section, are useful in PIV measurements, the main flow can be partially seeded.

The addition of particles usually introduces disturbances in the flow, which can be negligible in the main stream. However, they can alter the particle distribution in a test section, if the seeding location is too close. An example is illustrated in fig. 1. Oil droplets from the particle generator enter the flow from a series of small holes along a tube with an outer diameter considerably smaller than the characteristic dimensions of the flow channel. Depending on the flow conditions, the effect of the tube on the main stream my be negligible. However, the presence of the von Kármán vortex street downstream of the tube can alter the particle distribution in a periodic manner. If the seeding location is near the test section, the particle distribution in the measurement section will be inhomogeneous. In PIV records, this effect is visible as bulks of particles passing through the measurement section. In turbomachines, the location of seeding should be selected so that these disturbances be dissipated upstream of the measurement section.

Calibration and Distortion Compensation

The regular calibration of a PIV setup consists of the imaging of a geometrically known, or a reference, object placed in the light-sheet plane. In two-component PIV setups, if the optical distortion of the recorded images are negligible, the reference object need not fill in the whole visible range of the camera. However, if the image distortion is not negligible, for instance in an stereoscopic PIV configuration, the reference object should fill in the whole visible range of each camera and should contain the distribution of geometrically known patterns, such as a rectangular grid of points or a chessboard pattern.

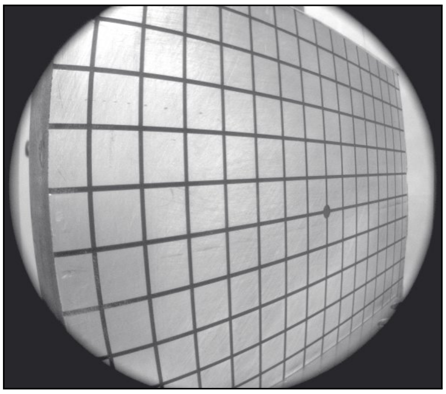


Figure 5: Calibration grid recorded by an endoscope

In closed channel measurements such as in turbomachines, access to measurement section can be limited and the placement of a reference object in the measurement section may not be practical. In such cases, the PIV configuration can be calibrated outside of the measurement section. In this method, the movement of the PIV assembly between the calibration and the measurement positions may be accompanied by a reduction of the measurement accuracy. In another approach, Wieneke [17] presents a calibration method for internal flow measurements, in which the calibration plane can be placed outside of the measurement section.

Besides geometrical scaling, calibration images provide the distortion information of a PIV setup. The images, which are recorded by camera objectives, usually have nearly linear distortions, which can effectively be corrected by analytic transformation functions such as polynomials or the ratio of polynomials [18]. Higher order distortions can occur in endoscopic imaging. Figure 5 illustrates a calibration image recorded by using an endoscope with an oblique viewing angle in an stereoscopic configuration, in which the curvature of the grid lines is an indication of a distortion of higher order than linear. Experiments have shown that this type of distortion cannot be effectively compensated by using polynomial-based transformation functions. The correction of such distortions requires the use of more advanced distortion compensation techniques such as the methods, which are based on partial differential equations (PDEs) [7]. The results of the application of a PDE-based method using the Poisson equation to the distortion type illustrated in fig. 5 are shown in fig. 6 for a calibration image and in fig. 7b for a PIV record.

In stereoscopic PIV, the part of the measurement section, which is recorded by all cameras, and for which the image distortion data is available, can be used in stereoscopic analysis for determining the velocity components. A mismatch between the visible ranges of the recorders can occur in endoscopic PIV due to the manufacturing accuracies of endoscopes. Fig. 2 illustrates how the measurable range is affected by partial overlap of the visible ranges of the recorders and fig. 6 shows a typical loss of signal, regions (a) and (b), in a reconstructed calibration image due to partial mismatch between the visible ranges.

Light-sheet Delivery

There are two common methods for delivering light-sheet to a measurement section. In the first method, laser light is guided to the measurement section by optical components such as prisms and mirrors mounted on the light path. In this method, the optical components can be designed

