General Disclaimer

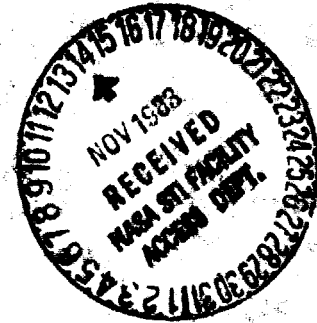**One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)

Temp.#42354

Application of Laser Anemometry in Turbine Engine Research

NOV 1983
RECEIVED
NASA STI FACILITY
ACCESS DEPT.

Richard G. Seasholtz
Lewis Research Center
Cleveland, Ohio

NASA

APPLICATION OF LASER ANEMOMETRY IN TURBINE ENGINE RESEARCH

Richard G. Seasholtz

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

ABSTRACT

The application of laser anemometry to the study of flow fields in turbine engine components is reviewed. Included are discussions of optical configurations, seeding requirements, electronic signal processing, and data processing. Some typical results are presented along with a discussion of ongoing work.

INTRODUCTION

Laser anemometry (LA)--also called laser velocimetry (LV), or laser Doppler velocimetry (LDV), or laser Doppler anemometry (LDA)--refers to the remote measurement of local flow velocity using laser light scattering. The chief virtue of the laser anemometer as a flow measurement instrument is that no physical probe is placed in the flow field. Insertion of probes, such as Pitot probes, temperature probes, or hot wires, can greatly alter the flow pattern under study. The applications of laser anemometry range from mapping the velocity profile within blood vessels of living animals to the measurement of atmospheric wind velocity many miles from the instrument.

The Lewis Research Center has an extensive program in computational fluid dynamics with the goal of developing computer codes which will accurately predict the detailed flow within turbomachinery components. Knowledge of the internal flow conditions is very important to designers of new high performance, fuel efficient, quiet aircraft engines. Being able to calculate the flow with confidence will enable a great reduction in the amount of expensive experimental testing needed in the development of new engine component designs. However, these new computer codes must be verified by comparing them with accurate experimental data obtained for well-defined geometries. It is in this role that laser anemometry is being extensively employed at Lewis.

In this paper we briefly review the fundamentals of laser anemometry. Included are discussions of single-beam and dual-beam laser anemometers. Two applications of laser anemometry at the Lewis Research Center are described. The first is a dual-beam LA designed for a compressor rotor facility, and the second is a single-beam system designed to measure the line-of-sight velocity component in a turbine stator facility. A summary of ongoing work concerned with the application of LA to high temperature flows is then given.

BASIC CONCEPTS

Laser anemometry uses radiation scattered by moving objects as a means of remotely measuring velocity. In some commonly used types of laser anemometers the physics of the technique can be described in terms of the Doppler effect. In other types of laser anemometers it is more appropriate to consider the measurement in terms of the time required for the flow to move a known distance.

Doppler Effect

The physical basis for most laser anemometers is the Doppler effect, named for Christian Doppler, who in 1842 theorized that since the pitch from a moving source varies for a stationary observer, the color of the light from a star should vary according to the star's velocity relative to the earth. Light reflected from an object that is moving toward a light source, when viewed from the source, is raised in frequency by an amount depending on the velocity of the object. For a receding object the frequency is lowered.

Consider a plane wave with wave vector k_0 (and frequency $f = k_0 c/2\pi$ where c is the velocity of light) that is scattered by a particle moving with velocity $\underline{v}$ (Fig 1a.). The frequency shift of the scattered light relative to the frequency of the incident light (the Doppler shift) is proportional to the particle velocity and is a function of the scattering angle χ_s (i.e., the angle between k_s and k_0). For Doppler shift frequencies much smaller than the frequency of the incident light, the Doppler shift is

$$f_d = f_s - f_o = (1/2\pi)(\underline{k_s} - \underline{k_o}) \cdot \underline{v} \qquad (1)$$

