Chapter

Advance Measurement Techniques in Turbomachines

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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 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  | Single 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 compressor | 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.
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

| 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.
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
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 filed 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 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  | Axial turbine          | 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                              |
| Woisetschlager 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].
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
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

| 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.
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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