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Advance Measurement Techniques in Turbomachines

Fangyuan Lou

Abstract

This chapter focuses on advanced measurement techniques that have been used in applications of turbomachines including temperature measurements, pressure measurements, velocity measurements, and strain/stress measurements. Though the measurement techniques are fundamentally the same as those used in other applications, the unique features associated with turbomachines place challenges in implementing these techniques. This chapter covers the fundamental working principles of individual measurement technique as well as the highlights of its application in turbomachines.

Keywords: measurement techniques, temperature-sensitive paint, pressure-sensitive paint, laser Doppler velocimetry, particle image velocimetry, hot-wire anemometry, strain gauges, nonintrusive stress measurement systems

1. Introduction

Turbomachine consists a wide and diverse class of devices that have been used in air, land, and sea. Below is a list of representative applications for turbomachines:

- Fans and blowers
- Compressors in aviation (gas turbine engines), transportation (turbocharging systems), and oil and gas applications including axial, radial, mixed, and scroll compressors
- Turbines in gas turbine engines, steam turbines, and hydraulic turbines
- Wind turbines
- Pumps
- Propellers and open rotors

The flow in turbomachines is highly three-dimensional, turbulent, and inherently unsteady. The unsteady nature of the flow in turbomachines is a result of work exchange between the machine and its working fluid. These complex flow phenomena affect the performance and operability. The interactions between the flow and hardware structures can result in undesired noise, vibration, and sometimes failure of the machine. On one hand, enhanced understanding of the complex flow

phenomena in turbomachines is essential for the development of better turbomachines in the future and, thus, requires experimental benchmark data associated with the flow including velocity, pressure, and temperature. On the other hand, better monitoring of the health status of the rotating groups (i.e., stress of rotors) is also of great importance for failure prevention.

Extensive experimental studies have been performed during the past few decades to investigate the complex flow as well as fluid-structure interactions in turbomachines. This chapter discusses the advanced techniques as well as highlights the challenges in implementing these techniques.

2. Velocity and turbulence measurements

This section discusses three techniques for velocity and turbulence measurements in applications of turbomachines including hot-wire anemometry, laser Doppler velocimetry (LDV), and particle image velocimetry (PIV). A brief introduction of the working principles, features associated with the measurement technique, and the challenges for implementation in turbomachines are presented. Lists of previous studies in the open literature applying these measurement techniques to turbomachines are also provided.

2.1 Thermal anemometer

Hot-wire anemometry is an intrusive measurement technique that provides instantaneous velocity and turbulence measurements. It allows characterizing high-frequency flow structures at relatively inexpensive cost when compared with alternative approaches such as laser Doppler velocimetry and other optical techniques. Below highlights the features of the hot-wire anemometry.

Intrusive velocity measurement. In contrast to techniques for the measurement of flow velocities employing probes such as pressure tubes or hot wires, the LDV technique features a nonintrusive nature eliminating the disturbances introduced by the presence of the probes.

Direct velocity measurement. The hot-wire anemometry does not require particle tracers and provides direct measurements of the fluid velocity and turbulence.

Point measurement. Hot-wire anemometry is a point-based measurement, and the measurement volume is determined by the dimensions of the employed wires.

A hot-wire probe consists of a short-length (on the magnitude of millimeter), fine-diameter (on the magnitude of micrometer) wire that is attached to two prongs. The technique relies on the changes in heat transfer between the heated wire and the fluid the wire is exposed. Heat is introduced in the sensor by Joule heating and is lost primarily by forced convection. A significant parameter that controls the operation of the sensor is the relative difference in temperature between the heated up wire and the flow, which is related to the overheat ratio of the sensor. Changes in the flow properties, such as velocity, density, temperature, and humidity, will cause a corresponding change in the heat transfer from the wire which can be detected and measured. Hot wires are typically run in either a constant temperature (CT) mode or constant current (CC) mode. A sketch of circuit for thermal anemometry operating in constant temperature mode is shown in **Figure 1**. Constant temperature anemometry utilizes a rapid-response servo circuit coupled with the Wheatstone bridge amplifier to control the applied voltage and maintain a constant wire resistance, which in turn maintains a constant wire temperature. It eliminates the effect of thermal inertial of the wire, as well as the system response time, and, thus, provides a better frequency response compared to the constant current

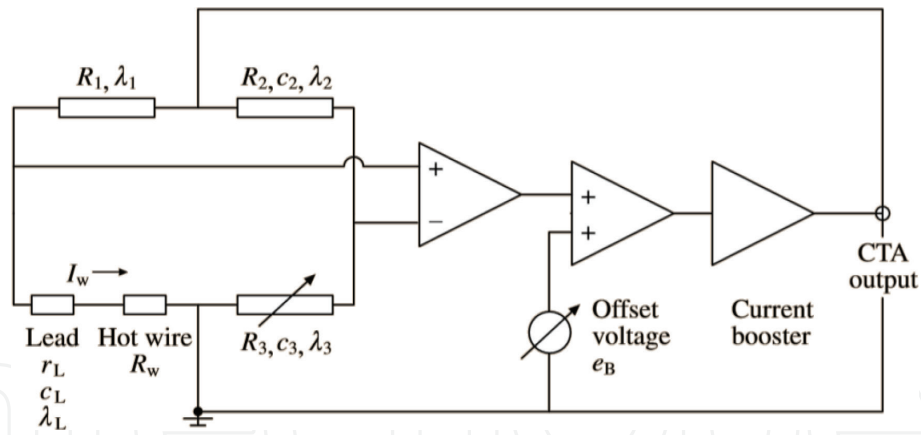


Figure 1.
 Circuit diagram of a thermal anemometer operating at constant temperature mode.

operation. Most velocity and turbulence measurements are acquired in this manner. Attributed to the extremely small thermal mass of the wire, this technique allows detection of very-high-frequency fluctuations in the flow. This is another advantage offered by the hot-wire anemometry.

