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# THE COMPARISON OF A NEW CONSTANT TEMPERATURE ANEMOMETER WITH SEVERAL LASER ANEMOMETER CONFIGURATIONS

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## ABSTRACT

This paper covers electronic design advances that have made it possible to adjust the frequency response of a film probe and make it comparable to that of a wire probe. Also, a test setup for the laser anemometer will be presented using the forward scattering technique. Sample data taken in a hydraulic loop will be related to the laser system output. Following the presentation of the anemometer and laser systems, five fluid flow measurement features will be discussed in order to help the experimenter choose the method most suited to his particular application.

## INTRODUCTION

The constant temperature hot-wire or hot-film anemometer is generally accepted as the best all around instrument yet developed for analysis of space and time variables of the microstructure in a flowing gas or liquid. Micro structure of a velocity field means the instantaneous velocity of small fluid particles, i.e., a volume element of the fluid; small compared to the stream, but large compared to the distance between the individual molecules.

Such studies are very important for the understanding and description of many complicated macro flow characteristics, such as: static and dynamic forces acting on bodies in a fluid; response times of valves and other flow regulating devices; flow resistance of pipelines; processes in boundary layers of flows; heat transfer; mixing rates of different liquids, etc.

Measurements of the micro structure of a stream require a very small sensitive element having short response time, sufficient sensitivity, and little disturbing effect on the original stream. Hot-wire and hot-film anemometer probes have been commonly used for these measurements.

However, the Laser Doppler Anemometer is a valuable supplement to the hot-wire/film instruments for the study of flow phenomena, particularly when turbulence is a factor. It does not need calibration nor does it disturb the flow. Compared with a miniature hot-wire, the spatial resolution can be made about one order of magnitude better, and the directional sensitivity is ideal for the measurement of two and three dimensional flow fields. Very high and extremely low velocities may be measured.

However, being an optical method based on frequency shift of scattered light, it has its limitations: the medium must be transparent and contain suitable scattering particles.

Apparently very little has been reported on time dependent velocity measurements. The bulk of reports on practical measurements with Laser Doppler Anemometers deal with laminar flow studies or with some statistical properties of turbulence obtained by processing the Doppler signal directly on a spectrum analyzer.

The primary goal for the development of a Laser Doppler Anemometer should be one that is capable of measuring "the instantaneous velocity". This has now been achieved by several companies. Some measurements of oscillatory flows performed to illustrate the precision and utility of the laser anemometer will be described.

## HOT-WIRE AND HOT-FILM PROBES

The sensitive element of the anemometer is either a thin wire[1] suspended between two prongs or a thin metal film[2] deposited on a quartz support. (See Figures 1a and 1b.) The wire or film is electrically heated, and the quantity of power supplied to it can be taken as a measure of the velocity of the flowing medium.

The mechanical strength of a wire probe is sufficiently high for applications in gases at rather high velocitees, (e.g. in atmospheric air up to near supersonic velocities), and in very clean, nonconducting liquids at low velocities.

Wedge type film probes are used chiefly for measurements in conducting liquids and replace wire probes in measurements in heavily polluted gas flows.

Fiber probes[3] have mechanical and electrical properties that place them in a position midway between hot-wire probes and hot-film probes. (See Figure 1c.) Their velocity-sensitive element is a film which is deposited on the surface of a short length of thin quartz fiber mounted between the prongs of a wire probe.

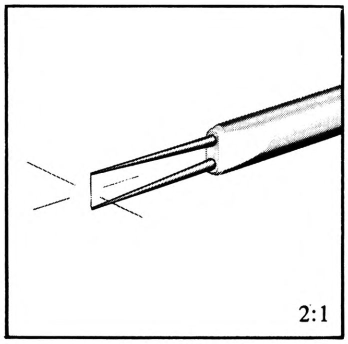

Figure 1a Hot-Wire Probe

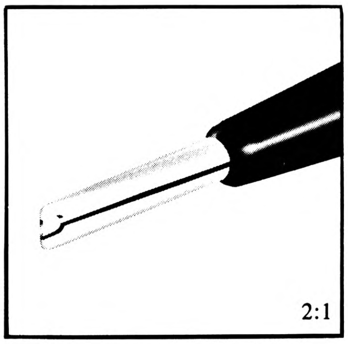

Figure 1b Hot-Film Probe

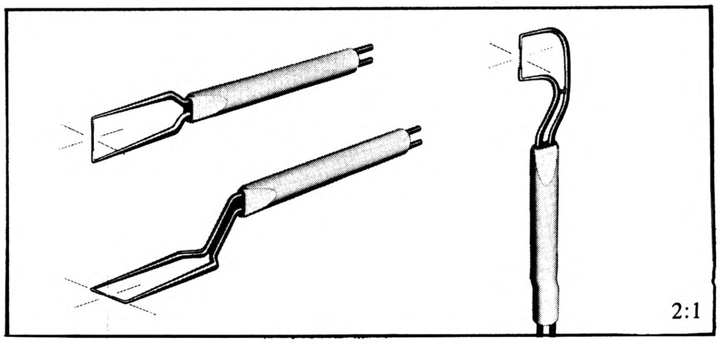

Figure 1c Fiber Film Probe

A thin quartz coating protects fiber and solid film probes from outside influences, such as conducting liquids.[4]

## THE CONSTANT-TEMPERATURE ANEMOMETER

The constant-temperature system is simple to operate and can measure large velocity fluctuations. The idea behind the constant temperature system is to minimize the effect of the sensor's thermal inertia by keeping the sensitive element at a constant temperature (resistance) and using the heating current as a measure of heat transfer, and hence, also of velocity.