Single Beam LA Systems

As described above, the Doppler shift of light scattered from a moving object is proportional to the component of the object's velocity normal to the bisector of the incident light wave and the scattered light wave. Thus, for a backscatter optical arrangement such as shown in Fig.1b,
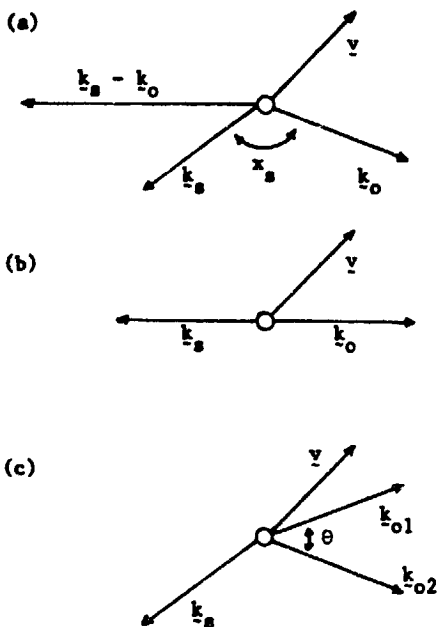
Fig.1. Wave vector diagram (a) general scattering (b) single-beam backscatter configuration (c) dual-beam configuration

the measured velocity component lies along the propagation direction of the incident laser beam. The Doppler shift for backscatter is given by

$$f_d = 2 \, v/\lambda \tag{2}$$

where v is the target velocity component along the beam and λ is the wavelength of the laser light. For visible light the Doppler shift is approximately 4 MHz/meter/sec.

Two approaches are used to measure the Doppler shift frequency. One is a heterodyne technique (called the reference beam technique) where the scattered light is heterodyned with a local oscillator signal obtained from the laser beam on a square law photodetector. The output of the photodetector (usually a photomultiplier tube) contains the difference frequency between the frequency of the scattered light and the frequency of the original laser light. This difference frequency is just the Doppler frequency. The heterodyne detection scheme was the basis for the first demonstration of a laser anemometer by Yeh and Cummins[1] in 1964. They measured the velocity profile of the laminar flow of water in a circular tube. The laser light was scattered, not from the water itself, but from small particles suspended in the flow. These particles, which are essential to almost all types of laser anemometers, can be either naturally occurring or intentionally added material (seed material).

One difficulty in using the reference beam approach with a backscatter geometry in turbomachinery applications is the large dynamic range in the Doppler frequencies. The high flow velocities, which can approach Mach 1, result in frequencies that exceed the frequency response of

commonly used photomultiplier tubes (about 200 MHz). Unfortunately, the backscatter geometry is usually the only feasible geometry in most turbomachinery test facilities.

Another difficulty with heterodyne systems is a fundamental limitation expressed by the Antenna Theorem,[2] which states that the maximum effective receiver aperture area is limited to λ^2/Ω, where Ω is the solid angle subtended by the probe volume at the receiver aperture.

The second approach to analysing the scattered light in a single-beam system is to use a high resolution interferometer to directly measure the Doppler shift. The interferometric approach offers the advantages of essentially no upper frequency limit* and a larger available receiver aperture. An interferometric type laser anemometer used to measure the radial velocity component in an annular stator cascade will be described below.

Dual Beam Systems

The most common type of laser anemometer is the dual-beam or fringe-type system. The reasons for its popularity are its ease of alignment, high light collection efficiency, and ability to measure velocity components normal to the viewing direction. In the dual-beam laser anemometer the single laser beam is divided into two parallel beams of equal intensity (Fig.1c). The two beams are focused at a common point. Near this point the two beams occupy the same spatial region, and particles passing through this region will simultaneously scatter light from both beams. The scattered light that is collected by the receiving lens (often the same lens used for focusing the incident beams) is detected by a square law photodetector.

