Laser Doppler Anemometer for Water Tunnel Applications

HARTMUT H. BOSSEL*
University of California, Santa Barbara, Calif.
AND
KENNETH L. ORLOFF†
NASA Ames Research Center, Moffett Field, Calif.

A laser Doppler anemometer for three-dimensional velocity measurement in liquids and gases under a wide range of laboratory conditions has been developed. The instrument is particularly well suited for water tunnel applications. It is portable, easily aligned, and inexpensive (excluding electronic units). It operates in backscatter or forward scatter mode. In both cases all optical components, including laser and photomultiplier, remain on a common base. The system has built-in traversing capability and an aiming device for visualizing the focal (test) point. Design details and representative velocity measurements are given.

1. Introduction

WATER tunnels typically have test section widths of less than 50 cm. Under normal operating conditions, probe stresses require probe sizes which are not small compared to any model being tested. Thus, in common water tunnels the distortion by probe insertion of the flowfield being measured must be expected to be significant, with corresponding error. The need for nonintrusive flow probing is obvious. We shall here describe a laser Doppler anemometer which we have used successfully to measure three-dimensional velocity fields around obstacles in 5-cm and 10-cm water tunnels.

Laser Doppler velocity measurements in fluids were first reported by Yeh and Cummins.[1] Since then, the technique has been applied in many variants[2-14] to problems ranging from the study of bloodflow in capillaries[15] to vortex trails in the atmosphere[16] and high-velocity, high-temperature gas flows.[14] Theoretical aspects of the optical design and signal detection are extensively discussed in Refs. 17 and 18. Advancements have been made in both design and technique, and newer systems offer high-spatial and temporal resolution[19] in addition to the capability of making accurate turbulence measurements.[20,21] In reviewing the techniques employed in applications, and duplicating and testing a number of them, we came to reject many of the schemes, and to modify others. The design reported here is the end result of a search for a useful, reliable, versatile, and inexpensive laboratory instrument, featuring simple alignment and operation and a low-power laser. We have used this instrument in several different modes to obtain velocity measurements in liquids and gases, and are more than pleased with it.

After a brief review of Doppler principles, the design philosophy for the instrument and its optical layout will be discussed. Design details follow, and a brief description of the electronic components will be given. Some velocity measurements are presented as examples.

2. Velocity Measurement by Doppler Shift

The operation of the laser Doppler anemometer is based upon the principle that coherent laser light scattered from a fluid moving with velocity $\mathbf{v}$ (Fig. 1) will be Doppler-shifted in frequency by an amount

$$\Delta\nu = (\mathrm{n}/\lambda_0)\mathbf{v}\cdot(\mathbf{k}_s - \mathbf{k}_i)$$

where λ_0 is the vacuum laser wavelength, and n is the index of refraction. $\mathbf{k}_s$ and $\mathbf{k}_i$ are unit vectors in the directions of the scattered and incident waves, respectively.

When the scattered wave and the incident (often called local oscillator) wave are recombined at the photocathode of a photomultiplier tube (the mixer), a beat signal is produced at the frequency $\Delta\nu$. The waves are considered to be plane and it has been shown[22] that efficient heterodyning will be obtained subject to the constraint $A_R\Omega_R \lesssim \lambda_0$ where A_R is the area of the receiving aperture at the photomultiplier and Ω_R is the solid angle subtended between scattered and reference beams. For our anemometer we find that with A_R of 1 mm diam, the optical alignment can be carried out easily. For a detailed account of the way in which the heterodyning occurs, which may affect design considerations, the reader is referred to Ref. 17.

Since only $\Delta\nu$ is detected by heterodyning, there exists an ambiguity of 180° in the velocity direction. This problem can be eliminated by employing a "Bragg cell" which acoustically "diffracts" the reference beam, yielding a shift of ν_B. This reference beam, when mixed with an unshifted ($\mathbf{v} = 0$) scattered beam will give heterodyning at the frequency ν_B. Now, when $\mathbf{v}$ is nonzero, the ambiguity is removed by observing whether the Doppler signal is higher or lower than ν_B. This technique has been reported by several investigators,[10,12] but has not yet been incorporated into our instrument.

