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## Summary

This report first presents a brief overview of the different laser anemometer (LA) optical designs available. Then, the LA techniques that can be used to design a three-component measurement system for annular geometries are described. Some of the facility design considerations unique to these LA systems are also addressed. Following this, the facilities and the LA systems that were used to successfully measure the three components of velocity in the blading of annular-flow machines are reviewed. Finally, possible LA system enhancements and future research directions are presented.

## Introduction

Three-dimensional velocity measurements are needed in turbomachinery components to gain a better understanding of the basic flow physics occurring in these geometrically complex machines. This information can be used to develop and verify computational fluid mechanics computer codes, thereby enabling better designed components. For those difficult situations that cannot be adequately modeled numerically, this basic information allows the flow to be empirically modeled.

Classical measurement techniques (e.g., pressure and temperature probes, hot wire and hot film anemometers, etc.) were used in the past to obtain the required experimental data. These techniques are cumbersome and, in some cases, impractical in the modern high-speed turbomachinery blading now being designed and built. With the development of the laser and the anemometer systems designed around it, a promising new nonintrusive measurement technique became available. Because of its complexity, only within the last decade or so has the laser anemometer (LA) been applied to three-component velocity measurements. The reviews of these three-component LA systems by Dancey (ref. 1), Boutier (ref. 2), and Meyers (ref. 3) generally include measurements made in free jets or in flows around test models in wind tunnels.

Only recently have the three-component LA measurement techniques been successfully applied to the passages of turbomachinery. The reasons for this delay are the limited optical access in these facilities and the need to use a backscatter configuration. Three-component LA measurements are reported by Stauter and Fleeter (refs. 4 to 7) and Seasholtz and Goldman (refs. 8 to 12) in stationary turbomachinery

cascades; Carey and Fraser (refs. 13 to 19) in a mixed-flow pump; Eroglu, Lakshminarasimha, Malakoff, et al. (refs. 20 to 22) in a radial inflow turbine stator; and Chesnakas and Dancey (refs. 23 and 24) in a single-stage axial-flow compressor rotor. As far as can be determined, these experiments are the only ones appearing in the open literature where three-component LA measurements were obtained in the blading of complex machines.

This report first presents a brief overview of the different laser anemometer optical designs available. Then, the LA techniques that can be used to design a three-component measurement system for annular geometries are described. Since the theory of laser anemometry is covered extensively in the literature (refs. 25 to 28) it is not discussed in any detail herein. Some of the facility design considerations unique to LA systems are then presented. Following this, the facilities and the LA systems that were used to measure the three components of velocity in the blading of annular-flow machines are reviewed. Finally, possible LA system enhancements and future research directions are presented.

## Laser Anemometer Techniques

### Laser Doppler and Time-of-Flight Anemometers

A laser anemometer measures fluid velocity indirectly by determining the speed of particles moving through the flow field. These particles, which may be occurring naturally or introduced artificially into the flow, must be sufficiently small so that they follow the flow closely. If this is the case, then the fluid velocity can be equated to the measured particle velocity. The two types of laser anemometers in common use are the laser Doppler anemometer (LDA) and the time-of-flight (TOF) anemometer.

The LDA is based on the physical principle that light scattered from a moving particle is Doppler shifted in frequency from that of the incident laser light. Measuring this Doppler shifted frequency allows the particle velocity to be calculated. The TOF (or two-spot or two-focus) anemometer is based on measuring the time it takes a particle to cross two discrete, but closely spaced, laser beams. Knowing the separation of the two beams allows the particle velocity to be calculated. The principal advantage of the TOF anemometer is that the laser power is concentrated into a smaller measurement region resulting in a larger signal-to-noise ratio.

Therefore, measurements can be made closer to surfaces (particularly normal surfaces) and smaller particles can be used to better track the flow. The main disadvantages are that the TOF method gives a lower data rate and is not usable in highly turbulent flows. Schodl (ref. 29) reviewed the available information on time-of-flight measurement systems. While the time-of-flight method has been used successfully in turbomachinery research, it has not yet been applied to three-component velocity measurements in these machines. Therefore, a further discussion of this type of anemometer is delayed until the **Future Developments** section (p. 14).

### Single-Component Systems

The mathematical analysis of the Doppler shifted frequency equation by Boutier et al. (ref. 2) led to their classification of the four types of single-component laser anemometers: spectrometer, Type 1a; reference beam, Type 1b; one beam, Type 1c; and fringe, Type 1d. Of these, the most widely used system today is the Type 1d or laser fringe anemometer (LFA) system. A schematic of a simple LFA system is shown in figure 1(a). The laser beam is first split into two equal intensity beams by a beam splitter (BS) before being focused by a lens (L1). A fringe pattern is created in the common region or probe volume (PV) of the beams. The advantage of the LFA system is its independence of the observation direction, allowing the use of large aperture collecting optics and, thus, better signal-to-noise ratios. The velocity component measured by the fringe system is normal to the laser beams bisector (optical axis) and lies in the plane of the two beams. However, no information is available as to the directional sense of the flow. When a frequency shift is introduced to one of the incident beams (e.g., with a Bragg cell), the fringe pattern appears to move. Therefore, the detected Doppler shift increases or decreases, depending on the sense of the particle velocity with respect to the moving fringes, and the directional ambiguity is removed.

The backscattered light from the moving seed particles (shown as dashed lines in fig. 1(a)) is collected through the focusing lens (L1). While more scattered light can be collected in the forward direction than in the backward direction, and this would be preferred, this is generally not possible in complex annular geometries. After reflection by a mirror (M), the scattered light is focused by another lens (L2) onto a photomultiplier tube (PMT). A pinhole (PH) is placed in front of the PMT to minimize the extraneous light incident on the detector. The signal coming from the LFA can be processed by correlators, frequency trackers, spectrum analyzers, counters, or frequency domain processors; counters are, however, the most widely used.

Another single-component laser anemometer technique that has found use in special circumstances is the spectrometer method (Boutier's Type 1a), which includes both Fabry-Perot interferometers (FPI) and Michelson interferometers. In turbomachinery applications, an FPI was used (ref. 10) to directly

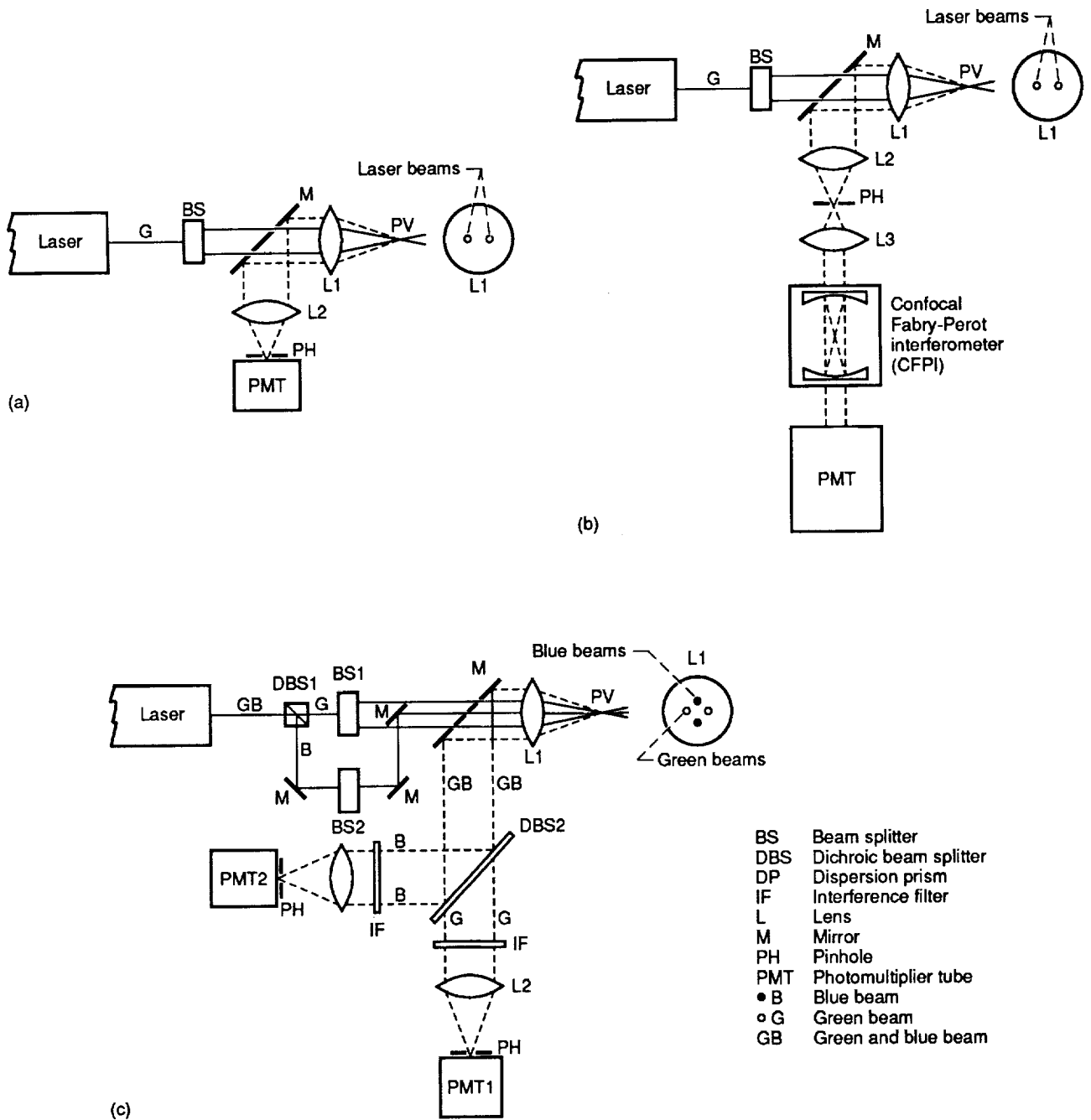
measure the Doppler shift at optical frequencies. A schematic of a single-component FPI system is shown in figure 1(b); it is similar to the LFA system discussed previously (fig. 1(a)). The basic difference is the addition (in the collection optics) of the FPI, which consists of two partially transmitting mirrors facing each other. These mirrors can be either flat or spherical. Spherical mirrors (shown in fig. 1(b)) are often used because the interferometer is less sensitive to mirror alignment for this configuration. If the spacing of the spherical mirrors is equal to their common radii of curvature, the FPI is referred to as a confocal interferometer. The mirrors of the FPI form an optical cavity in which successive reflections of the incident monochromatic light create multiple beam interference fringes. A PH aperture can be placed at the entrance of the FPI (as in fig. 1(b)) to restrict transmission to the central fringe. The wavelength of the transmitted light from the FPI is directly related to the mirror separation. Different wavelengths (or frequencies) are transmitted and can be measured by adjusting the mirror spacing using a piezo-electric element. In this mode of operation, the FPI can be considered a scanning optical spectrum analyzer. The principal advantages of the spectrometer method are that the velocity component measured is parallel to the optical axis (as opposed to normal in the LFA system) and that very large velocities can be measured easily.