The output of the photodetector contains a component with a frequency equal to the difference of the frequencies of the two scattered beams. This difference frequency is found by using equation 1.

$$f_d = f_{s1} - f_{s2} = (1/2\pi)(\underline{k}_{o2} - \underline{k}_{o1}) \cdot \underline{v} \tag{3}$$

Because f_d is independent of the direction of the scattered light, the aperture of the receiving lens may be of any size (i.e., the light collection solid angle is not limited by the Antenna Theorem as it is in a reference beam system). Also note that the difference frequency is proportional to the velocity component in the plane of the two incident beams normal to the bisector of the beams. Written in terms the angle θ between the beams and the wavelength of the laser light λ, this relation between the difference frequency and velocity becomes

$$f_d = (2 \, v \, \sin \theta/2)/\lambda \tag{4}$$

where v is the measured velocity component.

Fringe Model

The dual-beam laser anemometer is often explained in terms of a fringe model first proposed by Rudd.[3] In the fringe model the two inter-

2

secting beams are assumed to form interference fringes. These fringes are planes with normals in the plane of the two beams and perpendicular to their bisector; the fringe normal is then in the direction of the measured velocity component. The separation between the fringes is $s = \lambda/2 \sin \theta/2$. Thus, the relation between the observed frequency and the measured velocity component is

$$f = v/s \qquad (5)$$

which is interpreted as the rate that the target particle crossed the fringes. This fringe model, although not a rigorous physical description,[4] is adequate for most applications. It is also appropriate for the dual-beam laser anemometer using laser induced fluorescence that is described below.

Two-Spot Systems

Another type of laser anemometer is the two-spot, also called the dual-focus, or time-of-flight, or laser transit anemometer.[5] In this system the laser light is focused into two small diameter parallel beams in the probe volume; the beam diameters typically are about 20 micrometers and are spaced a few hundred micrometers apart. As a particle passes through the two beams in sequence, the scattered light is detected and processed to determine the time of flight between the two beams. The velocity is then calculated from the time and known beam spacing. This type laser anemometer offers the potential of being able to measure smaller particles than the dual-beam system because the laser light is more concentrated. However, a limitation is that in order to be measured a particle must pass through both beams; this means that the two beams must be aligned with the flow direction. For turbulent flow the flow direction fluctuates and only a fraction of the particles that pass through the first beam will also pass throught the second beam. This results in a reduced data rate compared to the data rate obtainable for laminar flow.

SIGNAL PROCESSING

The electronic processing of the signal from the photodetector to extract the Doppler frequency is a critical part of laser anemometers. In this section signal processing in dual-beam laser anemometers will be discussed. The Doppler frequency, as discussed above, is proportional to the velocity of the particle passing through the probe volume.

Doppler Burst Signals

A Doppler burst occurs when a particle passes through the probe volume. As shown in Fig. 2a, the burst signal from the photodetector in a dual-beam LA, without considering noise, has the envelope of the Gaussian laser beam profile with modulation at the Doppler frequency. The bursts occur at random times at an average rate that is determined by the concentration of particles in the flow. With lightly seeded gas flows, the Doppler bursts rarely overlap, so each may be treated in-
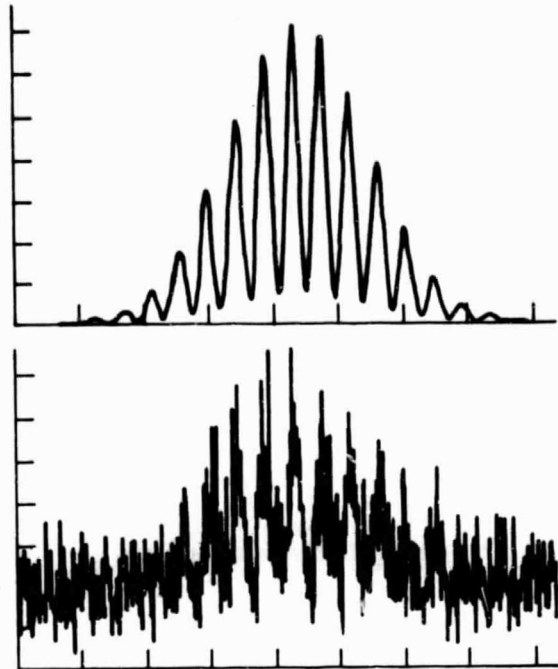