The constant-temperature principle of operation was first proposed by Kennelly as early as 1909. However, this principle requires a sophisticated and well-designed electronic system. (See Figure 2.) Under conditions of bridge balance a voltage is present across the vertical bridge diagonal. This voltage is supplied by the servo amplifier. A slight change in the convective cooling of the sensor will cause a small voltage to appear across the horizontal diagonal. The latter voltage, after undergoing considerable amplification, is fed back to the vertical bridge diagonal, its polarity being selected so that it will automatically balance the bridge.

In this way, the temperature variations of the sensor are kept extremely small, and it can be shown that the upper frequency limit of the sensor is increased by a factor of:

$$g \simeq 2aRS$$

where $a = (R-R_o)/R_o$ is the overheating ratio and S is the servo amplifier gain factor (transconductance). Improving the frequency response by increasing the amplifier transconductance is difficult due to the appearance of high-frequency oscillations in the closed-loop system.

The art of constant-temperature anemometry is therefore mainly based on the design of a stable servo system having very high closed-loop gain, and a well balanced differential amplifier with like characteristics at DC as well as high frequencies.

In turbulence measurements, the bandwidth is limited by the spatial resolution of the probe; but the high system bandwidth reduces phase shift and can be utilized in measurements of step functions such as flow in shock tubes.

## IMPROVEMENTS IN ANEMOMETER FREQUENCY RESPONSE

Now, more specifically, we must once again emphasize that the bridge balance is important for stability and accuracy, making it necessary either to readjust the amplifier's operating point in the case of mean velocity changes or to provide so much DC gain that this is unnecessary. The latter solution is the one employed in DISA anemometers.[5] Conversely, it is necessary to reduce the gain at high frequencies, more or less, depending on measuring conditions. At frequencies around the upper frequency limit of the system, the demand for flat frequency response imposes a limit on how steeply the amplifier's frequency response can be permitted to decrease with frequency as this will inevitably introduce added phase shift.[6] A falling gain characteristic may then be introduced at frequencies that are so low that this will be no problem (for conventional probes), and this is the solution we used. In the 55M-system an entirely new feature has been introduced: an amplifier frequency response that falls smoothly throughout the range up to approximately 100 KHz. (See Figures 3a and 3b.) This eliminates the danger of instability with high time-constant probes, but, more important, by imparting a suitable degree of slope to the amplifier's frequency response, the overall system obtains a smoother frequency response. Thus, with film probes, a response is obtained that is comparable to that obtained previously only with wire probes.[7] (See Figures 4a, 4b, 4c, and 4d.) This is accomplished by giving the amplifier response a slope of 3 db/octave (45° phase shift). With wire probes a slope of approximately 1.2 db/octave (18° phase shift) will produce optimum flat response for the system.

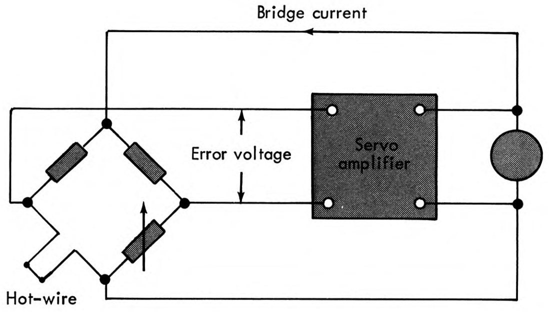

Figure 2 Principle of Constant Temperature Anemometer

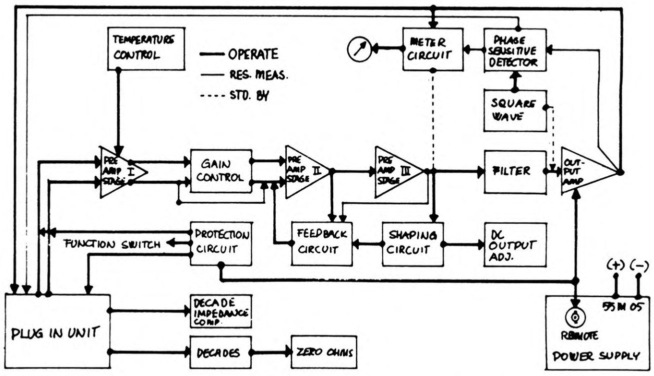

Figure 3a Simplified Block Diagram of Type 55M01 Main Unit

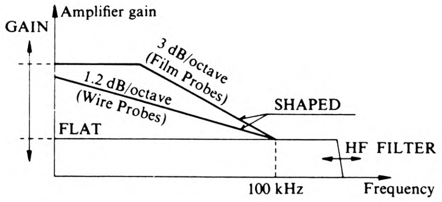

Figure 3b Showing the Fundamental Ways in which the Gain Characteristic of the 55M01 Main Unit can be Varied