The hot wires can be configured in the manner of single wire, cross wires, and triple wires. The single wire is primarily useful for mean flow quantity measurements and is not as accurate as triple wire simultaneous measurements for turbulence and Reynolds stress measurements.

Because of the small size and high-frequency response offered by hot-wire anemometer, the technique has been used extensively in investigations of the flow fields in turbomachines. While early investigations using hot-wire/hot-film probes were mostly qualitative, substantial amounts of quantitative investigations have also been carried out in the past few decades on various aspects, using many different types of hot-wire and hot-film probes. **Table 1** provides a list of representative studies in applications of turbomachines.

2.2 Laser Doppler velocimetry (LDV)

Laser Doppler velocimetry is an optical nonintrusive technique which measures the instantaneous velocity at a given point in a flow field. It was first developed by Yeh and Cummins in 1964 and is now a well-established technique. This technique has been widely used in all kinds of fluid flow applications, including laminar flow, turbulent flow, flow inside turbomachinery, and flow inside combustion chambers. Because of its high accuracy, it is also used as a benchmark validation tool for planar velocimetry techniques (i.e., PIV, PTV). Below lists the features in the LDV measurement technique:

Nonintrusive velocity measurement. In contrast to techniques for the measurement of flow velocities employing probes such as pressure tubes or hot wires, the LDV technique features a nonintrusive nature eliminating the disturbances introduced by the presence of the probes.

Indirect velocity measurement. The LDV technique measures the velocity of a fluid element indirectly in most of cases by means of the measurement of the velocity of tracer particle being added to the flow.

Point measurement. The same as hot wire, the LDV is a point-based measurement technique that characterizes the velocity in its measurement volume.

A sketch of the LDV working principle is shown in **Figure 2**. The system shown in the sketch is a 1-D LDV system operated in backscattering mode, but the working theory is the same for all the LDV systems. A single laser beam is emitted from a

Author(s)	Year	Sensor type	Type of machine	Subject of study
Lakshminarayana and Poncet [1]	1974	Singe and cross wire	Axial inducer	Rotor wakes
Gorton and Lakshminarayana [2]	1976	Triple wire	Axial inducer	Mean flow and turbulence
Hah and Lakshminarayana [3]	1980	Triple wire	Axial compressor	Freestream turbulence on a rotor wake
Hodson et al. [4]	1994	Hot film	Low-pressure turbine	Rotation and blade incidence on rotor wake
Camp and Shin [5]	1995	Hot wire, hot film, single sensor	Axial compressor	Turbulence intensity and length scale
Witkowski et al. [6]	1996	Hot film (triple wire)	Axial compressor	3-D wake decay and secondary flows
Halstead et al. [7]	1997	Surface-mounted hot film/hot wire	Axial compressor and turbine	Unsteady boundary layer
Hsu and Wo [8]	1997	Slanted hot wire	Axial compressor	Unsteady wake
Ristic and Lakshminarayana [9]	1998	Cross wire	Axial turbine	3-D boundary layer
Furukawa et al. [10]	1998	Hot wire	Diagonal flow rotor	Tip flow field
Sentker and Riess [11]	2000	Split hot film	Axial compressor	Wake-blade interaction
Velarde-Suarez et al. [12]	2001	Cross wire	Centrifugal fan	Unsteady flow
Pinarbasi [13]	2008	Triple wire	Centrifugal compressor	Diffuser flow
Goodhand and Miller [14]	2011	Single wire	Axial compressor	Boundary layer development during spike-type stalling
Weichert and Day [15]	2014	Single wire	Axial compressor	Tip region flow during spike-type stalling

Table 1.
Representative studies that have used thermal anemometer technique in studying the flow field of turbomachines.

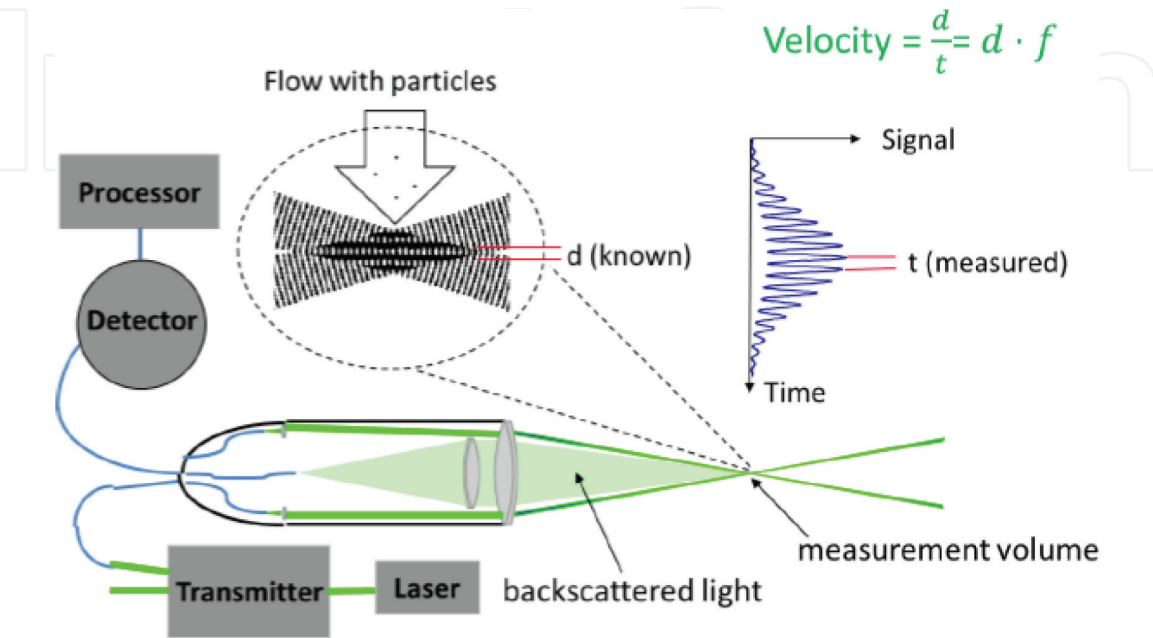


Figure 2.
Sketch of 1-D backscattering LDV system.