Fig. 2. Doppler burst (a) burst signal no noise (b) burst signal with noise

dependently. However, because of the spread in particle sizes and because of the random nature of the individual particle trajectories, the amplitudes of the Doppler bursts are random. Furthermore, actual signals include a noise component as shown in Fig. 2b. The noise is a result of the discrete photon nature of light (shot noise).

The lower error bound for the measurement of the velocity of a single particle is found using maximum likelihood estimation methods[6] to be

$$\left(\frac{\sigma_v}{v}\right)_F = \frac{2\sqrt{2}}{\pi^{\frac{1}{4}}} \left(\frac{hc}{\eta\lambda\sigma\Omega}\right) \frac{\Gamma_o^{\frac{1}{2}}}{P_1} \frac{v^{\frac{1}{4}}w_o^{3/2}}{N\sqrt{1 + 18/\pi^2 N^2}} \qquad (6)$$

This expression was derived for the case where the background light amplitude Γ_o is larger the peak Doppler burst amplitude. It shows that the error becomes smaller for lower velocities v, larger light scattering cross sections σ, higher laser power P_1, smaller probe volume diameters $2w_o$, larger solid viewing angle Ω, and a larger number of fringes N. Also, h is Planck's constant, c is the velocity of light, and η is the quantum efficiency of the photodetector.

Since each Doppler burst measurement gives the instantaneous velocity, it is necessary to take many individual measurements (often 1000 or more) to obtain the statistical parameters such as mean and standard deviation that describe a turbulent flow.

The rate of measurements of the individual particles in the flow is very important because it determines the type of information obtainable from

3

the measurements as well as the experimental run time. For example, if turbulent scale and power spectra are to be determined, the data rate must be high enough so that a significant fraction of the times between the measurements is less than the Nyquist sampling period. (Because of the random sampling times, the mean data rate does not need to be greater than the Nyquist rate.) On the other hand, sampling at rates in excess of the correlation time of the flow does not give independent samples.[7]

Spectrum Analysis

The signal may either be processed in the frequency domain or in the time domain. The simplest method to determine the Doppler frequency is to use a spectrum analyser. A conventional swept frequency spectrum analyser was used in much of the early work. However, because it only has a single narrow bandpass filter, it is an inefficient burst processor. A real-time spectrum analyser, such as a filter bank, provides a much more efficient means of processing the Doppler bursts.

Counter Processors

Special purpose signal processors that operate in the time domain have been developed and now are commercially available. These so called "counter processors" operate by first high pass filtering the Doppler burst to remove the low frequency component of the burst, and then measuring the frequency by measuring the time between the zero crossings of a fixed number of cycles. These processors use the amplitude of the burst to enable the time interval measurement circuitry so low level noise is not measured. The accuracy of the time interval measurement, which determines the ultimate accuracy of the measurement of the frequency of a single burst, typically is 1 nanosecond. The maximum burst processing rate is usually set by the associated data acquisition equipment; using DMA, rates in excess of 200,000 measurements per second can be realized. However, the actual rate achievable in experiments is usually set by the concentration of particles in the flow. In most gas flow experiments the natural particulates do not have a high enough number density to provide the desired data rate, so additional particulates are introduced into the flow. This is commonly referred to as seeding the flow.