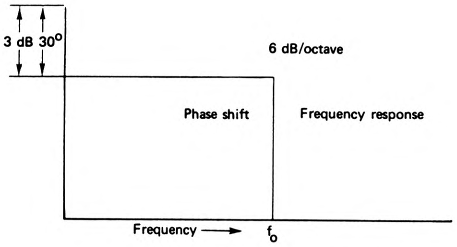

Figure 4a Dynamic Behavior of Hot-Wire Probes in the Presence of Sinusoidal Velocity Changes (in gas flow).

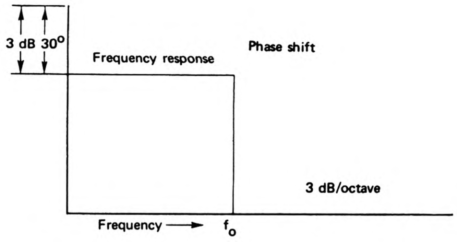

Figure 4b Dynamic Behavior of Hot-Film Probes in the Presence of Sinusoidal Velocity Changes (in gas flow).

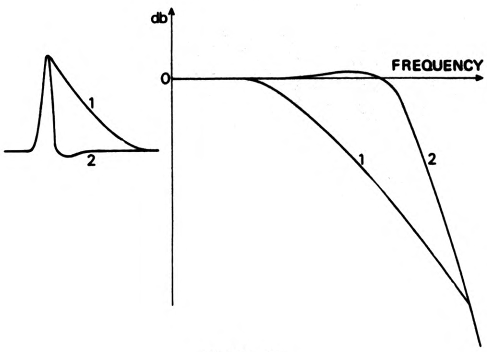

Figure 4c.

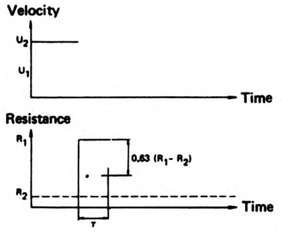

Figure 5 Response of Hot-Wire to Sudden Increase in Flow Velocity

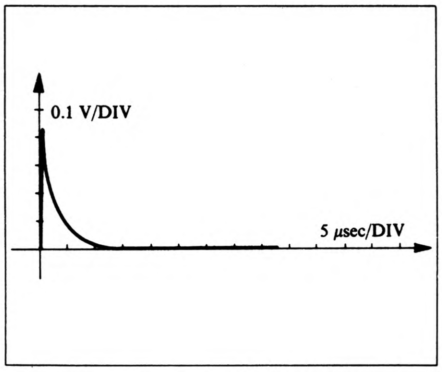

Figure 6 Typical Appearance of Square-Wave Test Signal with Hot-Film Probe Obtainable with Shaped Gain Characteristic

## OPTICAL SYSTEM OF THE LASER DOPPLER ANEMOMETER

The new measuring technique utilizes the change of frequency, the Doppler shift, of laser light when it is scattered by particles moving along with the fluid flow.

The angular frequency $W_{sc}$ of scattered light from a single particle moving with a velocity U is given by the nonrelativistic Doppler formula:

$$W_{sc} = W_i + (\bar{k}_{sc} - \bar{k}_i) \cdot \bar{U}$$

or

$$W_{sc} = W_i + \frac{2\pi}{-\lambda} (\bar{e}_{sc} - \bar{e}_i) \cdot \bar{U} \qquad (1)$$

since the particle velocity is very much smaller than the speed of light. $\bar{k}_{sc}$ and $\bar{k}_i$ are the wave vectors of the scattered and the incident light, *respectively*, and $\bar{e}_{sc}$ and $\bar{e}_i$ are unit vectors in the direction of the wave vectors.