Two-component and three-component LA measurement systems can be built from the aforementioned single-component or single-channel measurement methods. A single channel is used herein to refer to the use of an optical train with a single PMT in the LA system. Thus, two- or three-channel systems would have two or three PMT's, respectively. Two-component and three-component systems are described in the next two sections.

### Two-Component Systems

Two-component LA measurements are commonly made with either a single-channel fringe system or a two-channel, two-color fringe system. In the single-channel fringe system the laser beams are rotated about the optical axis allowing the measurement of velocity components in the plane normal to the optical axis. Measuring two different components of velocity allows the velocity magnitude and flow direction to be calculated in this plane.

The two-channel fringe system, shown schematically in figure 1(c), is essentially a combination of two single-channel fringe systems that use two different colors from a laser operating in a multiline mode. Two different components of velocity can be measured simultaneously with this system using a signal processor and PMT in each channel. For argon-ion lasers, the green and blue lines are usually used since they are the most powerful ones available. Because the measurements of each channel can be forced to be coincident in time, correlated turbulence information can also be determined. Two-channel fringe systems can use either three or four beams, but four beam systems are more common. As shown in



(a) Single-channel fringe system (backscatter configuration).  
 (b) Single-channel Fabry-Perot interferometer system (backscatter configuration).  
 (c) Two-channel, two-color, four-beam fringe system (backscatter configuration).

Figure 1.—Schematic of single-channel and two-channel fringe laser anemometer systems.

figure 1(c), in the four beam system, the two green (G) beams are in the horizontal plane while the two blue (B) beams are in the vertical plane. The optical axis is in the middle of the four beams. In a three beam system, one beam is made up of overlapping a green and a blue beam. The optical axis is usually the overlapping green-blue beam. In addition to using different colors to separate the two channels, different polarizations or different frequencies can also be used; however, these techniques are not as widely used.

### Three-Component Systems

The different three-component measurement techniques that have been successfully employed in annular geometries can be categorized as follows: single-channel fringe system, Type 3a; two-channel fringe system, Type 3b; three-channel fringe system, Type 3c; and mixed configuration system, Type 3d. In fringe systems of Type 3a or 3b, the basic idea is to make the three noncoplanar component measurements needed to resolve the velocity vector using separate orientations of the optical axis. This is accomplished by sequentially changing the position of the optical axis relative to the facility hardware while keeping the probe volume location fixed. For a single-channel system (Type 3a) with fringe rotation, measurements are needed at only two orientations of the optical axis. However, at one of these positions, the fringes must be rotated to obtain a third noncoplanar component measurement. With a two-channel, two-color fringe system (Type 3b), measurements are again needed at only two directions of the optical axis. For a three-channel fringe system (Type 3c), a third laser color (i.e., violet for an argon-ion laser) can be used in a separate optical train (as in fig. 1(a)) set at an angle to a two-channel, two-color fringe system (as in fig. 1(c)) so that three simultaneous measurements can be made. Three signal processors and PMT's are needed for this system, but component measurements are needed at only one orientation of the laser optics.

For these fringe systems, the angle between the different optical axes is generally less than 90° because of the geometric constraints of the facility hardware. This has a negative impact on the accuracy of measuring the velocity component parallel to the optical axis and is discussed in the **Laser Anemometer Design Considerations** section.

In the mixed configuration system (Type 3d), a spectrometer channel (Boutier's Type 1a) is used in conjunction with a fringe system (Boutier's Type 1d) to measure all three components with a single optical axis or viewing direction. For a single-channel fringe system, rotating the fringe pattern (needed for the third velocity component measurement) prevents this technique from making simultaneous measurements. Small on-axis component measurements are difficult to do using the spectrometer technique because of the presence of large amounts of light scattered off walls normal to the optical axis. The four different three-component systems just discussed are listed in table I for future reference.

TABLE I.—THREE-COMPONENT TURBOMACHINERY LASER ANEMOMETER SYSTEMS

Designation	Method
Type 3a	Single-channel fringe system with fringe rotation and variable optical axis orientation
Type 3b	Two-channel, two-color fringe system with variable optical axis orientation
Type 3c	Three-channel, three-color fringe system with two optical axes at fixed orientation
Type 3d	Single-channel fringe system with fringe rotation combined with a single-channel Fabry-Perot interferometer with a single optical axis or viewing direction

## Laser Anemometer Design Considerations

### Cascade Design

The laser anemometry techniques discussed previously can be applied equally well to turbine or compressor components. Generally, LA measurements are easier to make in axial machines than in radial machines. This is because blade heights are smaller in the radial machines and measurements near surfaces normal to the optical axis are more difficult to make because of the diffuse light scattered off these surfaces. Collecting this scattered light by the photodetector results in lower signal-to-noise ratios. As the probe volume moves away from the endwall surface and less light is scattered off these surfaces, the measurements become easier. For similar reasons, LA measurements are generally easier to make in large-scale turbomachinery than in actual-size hardware. Therefore, large-scale turbomachinery would be preferred from an LA measurement standpoint. However, these facilities often require being operated at lower-than-design velocity levels.

Laser anemometer measurements can also be made in stationary or rotating turbomachinery. If the blade row is stationary, the probe volume must move in all three dimensions, if the flow field is to be mapped completely. For a rotating blade row, one type of motion is already provided by the rotation. Therefore, to completely map the flow field in this situation, only axial and radial motion of the probe volume would be necessary. However, additional information is needed to provide the probe volume circumferential position relative to the rotating blading for each laser measurement. Strazisar (ref. 30) reviewed the different methods for determining the rotor rotational position using a once-per-revolution or a once-per-blade timing signal.

### Optical Elements

To obtain the best LA measurements possible, the optics should employ high-quality, fast (low f-number) lenses. Faster optics permits collecting more of the scattered light and,



thereby, increases the signal-to-noise ratio. Faster optics is particularly important for turbomachinery applications where backscatter collection is required. Lenses of  $f/2.5$  or less are common in advanced system designs. Antireflective coatings increase light transmission efficiency and should also be used on all optical elements, including the optical access window. In addition, better measurements are possible by using higher power argon-ion lasers to increase the laser light intensity in the probe volume, thus increasing the signal-to-noise ratio.

### Optical Access

Optical access to the flow field is required for making laser anemometer measurements. The window needed to provide this access can either be flat or curved. In annular machines, flat windows can lead to flow distortions and are generally not employed. Curved windows must be used with care since they act like lenses in the optical system. Because of this, windows are usually made as thin as safely possible to prevent the laser beams from uncrossing when passing through them.

Generally, windows are made from glass or plastic material. Our experience with plastic windows has not been good. We found that the focused laser beams can damage the plastic (possibly by local melting) when the probe volume is close to the window surface. The very fine scribe lines observed on the plastic prevented further high quality signals from being obtained in these window areas. It is recommended, therefore, that glass be used for the window material whenever possible.

### Flow Seeding

The seed particles added to the flow must be small enough to accurately track the flow changes that occur in passing through the machine. A particle dynamics calculation should be made before the experiment to determine the size of the seed needed. Since commercially available seed generators produce a distribution of particle sizes, it is important to also estimate the actual size of the seed particles detected by a specific LA system. The laser system parameters that effect this detected size are discussed in reference 12.

### Statistical Accuracy

For three-component fringe LA measurement systems, the statistical accuracy of measuring the on-axis component is generally less than that for the transverse components. Orloff and Snyder (ref. 31) determined that the accuracy of the on-axis velocity component is strongly dependent on the included angle between the two optical axes or optical orientations used in the LA system; the smaller the angle, the more inaccurate the calculation of this component. For turbomachinery applications, this included angle is limited by geometric constraints to values typically between  $30^\circ$  and  $40^\circ$ . These small angles result in the statistical accuracy of the calculated on-axis component being significantly less than that for the transverse components. By contrast, the spectrometer

technique measures the on-axis component directly and would be expected to provide better statistical accuracy than that from the three-component fringe system. This was confirmed in the measurements by Goldman and Seasholtz (ref. 9) where similar accuracies were obtained for all three components.

Orloff and Snyder (ref. 31) also found that correlated (simultaneous) measurements are more accurate than uncorrelated (sequential) measurements. Only the three-channel fringe system (Type 3c, table I) described previously is capable of simultaneous velocity component measurements. A system of this type that does not use coincidence to insure simultaneous velocity component measurements from all three channels would seem inappropriate, but the advantages must be weighed against the significantly lower data rates that occur by forcing simultaneity.