SEEDING

Although the physical parameter of interest is usually the fluid velocity, it is actually the velocity of small particles suspended in the flow that is measured with a laser anemometer. In order to identify the particle velocity with the fluid velocity, which is the usual assumption, the particle must accurately follow the motion of the fluid. This ability of the particle to "follow" the flow is determined by its size and mass density; small particles with low mass density are desirable. However, the intensity of the scattered light is a strong function of the size of the particle as well as its refractive index. The
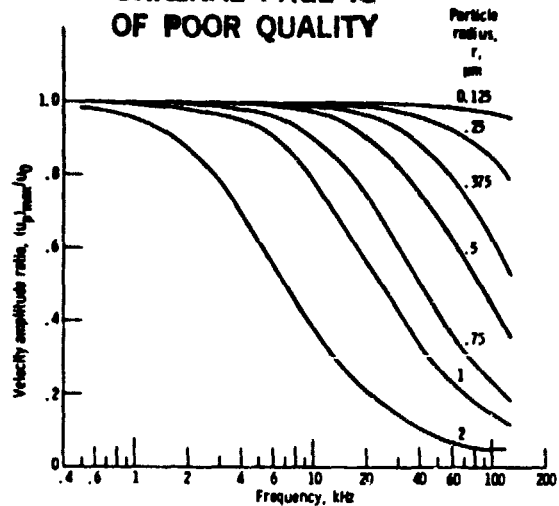
Fig. 3. Influence of particle size on particle tracking in oscillating flow field. Particle mass density, 1 g/cm^3; maximum gas velocity, 15.2 m/sec

problem thus faced by the laser anemometrist is to select particles small enough to follow the flow, but large enough to scatter sufficient light to allow the accurate measurement of the particle's velocity. An indication of the size of particles needed is given by Fig. 3 which shows the frequency response of particles in an oscillating flow. The particles used in laser anemometry in turbomachinery typically have diameters of about 1 micrometer. Either liquid or solid aerosols may be used depending on the application. Liquid aerosols, such as mineral oils or silicone oil, are easily produced and are commonly used for low temperature applications.

When particles with accurately known sizes are needed, polystyrene latex spheres are often used. For high temperature applications, where liquid aerosols cannot survive, solid refractory materials such as metal oxides are used. Commonly used refractory seed materials include aluminum oxide and titanium oxide.

LASER INDUCED FLUORESCENCE

The phenomenon of laser induced fluorescence is used in some applications where laser light scattered from surfaces near the desired measurement point causes a decrease in the signal-to-noise ratio, which consequently limits how close measurements can be made to the surface. With this technique, a fluorescent seed material is used, which when irradiated by laser light at one wavelength, radiates at a longer wavelength.[8] An optical filter placed in the receiving optics is used to block the light at the original laser wavelength while passing the longer wavelength fluorescent radiation. This technique is used for cold flow studies at Lewis; one application is discussed in the Applications section.

4

Fig. 4. Optical layout of anemometer for compressor rotor

CD-12287-36

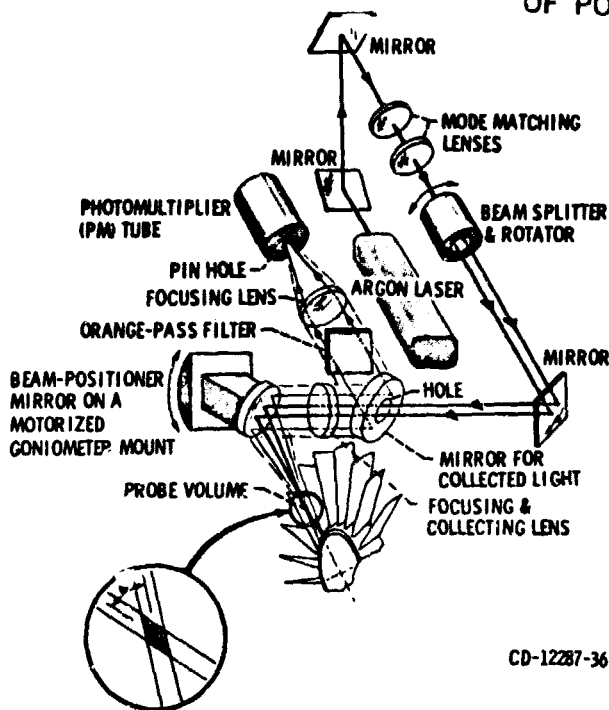Fig. 5. Block diagram of complete anemometer for compressor rotor

APPLICATIONS

Two specific applications of laser anemometry in turbomachinery studies at the Lewis Research Center will be described. One is the mapping of the velocity in a single stage transonic compressor rotor facility using a dual-beam fringe type laser anemometer. The other is the measurement of the radial velocity component in an annular turbine stator cascade facility using an single-beam system with an optical interferometer.