Detection of the Doppler frequency is accomplished by an optical heterodyne process using a reference beam from the same laser as a local oscillator. The resultant heterodyne or beat frequency is equal to the difference between the frequencies of the scattered light and the reference beam; the latter frequency is in this case equal to that of the incident *beam.*

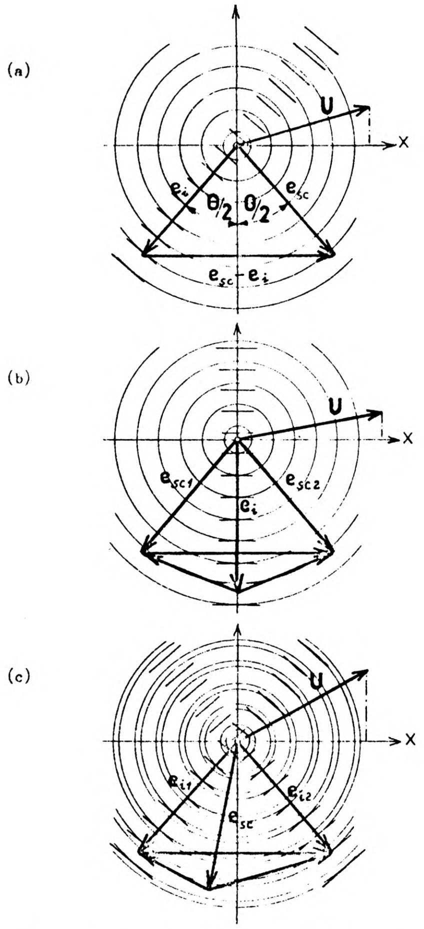

Figure 7a Doppler Shift of Light Scattered from Moving Particle

Figure 7b Differential Doppler Shift with One Incident Beam

Figure 7c Differential Doppler Shift with Two Incident Beams

The Doppler frequency:

$$f_D = \frac{1}{2\pi} \left| W_{sc} - W_i \right| = \frac{1}{\lambda} \left| (\bar{e}_{sc} - \bar{e}_i) \cdot \bar{U} \right|$$

or

$$f_D = (1/\lambda)\ 2 \sin(\theta/2) \left| U_x \right| \qquad (2)$$

is seen to be directly proportional to the component of the velocity in the direction $\bar{e}_{sc} - \bar{e}_i$, which in Fig. 7 is taken to be the x-direction. It should be noted that Eq. 2 gives only the magnitude of the velocity component $U_x$ from measurements of $f_D$.

Figure 7a shows a vector diagram for the case of scattering from a single particle in a single laser beam. Instead of measuring the Doppler frequency directly by using a reference beam as a local oscillator, one may use one of two differential Doppler heterodyning techniques, as illustrated in Figures 7b and 7c. The idea is that a beam frequency proportional to the flow velocity can be obtained by optical mixing of light scattered in two different directions from a single laser beam or by mixing of light scattered in the same direction from two intersecting primary beams.

The differential Doppler frequency $f_D$ in case (b) may be derived by using Eq. 1 for the two scattering directions $\bar{e}_{sc}1$ and $\bar{e}_{sc}2$. Thus we get:

$$f_D = \frac{1}{2\pi} \left| W_{sc}1 - W_{sc}2 \right| = \frac{1}{\lambda} \left| (\bar{e}_{sc}1 - \bar{e}_{sc}2) \cdot \bar{U} \right| \qquad (3)$$

In the same way we get in case (c):

$$f_D = \frac{1}{2\pi} \left| W_{sc}1 - W_{sc}2 \right| = \frac{1}{\lambda} \left| (\bar{e}_i2 - \bar{e}_i1) \cdot \bar{U} \right| \qquad (4)$$

From Figure 7 and Eqs. 3 and 4 we see that the differential Doppler frequency in case (b) does not depend on the direction of the incident beam and in case (c) does not depend on the scattering direction. We shall not discuss the choice of mode of heterodyning in detail here, but confine ourselves to a few practical remarks.

The reference beam method (a) is very easy to use if the reference beam is divided through the flowing medium and straight into the photodetector through a small aperture. The condition for heterodyning, i.e., the alignment tolerance necessary to keep the wave fronts of the scattered light and the reference beam parallel within $\lambda/4$ over the surface of the photodetector, is automatically met if the reference beam intersects the primary beam and the point of intersection, the measuring point, can be observed. The method requires a fairly high concentration of scattering particles and relatively high laser power. It has not so far been feasible in air without additional smoke when using laser power of the order of 5mw. The differential method with two incident beams -- also called "the fringe method" because the beams form a fringe system in the volume of intersection -- is used where the intensity of scattered light is low. In this case scattered light can be picked up over a wide angle since the differential Doppler frequency is independent of direction of detection.

Method (b) requires critical alignment of the optical system and it does not have any of the advantages of the other systems. However, it does offer a simple solution to the problem of measuring in two or three dimensions since scattered light can be picked up in two or three mutually perpendicular planes.

## NATURE OF THE DOPPLER SIGNAL

The real Doppler signal as obtained directly from the photodetector is modulated in frequency and amplitude and is superimposed with noise. Because of the complex nature of the signal, it is not a simple matter to measure the time variation of the Doppler frequency and thereby fluctuations of velocity. It will in general be necessary to process the signal in a narrow band filter, which automatically tracks the Doppler frequency.

Let us briefly review some of the main causes of the complex nature of the signal.

Each stage of the measuring system may contribute to a reduction of the signal quality either by adding noise or by broadening the Doppler frequency.

Noise may originate from the laser itself, from the photodetector, and from the electronic system used for the amplification of the photocurrent.