3. Design Philosophy and Over-All Description

To justify the developmental expense we decided to design not a specialized piece of equipment, but rather a general, portable, versatile instrument which could be used in a variety

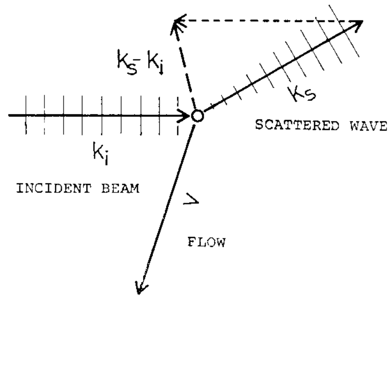

Fig. 1 Vector relationships.

Received September 27, 1971. The instrument was designed by the first author; the experiments leading to this design, and the velocity measurements reported here were performed by the second author. O. Highland built the instrument, as well as experimental units for prototype development. The work was supported by NASA Grant 05-010-025.

* Associate Professor, Mechanical Engineering Department. Member AIAA.

† National Research Council Associate, Large Scale Aerodynamics Branch. Member AIAA.

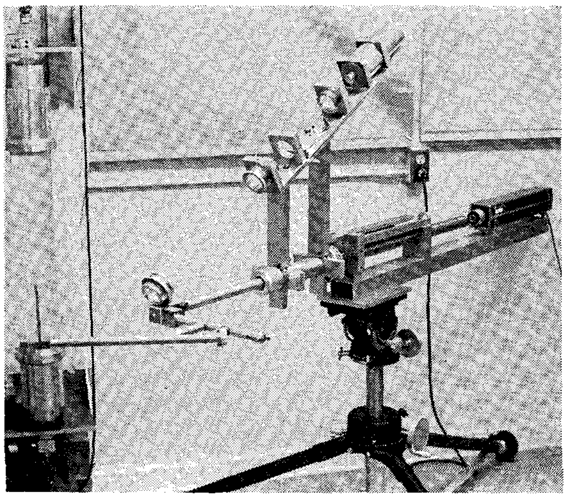

Fig. 2 Laser Doppler anemometer on tripod (f = 10 cm configuration).

of configurations on a variety of problems likely to come up in our laboratory. In particular, this meant the capability of three-dimensional velocity measurement in liquids and gases at speeds between approximately 1 cm/sec and 30 m/sec, use on flow tubes of 1 cm diam, in water tunnels of up to 10 cm diam, and on a wind tunnel of 60 cm diam, and traversing capability. In contrast to most other designs, we required that the instrument was to be one-sided; i.e., with no separate adjustable components on the other side of the test section. This would eliminate a large base, simplify alignment, make the instrument portable, and require only one simple traversing slide. It also limits laser size, since the laser must be supported on the same base as all other components. The instrument is shown in Figs. 2 and 3.

This instrument weighs approximately 25 lb and has the following features. The cost of mechanical and optical components (less beam rotator and laser) is approximately $200. A low power 5 mw He-Ne laser is mounted on the instrument frame. The instrument frame is supported on a heavy tripod, or alternatively, on three adjustable leveling screws with approximately 5 cm vertical adjustment. There are up to four observation heads (permitting simultaneous three-dimensional velocity measurement) mounted on a hollow central shaft centered on the laser beam. The heads can be