General Approach

The general approach that has been taken in the design of laser anemometer systems for turbomachinery facilities at Lewis can be summarized as follows:

1) Use window designs that do not affect the flow under study; this means that windows must be curved to match the contour of the test rig; such curved windows introduce astigmatism into the optical system which can either be minimized by making the windows thin, or can be compensated for by using auxiliary optical components.

2) Keep the optics as simple as possible; this has included using only single velocity component measurements (optics are mechanically rotated to obtain other components); also, all optics and the laser are mounted on a single rigid plate, which is moved to position the probe volume.

3) Use rapid data acquisition equipment and computerized control of optics positioning; minicomputers are used for these functions, and the
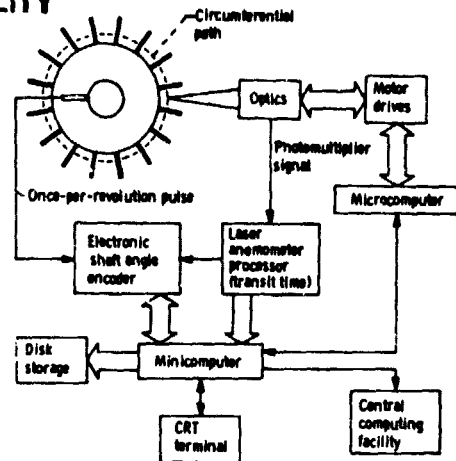
development of software is a major part of the system development.

Dual Beam Fringe Type LA for Compressor Facility

This laser anemometer system was designed to map flow velocity within the rotor passage of a transonic compressor rotor. An LA was selected for this application because, in addition to the usual flow interference problems, it is only with extreme difficulty that probes can be used to measure the flow within rotating components. System design emphasized rapid and efficient data acquisition under computer control.

The optical layout of the dual-beam system is shown in Fig. 4. It is an on-axis backscatter system that uses the 514.5 nm line of an argon-ion laser. As discussed above, the particular component being measured lies in the plane of the two beams and is perpendicular to the bisector of the beams. Thus, any component in the axial-tangential plane can be measured with this system by rotating the splitter to the desired angle. Fluorescent seed particles coupled with an orange-pass optical filter in the receiving optics reduce detection of unwanted scattered light. This allows measurements near the rotor hub and casing window.

A simplified block diagram of the complete system is shown in Fig. 5. Velocity measurements occur randomly along the measured circumferential path since a measurement depends upon a seed particle passing through the probe volume. At any given time, the system accepts measurements from any of 1000 sequential angular positions along this circumferential path. The position information for each velocity measurement is provided by an electronic shaft angle encoder that was developed for this system. When a measurement is obtained, the particle velocity and the rotor position are recorded and processed by the minicomputer. In this way, velocity measurements are accumulated along a circumferential path. A complete velocity map is obtained by determining
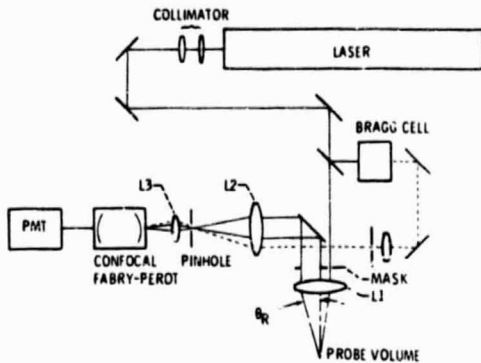
5

Fig. 6. Optical system for single-beam anemometer for stator

Fig. 7. Turbine stator showing cutout for laser window

veloc. y profiles at a sequence of axial and radial positions. Details of this system are found in reference 9.