Author(s)	Year	Type	Type of machine	Subject of study
Wisler and Mossey [16]	1973	1-D	Axial compressor rotor	Rotor passage relative flow
Pierzga and Wood [17]	1985	1-D	Axial fan rotor	3-D flow field in a transonic rotor
Strazisar [18]	1985	1-D	Axial fan rotor	Flow structure in transonic fan rotor
Murthy and Lakshminarayana [19]	1986	1-D	Axial compressor	Rotor tip region flow
Beaudoin et al. [20]	1992	2-D	Centrifugal pump	Effects of orbiting impeller
Hathaway et al. [21]	1993	3-D	Centrifugal compressor	3-D flow structure
Farrell and Billet [22]	1994	na	Axial pump	Tip vortex cavitation
Fagan and Fleeter [23]	1994	1-D	Centrifugal compressor	Flow structure
Abramian and Howard [24]	1994	1-D	Centrifugal impeller	Impeller relative flow field
Zaccaria and Lakshminarayana [25]	1997	2-D	Axial turbine	Rotor passage flow field
Adler and Benyamin [26]	1999	2-D	Axial turbine	Stator wake propagation
Ristic et al. [27]	1999	3-D	Axial turbine	3-D flow field downstream of rotor turbine
Faure et al. [28]	2001	2-D	Axial compressor	Flow structure
Van Zante et al. [29]	2002	2-D	Axial compressor	Blade row interactions
Ibaraki et al. [30]	2003	2-D	Centrifugal impeller	Impeller flow
Higashimori et al. [31]	2004	2-D	Centrifugal impeller	Impeller flow field
Faure et al. [32]	2004	3-D	Axial compressor	Reynolds stresses measurements
Schleer et al. [33]	2004	2-D	Centrifugal compressor	Impeller discharge flow
Ibaraki et al. [34]	2009	2-D	Centrifugal impeller	Impeller flow field
Gooding et al. [35]	2019	3-D	Centrifugal compressor	Diffuser flow

Table 2.
Representative studies that have used LDV technique in studying the flow field of turbomachines.

laser head operating in continuous mode and then enters into the optical transmitter. Inside the transmitter, this single beam is split and frequency shifted using the beam splitter (BS), an achromatic lens, and a Bragg cell. Pairs of monochrome laser beams (depending on the number of velocity components needs to be measured: one pair for a 1-D system, two pairs for a 2-D system, and three pairs for a 3-D system) generated by the transmitter are then conveyed to the optical probes using fiber cables. The laser beams coming out of the probe intersect at the focal point of the front lens. At this focal point, at which the measurement volume is located, an ellipsoidal volume with bright and dark fringe patterns is formed by the interference of the laser beams. As flow particles traverse through this measurement volume, the backscattered light is collected by the receiving optics inside the probe and further processed by a burst spectrum analyzer. Inside the spectrum analyzer, the time intervals for the burst traveling through the bright and dark patterns are measured. Those measured time intervals, combined with the known distance between the adjacent bright and dark strips, yield the calculation of velocity.

This nonintrusive feature of the technique attracted the attention of experimentalist in the field of turbomachines soon after it was introduced in the 1960s. In addition to being nonintrusive, it allowed the velocity measurements in the rotating

reference frame without having to use complex rotating probe traverse or data transmission mechanisms (i.e., slip ring or telemetry system). A list of representative studies using LDV for measurements in turbomachines is provided in **Table 2**.

One of the earliest applications of LDV to turbomachinery was conducted by Wisler and Mossey [16] to measure the relative velocity across the first-stage rotor blade row using a single-component LDV system. The flow was seeded by spray atomizing a dilute water suspension of 1- μm -diameter polystyrene latex particles. A sketch of the experimental setup and a sample contour plot of relative velocity within the rotor passage at mid-span (50%) are shown in **Figure 3**. In addition, a sketch of experimental setup for three-component LDV in a centrifugal compressor is presented in **Figure 4**. As summarized in the table, majority of the investigations involving LDV have been performed in a stationary frame of reference. To measure the flow field in rotors, the rotor passage period has been discretized into bins, each with a finite time interval. The results in each bin were ensemble averaged to obtain the mean velocity and turbulence parameters across the rotor passage. To reach convergence in mean velocity and turbulence parameters, a large data set per bin is favored which requires a larger bin size. However, an increase in the bin size introduces the effects of spatial variations in the flow structure. An alternative approach is to conduct measurements in the rotating frame of reference. However, this makes the experimental very challenging, and the only study reported in the open literature of this category was performed by Abramian and Howard [24]. The experiment was conducted in a centrifugal impeller using a Dove prism to transfer the laser beams to the rotating frames of reference.