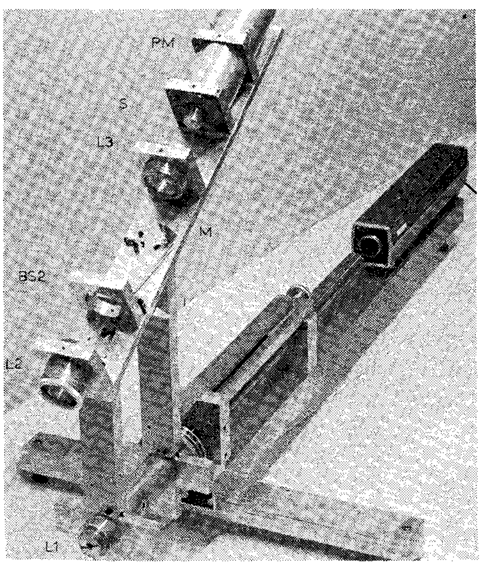

Fig. 3 Laser Doppler anemometer in f = 50 cm configuration.

moved jointly 30 cm forward and backward to scan the test section in the direction of the laser axis, and can be rotated about that axis and stopped in 15° increments. The basic instrument operates with a 50-cm focal length. One attachment changes this to 10-cm focal length. The basic mode of operation is backscatter. A small mirror attachment provides forward scatter capability. Dual beam and multibeam arrangements are also possible. An aiming device permits visual location of the focal point. These features will be explained in more detail below.

4. Optical Layout

The basic optical layout of the instrument is for backscatter measurement. It is shown in Fig. 4. The incident laser beam passes beamsplitter BS1 and is focused through lens L1 on the test point T. Scattered light from this point is collected by lens L2 and focused through lens L3 on the photomultiplier cathode. A small percentage of the incident beam is deflected by beamsplitter BS1, attenuated by neutral density filter NF, and mixed with the scattered beam by beam-splitter BS2 to produce heterodyning at the photo cathode. Both beamsplitters BS1 and BS2 are clear glass of 0.5 mm thickness (microscope slides). Stop S limits light received to that from the test point T, and the filter F restricts its wavelength to that of the laser light. All lenses are fine-adjustable in axial directions. Beamsplitter BS1 can be moved in the direction of the reference beam, and rotated about this axis. Beamsplitter BS2 provides for linear motion in the direction of the scattered beam and can be rotated about two perpendicular axes to permit complete adjustment of the reference beam. Beamsplitter BS2 consists of a small strip of glass and therefore occupies only a small percentage of the scattered beam cross section. The scattered beam reaches the photomultiplier practically without attenuation. In order to insure coplanar polarization of the incident and scattered beams, a polarization rotator is mounted on the laser, and is adjusted for maximum signal following a rotation of the instrument.

A unique feature of the design is an aiming device which permits precise visual location of the test point T at any time. The device has been found extremely valuable in probing flows. By moving the aiming lever L (Fig. 3), the neutral filter NF is removed from the reference beam path, and a small mirror M is inserted into the scattered beam path (Fig. 4). This mirror now reflects the reference beam through the beamsplitter BS2, and lens L2 focuses it on the test point T. This point is now clearly located as the cross point of the two beams (incident beam and aiming beam).

The basic backscatter layout is easily modified for a number of alternative schemes. We have used the instrument extensively in a forward scatter mode using a light mirror attachment (Fig. 5). Dual and multibeam modes are also possible (Fig. 6).

In all modes (backscatter, forward scatter, dual mode) three-dimensional velocity measurements are possible by either simple rotation of the observation head about the laser

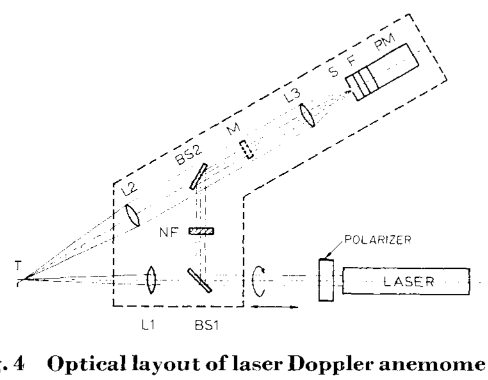

Fig. 4 Optical layout of laser Doppler anemometer.

beam axis and successive measurements from different angles, or simultaneous measurement from up to four observation heads mounted on the four spokes (Fig. 3). If a frequency shift is introduced into the reference beams by use of Bragg cells or diffraction techniques, the 180° ambiguity in Doppler measurements in each direction can be removed, and the measurements from three heads suffice to determine the velocity vector uniquely. In many flows the flow direction is known approximately, and the ambiguity is no obstacle, even if a frequency shift is not introduced.