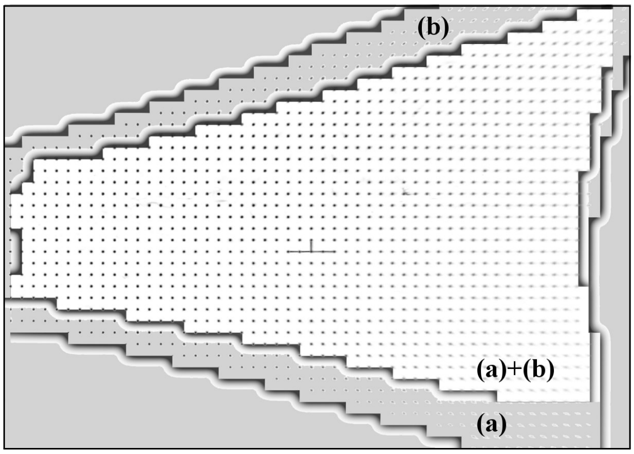
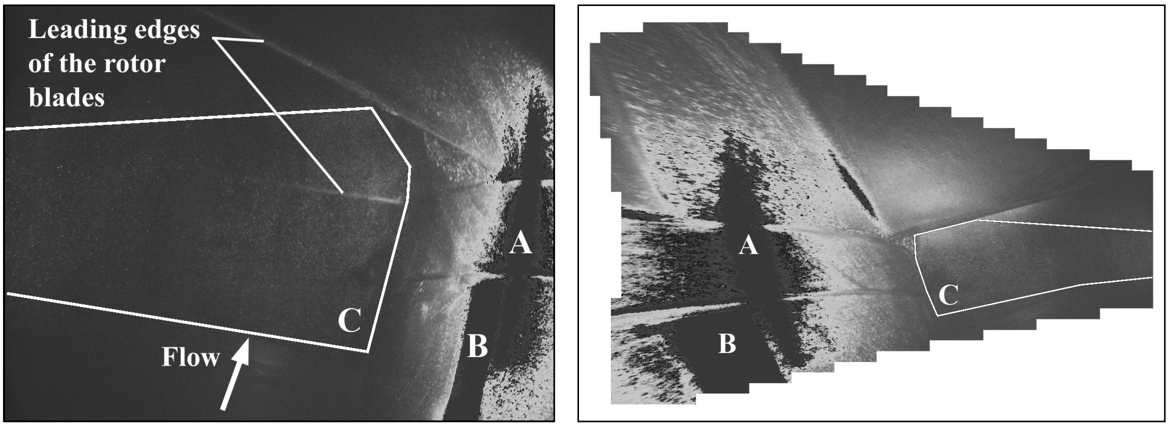


Figure 6: Reconstructed calibration grids of the two cameras in the stereoscopic configuration of fig. 4. Region (a)+(b) is the common region recorded by the cameras, which is used in the stereoscopic analysis. Regions (a) and (b) lie out of the common visible range of the cameras and the signals in these regions are lost.



(a) (b)

Figure 7: Typical endoscopic stereoscopic PIV records of the setup in fig. 4, (a) the PIV record of camera 1 and (b) the reconstructed image of camera 2. Region A is the reflection of the light-sheet and region B is a rectangular marking on the rotor for the adjustment of the light-sheet. The light-sheet should be parallel to this rectangular region. Regions C show the measurable part of each image, where the illuminated particles are distinguished from the background. The original gray-scale levels are modified for better visibility [7].

to have no physical connection and, therefore, the effect of machine vibration on the optical settings is minimized. Besides, the optical components are accessible for adjustments. However, since the laser light is exposed, the measurement area should be protected according to laser safety requirements.

In the second method, the laser light is guided to the measurement section through a laser-arm, which consists of 45° mirrors, mounted at the end of metal tubes which are linked to each other with flexible joints. In this method, the laser light is protected, which allows personnel access to the measurement area during operation. However, machine vibration can alter the optical settings, which can result in the displacement of the laser beam from its adjusted position. This displacement can be negligible in the light-sheet optics, in which the sizes of the optical components are considerably larger than the displacement of the laser beam. However, it can cause considerable changes in the light-sheet provided by a light-sheet endoscope. Figure 9 illustrates an example of the effect of machine vibration on the position of the light-sheet, which is delivered through a laser-arm and a light-sheet endoscope. The reflection pattern of the light-sheet on the metal surface, region A, should be parallel to mark B on the impeller. The displacement of the laser-arm due to machine vibration, has caused the movement of the light-sheet out of its adjusted position.

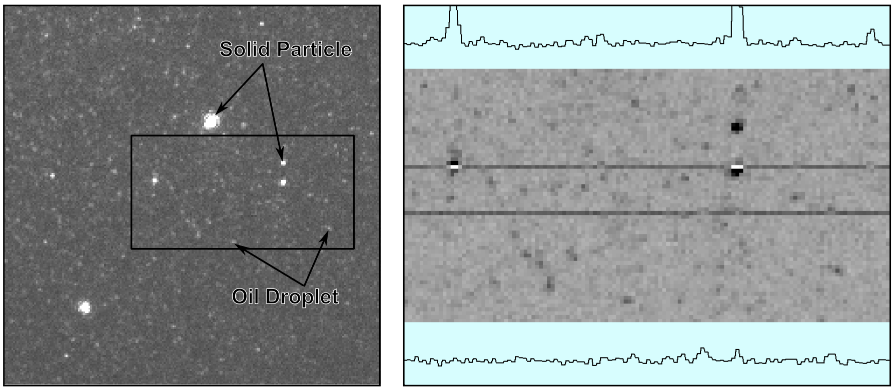
PIV Records

The quality of a PIV record is dependent on several parameters such as device noise, background illumination, and the quality of particle images. Device noise is the noise added to a PIV record by a recorder such as a digital camera. It is generally of random nature and its level is a measure of the minimum signal intensity, which can be recorded. In most of PIV setups which use objectives for imaging, the effect of this type of noise is negligible. Its effect becomes considerable at low light intensities, such as in endoscopic imaging. Since the internal noise cannot, in general, be controlled during a measurement, the particle images or the signal should be strong enough to suppress this noise effect.