There are challenges in implementing LDV to turbomachines. Generally speaking, the challenges can be categorized into the optical accessibility-related issues and particle related. Typically, the three-dimensional twisted rotor blades make it difficult to shine laser beams to the interested measurement locations and require the LDV system operating in backscatter mode. Comparing to the favorable forward-scatter configuration, the signal-to-noise ratio of backscatter mode is commonly one to three orders of magnitude smaller. Additionally, the signal-to-noise ratio gets further deteriorated at measurement locations close to metal surfaces due to reflections and in applications of curved optical windows due to the distortion of laser beams through the windows. These distortions increase the uncertainty of the measurements by deforming the measurement volume and changing the measurement location. It is also challenging to deliver particles to target measurement locations due to the strong secondary flow in turbomachines.

2.3 Particle image velocimetry (PIV)

In addition to LDV, particle image velocimetry is another *nonintrusive* technique for velocity measurements. The same as LDV, PIV is also an *indirect* measurement technique and requires tracer particles. Different from LDV and thermal anemometer which are point-based measurement technique, PIV offers *full-field* measurements and allows mapping of large parts of flow field. The working principle of PIV is schematically described in **Figure 5**. The principle of PIV is based on the measurement of the displacement of small tracer particles during a short time interval. This indirect measurement nature requires the tracer particles to be sufficiently small to precisely follow the motion of fluid. The tracer particles are typically illuminated using a thin light sheet generated from pulsed laser head. A pair of images for the illuminated flow field is taken by a digital imaging device, typically a CCD camera. Depending on the number and configuration of camera employed, either 2-D or 3-D flow field could be obtained using cross-correlation analysis to measure the displacement

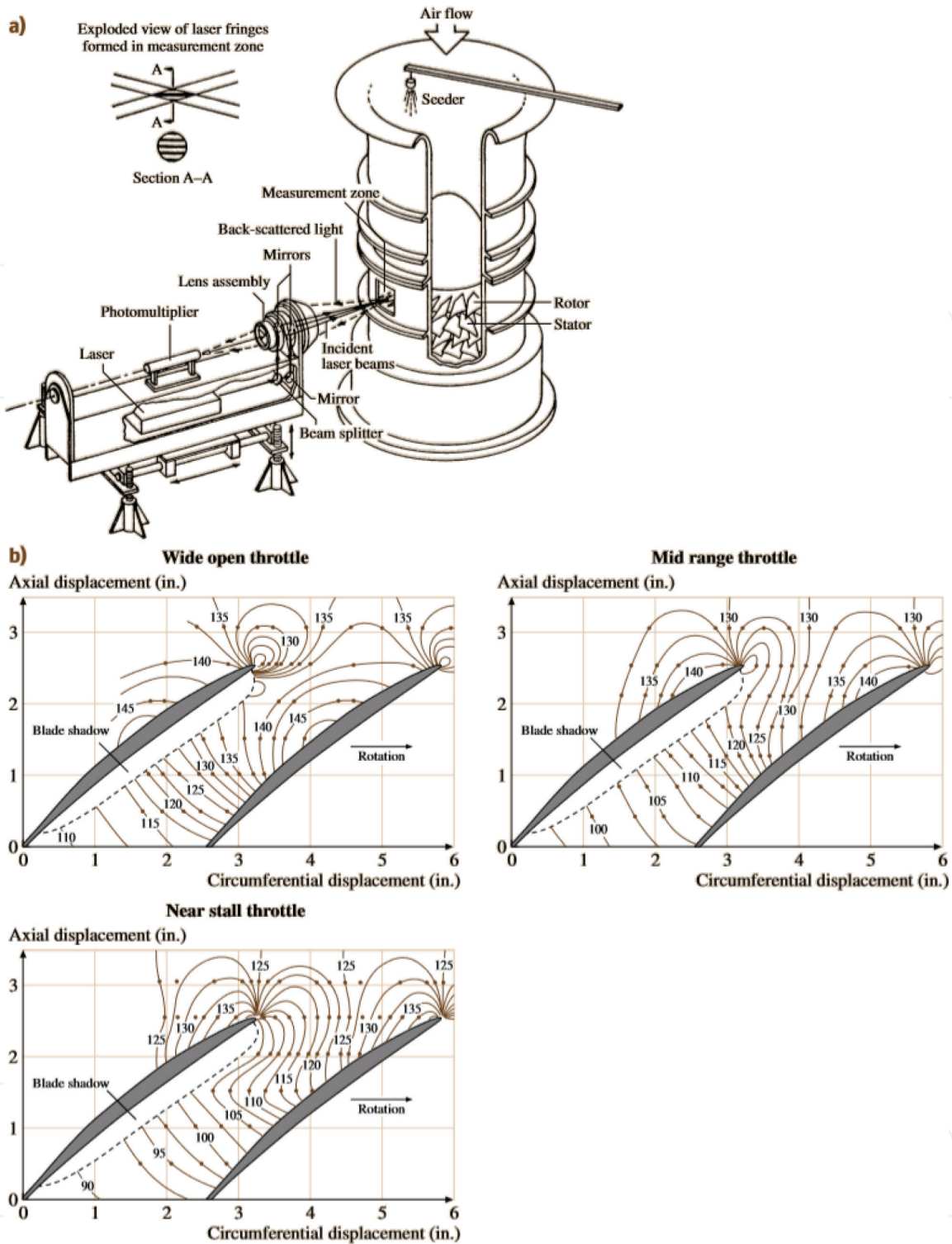


Figure 3. The LDV setup (a) and measured relative velocity contours within the rotor passage of a low-speed research compressor (b) Wisler and Mossey [16].

of particles in each small interrogation areas. A single-camera system allows characterization of the two velocity components within the measurement plane, while stereo imaging using two inclined cameras provides all three components of the velocity in the illuminated plane.