5. Design Details

The observation heads are mounted to the central shaft on two spokes each (Fig. 3). The inclination of the heads was chosen as 30° to give Doppler frequencies between approximately 1 kHz and 10 MHz for the velocities encountered in our experiments. This inclination is easily changed by using spokes of different lengths. More acute angles are advisable for high velocities. The central shaft slides and rotates in two Teflon bushings. The observation assembly is moved forward and aft by a 30-cm slider unit with a vernier which permits accurate position reading to 0.1 mm. A claw on the forward extension of the slider arm engages a deep groove in the cylinder housing the clamping device which connects the observation assembly to the central shaft. Claw and groove permit free rotation. A pin is used to lock the assembly at 15° rotational increments. The support base is designed sufficiently wide so it will not topple even with the observation assembly in extreme positions.

In the 50-cm system, a lens of 50-cm focal length screws centrally into the forward hub and focuses the laser beam on the test point (Fig. 3). The scattered beam is picked up by another 50-cm lens in the observation head. The central lens can be replaced by a special attachment for 10-cm focal length. This attachment consists of a hollow shaft with two adjustable 10-cm focal length lenses for the incident and scattered beams.

To enhance signal intensity, we use a forward scatter attachment where possible. This attachment is mounted in place of the incident beam focusing lens L1 in the 10 cm attachment. It consists of light aluminum tubing supporting three small adjustable mirrors and a focusing lens. The beam is deflected through the tube around the test section and enters from the opposite side. Each of the three mirrors permits adjustment by rotation, axial movement, and the tilt of the mirror.

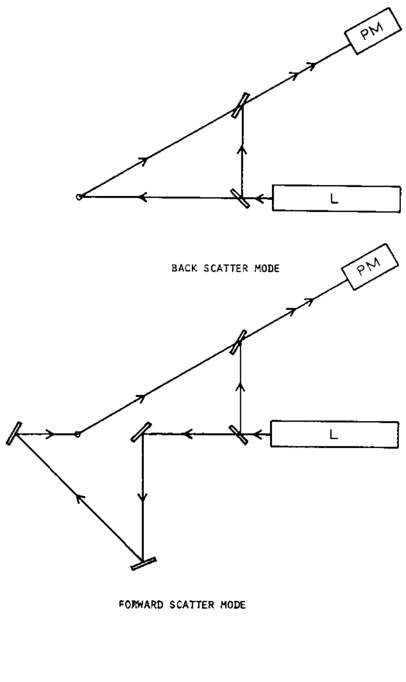

Fig. 5 Backscatter and forward scatter modes.

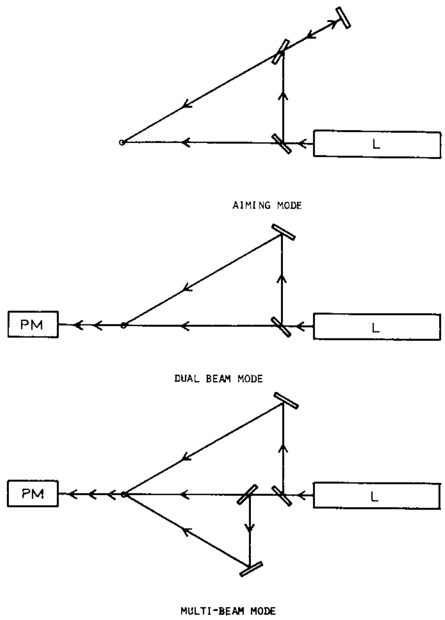

Fig. 6 Aiming, dual beam, and multibeam modes.