## Three-Component Laser Anemometer Measurement Systems

Descriptions of the facilities and the laser anemometer systems that have been used to obtain three-component velocity measurements in annular geometries are reviewed in this section. Also discussed are the methods of optical access, flow seeding, and probe volume positioning. Single-channel LA designs are presented first followed by two- and three-channel designs (see table I). Within these categories, as appropriate, laser anemometers for stationary blading are discussed before those for rotating blading. The main features of these facilities and laser anemometer systems are summarized in table II.

### Purdue Annular Cascade

Three-component velocity measurements by Stauter and Fleeter (refs. 4 to 6) were made with a single-channel fringe laser anemometer (Type 3a, table I) in a stationary subsonic annular cascade of compressor blades. A principal design goal for the facility was to make the flow passages large enough to amplify the basic flow phenomena occurring so that miniaturization of the instrumentation was not necessary. Details of the facility design are given in reference 7. The overall objective of the research was to provide a complete three-dimensional data set to verify turbomachine blade row numerical codes.

The facility, shown in figure 2, consists of an inlet section, a test section, and an exit section. The inlet section bellmouth was designed to minimize the entrance pressure losses and to provide a well-behaved boundary layer at the inlet of the test section. Flow straighteners were placed downstream of the bellmouth to remove any residual swirl in the flow. In the test section there were 36 zero-twist airfoils, each having a 152.4-mm span and a 152.4-mm chord. The airfoil profile was based on the NACA 65-10 series compressor blade with a 1.5-percent-thick trailing edge and a  $40.75^\circ$  flow turning. Results with the airfoils set at a  $1.0^\circ$  incidence angle were

TABLE II.—FACILITIES USED FOR THREE-COMPONENT LASER ANEMOMETER MEASUREMENTS

	Purdue University	NASA Lewis Research Center	Strathclyde University	Cincinnati University	Virginia Polytechnic Institute
Facility: Machine Flow Blading Machine size	Compressor Axial Stator Large	Turbine Axial Stator Actual	Pump Mixed flow Rotor Model	Turbine Radial Stator Actual	Compressor Axial Rotor Large
Laser system: Design (table I) Laser power, W Probe volume size	Type 3a 4 100 $\mu\text{m}$ diam. $\times 1$ mm	Type 3d 4 100 $\mu\text{m}$ diam. $\times 1$ mm	Type 3b 2 80 $\mu\text{m}$ diam. $\times 1.4$ mm	Type 3c 5 50 $\mu\text{m}$ diam. $\times 0.6$ mm	Type 3c 4 65 $\mu\text{m}$ diam. $\times 1.3$ mm
Optical access: Window type Window material	Curved Plexiglas	Curved Plexiglas	Curved Acrylic	Flat Plexiglas	Flat Plexiglas
Seeding: Material Particle size, $\mu\text{m}$ diam.	Propylene glycol 0.6	Fluorescent dye 1.2	Oil 2.0	Propylene glycol 2.0	Sugar 2.0
Traversing system: Types of motion, no. Stage accuracy, $\mu\text{m}$	5 30 to 300	5 12	4 200	3 25	3 50

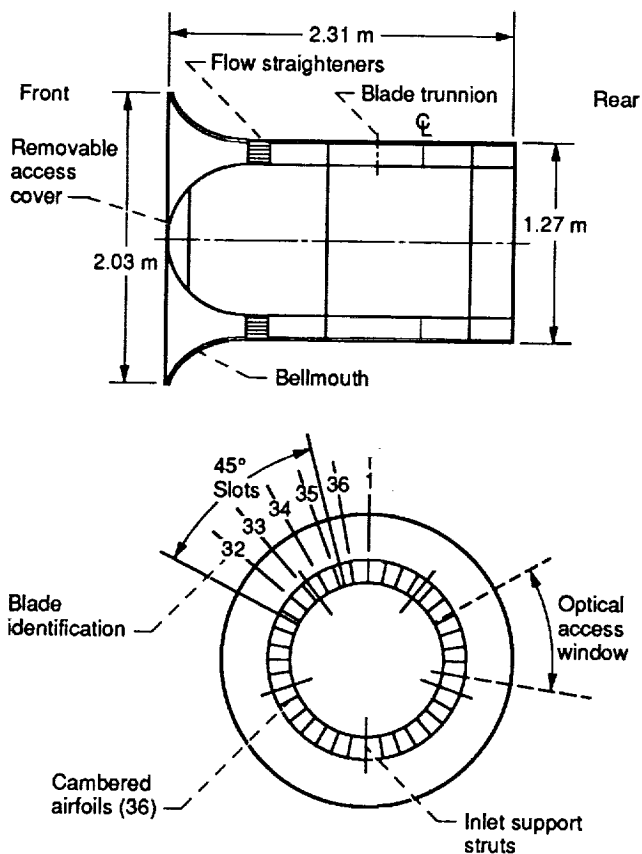


Figure 2.—Schematic of Purdue annular cascade facility.

reported in reference 4. Tests were also made at incidence angles of  $15.6^\circ$  and  $-9.9^\circ$  (ref. 6) by setting the airfoil stagger angle. After the flow exited the facility it underwent a sudden expansion into a  $24\text{-m}^3$  plenum chamber, which provided a uniform exit pressure to the cascade. From the plenum chamber the flow was drawn through ducting by a centrifugal compressor which acted as the facility exhauster. The capacity of the exhauster was  $350\text{ m}^3/\text{s}$ , and it was powered by a 300-hp induction motor.

Optical access to the test section was provided by a curved, 1.6-mm-thick, Plexiglas window covering  $40^\circ$  of circumferential arc. The five airfoils centered on the window were cantilevered from the hub to provide maximum optical access for the laser.

The laser anemometer system used was a commercial, single-channel, dual-beam fringe system (Type 3a, table I). A 4-W argon-ion laser operating in a single line mode at a 514.5-nm wavelength (green line) produced a maximum of 2.3 W of power. The backscatter optical design included beam expansion (to decrease probe volume size) and frequency shifting. A field stop was utilized in the system to provide good spatial resolution for the receiving optics. This allowed measurements to be made to within 3.5 mm (2.2 percent of span) of the cascade endwalls. The probe volume was about 1 mm long and less than  $100\text{ }\mu\text{m}$  in diameter and contained 30 fringes. Signal detection and processing were done with a photomultiplier tube and a counter-type processor.

The flow was seeded upstream of the bellmouth with 0.6- $\mu\text{m}$ -diameter propylene glycol particles. A specially designed seed injector (ref. 6) provided particles with the same velocity as the inlet flow provided and with minimal injector wakes.

The traversing system (fig. 3) had four types of motion: axial, vertical, tilting (corresponding to tangential motion), and radial (along the optical axis). Axial motion was accomplished by sliding the positioning superstructure along the substructure with a leadscrew. The vertical and tilting motions were obtained from two independently controlled leadscrews that supported both ends of the optic table. Radial motion was accomplished by moving the focusing lens with a fourth leadscrew. These leadscrews were driven by stepper motors and had a positioning resolution of 0.0064 mm, except in the axial direction where the resolution was 0.025 mm. A fifth type of motion (fringe rotation) was provided by rotating the optical train of the laser anemometer. A computer controlled moving the traversing system to the proper locations to obtain measurements at a specified probe volume position. In addition, the computer allowed corrections to be made to take into account the optical deviations caused by the curved window.

The axial velocity component was measured directly by orienting the beam plane parallel to the cascade axis. The tangential and radial components were determined by placing the beam plane perpendicular to the cascade axis and by obtaining two separate measurements each with the optical axis at different angles to the radial direction. The optimum angles (largest values consistent with the hardware geometry) were

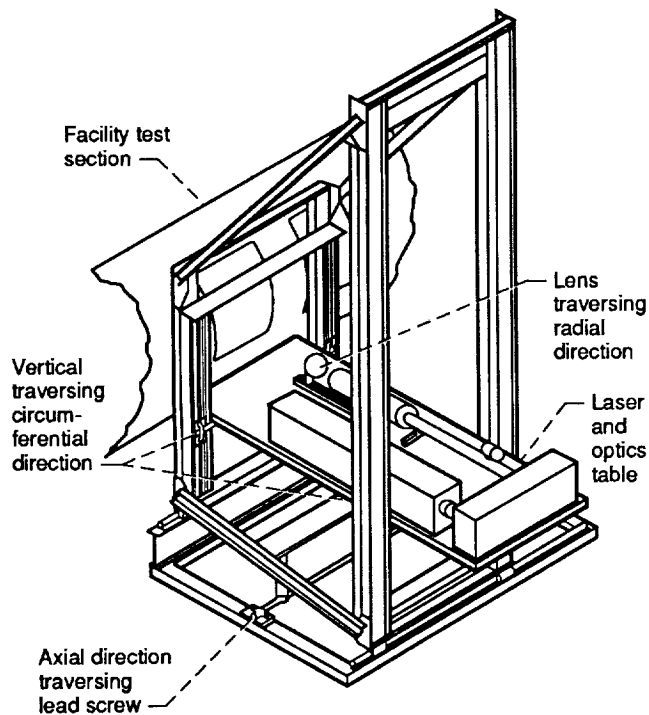


Figure 3.—Schematic of traverse system of Purdue annular cascade facility.

computed automatically, depending on the desired probe volume location. At each probe volume orientation for a specified measurement location, 3000 data points were acquired within typically 30 to 45 seconds.

### NASA Lewis Research Center Annular Cascade

The three-component velocity measurements of Seasholtz and Goldman (refs. 8 and 9) were performed using a two-channel mixed configuration laser anemometer (Type 3d, table I) in a stationary annular cascade of core turbine vanes. The laser anemometer consisted of a single-channel fringe system (with fringe rotation) combined with a single-channel spectrometer system (Fabry-Perot interferometer). Feasibility tests and preliminary measurements using the spectrometer technique are reported in reference 10. The cascade facility was initially designed to determine the aerodynamic performance of full-sized cooled vanes but later was modified to permit measurements using laser anemometry. The cascade design is described fully in references 11 and 12. The more recent research was to provide a three-dimensional data set to validate existing computer codes.