Effort of implementing PIV in investigations of turbomachinery flow field has been entertained since the emergence of the technique. Previous researchers have performed both two-dimensional and stereoscopic PIV measurements within various axial and centrifugal turbomachinery facilities. A few highlights of selected previous research are presented, and a more extended set of references is provided in **Table 3**.



Figure 4.
Photo of experimental setup for study of flow in a centrifugal compressor using three-component LDV.

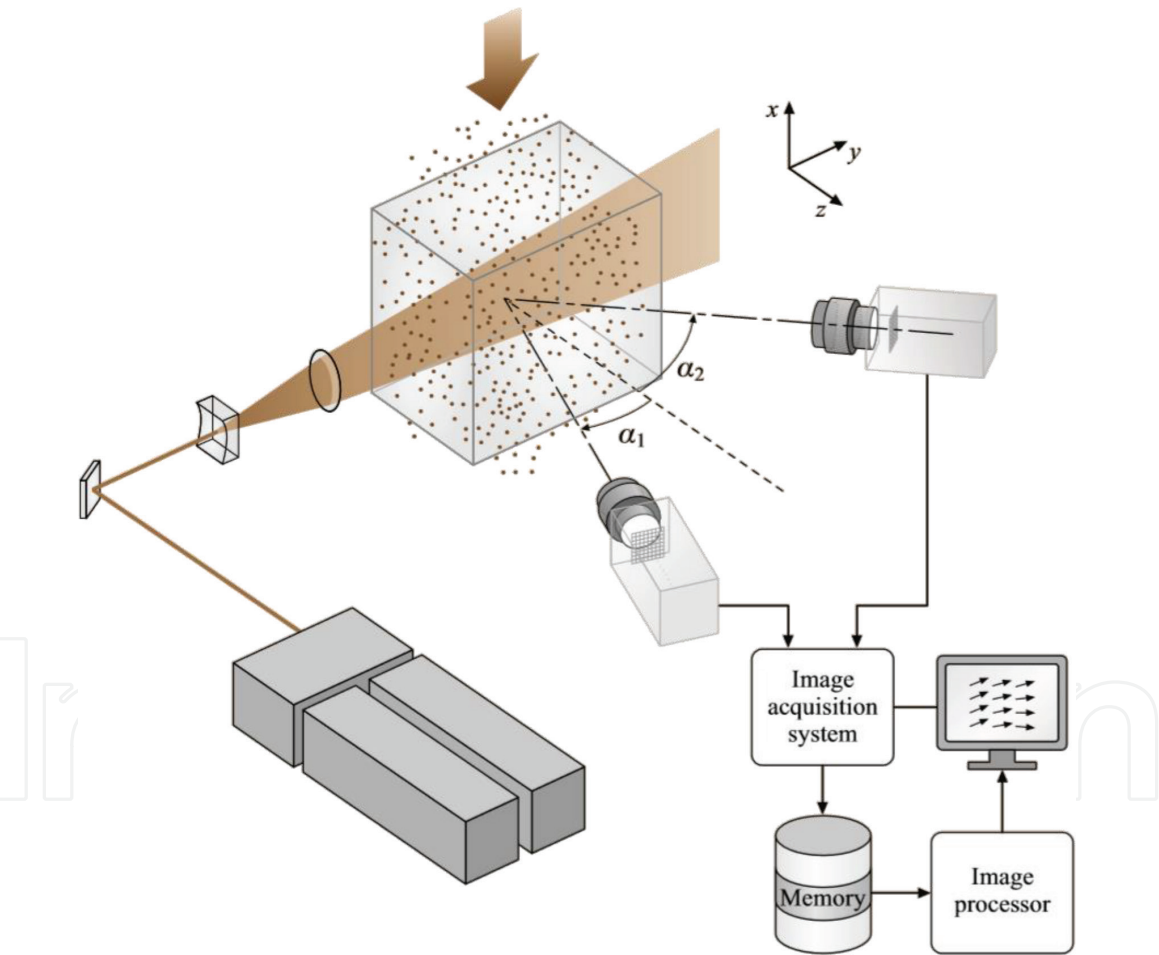


Figure 5.
Sketch of typical PIV setup [36].

Figure 6 presents sample results from the two-dimensional measurements performed in an axial pump at Johns Hopkins University. The distribution of phase-averaged velocity, vorticity, and turbulent kinetic energy at the mid-span of the second stage was characterized [37]. **Figure 7** shows sample data obtained in a high-speed centrifugal compressor operating both at the design point and during surge [43, 46]. As summarized in the table, majority of these studies insert a periscopic optical probe into the flow for light sheet delivery. This results in invasive measurement and also