The unit is aligned by changing one variable at a time and proceeding in a step-by-step manner. No trial and error is involved. We can align the unit "from scratch" and obtain a good Doppler signal in approximately one hour. Once the unit has been aligned, adjustments are rarely required. We use a series of plexiglass plugs with small concentric holes as alignment aides.

6. Electronic Components

Our anemometer uses a Spectra Physics Model 120 Helium-Neon laser with an output power of 5 mw, and a beam diameter of approximately 1 mm. Early tests with other lasers revealed that one must insure that the laser output is not time-varying, since these variations are detected at the photocathode and show up on the spectrum analyzer as several "wandering" beat frequencies making it extremely difficult to discern the actual Doppler signal.

We are in agreement with the results of Rolfe et al.[19] that the most sensitive part of the instrument is the photomultiplier tube and the focusing at the photocathode. It is desirable to have high quantum efficiency at the laser wavelength and good frequency response. The latter is no problem for phototubes unless beat frequencies above about 200 MHz are to be detected. Cooling of the tube is unnecessary when it is used as a mixer. Others have reported using phototubes with an S-20 response (5.0% quantum efficiency at 632.8 nm). Our first work was done with an S-11 tube (0.5% efficiency) and good responses were still obtained, but we now use an RCA Developmental Type C7164R (8.0% at 632.8 nm).

The photomultiplier anode output is fed to a video amplifier which raises the signal by 20 db or 40 db. The Doppler signal frequency is then measured by either a wave analyzer (for $\Delta\nu$ below 100 kHz) or a spectrum analyzer, tracking generator combination. The tracking generator produces a "marker blip" for each sweep of the spectrum analyzer. By aligning this marker with the Doppler peak, the frequency can be read directly off of the digital display of the tracking generator. One advantage this has is that the marker greatly enhances the Doppler peak when they coincide so that "weak" heterodyne signals may still be measured.

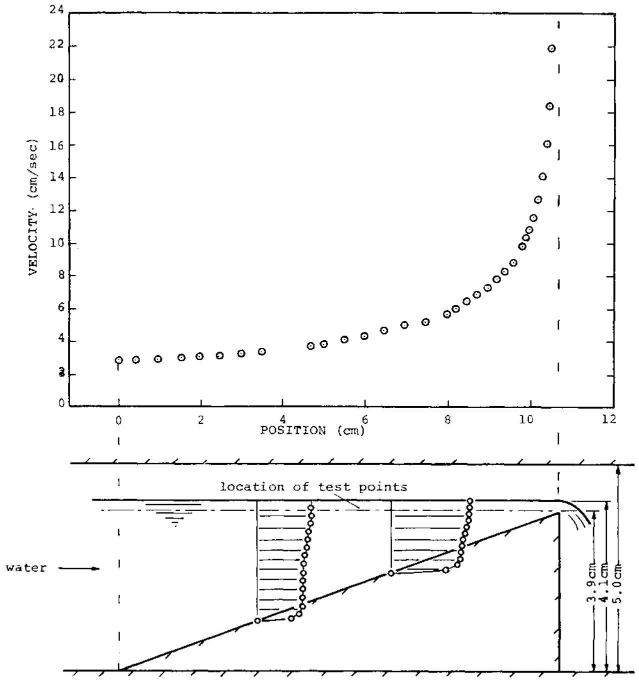

Fig. 7 Velocity measurements in a water channel.

7. Representative Measurements

In our water tunnel measurements, polystyrene latex spheres of 0.5 μ diam were added to the water to give good scattering, but an adequate signal is also obtained from the impurities contained in common tapwater.

Our initial flowfield measurements were made in a small water tunnel of square (5 cm × 5 cm) cross section. A wedge was inserted into the water tunnel and the resulting weir flow was probed with the anemometer. Only the velocity component parallel to the axis of the tunnel was measured. The results are shown in Fig. 7. The resolution of the instrument is several points per mm; not all measured points are shown in the figure. A typical signal is shown in Fig. 8 as it appears on the spectrum analyzer, the frequency simultaneously being displayed on the tracking generator.