The Doppler signal is produced by optical mixing of light scattered from a random distribution of particles in the measuring volume. Each particle produces a wave train of a certain length determined by the size of the measuring volume and the speed of the particle. The individual wave trains are random in phase and of different amplitude and they add up vectorially to a total Doppler signal. The vector sum may occasionally take values close to zero in which case the Doppler signal disappears in the background noise. These so-called "drop out periods" obviously increase when the laser power or the particle density is low.

The limited number of oscillation periods in each wave train and their random phase relation gives rise to frequency broadening, usually known as ambiguity broadening. This type of broadening, and thereby the uncertainty of the Doppler frequency, increases when the effective scattering volume is made smaller. Other effects may contribute to frequency broadening such as insufficient coherence length of the laser, uniform velocity of the different particles in the scattering volume, and mechanical vibrations in the optical system. Obviously, the total broadening sets a lower limit for the intensity of turbulence which can be measured.

## AUTOMATIC TRACKING OF THE DOPPLER FREQUENCY

For the measurement of the turbulence spectra, turbulent shear stress and space-time correlation, information about the instantaneous velocity vector is needed. This information is obtained from the instantaneous Doppler frequency, which, in a turbulent flow, varies rapidly about a mean frequency and is at the same time partly blurred in noise.

Frequency-to-analog conversion of signals with high frequency modulation index and low signal-to-noise ratio is in general not feasible with a conventional FM discriminator, and for this reason a special Frequency Tracker must be developed specifically for the processing of laser Doppler signals.

A block diagram of the Tracker is shown in Fig. 8. The Doppler signal from the photodetector is amplified and filtered in a preamplifier stage and then fed into a mixer together with the output of a voltage-controlled local oscillator (VCO). The difference frequency appearing at the mixer output is amplified and narrow-band filtered in the I.F., A, with a filter bandwidth, $f_A$, and a center frequency, $f_o$. This removes most of the noise, and the signal is then passed through a limiter in order to remove the amplitude variations inherent in the Doppler signal.

The signal, now in the form of a square wave, is fed into a sensitive frequency discriminator, which provides a DC output proportional to the instantaneous deviation of the I.F. frequency, f, from the fixed center frequency, $f_o$. This deviation is smooth with a long time constant, $T_o$, and after suitable DC amplification the resulting error voltage is used to control the frequency of the VCO. Providing a suitable loop gain, L, has been selected, the VCO frequency will vary in such a way that $f_{VCO}$ is nearly equal to the incoming Doppler frequency, $f_D$, plus the intermediate frequency, $f_o$. A steady-state analysis of the feedback loop shows that the following relation holds:

$$f_{VCO} = \frac{L}{1 + L} f_D + f_o + \frac{1}{1 + L} f_{Do} \tag{5}$$

where $f_{Do}$ is the Tracker input signal at the center of the tracking range.

For L >> 1 we get:

$$f_{VCO} = f_D + f_o + \frac{1}{L} (f_{Do} - f_D) \tag{6}$$

Thus, for say L = 700 and a Doppler frequency close to the center of the range, we may get a very accurate measurement of the mean Doppler frequency by counting the local oscillator frequency, $f_{VCO}$.

However, the most exciting feature of the Tracker is its ability to track large fluctuations of the Doppler frequency.

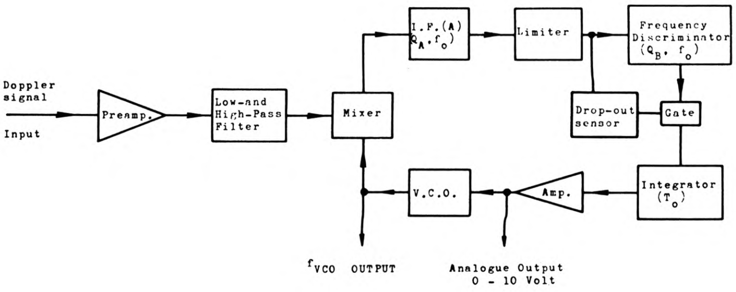

Figure 8 Disa Frequency Tracker, Type 55L20

The Tracker covers a total frequency range of 2 KHz - 15 MHz and the corresponding range of flow velocity is shown in Fig. 9 as a function of scattering angle for a wave length of 6328 Å (He-Ne). The total frequency range is divided into 7 stops, each has a range of 1:6.7, within which the Doppler frequency is tracked automatically.

The maximum tracking rates and thereby the upper frequency limit for a given turbulence intensity are now being investigated. Preliminary experiments using artificial Doppler signals show that a high frequency response similar to that of a hot wire anemometer may be attained.