Author(s)	Year	Type	Type of machine	Subject of study
Paone et al. [38]	1989	2-D	Centrifugal pump	Flow structure
Chu et al. [39, 40]	1995	2-D	Centrifugal pump	Unsteady flow and pressure fluctuations
Day et al. [41]	1996	2-D	Axial turbine	Effect of film cooling on flow structure
Dong et al. [42]	1997	2-D	Centrifugal pump	Unsteady flow and noise
Wernet [43]	2000	2-D	Centrifugal compressor	Diffuser flow structure
Sinha and Katz [44]	2000	2-D	Centrifugal pump	Diffuser flow field
Uzol and Camci [45]	2001	2-D	Axial turbine cascade	Trailing edge coolant ejection
Wernet et al. [46]	2001	2-D	Centrifugal compressor	Diffuser flow during surge
Chow et al. [37]	2002	2-D	Axial pump	Wake-wake interactions
Uzol et al. [47]	2002	2-D	Axial pump	Unsteady flow and deterministic stresses
Sanders et al. [48]	2002	2-D	Axial compressor	Blade row interactions
Estevadeordal et al. [49]	2002	2-D	Axial compressor	Wake-blade interactions
Woischlager et al. [50]	2003	2-D	Axial turbine cascade	Turbine wake
Uzol et al. [51]	2003	3-D	Axial pump	3-D wake structure and tip vortex
Lee et al. [52]	2004	3-D	Marine propeller	Propeller wake
Wernet et al. [53]	2005	3-D	Axial compressor	Tip region flow
Yu and Liu [54]	2006	3-D	Axial compressor	Unsteady flow
Ibaraki et al. [55]	2007	2-D	Centrifugal compressor	Unsteady diffuser flow
Estevadeordal et al. [56]	2007	3-D	Axial compressor	Wake-rotor interactions
Voges et al. [57]	2007	2-D	Centrifugal compressor	Diffuser flow
Voges et al. [58]	2012	3-D	Axial compressor	Tip region flow
Guillou et al. [59]	2012	3-D	Turbocharger compressor	Impeller inlet flow
Gancedo et al. [60]	2016	3-D	Turbocharger compressor	Impeller inlet flow
Bhattacharya et al. [61]	2016	3-D	Axial compressor	Rotor flow field

Table 3.
Representative studies that have used PIV technique in studying the flow field of turbomachines.

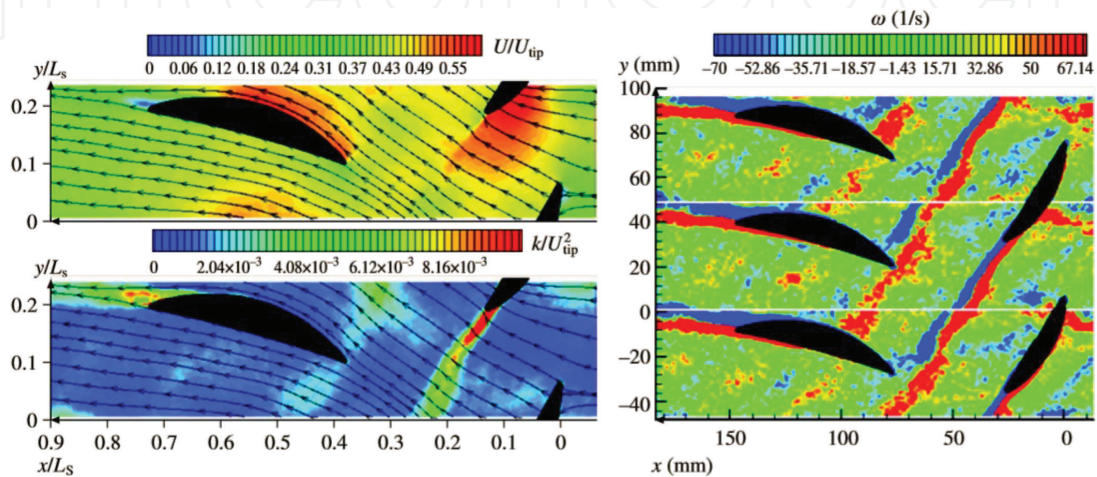


Figure 6.
Sample PIV data obtained in an axial pump facility at Johns Hopkins University: Phase-averaged velocity field (top left), turbulent kinetic energy (bottom left), and vorticity (right) at mid-span within an entire stage [37].

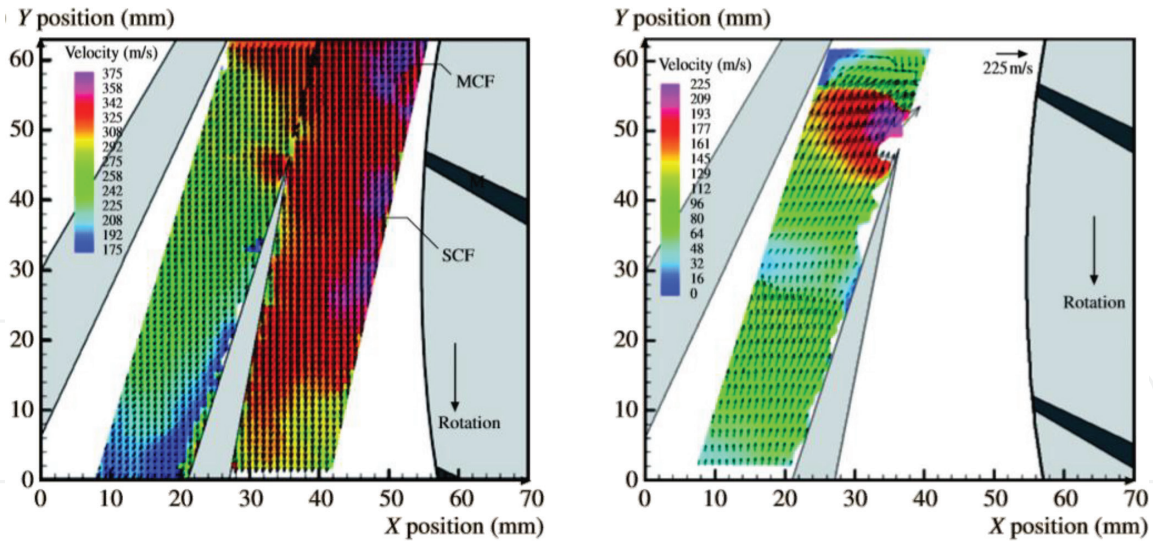


Figure 7. Sample PIV measurements in the diffuser passage of a high-speed centrifugal compressor at both the design point (left) [43] and during a surge (right) [46].