The 508-mm tip diameter cascade facility, shown schematically in figure 4, consists of an inlet section, a test section, and an exit section. In operation, atmospheric air was drawn through the inlet section, the vanes, and a dump-diffusing exit section before it was exhausted through the laboratory altitude exhaust system. Before entering the altitude

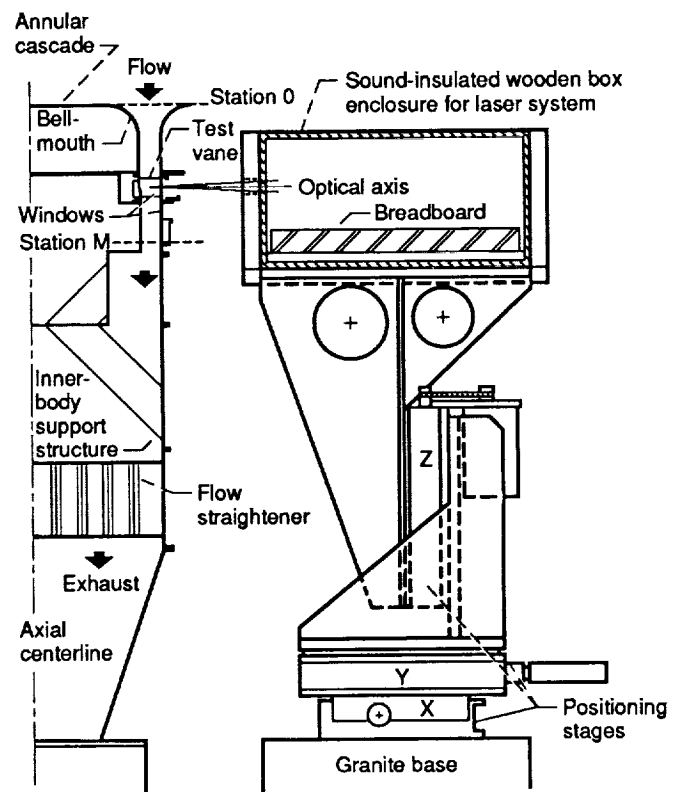


Figure 4.—Schematic cross-sectional view of core turbine stator cascade and laser positioning system at NASA Lewis Research Center.

exhaust system the flow passed through a flow-straightening section which removed the swirl created by the stator vanes. The inlet, consisting of a bellmouth and a short straight section, was designed to accelerate the flow to uniform axial-flow conditions and to provide a thin boundary layer at the vane inlet. The test section consisted of a full-annular ring of 36 vanes. The vanes had a 38.23-mm axial chord and produced 67° of flow turning.

For the three-component measurements of references 8 and 9, the hub endwall had an s-shaped contour with an inlet-to-exit passage-height ratio of 1.25. The exit vane height was 38.1 mm. This s-wall geometry produced a highly three-dimensional flow field with a significant radial velocity component. The tip endwall had a constant diameter of 508 mm to facilitate installing a window in this surface. The s-wall between the four vanes in the window area was polished to a mirrorlike finish to minimize diffuse scattering of the laser beams from this surface. Measurements were also made for a cylindrical hub endwall configuration (refs. 10 and 11) with a constant diameter of 431.8 mm. Only a limited number of three-component measurements were presented in these references as the feasibility of the technique was being investigated.

Optical access for the laser beams was provided by cutouts in the outer vane ring and in the cascade outer housing located downstream of the vane row (fig. 4). In the window region the vanes were machined to the vane tip radius to permit the window to fit flush with the tip endwall. Both windows were made from 3.175-mm-thick window glass. These windows were formed into a cylindrical shape that matched the tip radius by sagging them in a vacuum furnace onto a machined graphite form (ref. 12). At the vane row, the window covered about 39° in the circumferential direction and was 4 cm high. At the downstream location, the window covered 56° in the circumferential direction and was also 4 cm high.

The laser anemometer consisted, in part, of a single-channel fringe configuration (Boutier's, Type 1d) with fringe rotation. A fluorescent aerosol seed was used to measure the transverse (axial-tangential plane) velocity components. The radial component was measured with a scanning confocal Fabry-Perot interferometer (Boutier's, Type 1a) using the light elastically scattered by the seed particles (i.e., not the fluorescence). The two configurations, which were to operate simultaneously, were combined in a single optical system (Type 3d, table I). However, since the measurements with the Fabry-Perot interferometer required much more time than those with the fringe system, simultaneity could not be achieved.

A schematic of the optical layout of the laser anemometer is shown in figure 5. The 4-W argon-ion laser was equipped with a temperature-controlled etalon and had a maximum output power of 0.8 W at a 514.5-nm wavelength (green line). As shown in figure 5, lenses L1 and L2 functioned as mode-matching lenses to position the beam waists at the focal plane of lens L3. The beam divider (constructed from two

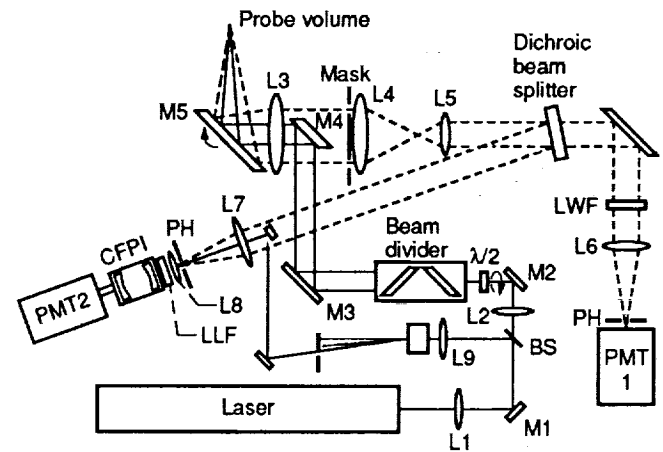


Figure 5.—Optical layout of system at NASA Lewis Research Center.

appropriately coated fused silica plates) split the single beam into two equal intensity parallel beams. The divider was mounted in a motor-driven rotary mount so that the orientation of the fringes could be set at any desired angle.

The two parallel beams from the beam divider were focused by lens L3 (250-mm focal length) after being reflected by mirror M5. Since this mirror was mounted on a motor-driven goniometer stage, the optical axis could be positioned along the radial direction in the stator cascade. This allowed a direct measurement of the radial velocity component with the Fabry-Perot interferometer.

The probe volume was about 100  $\mu\text{m}$  in diameter and 1 mm long with about eight fringes. Light scattered from particles passing through the probe volume was collimated by lens L3. The collected light was then split with a dichroic beam splitter, which reflected the green light and passed the longer wavelength fluorescence orange light.

After passing through a long wavelength pass filter LWF (to remove any residual green light), the fluorescent beam was collected by a photomultiplier tube PMT1 (RCA 4526). The signal from PMT1 was processed by a counter-type processor, using four fringe crossings, to provide velocity components transverse to the optical axis (in axial-tangential plane).

The light reflected by the dichroic beamsplitter was passed through a narrow band laser line filter (LLF) to remove any residual fluorescence before entering the confocal Fabry-Perot interferometer (CFPI), which had a free spectral range of 3 GHz and a maximum transmission of about 10 percent. The CFPI was scanned with a linear ramp generator. Because of this scanning, velocity versus time information was not available. The light exiting the CFPI was detected by photomultiplier PMT2 (RCA 8850). Photon counting electronics provided a digital count rate corresponding to the light intensity passed by the CFPI. Additional factors to be considered when using a CFPI for laser anemometry are discussed in reference 10.

A Bragg cell was included in the optics (fig. 5) to generate a reference signal offset from the laser frequency by 400 MHz.

Since this signal allowed the CFPI to be scanned over a frequency range less than its 3 GHz free spectral range, data acquisition was faster. Further details of the optical design can be found in references 8 and 9.

The laser optics were mounted in a wooden box covered with a layer of acoustic shielding to reduce the vibration of the laser. Any laser vibration would cause jitter in the laser frequency, making the Fabry-Perot measurements impossible. (The acoustic noise level near the cascade was 105 dB.)

A fluorescent dye aerosol (ref. 32) was used as the seed material. This material allowed measurements to be made by the fringe part of the anemometer system close to the hub, vanes, and windows. Fringe measurements could be made to about 1 mm of the hub (about 2.5 percent of span), while Fabry-Perot measurements could only be made to about 3 mm of the hub (about 7.5 percent of span). A liquid dye solution (rhodamine 6G in a mixture of benzyl alcohol and ethylene glycol) was atomized with a commercial aerosol generator. The seed particles (1.0- to 1.5- $\mu\text{m}$  diam) were injected through a 6-mm-diameter tube into the flow at the entrance of the bellmouth. The CFPI required a higher seeding rate (typically 10 kHz) to obtain high quality signals than was necessary for the fringe system.

A three-axis positioning system with a 12- $\mu\text{m}$  positioning accuracy and 1- $\mu\text{m}$  resolution was used to move the laser and optics. The positioning system was controlled by a remotely located minicomputer. The beam divider and the goniometer mounted mirror were also controlled by this system.

With the fringe system, seven independent components of the transverse velocity were measured at 10° intervals centered about the expected flow direction. This allowed not only the axial and tangential velocity components to be determined by least-squares techniques (ref. 11) but also provided an estimate of their statistical accuracy. For the Fabry-Perot system, radial velocity measurements were made at each of the seven orientation angles used for the fringe system transverse component measurements. The standard deviation of these seven measurements provided an estimate of the statistical accuracy of the averaged radial velocity component.