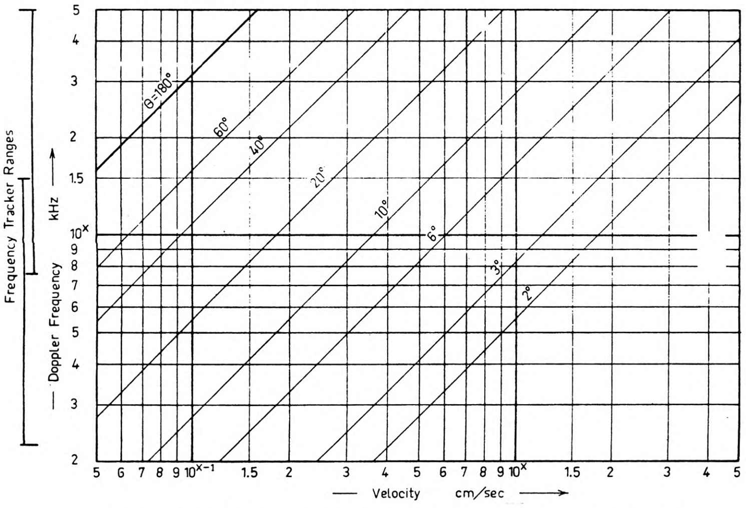

Figure 9 Doppler Frequency as a Function of Scattering Angle θ and Flow Velocity

## MEASUREMENT OF VORTEX SHEDDING AND OSCILLATION IN A BOUNDARY LAYER FLOW

A practical experiment with oscillating water flow was designed as a means of testing the performance of the Laser Anemometer.

Normal tap water without any addition of scattering particles was fed through a 13 mm diameter glass tube and a cylindrical body with a flat front was set up across the flow to generate an oscillating flow by vortex shedding.

Previous measurements with hot film sensors had shown that the vortex shedding at the edge of the body creates an almost sinusoidal velocity variation in the boundary layer on the front of the body even at high Reynolds numbers.

The reference-beam method was used with a scattering angle of 12.6 degrees (θ) and the beams were focused to a diameter of about 50 μm in their point of intersection. The Doppler frequency may be calculated from Eq. 2 with $\lambda = 6328 Å$:

$$f_D = \frac{1}{\lambda} 2 \sin(\theta/2) U_x = 3.46 \cdot U_x \left[\frac{\text{KHz}}{\text{cm/sec}}\right]$$

The complete experimental arrangement is shown in Fig. 10.

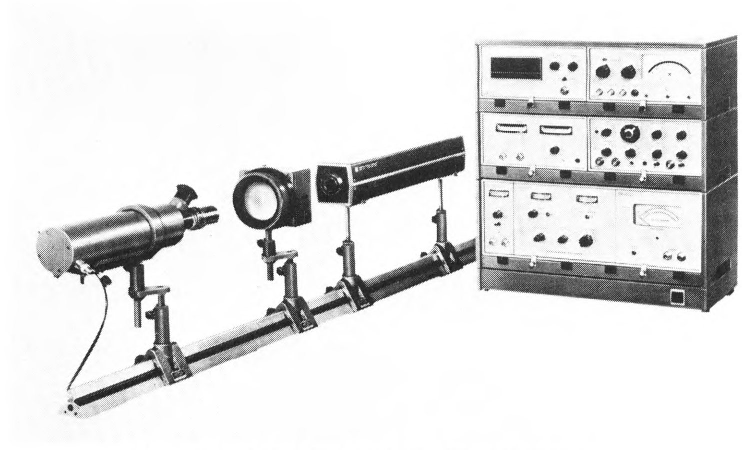

Figure 10 Disa Type 55L Laser Doppler Anemometer

The velocity fluctuations were first measured in the axial direction of the tube between the wall and the vortex generating body. The DC coupled output from the Tracker is shown in Fig. 11 together with the corresponding spectrum of the Doppler frequency. The vortex frequency appears as a 55 Hz oscillation with higher frequency turbulence and noise superimposed.

Measurements were then taken in the oscillating boundary layer in front of the body. The radial velocity was measured at a point 0.3 mm from the surface of the body and 1 mm from the edge. The body itself was 3.1 mm wide. The measuring point was chosen outside the oscillation zone of the stagnation line in order to avoid reverse flow, since the present Laser Anemometer is unable to indicate flow direction.

