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LIQUID TURBULENCE AND ITS MEASUREMENT

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ABSTRACT

This paper covers several principles which have been successfully developed over the past few years and used in the measurement of liquid flows. In particular, ultrasonics, electro-magnetics, thermal heat transfer and optical light transmission will be discussed. Each concept will be covered by basic definitions and laws, theory of operation and application where measurement parameters will be highlighted, thus allowing the user to choose the best instrument to fit his experimental needs.

INTRODUCTION

Turbulence is basically described as flow in a fluid characterized by constant changes in direction and velocity at any particular point. When considering how to measure turbulence in fluids, the first methods which usually come to mind are the so-called traditional ones and might start with a pitot tube. Other devices which have been used are orifice plates (1), flow nozzles, venturi nozzles, variable area flowmeters, magnetic-type flowmeters, positive displacement flowmeters, rotating disc flowmeters, impeller flowmeters, piston flowmeters, turbine flowmeters, coriolis flowmeters, gyroscopic, thermopile, ultrasonic, vortex shedding, heat transfer, and optical.

After reviewing these and other types of flow-measuring devices, it is found that many have frequency limitations, such as with the pitot tube, a typical manometer, has a natural frequency of about 0.5-1.0 cycles per second. When reviewing work going on at university, government, and industrial laboratories, we find the need for a turbulence-measuring system which possesses the following characteristics:

Small sensor size.
Sensitivity to very small velocity changes.
High frequency response which is suitable for turbulence measurements.
Adaptability covering very low, intermediate, and high fluid velocities.

After a review of the previously mentioned flowmeters (2) and their principles we find that the principles which apply to the measurement of liquid flow and turbulence are:

Transmission of sound.
Stresses by moving fluids.
Reaction rates.
Hall Effect (magnetic field).
Heat transfer.
Scattering of light.

SOUND

Ultrasonic flowmeters (3) in large sizes are less expensive than turbine, or positive displacement meters, but are not as accurate as orifice plates, venturi's or electromagnetic flowmeters. The ultrasonic flowmeter cost and accuracy is similar to, or lower than, the previously mentioned flowmeters while its very low pressure drop and rangeability is superior.

The ultrasonic flowmeter detects the time difference between upstream and downstream sound wave travel and measures the velocity of the flowing fluid by the following relationship:

$$u = \left(\frac{c^2 \tan \theta}{2D}\right) \Delta t$$

where

u - Velocity of flow
c - Velocity of sound in the liquid
θ - Angle of sonic beam
D - Inside pipe diameter
Δt - Difference between upstream and downstream transit times.

Because sound velocity (c) is not a constant but a function of liquid composition, temperature, and density, this technique requires compensation networks to eliminate these sources of error. Other limitations exist; for instance, in small pipes the micro-sound time difference becomes very difficult to measure accurately.

The technique in Figure 1a shows the wave passing through the liquid in the upstream direction and it is compared to another continuous wave directed downstream. The phase shift between the two is an indication of the velocity. Figure 1b shows the most widely used technique. Here, the velocity of the liquid is determined by the measurement of the difference between upstream and downstream frequencies. The frequency of a pulse is the inverse of the transit time; but when a frequency difference is used, the dependence upon the sound velocity (c) is eliminated,

$$u = \frac{D}{\sin 2\theta} \Delta f$$

where ΔF is the difference between the upstream and downstream frequencies. Because ΔF is proportional to u with no dependence upon (c), and because frequency difference is easily measured, this approach is widely used.

Figure 1c shows a transducer transmitting a beam perpendicular to the pipes' axis, deflected by the distance y which is a function of flow velocity, where y is the distance of deflection and s is the source strength. This method also requires composition and temperature compensation networks because it can measure the flow velocity only if the sound velocity (c) is constant. Another element of uncertainty is the dependence of the deflection on the magnitude of the sound s.

The Doppler-type (scatter frequency shift method) is used in many instruments in addition to ultrasonic wave lengths. Other forms of radiation including I R and U V are utilized to obtain information on solid-particle velocity in fluidized beds, and to determine pollutant concentrations with remote sensing spectrometers. Figure 1d shows the Doppler method applied by projecting sound waves along the flow path and measuring the frequency shift in the return signal from the scatterers in the fluid. The scatterers can be solid particles or gas bubbles moving at the same velocity as the fluid. The frequency shift (difference between transmitted and received frequencies) is related to flow velocity in an equation,

$$u = \frac{c}{2F_t \, V \cos \theta} \Delta F$$

where F_t is the frequency of the transmitted signal, and ΔF is the difference between transmitted and received frequencies. Limitations of this technique include the need for fluid composition and temperature compensation circuits and, finally, the presence of scatterers. This design senses only in a small region where the transmitter and receiver signals cross. The advantage of this technique is that it can measure in difficult streams, such as slurries, fluidized solids, or gas-liquid mixtures, where the liquid is the continuous phase.

Figure 1e shows a common vortex-shedding flowmeter which uses ultrasonic pulse pick-up elements. Another form of the ultrasonic vortex-shedding flowmeter is built by J-Tec Associates, Inc. (4). The sensor counts the frequency of the vortex street formed behind a strut in the fluid flow and is not affected by changes in temperature, density, or pressure. A very low threshhold permits accurate measurements of speeds below the capabilities of conventional sensors. The response of this type of flowmeter is very fast and equal to the reciprocal of the output frequency detected between the vorticies.

Figure 1f shows a passive ultrasonic device. The transducer does not generate an ultrasonic signal while with an active device it does. In this unit the ultrasonic sensor picks up the noise generated in the pipe. As flow in the pipe increases, the sound level also increases.