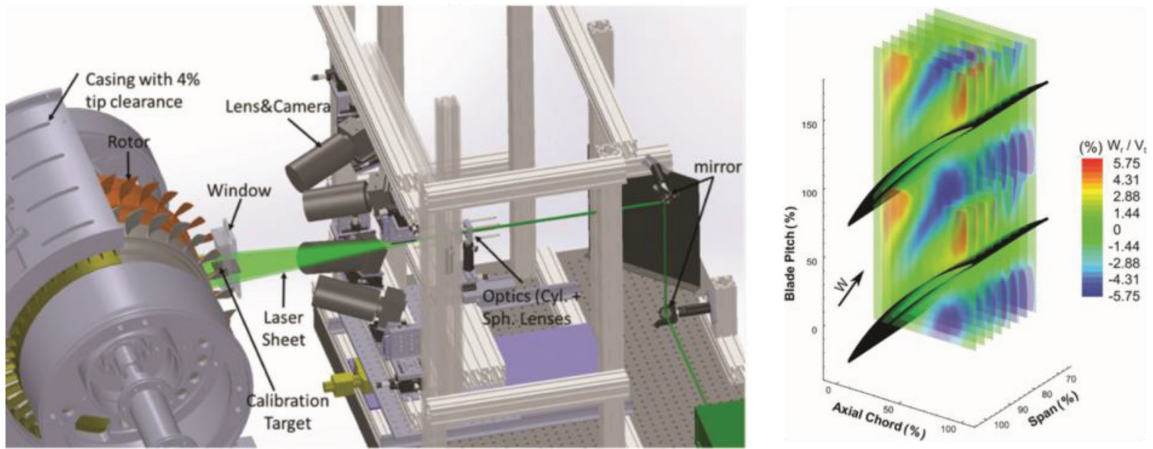


Figure 8. Experimental setup for PIV measurements performed at Purdue University (left) and sample results (right) of normalized radial velocity at fixed spanwise locations for stereo reconstructed velocity field [61].

significantly limits the region of flow field that can be imaged. To address these challenges, a new approach was introduced in a recent study performed at Purdue University in a multistage axial compressor [61]. The same window was used for both laser sheet delivery and image recording. By doing so, it eliminates the presence of invasive probe for light sheet delivery. A sketch of the experimental setup and sample results is shown in **Figure 8**. As illustrated in the figure, the PIV measurements were performed in the second-stage rotor passage (rotor 2). To eliminate light reflections from the blade surface and hub, fluorescent dye with sufficiently separated absorption and emission wavelengths was introduced with the seeding fluid, and lens filters blocking wavelengths below 540 nm were used to filter laser reflections. Slices of normalized radial velocity at fixed spanwise positions were presented to illustrate the development of the tip leakage flow across the rotor passage.

3. Pressure-sensitive paints

Conventionally, surface pressures are measured using hundreds of pressure taps or flush-mounted transducers to obtain a reasonable spatial distribution. This makes

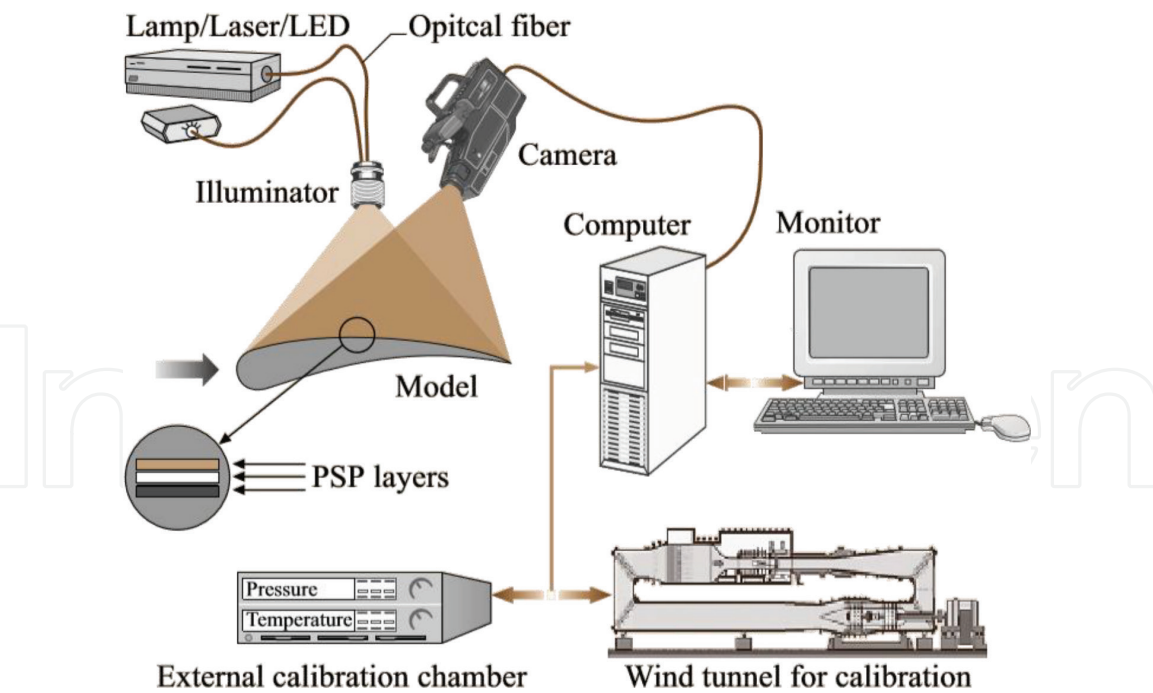


Figure 9.
Schematic of pressure-sensitive paint measurement system [36].