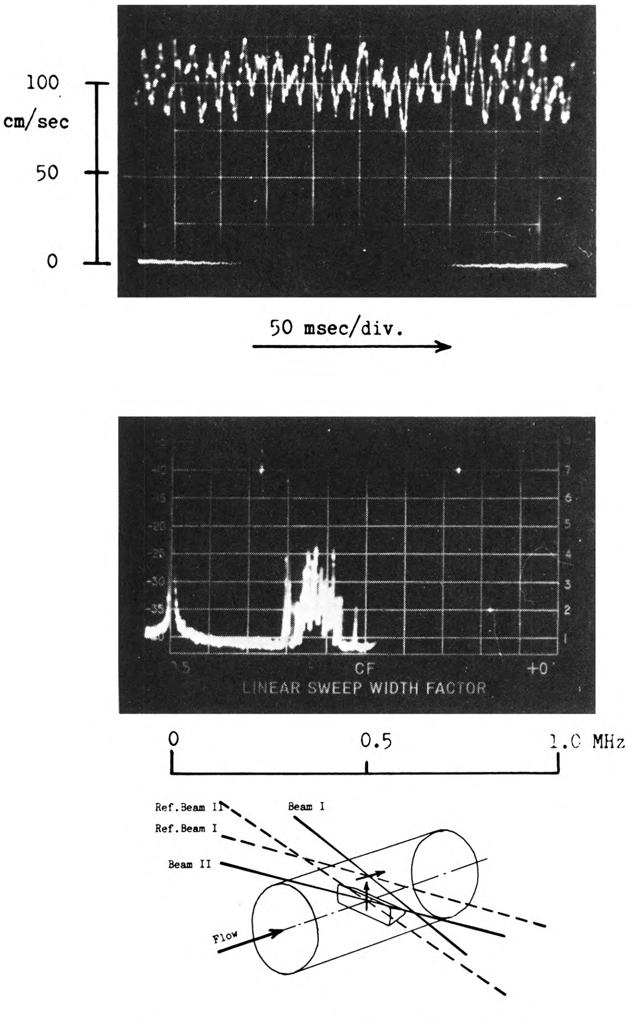

Figure 11 Measurement of Vortex Shedding

The spectrum of the Doppler signal, which covers a frequency band of 50 - 220 KHz, is shown in Fig. 12 (a), and the time variation of the Doppler frequency represented by the 100 Hz low-pass filtered output from the Frequency Tracker is shown in Fig. 12 (b). The 75 - 500 KHz range of the Tracker was used in both cases, and in this particular boundary layer experiment, the Tracker was therefore operating close to the lower limit of the range. Fig. 12 (c) shows an example of the distortion of the velocity measurement when the Doppler amplitude sweeps below the range. In order to make use of the full capability of the Tracker to track frequency variations of ± 70% about the mean, one may shift the scattering

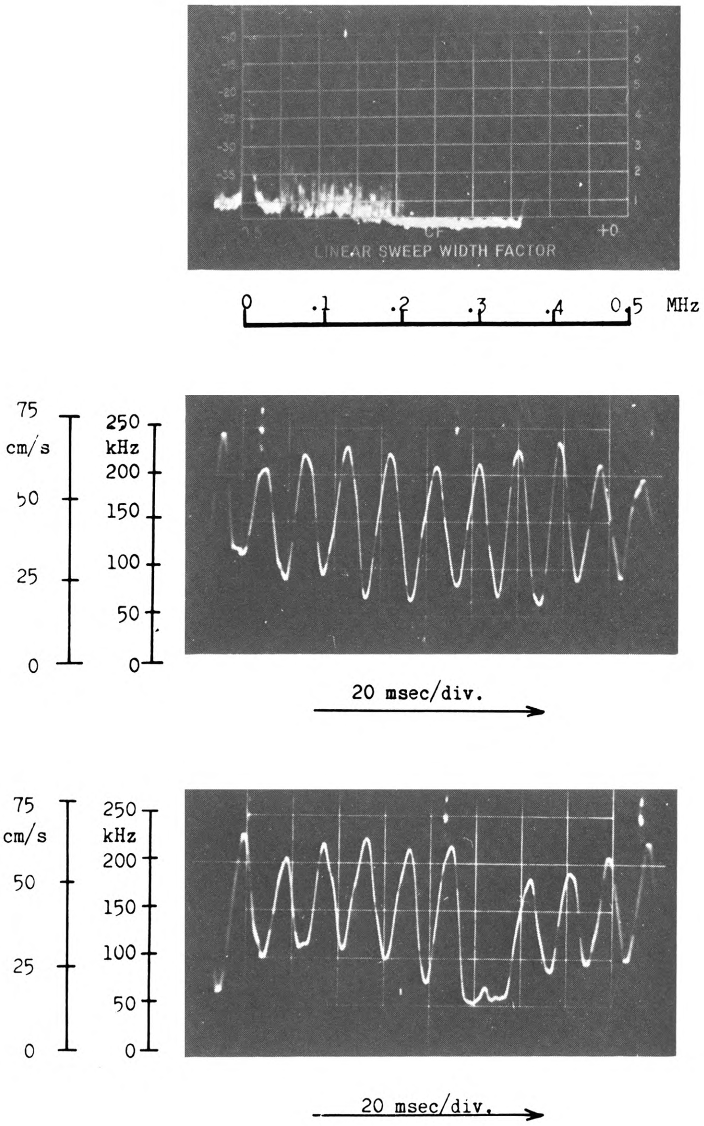

Figure 12 Measurements of Oscillatory Flow in the Boundary Layer in Front of a Blunt Body

angle and thereby center the Doppler frequency in one of the operating ranges of the Tracker.

## CONCLUSIONS

The Laser Doppler Anemometer is a valuable new tool for the fluid mechanics research. It can be used in transparent gases and liquids provided a certain amount of natural scattering particles of suitable size, i.e., 0.1 - 10 μm, is present or if "artificial" particles are added to the flow.