Figure 8 shows a comparison between solid particle and oil droplet images recorded by using a camera endoscope. The images of solid particles are considerably brighter, than that of the oil droplets. The light intensity distribution diagrams in fig. 8b, corresponding to the inverted lines of pixels, show the signal quality as compared with the image noise. The image noise in this figure is the resultant of all effective noise sources, such as the device noise and background illumination. The global reduction of light intensity by camera endoscope, has brought the signal level of the oil droplets to the noise level, which has caused partial loss of their signals. Where applicable, the strong reflective properties of solid particles makes them a suitable choice for endoscopic measurements.

Background illumination plays a major role in internal flow measurements. Laser light reflection from visible boundaries is strong enough to ruin the signal in a visible reflection region and its close vicinity, region A in fig. 7. Laser flare and light reflection from the boundaries outside of the measurement section can cause secondary illuminations of the visible background, which interfere with the particle signals.

One method for reducing the effect of the secondary light reflections is the use of black paint on the boundaries. A black paint with strong reflecting property is suitable for guiding an incident beam away from the measurement section, such as in near wall flow measurements. A paint with good light absorbing property is suitable for reducing the effect of the secondary light



(a) (b)

Figure 8: Comparison between the image quality of oil droplets and solid particles in an endoscopic PIV record of an air stream, (a) a PIV image with both solid particles and oil droplets and (b) inverted enlarged image of the marked section in image a. The upper and lower graphs show the light intensity distribution along the upper and lower rows of the pixels with inverted colors, respectively.

reflections. Painting is not a suitable solution for direct light reflections, and it is best to remove such reflections from the visible range of the recorders during the design of a PIV setup.

In the case of seeding with liquid droplets, they can attach to the boundaries and form a liquid layer, which affects the reflectivity and reflection patterns of the internal surfaces. This effect is illustrated in fig. 9, in which the formation of a droplet on the endoscope window has affected a part of the signal. Hence, cleaning methods for optical components, which are in direct contact with the particle stream, should be included in the design of a PIV setup.

Summary

Several technical aspects of the application of PIV in turbomachinery has been presented, which are encountered during the design, installation, calibration and measurement by a PIV setup. After a brief introduction to the PIV measurement technique, common PIV setups are discussed, in which the role of the light-sheet and camera endoscopes are considered and the advantages of different setups are presented. It is followed by several practical considerations on seeding, calibration, image distortion and distortion compensation, PIV record quality, and light-sheet delivery, together with several examples, which can be helpful in designing successful PIV measurement setups for internal flow and turbomachinery applications.

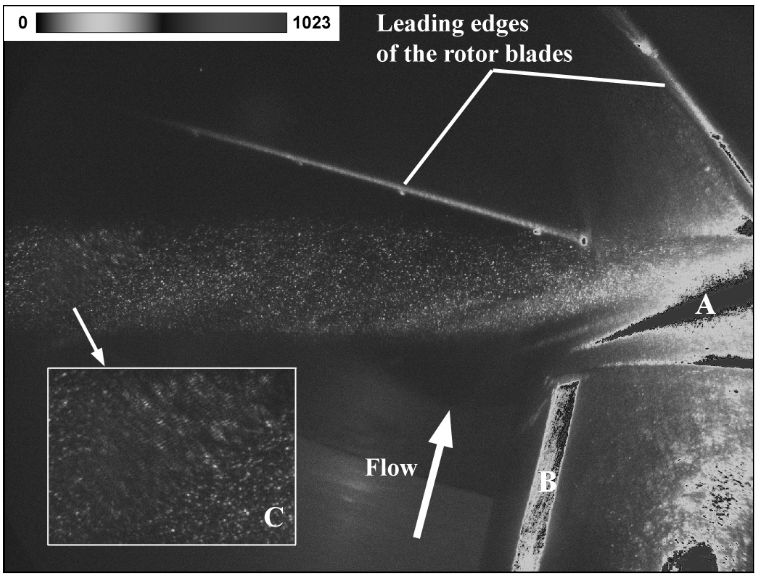


Figure 9: Rotation of the light-sheet, region A, from its expected direction, which is along the machine axis and parallel to the rectangle B, and the effect of droplet formation on the front window of a camera endoscope, region C. The original gray-scale levels are modified for better visibility. The color strip indicates gray scale intensities corresponding to the color distribution.

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