For the mixed configuration LA system, on-axis velocity component measurements using the CFPI were made (refs. 8 and 9) only in regions of the s-wall hub contour. For this situation, the optical axis was about 45° to the mirrorlike-finished s-wall, and the light scattered from this surface tended to be reflected away from the collection optics backscatter direction. In areas upstream and downstream of the s-wall, where the hub was cylindrical, CFPI measurements were not possible. Here, the optical axis was normal to the endwall and large amounts of light were collected, resulting in an inability to extract the small on-axis signal from the noise. The mirrorlike finish was probably a detriment on these cylindrical surfaces, since the light was reflected mainly in the backscatter direction. This is supported by the fact that interferometer measurements were previously made with a cylindrical hub configuration (ref. 10) when the endwall was not polished.

## Strathclyde University Model Mixed-Flow Pump

The three-component velocity measurements by Carey and Fraser (refs. 13 to 18) were made with a two-channel fringe laser anemometer system (Type 3b, table I) in a model mixed-flow pump. References 13 to 15 present results for the rotating blading (impeller) while references 16 and 17 give data for the vaneless region downstream of the rotor. Because of the desire to make LA measurements, the facility was designed to allow the pump to operate in air. This was done because of the difficulty of designing a window that could withstand the high pressure occurring in a water pump. Details of the facility design are given in reference 19. The research was intended to (1) provide an understanding of the losses occurring in the pump to improve future designs and (2) produce experimental data to verify the predictive codes used in these designs.

A sectional view of the facility is shown in figure 6. Air was drawn from the room through a 430-mm-diameter inlet cone and then passed through a honeycomb flow straightener before it entered the ducting connecting the model pump. The air was discharged from the pump into a coaxial duct which was exhausted by an axial two-stage booster fan located far downstream of the model. The pump was driven by a 5-kW electric cradle dynamometer suspended on air bearings.

A schematic view of the model mixed-flow pump is shown in figure 7. Five rotor blades were mounted on the conical hub of the pump, as shown in figure 8. Nine stator blades were mounted in a diffuser that was designed to bring the diagonally outward flow exiting from the rotor back to the axial direction. The model pump had a rotor outlet diameter of 430 mm and blade chord at midspan of approximately 275 mm. The rotor blade height was about 123 mm at the inlet and about 82 mm at the exit with a tip clearance of 1.1 mm. Tests were conducted with the pump operating at its best efficiency of 87 percent (ref. 14) and at a rotor speed of 1200 rpm. At these conditions, the flow rate was 1.01 m<sup>3</sup>/s. Operation of the pump at off-design conditions is reported in reference 15.

Access for the laser beams was provided by two large windows that covered the region from the rotor inlet to the stator exit. The windows were molded from 2.5-mm-thick acrylic sheet to conform to the rotor and stator casing profiles. Both moldings were done on forms in a furnace and the windows were then polished to give good optical clarity. The rotor window covered approximately 20° of circumferential arc while the stator window covered 90° of arc. In addition, the stator window was designed to be easily removable so that the inner surfaces of both windows could be cleaned periodically.

The laser anemometer consisted of a commercial two-channel, two-color, three-beam, color separation system (Type 3b, table I) with confocal backscatter collection optics. A 2-W argon-ion laser provided green and blue lines. An achromatic focusing lens (310-mm focal length) produced a probe volume of 80  $\mu\text{m}$  in diameter and 1.4 mm long. The probe volume

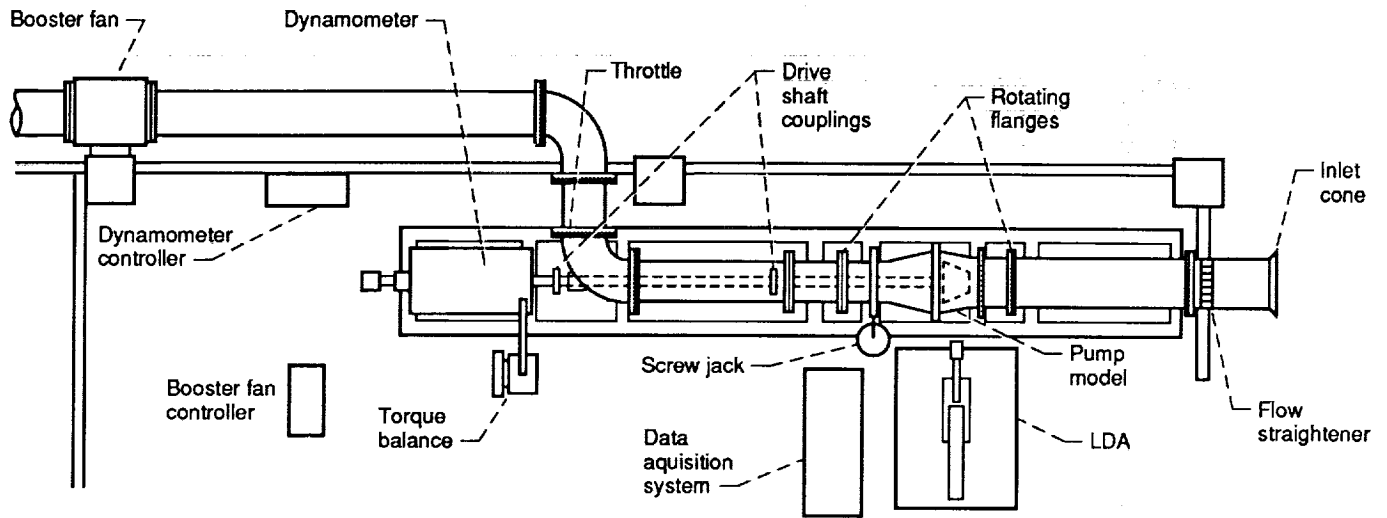


Figure 6.—Plan view of mixed-flow pump facility at Strathclyde University.

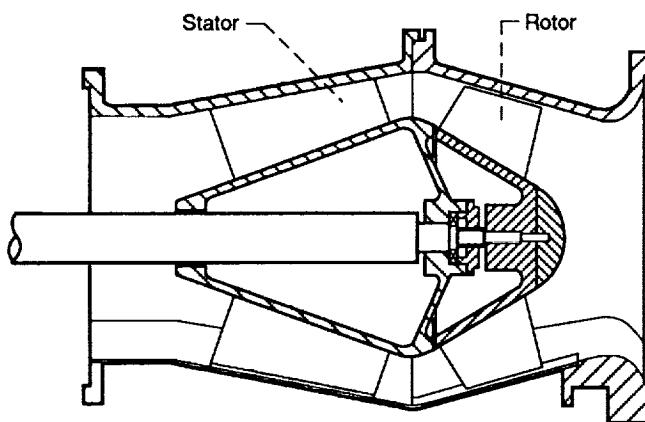


Figure 7.—Sectional view of model mixed-flow pump at Strathclyde University.

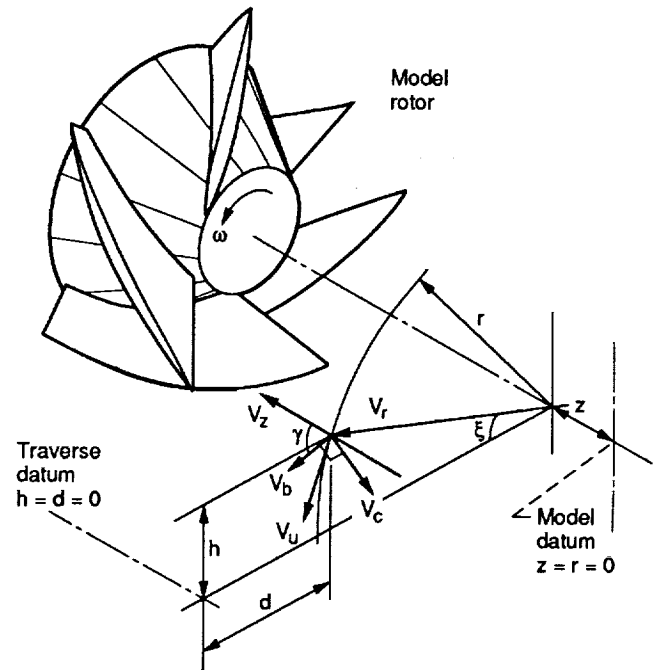


Figure 8.—Relationship between model and traverse coordinate systems and measured velocity components at Strathclyde University.

contained orthogonal sets of green and blue fringes with spacings of about 4.7 and 4.2  $\mu\text{m}$ , respectively. A Bragg cell was used to frequency shift the combined green-blue beam. The effective velocities of the green and blue fringes could be independently varied using separate photomultiplier signal mixers.

The flow in the pump was seeded by injection of 2- $\mu\text{m}$ -diameter oil droplets produced by a blast atomizer. When the seed particles passed through the probe volume the signals from the green and blue channels were measured by a pair of counter-type processors. The digital outputs from the counters were sent to a computer-controlled data acquisition system. Information obtained from an optical encoder on the rotor shaft enabled the computer to calculate the relative shaft position associated with each burst. Whenever burst frequency measurements were made on both channels simultaneously from a single particle, the computer recorded the two frequencies together with the angular position of the shaft at the time of the measurement. The rotor blade pitch was divided into 40 equiangular sectors (or windows) and the data were sorted into these sectors according to the rotor position. The average number of two-channel observations obtained in each sector was 1000, with a minimum of approximately 400.