Because the dual-beam LA measures only velocity components transverse to the optical axis, the radial velocity component is not directly measured with this system.

Single Beam LA for Turbine Stator Rig

In this laser anemometer the single-beam optical system shown in Fig. 6 was used to measure the radial component in the annular stator cascade shown in Fig. 7. The optical system has both the axis of the incident beam and the axis of the receiving optics at a 3 degree angle to the axis of the focusing lens. This near backscatter geometry results in a Doppler shift frequency proportional to the velocity component along the optical axis, which is in the radial direction of the stator.

The scattered light is passed through a confocal Fabry-Perot interferometer operated in a scanning mode. This is the optical analog of a swept frequency rf spectrum analyser. The system also includes an acousto-optic modulator (Bragg cell) used to generate a reference signal offset from the laser frequency by 78 MHz. Figure 8 shows typical spectra taken inside the stator passage. The spectra shown in Figs. 8a and 8b are for unseeded and seeded flow, respectively. The unseeded spectrum shows two peaks: the peak on the left is due to the non-Doppler shifted laser light scattered from surfaces located near the probe volume, and the peak on the right is due to the frequency shifted light from the Bragg cell. The seeded spectrum in Fig. 8b shows the Doppler shifted light as well as the non-Doppler shifted and Bragg shifted peaks.

Note that because the radial velocity component is small, the Doppler shift is also small; and the Doppler shifted light from the seed particles overlaps the non-Doppler shifted light. The difference between the seeded and unseeded spectra, which contains the desired information, is shown in Fig. 8c. The Doppler shift here is about 25 MHz, which corresponds to a radial velocity component of about 6 m/sec. Note that the flow at this location is predominately in the axial-
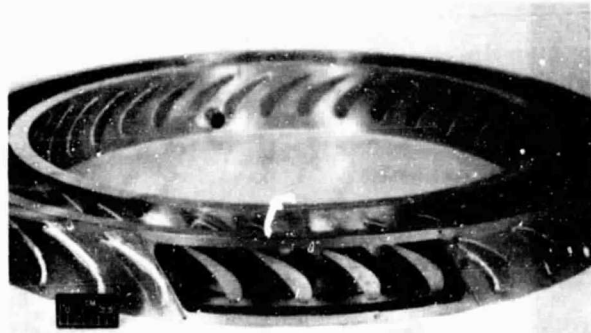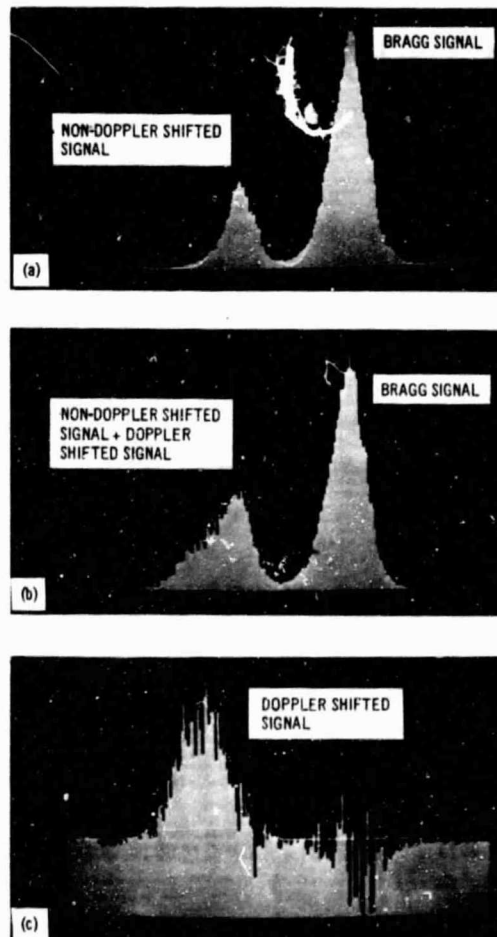

Fig. 8. Optical spectra for single-beam anemometer taken in stator passage (a) no seeding (b) with seeding (c) difference of seeded and unseeded spectra

tangential plane; previous measurements made with
a dual-beam LA gave an axial-tangential velocity
magnitude of 185 m/sec.