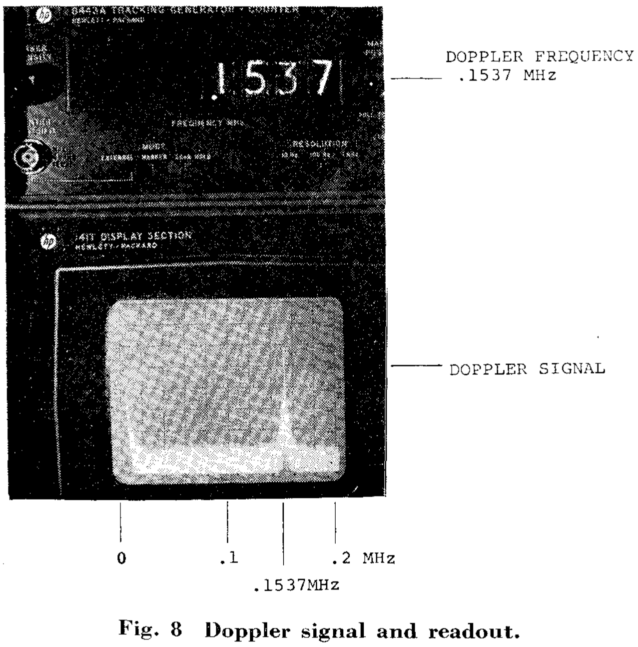

Fig. 8 Doppler signal and readout.

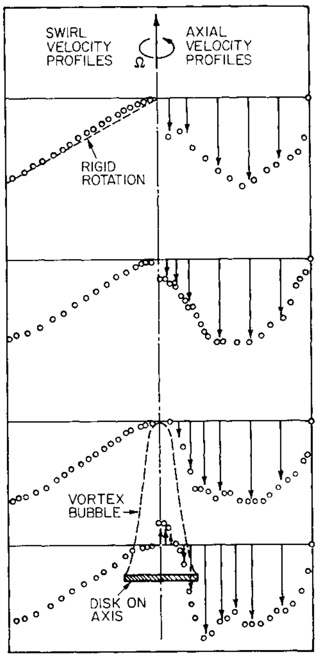

Fig. 9 Axial and swirl velocity measurements in a rotating tube.

We have also applied the instrument to the measurement of the axial and swirl velocity profiles in swirling flows in a rotating test section with and without obstacles present in the flow.[23] Figure 9 shows a representative set of data. The axial velocity profiles very clearly show a free stagnation point on the axis, and reversed flow in the "vortex bubble" upstream of the obstacle. This data set is a good example of the capabilities of nonintrusive laser Doppler flow probing—since vortex flows are particularly sensitive to probe insertion, even the smallest probe would have destroyed the flowfield.

We have made cursory measurements in air with smoke as the scattering medium. However, difficulties in maintaining the smoke density constant resulted in corresponding variations in the heterodyning efficiency.

8. Conclusion

We have described in some detail a laser Doppler instrument for three-dimensional velocity measurement in liquids or gases. The design evolved from a critical examination of many design alternatives from the point of view of practicality for the average laboratory. The instrument is useful in a wide variety of laboratory applications, and in particular for flow probing in small water tunnels. It requires a minimum of specialized components, alignment and cost. With the present arrangement some twenty datapoints of a velocity traverse can be obtained in less than 10 min. The system incorporates an aiming device which permits easy location of the test point at any time.

We have used the system for some time now and have found little we would change in a redesign. Of the many parameters involved in the system and its operation, we found that only a very few had critical effects on normal operation: 1) the parallel alignment of reference and scattered beams (or lack thereof); 2) the size of the aperture in front of the photomultiplier (the smaller the better); 3) the quantum efficiency of the photomultiplier; and 4) the intensity of the scattered light received.

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