The optical system was mounted on a traversing table that allowed movement in a horizontal plane in two perpendicular directions—one direction being parallel to the pump shaft axis or  $z$ -direction (see fig. 8). Vertical movement of the table along its support structure was also possible. The optical axis of the laser anemometer was always horizontal and normal to the vertical plane of the pump shaft axis. Therefore, displacing the optical axis from the horizontal plane of the pump shaft by a distance  $h$  (see fig. 8) was equivalent to inclining the optical axis to the radial direction of the pump by an angle  $\xi$ . Two-channel measurements taken with the optical axis at two different vertical displacements allowed all three components of velocity to be calculated. In addition, tilting the optical axis from the radial direction was used to minimize the size of the region not accessible to the laser beams because of the shadowing caused by the blade twist. Also, the position of the window in the rotor casing could be adjusted, depending on the vertical position of the optical axis, by rotating the model pump casing about the shaft axis.

### University of Cincinnati Radial Inflow Turbine Stator

Three-component velocity measurements were made by Eroglu and Tabakoff (ref. 20) with a three-channel fringe laser anemometer (Type 3c, table I) in the guide vanes of a radial inflow turbine. For this same turbine configuration, data were obtained in the vaneless region by Lakshminarasimha et al. (ref. 21) and in the turbine scroll by Malak et al. (ref. 22). For all these tests, the rotor was not used and was replaced by a body of revolution installed to provide a smooth continuous flow path downstream of the nozzles. The objective of the research was to provide a data base for the development,

improvement, and verification of turbomachinery computer programs.

The facility, shown in figure 9, was supplied through a settling chamber by high-pressure air that passed through a remotely controlled pressure regulating valve, a standard orifice meter, and a flow regulating valve. The air from the settling chamber was fed to the scroll through a converging duct of circular shape that blended smoothly into the scroll inlet. After passing through the radial turbine the air exited to a low-pressure exhaust system.

The radial turbine is shown schematically in figure 10. The turbine scroll had a nearly square cross section at the inlet and over most of its circumference. As seen in the figure, one side of the scroll's square cross section lines up with the nozzle side wall. This flat wall, which was made of 6.45-mm-thick Plexiglas, allowed access for the laser measurements. A vaneless region downstream of the scroll was followed by nozzle vanes placed between 112 mm and 85 mm radii. There were 18 slightly cambered nozzle vanes; each vane had a chord of 50 mm and a height of 12.7 mm. Downstream of the nozzle vanes was a vaneless space (vortex region), also with a 12.7-mm height. Measurements were generally obtained at a weight flow of 0.0907 kg/s. Further geometric details of the nozzles are given in reference 20.

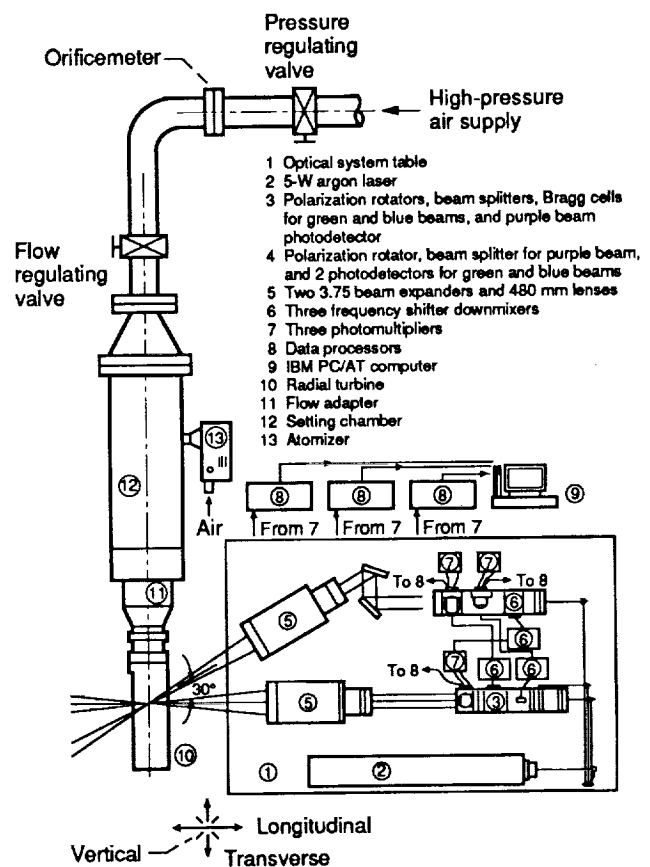


Figure 9.—Schematic of radial inflow turbine stator LDV system at University of Cincinnati.

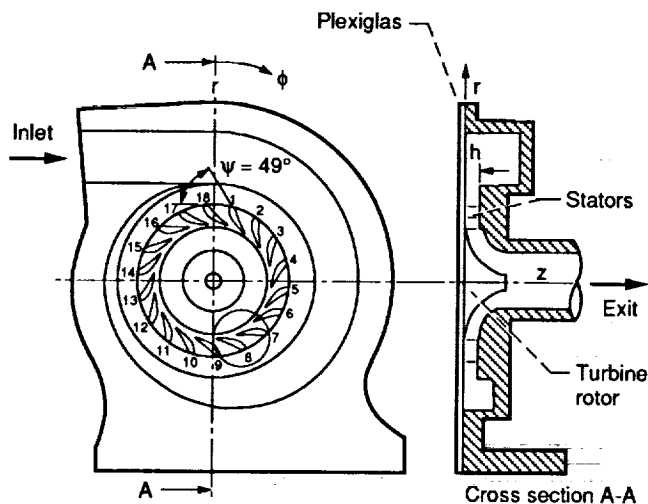


Figure 10.—Schematic of experimental turbine configuration at University of Cincinnati.

The three-channel laser anemometer system (Type 3c, table I) shown in figure 9 used a 5-W argon-ion laser as its light source. The laser light was split into its three strongest components (green, blue, and violet) by a dispersion prism. Polarization of each beam was adjusted with a polarization rotator, and each beam was split into two equal intensity components by beam splitters. Frequency shifters were used between the beam splitters and the collecting optics to reduce fringe bias and to determine flow direction. The blue and green beams were used in an optical train in the axial direction of the turbine and measured the horizontal and vertical components of velocity. The violet beam passed through a second optical train at a  $30^\circ$  angle to the axial direction and measured a nonorthogonal component of velocity (fig. 9). The orthogonal on-axis component of velocity was calculated from a transformation relation between the measured blue and violet components (ref. 20). Two separate beam collimators, one on the blue-green train and the other on the violet train, were used before the beamsplitters to insure that the focused beam pairs intersected at the beam waists. The focal length of each focusing lens was 480 mm. All six beams crossed at a common measuring point resulting in a probe volume of about  $50 \mu\text{m}$  in diameter by 0.6 mm in length and containing about 19 fringes. Scattered light from particles passing through the probe volume was collected in the off-axis backscatter mode to reduce the effect of wall flare. In addition, the shroud (back) endwall was coated with flat black paint to reduce reflections from the laser beams. The closest that measurements could be made was 1 mm or 7.9-percent span from the front Plexiglas endwall and 3 mm or 23.6-percent span from the back endwall. It was possible to measure as close as 0.5 mm from the blade surface when the blade geometry did not shadow the measuring region.

A commercial atomizer was used to seed the flow with  $2\text{-}\mu\text{m}$  diameter propylene glycol particles. The atomizer was connected to the bottom of the settling chamber upstream of

the radial turbine (see fig. 9). The signals from the laser anemometer were processed by three counter-type signal processors. Data from the signal processors were transferred to a computer for further processing and data storage (ref. 20). Coincidence of the three velocity component measurements was not used for these tests because of the long experimental times (low data rates) needed to obtain simultaneous data. Therefore, data were collected independently from the three channels.

The laser anemometer system was mounted on a milling machine table which could be traversed 254 mm in the axial, 457.2 mm in the transverse, and 558.8 mm in the vertical directions. The accuracy of the traversing system was  $25 \mu\text{m}$  in all three directions.

### Virginia Polytechnic Institute Low-Speed Compressor

Simultaneous three-component velocity measurements were made by Chesnakas and Dancy (refs. 24 and 25) with a three-channel fringe laser anemometer (Type 3c, table I) in a low-speed, axial-flow, research compressor rotor blade passage. The compressor could be operated with two stages, but for these tests a single-stage configuration was used. The objective of the research was to examine the suitability of using a three-color, three-component LA system to measure the total velocity vector inside turbomachinery blade passages.

Figure 11 shows the facility which consisted of an inlet, a research compressor, a plenum chamber, and exhaust ducting. A smooth bellmouth supported by six radial inlet struts comprised the inlet to the compressor. The compressor consisted of an axial-flow fan directly coupled to a 7.5 hp, 0 to 3000 rpm, dc motor. Geometrically, the compressor had a hub radius of 156.5 mm with a blade height of 70.2 mm and consisted of a 24-blade rotor followed by a 37-blade stator. A RAF-6 propeller section profile with  $4^\circ$  of twist from hub to tip and a chord length of 43.36 mm was the basis of the blade design. The rotor blades had stagger angles of  $43.5^\circ$  and  $47.5^\circ$  at the hub and tip, respectively. Black paint was used to coat the blades to minimize reflections from these surfaces. At the operational speed of 2900 rpm, the rotor tip speed was 69.0 m/s with a tip clearance of 0.6 mm. The stator, which was located 26 mm behind the rotor, had a flow turning of  $27^\circ$  with stagger angles of  $11^\circ$  at the hub and  $19^\circ$  at the tip. Solidity was 0.84 for the rotor and 1.36 for the stator. Downstream of the stator, the flow discharged into an annulus that extended 1.0 m to a cubic plenum chamber 1.2 m on a side. Airflow was regulated by a valve located in a large exhaust duct and was discharged into the room.