For larger radial velocity components the
peak caused by the Doppler shifted light will be
separated from the non-Doppler shifted peak, and
thus will be easier to analyse than the example
given here.

Details of this system are found in reference
10.

ONGOING WORK

Current work is concentrated in two areas.
One objective is to develop a system that combines
a dual-beam LA with a single-beam LA; the combined
system will be able to measure all three compo-
nents in turbomachinery from a single viewing
direction. This system will be used in tests of
new turbine stator designs that have curved end
walls. These stages will have large radial veloc-
ity components, and data taken with the combined
LA system will be used to verify new 3D computer
codes.

The second area of work is to develop laser
anemometer systems for use in high temperature
turbine facilities. The laser anemometer is the
ideal instrument for such studies in hostile envi-
ronments because of its non-intrusive nature.
Work is being done to extend the techniques
developed for cold flows to the high temperature
regime. The main effort is to develop windows
capable of withstanding the high temperature envi-
ronment and to find appropriate seed materials and
methods of generation. Also, the effect of the
hot turbulent flow on the operation of the optical
system is under study.

REFERENCES

1. Y. Yeh and H. Z. Cummins, "Localized fluid flow
   measurements with an He-Ne laser spectrometer,"
   Appl. Phys. Lett., vol. 4, pp. 176-178, 15 May
   1964.
2. A. E. Siegman, "The antenna properties of opti-
   cal heterodyne receivers," Proc. IEEE, vol. 54,
   pp. 1350-1356, October 1966.
3. M. J. Rudd, "A new theoretical model for the
   laser dopplermeter," J. Sci. Instrum., vol. 2,
   pp. 55-58, January 1969.
4. F. Durst, "REVIEW-Combined measurements of
   particle velocities, size distributions, and
   concentrations," J. Fluids Eng., vol. 104,
   pp. 284-296, September 1982.
5. R. Schodl, "A laser dual-beam method for flow
   measurements in turbomachines," ASME Paper
   74-GT-157, 1974.
6. L. Lading, "The time-of-flight laser anemometer
   versus the laser doppler anemometer," in Laser
   Velocimetry and Particle Sizing, H. D. Thompson
   and W. H. Stevenson, eds. Washington: Hemi-
   sphere Publishing Corp., 1979, pp. 26-40.
7. R. V. Edwards and A. S. Jensen, "Particle-
   sampling statistics in laser anemometers:
   sample-and-hold systems and saturable systems,"
   J. Fluid Mech., vol. 133, pp. 397-411, August
   1983.

8. W. H. Stevenson, R. dos Santos, and S. C.
   Mettler, "A laser velocimeter utilizing laser-
   induced fluoresence," Appl. Phys. Lett., vol.
   27, pp. 395-396, 1 October 1975.
9. J. A. Powell, A. J. Strazisar, and R. G.
   Seasholtz, "High-speed laser anemometer system
   for intrarotor flow mapping in turbomachinery,"
   NASA TP-1663, 1982.
10. R. G. Seasholtz and L. J. Goldman, "Laser ane-
    mometer using a Fabry-Perot interferometer for
    measuring mean velocity and turbulence inten-
    sity along the optical axis in turbomachinery,"
    in Engineering Applications of Laser Velo-
    cimetry, H. W. Coleman and P. A. Pfund, eds.
    New York: American Society of Mechanical
    Engineers, 1982, pp. 93-101.