Author(s)	Year	Type of machine	Subject of study
Sabroske et al. [63]	1995	Axial compressor	Blade pressure distribution
Liu et al. [64]	1997	High-speed axial compressor	Blade surface pressure
Navarra [65]	1997	Axial compressor	Blade surface pressure
Bencic [66]	1998	Axial fan	Blade surface pressure
Engler et al. [67]	2000	Axial turbine	Shock movement and corner stall
Navarra et al. [68]	2001	Axial compressor	Blade surface pressure in transonic conditions
Gregory et al. [69]	2002	Centrifugal compressor	Blade surface pressure
Lepicovsky and Bencic [70]	2002	Supersonic through flow fan	Effect of change operating conditions
Gregory [71]	2004	Centrifugal compressor	Effect of inlet distortion on surface pressures
Suryanarayanan et al. [72]	2010	Axial turbine	Filming cooling
Narzary et al. [73]	2012	Axial turbine	Effect of coolant density on turbine film cooling

Table 4.
Representative studies that have used PSP technique in turbomachines.

the measurements time-consuming and expensive. Recently, the introduction of pressure-sensitive paint (PSP) provides a new method for surface pressure measurement. Comparing to the conventional approaches by means of pressure taps or transducers which can only provide data at discrete points and are limited by installation locations, the PSP technique is very attractive; hence, it provides high-spatial-resolution pressure measurements without taps or transducers. The PSP technique is based on covering a surface with luminescent coatings. The luminescence of the coating is dependent on surface static pressure. With proper illumination, the surface pressure

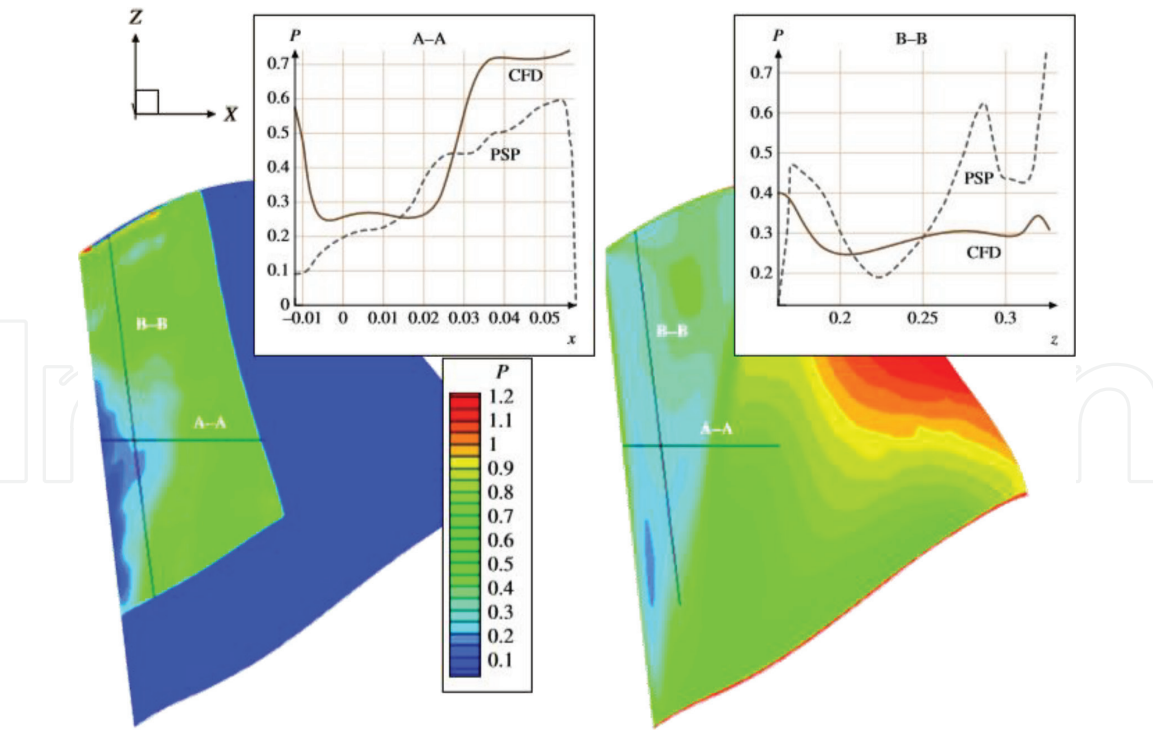


Figure 10. Comparison of surface pressure distribution on a rotor suction side in a transonic axial compressor obtained using PSP (left) to CFD predictions (right) [68].

distribution is obtained from images of illuminated surface. **Figure 9** shows all the essential optical and electrical components of a PSP system. It consists of various illumination devices, a local image and data-acquisition system, and an external calibration chamber.

The first aerodynamic study using PSP is performed by Pervushin et al. in 1985 to measure the pressure of air on the surface of wind tunnel models [62], and since then, numerous studies using PSP in external aerodynamics research have been conducted. However, unlike the well-established applications in external aerodynamic research, the application of PSP in turbomachines is quite limited. **Table 4** lists the studies in the open literature that have used pressure-sensitive paint in turbomachines. A sample result of the PSP measurements together with the comparison to CFD results from the study conducted by Navarra et al. [68] is shown in **Figure 10**. The PSP measurement was conducted on the suction surface of the first-stage rotor of a state-of-the-art, full-scale transonic compressor.

4. Conclusions

This chapter attempts to provide a comprehensive but brief summary of several advanced measurement techniques that have been used in turbomachines. For each measurement technique, the fundamental working principle was provided first and followed by discussion of its application in turbomachines. A list of representative research from the open literature was also provided for reference.

Conflict of interest

The author claims there is no conflict of interest.

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