Optical access to the rotor blade passage was provided by a 6.4-mm-thick, flat, uncoated Plexiglas window. The use of a flat window caused a maximum deviation of 0.8 mm from the contour of the cylindrical casing. The window dimensions allowed optical access from 17 mm upstream of the rotor to 12 mm downstream of the rotor. Access in the spanwise direction was limited by the window size, the angle of



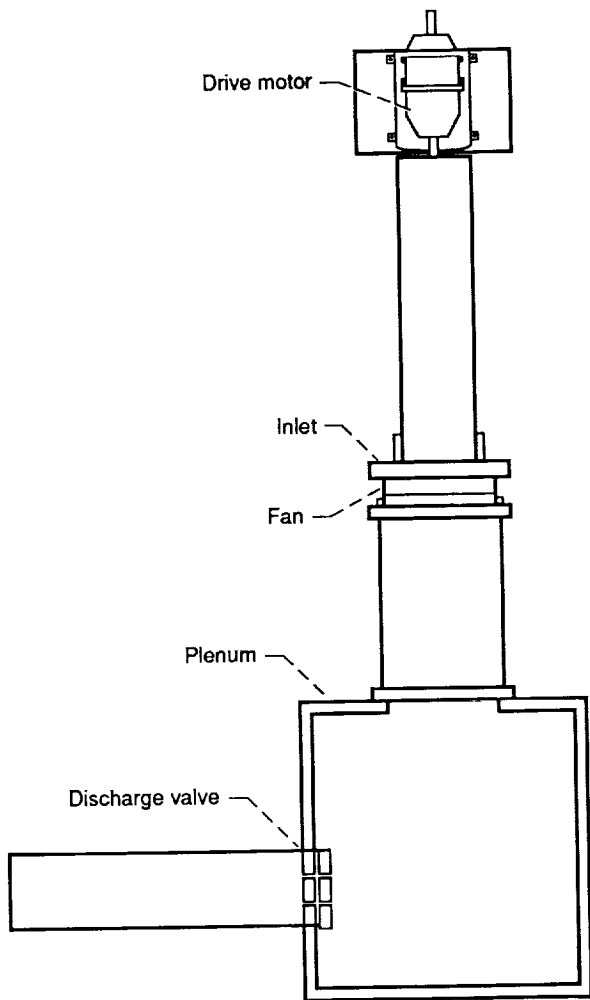


Figure 11.—Plan view of axial flow research compressor facility at Virginia Polytechnic Institute and State University.

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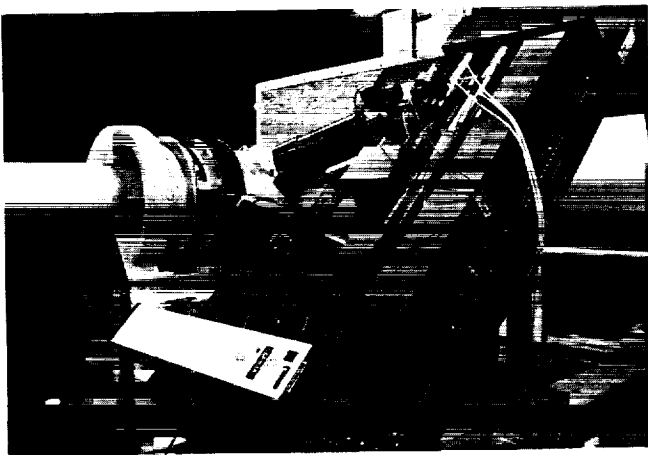


Figure 12.—Low-speed axial flow compressor and LDA system at Virginia Polytechnic Institute and State University.

separation of the two optical axes, and the tilt of the optic table to values from 45-percent span out to the blade tip. Measurements near the hub endwall could, therefore, not be made with this optical setup.

The laser anemometer system, shown in figure 12, was a commercial three-channel, three-color fringe system (Type 3c, table I) with a 4-W argon-ion laser. This LA system was similar to the University of Cincinnati system described previously. The blue, green, and violet lines were split with beamsplitters, and one beam of each color was shifted 40 MHz with Bragg cells. The blue and green beams were transmitted along a common optical train while the violet beams were transmitted along a separate optical train. The angle between the blue-green optical axis and the violet optical axis for this setup was approximately 40°. To minimize the size of the measurement volume, off-axis backscatter collection was used. Collection optics for the blue and green beams were located along the violet optical axis, while signals from the violet beams were collected along the blue-green axis. The six beams were focused to a single spot producing a probe volume of 65  $\mu\text{m}$  in diameter and containing about 13 fringes.

Each of the three optical signals was focused on a photomultiplier tube and the output downmixed to provide an effective frequency shift of 0 to 10 MHz. The amount of downmixing was varied at each measurement location in order to facilitate filtering the output signal and to maximize the data rate. These downmixed signals were amplified, filtered, and then measured with counter-type signal processors using a 2-percent comparison for noise suppression. Eight fringe crossings were used for each individual burst and measurements were only accepted when all three channels recorded bursts within a 50- $\mu\text{s}$  coincidence window. It was found that the data rate for the violet channel was, in general, five to eight times lower than either the blue or green channels and was rarely above 100/s.

The position of the compressor shaft was encoded, with one shaft revolution being divided into 480 windows, so that each rotor blade passage contained 20 measurement zones. Data were recorded only when a window was enabled. At midspan each window was 2.5 mm long. The relatively large window size was chosen to maximize the data rate at the expense of spatial resolution. In addition, the measurements were averaged over all blade passages to increase the data rate. This method of taking data allowed the filter settings for each window location to be adjusted depending on its velocity level (which can vary widely in going from blade pressure to suction side of the passage).

The flow was seeded with sugar particles generally less than 2  $\mu\text{m}$  in diameter. The selection of this seed satisfied the criteria that it be benign, since the flow from the compressor dumped directly into the room. The sugar seed was generated by supplying an aerosol seeder with a solution of sugar and water. Evaporation of the water resulted in spherical sugar particles; this was verified by scanning electron microscope photographs of the seed collected on glass slides. A solution

of 11 parts water to 1 part granular sugar by volume was found to produce the best particle size distribution. The seed was introduced locally in the flow, about 150 mm upstream of the compressor bellmouth. This resulted in a maximum data rate of about 500/s when collecting data in a single encoder window and averaging over all blades. The seed injection position was chosen to minimize flow disturbances at the measurement location while maintaining some control over the seed trajectory. Evaporation of the water to assure solid sugar particles at the probe volume location was tested by running with pure water. A disappearance of the LA signal confirmed that all the water evaporated before reaching the measurement location.

The laser system was mounted on a single optical table which was attached to a mechanical traversing mechanism (see fig. 12). With this device, the optical table could be moved parallel and perpendicular to the compressor axis (x- and r-directions). Manually powered machine screws attached to a dial index allowed positioning to within 0.05 mm. Rotation of the rotor allowed for a third probe volume motion within the blade passage. In addition, the optical table could be rotated about the r-axis of the compressor. To maximize optical access to the blade passage, the table was tilted at an angle of  $45^{\circ}25'$ , approximately the stagger angle of the blades.

## Laser Measurement System Enhancements

### Optical Improvements

The method of improving the performance of three-color LA systems suggested by Boutier (ref. 2) involves using a second laser source dedicated to generating a violet laser line. When a single laser is used for all three colors, the power of the violet line is much less than that for the green or blue lines. Therefore, using a second laser allows more power for the violet line and results in each of the three fringe patterns receiving more equal light energy. Boutier's anemometer system used two 15-W argon-ion lasers as light sources. One laser was operated at 8 W using all lines, which produced 3-W green and blue lines. The second laser was used at maximum power producing a 2.7-W violet line.

Another method of improving the performance of LA systems is the use of beam expansion to reduce the probe volume size. This concentrates the laser power in a smaller region and results in better signal-to-noise ratios. The main problem caused by decreasing the beam diameter is the possible uncrossing of the laser beams in passing through the curved turbomachinery window. To overcome this difficulty, these systems may require the use of window correction optics. The basic idea is to have the window correction optics *uncross* the laser beams so that the window (which acts like a lens) can *cross* them again. For cylindrical windows, the design of window correction optics is described by Wernet

and Seasholtz (ref. 33). Even for this situation, the position of the correction optics must move relative to the focusing lens depending on how far from the curved window the laser probe volume is located. Obviously, this makes for a more complicated system. In addition, the glass windows used in these systems must be of high optical quality since it is now a more critical optical element. Uncrossing of the beams can also occur if the optical axis is not normal to the window. Therefore, this technique may only be useful for the combined fringe and Fabry-Perot interferometer system (Type 3d, table I) since only a single optical axis orientation (which can be normal to the window) is needed for all the velocity component measurements.

A laser fringe anemometer system incorporating this technique and designed with beam diameters of  $50\ \mu\text{m}$  and an  $f/2.5$  focusing lens has been used recently by the author. Comparing this newly designed system with the original (beam diameters of  $100\ \mu\text{m}$  and an  $f/4$  focusing lens) confirmed the improvements possible with the new technique: the signal-to-noise ratio of the measurements are higher, measurements from smaller sized particles are being obtained, and measurements closer to the endwalls are possible without using the fluorescent dye technique. The increased level of complexity makes this LA system more difficult to optically align and operate. Expertise in optical design may also be necessary to build and fine tune a system of this type.

### Enhanced Data Acquisition

A single- or two-channel laser anemometer system can resolve the velocity vector, if three noncoplanar velocity components are measured. As discussed previously, this is accomplished by moving the optical axis of the anemometer relative to the hardware while maintaining the probe volume position constant. Improvements in the accuracy of the calculated velocity can be obtained by making more than three velocity component measurements. A similar method of data acquisition for coplanar measurements was described previously for the NASA Lewis Research Center annular cascade laser anemometer. In this method, seven independent velocity components were measured, and least-squares techniques were used to obtain the two transverse velocity components and estimates of their statistical accuracies. Of course, for the present situation, noncoplanar velocity component measurements must be obtained to determine all three velocity components. This type of data acquisition takes longer to accomplish not only because more data is taken but also because the positioning system must move to adjust the optical axis for each measured velocity component.