A comparison of several measurement features of thermal and laser anemometry shows that each has particular advantages:

| | LA | CTA |
|---|---|---|
| 1. Calibration of $\overline{u}$ | E | A |
| 2. Resolution | E | A |
| 3. Dynamic Frequency Response | A | E |
| 4. Dynamic Range | E | E |
| 5. Turbulence Intensity, u' | E | A |

where E stands for Excellent and A, Average.

From the chart shown above, it appears that the laser is the better tool from a technical standpoint, but in this we have not taken into consideration the practical aspects of total cost, type of staff and interpretation of data for the laser anemometer.

The laser does not disturb the flow except for a small heating, which in most cases is negligible. It is, therefore, ideal for the study of stability of flow, boundary layers, and flow in narrow channels. Its inherent linearity and simple directional sensitivity makes it possible in a simple manner to study two- and three-dimensional flow. Moreover, it offers a solution to the problem of measuring high turbulence intensity, a problem which has long been a challenge to experimental fluid dynamicists.

The measurement of low turbulence intensities is limited by different frequency broadening effects, but we anticipate that the noise level may be minimized to an equivalent turbulence intensity of 0.1 per cent.

The scattering volume can be made very small so that two-point correlations in turbulent flow can be made with far better spatial resolution than has previously been possible. Thus, we will be able to obtain better information about the dissipation scale of turbulence. The Laser Doppler Anemometer is particularly suited for such applications where the flow is too hostile to be probed by a sensor in physical contact with the fluid medium, such highly corrosive media, or in two-phase flow where the feature of no physical contact is essential to avoid disturbance of the boundary conditions between the two phases.

## SYMBOLS

| | |
|---|---|
| $a$ | Overheating ratio |
| $\overline{e}_i$ | Unit vector in the direction of the incident light |
| $\overline{e}_{sc}$ | Unit vector in the direction of the scattered light |
| $f$ | Tracker I.F. fixed center frequency |
| $f_D$ | Doppler frequency |
| $f_{Do}$ | Tracker input signal at the center of the tracking range |
| $f_{VCO}$ | Frequency of the voltage controlled oscillator |
| $g$ | Upper frequency increase factor |
| $\overline{k}_i$ | Wave vector of Doppler incident light |
| $\overline{k}_{sc}$ | Wave vector of Doppler scattered light |
| $L$ | Loop gain |
| $R$ | Operating resistance of the probe |
| $R_o$ | Probe resistance at ambient temperature |
| $S$ | Servo amplifier transconductance |
| $\overline{U}$ | Velocity vector |
| $U_x$ | Component of velocity perpendicular to beam intersection |
| $W_i$ | Angular frequency of incident light |
| $W_{sc}$ | Angular frequency of Doppler scattered light |
| $\lambda$ | Wave length |
| $\theta$ | Scattering angle |

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## DISCUSSION

G. OFFEN (Stanford University): Have you looked into the possibility of using the back scatter laser technique, probably with a more powerful laser, to monitor effluents coming out of chimneys and smokestacks in pollution control type studies?

HUMPHREY: Yes, we have explored the back-scatter technique with more powerful lasers. However, due to the severe optical requirements, we are only planning to offer solutions to studies at close distances, say a few inches to a few feet.

D. McLAUGHLIN (Oklahoma State University): Do you know of anyone who has a system working with the back-scatter laser technique or have you yourself?

HUMPHREY: We have worked with the back-scatter mode with a five-milliwatt laser doing actual experimental work under laboratory conditions.

Dr. Colin Hackett at MIT has been successful with back-scatter measurements for his PhD thesis at Brown University.

L. D. NYSTROM (Thermo-Systems Inc.): In discussing the frequency response of hot-film type sensors, you have indicated that with anemometers built in the past, film sensors have been difficult to optimize - that is, at higher frequencies, response curves have tended to decrease prematurely. Is that not due to inadequate gain at high frequencies?

HUMPHREY: Not really. If I could redraw the Bode plot that I previously had on the screen, you would soon find out by increasing the gain that it is not so much the amplitude but the phase shift that causes the amplifier to go unstable. It causes the system to exceed $135^\circ$ which is the magic number for the system. This is why we have introduced in our feedback loop a shaping network. If one would try to just increase the gain, and thus match the Bode plot of the probe alone, the system would go unstable for any other probe or measuring condition.

NYSTROM: In our anemometers we've been keeping our gain high and flat all the way out and, having designed with both hot films and hot wires in mind. The TSI anemometers have not had any difficulty optimizing responses in film sensors or wires.

HUMPHREY: I am not talking about optimization of the frequency response in film or wire sensors. Our new system actually increases past system performances by shaping the feedback loop gain to match the Bode of film probes. With all previous anemometer systems, if one makes a Bode plot with hot-film response data, a marked fall-off in film frequency response will be noted compared to that in the wire sensor.