### Future Developments

In addition to the possible LA system enhancements discussed previously, some promising developments in the

design of miniature three-dimensional laser anemometer probes using fiber optics have occurred that may be applied to turbomachinery research in the near future. These techniques are useful in situations constrained to use small windows, such as in centrifugal compressors. The laser anemometer system must, therefore, be able to obtain all the velocity component measurements using a single optical train for both the transmitting and receiving optics. Two promising LA systems using fiber optics are described by Ahmed et al. (ref. 34) for a fringe system and by Schodl and Forster (ref. 35) for a time-of-flight system.

### Fiber Optic Fringe System

A miniature fringe-type laser anemometer instrument based on fiber optics was developed by Ahmed et al. (ref. 34). This probe was intended for measuring the boundary layer in centrifugal compressors, and the design was based on a laser Doppler system using a digital correlator for signal processing. To obtain the three-dimensional measuring capability, the optical axis was designed to be at an angle (about  $22.5^\circ$ ) to the mechanical axis of the probe, as shown in figure 13. Three component measurements can be obtained by positioning the laser beams at three different angles by rotating the probe about its mechanical axis. The flow vector can then be resolved from these three measured velocity components.

The probe was designed to measure speeds up to 150 m/s using a 10-mW helium-neon laser operating at a 632.8-nm wavelength for the light source. The probe volume consisted of a  $80\text{-}\mu\text{m}$  cube that was situated 12 mm from the front face of the probe. A fringe spacing of about  $5\text{ }\mu\text{m}$  gave 15 fringes in the probe volume. Further details of the probe design can be found in reference 34.

Initial tests of the instrument were made in a one-dimensional flow of air in a square duct. Measurements were made at six angular positions (only three required) of the optical axis, and the consistency of the calculated velocity was found to be very good. These tests also indicated that the laser produced insufficient light intensity in the probe volume, resulting in measurements limited to low flow velocities. A 30-mW laser diode was considered as a light source to overcome this problem.

### Fiber Optic Time-of-Flight System

Similarly, Schodl and Forster (ref. 35) developed a multicolor fiber optic probe based on the time-of-flight laser anemometer technique for three-dimensional flow measurements. In this probe (fig. 14) the light from an argon-ion laser operated in multicolor mode was coupled to a single-mode fiber and guided to the optical head. The laser beam passed through a Wollaston prism, which produced two slightly diverging beams of orthogonal polarization. The two colors were then focused in the measurement region. Because of the chromatic aberration of the focusing lens each color

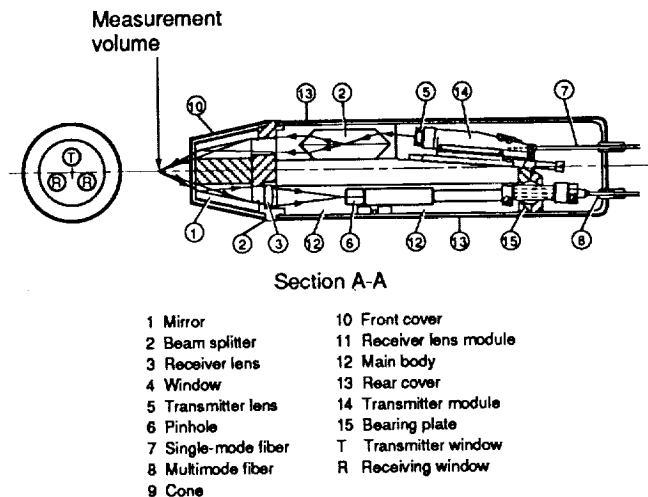


Figure 13.—Sketch showing general arrangement of three-dimensional microlaser anemometer.

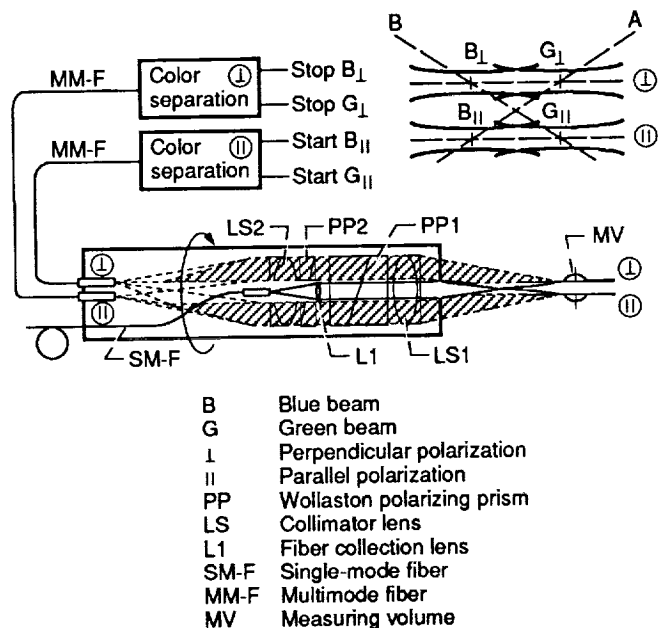


Figure 14.—Beam path of three-dimensional multicolor L2F velocimeter.

was focused with a slight displacement along the optical axis (fig. 14). This three-dimensional measurement system consists basically of 2 two-dimensional time-of-flight systems. The first system (system A) measured the TOF between beams  $B_{\perp}$  and  $G_{\perp}$  and the second system (system B) measured the TOF between beams  $G_{\parallel}$  and  $B_{\perp}$ . The measurement frequency (or data rate) of each system depends on the flow angle with respect to the two beams and is a maximum for flow going through the centers of the two beams. For a given flow direction, the measurement rate cannot be a maximum for both systems A and B. Therefore, the ratio of the measurement frequency of these two systems (i.e.,  $(A - B)/(A + B)$ ) was found to be a sensitive measure of the axial (or on-axis) velocity component

(ref. 35). Data acquisition was obtained simultaneously from each channel using two sets of electronics. It would seem that this technique for measuring the on-axis component would be quite sensitive to the turbulence level (similar to the standard two-dimensional TOF systems) and to the uniformity of the seeding rate.

Preliminary tests using this laser anemometer probe were made on a small free jet. The laser anemometer had a beam waist diameter of  $8\ \mu\text{m}$  and an axial center displacement of 0.2 mm for the green and blue beams and a separation of the different polarized beams of 0.2 mm. Measurements were made on the nozzle axis (one nozzle diameter downstream of the exit) at different orientations of the instrument axis to the nozzle axis. The experimental results showed good agreement with the theoretical predictions. It was estimated that the probe was capable of determining the flow vector to an angular resolution of about  $1^\circ$ .

## Concluding Remarks

The laser anemometer systems described in this report are capable of measuring the three velocity components in annular geometries in both stationary and rotating blades. Generally these systems use fringe-type laser anemometers in single-channel, two-channel, or three-channel designs. The major difficulty with these designs is the large uncertainty when determining the on-axis component as compared to the transverse components. This uncertainty results from the geometric constraint of the hardware that limits the orientation of the three different optical measurement planes. The maximum angles between the different optical orientations in these systems are about  $30^\circ$  to  $40^\circ$ . The addition of a scanning confocal Fabry-Perot interferometer to a conventional fringe-type anemometer allows the direct measurement of the on-axis velocity component with a backscatter configuration. Only a single optical axis orientation is needed for this system to measure all three velocity components. The advantages of this system for turbomachinery research are that it does not require a large optical access port and that it is capable of measuring a relatively small radial velocity component when the transverse component is much larger. The system also appears capable of obtaining measurements with smaller sized seed particles than are possible for the fringe system.

However, the Fabry-Perot interferometer does have some disadvantages when compared to the fringe systems used for the transverse velocity measurements. These disadvantages include the following: (1) inability to make measurements when the optical axis of the anemometer was normal to the endwall surface (probably caused by the mirrorlike finish on the hub endwall since interferometer measurements were previously made when testing a cylindrical hub endwall that was not polished), (2) increased data acquisition time, (3) requires higher seeding rates, (4) possible need for an acoustic enclosure to protect the laser from high noise levels (105 dB), and (5) inability to obtain velocity time history information.

Some laser anemometer design considerations and potential problems were also discussed. Caution is necessary when using plastic windows because of possible damage to the plastic from the laser beams. The dynamics of the seed particles to faithfully track the flow must also be carefully examined. To do this calculation properly, the size of the seed particles actually detected in the LA measurement process must be determined, as aerosol generators produce a distribution of particle sizes. The statistical accuracy of the LA data is not only compromised by the small angles between the different optical orientations used for the component measurements but also by the use of sequential (uncorrelated) data acquisition. Only the three-channel, three-color fringe system allows coincidence of the velocity component measurements, and this possibly results in higher accuracy in the calculated velocity vector.

Possible enhancements to the three-component laser anemometer measurement systems are also suggested. These include the following: (1) dual lasers for three-color systems, (2) smaller diameter laser beams (smaller probe volume), and (3) multiple noncoplanar velocity component measurements. In addition, future developments in laser anemometer systems were discussed: they include promising miniature three-dimensional fiber optic probe designs based on both fringe-type and time-of-flight techniques.

Lewis Research Center  
National Aeronautics and Space Administration  
Cleveland, Ohio, July 23, 1990

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16. Abstract <p>This report first presents a brief overview of the different laser anemometer (LA) optical designs available. Then, the LA techniques that can be used to design a three-component measurement system for annular geometries are described. Some of the facility design considerations unique to these LA systems are also addressed. Following this, the facilities and the LA systems that were used to successfully measure the three components of velocity in the blading of annular-flow machines are reviewed. Finally, possible LA system enhancements and future research directions are presented.</p>					
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