STRESSES

When reviewing stresses by moving fluids, methods such as vane meters, dynamic pressure measurements, including orifice plates and fluidic devices are used in various industries. (See Figure 2.)

Figure 3 shows a typical fluidic flowmeter (5), such as the one offered by Moore Products. This type of liquid flowmeter exploits the Coanda effect. Liquids will generally flow straight through this type of configuration, but will initially attach to one side wall or the other, then cycle back; the frequency of attachments being proportional to the flow volume.

A miniature turbulence gauge utilizing aerodynamic lift similar to a vane meter, however much further developed, operates on the principle that the angle of attack fluctuations in an unsteady flow will cause lift forces against an air-foil (6) (tiny aero dynamic lifting surface). Figure 4 shows a flow incident on the probe with velocity V at some angle of attack α to the probe axis. The probe is presumed to be aligned with the direction of the mean flow. In turbulent flow V and α vary in a random fashion. Turbulence will act on the nose piece of the probe and be proportional to the effective angle of attack when its level is not too high (less than 30 percent). Typical sensitivity is 1 millivolt per millimeter of H_2O, with a frequency response of 10 Hz to 10 KHz.

REACTION RATES

Fluid reaction rate flowmeters, such as the corona-discharge anemometer (2) (glow discharge) use sharp electrodes with a gap of approximately 100 mm. The electrodes require a voltage potential of several hundred volts and a current of 10 milliamps.

Another reaction rate technique has been developed to be used to study turbulence in the vicinity of a pipe wall (7). A reaction is conducted on an electrode mounted flush with a solid wall with high enough voltage to reduce concentration of the reacting species to zero at the surface. Under these conditions, the rate of reaction is controlled by the rate of mass transfer. The electrode is analogous to a constant-temperature hot-wire anemometer in that the surface concentration is kept constant and the current flowing in the circuit is related to surface shear stress. For fully-developed turbulence, the limiting turbulence intensity is 0.32, based on the local average velocity.

MAGNETICS

One example of a Hall-Effect flowmeter is the electromagnetic flowmeter (2). (See Figure 5.) The principal of operation is based on Faraday's law of electromagnetic induction E = BLV x 10-8 where E is the electromotive force in volts, B the magnetic field in gauss, L the electrode diameter in cm, and V the velocity of the liquid in cm/s. The law states that when a conductor moves through a magnetic field, an electromotive force (voltage) is generated in a direction mutually perpendicular to both the magnetic field and the direction of flow. In the operation of this transducer, two electrodes located 180 degrees apart are held rigidly in the inter-circumference of the pipe. As the fluid moves through the constant area of the cross-section of the magnetic field, a voltage is produced directly proportional to the rate of flow. The flow signals are conditioned and displayed on a meter, scope, or strip-chart recorder. Some special features of this method are: a) calibration is not required; b) flow direction is indicated; c) both mean and turbulent flow can be measured simultaneously; d) it's simple, portable, and lightweight. In particular, the electromagnetic flowmeter offers the direct proportionality between induced voltage and mean flow velocity. It is virtually independent of sensitivity changes due to different types of fluids and offers no interference to the flow (pressure drop).

HEAT TRANSFER

Heat transfer methods, such as hot-wire and hot-film anemometry offer the most promising characteristics for the measurement of turbulence (8).

The sensitive element of the thermal anemometer is either a thin wire suspended between two prongs or a thin metal film deposited on a quartz support. (See Figures 6a and b.) 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 velocities (e.g., in atmospheric air up to supersonic velocities), and in non-conducting liquids at low velocities.

Film probes are used chiefly for measurements in conducting liquids and replace wire probes in measurements within heavily polluted gas flows.

Fiber probes have mechanical and electrical properties that place them in a position midway between hot-wire probes and hot-film probes. Their velocity-sensitive element is a film which is deposited on the surface of a short length of a thin quartz fiber mounted between the prongs of a wire probe. A thin quartz coating protects fiber and film probes from outside influences, such as conducting liquids.

The constant-temperature system electronics are simple to operate and can measure large velocity fluctuations. The idea behind the constant-temperature system is to minimize the effect of probe 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 7.) 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 hot-wire sensor are kept extremely small, and it can be shown that the upper frequency limit is increased by a factor g:

$$g = 2aRs$$

where $a = (R - R_O)/R_O$ is the overheating ratio and s is the servo-amplifier 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 hot-wire anemometry is therefore based on the design of a stable servo system having very high closed-loop gain, and a well-balanced differential amplifier having flat characteristics from dc to high frequencies.

In turbulence measurements, the bandwidth is limited by the spatial resolution of the probe, but a high system bandwidth reduces phase shift and now can be utilized in liquid turbulence measurements.

Recent advances in anemometry circuitry allow a building-block-instrument with a variety of plug-ins, thus allowing the researcher to optimize the instrument for his particular experiment (9). By means of a special feedback network, either a flat- or shaped-frequency response can be obtained. Thus frequency response can be optimized for a film probe used in liquids. In this particular case, the amplifier has the same gain at 100 KHz as when strapped for flat-frequency response, but its gain increases with decreasing frequency response of the film sensor towards a maximum gain figure of 70,000. Typical problems encountered when using hot films are mechanical breakage, surface contamination, frequent calibration (i.e., correcting for differences in the test fluid and calibration fluid), electrical insulation of the film from conducting liquids.

Film probes, wire coils, and other semi-conductor elements are used as sensors for present vortex-shedding flowmeters (11). The present vortex-shedding flowmeter was developed through a series of studies which included the vortex whistle, a modified vortex whistle and finally, the swirl meter which was the predecessor to the present vortex flowmeter (9). (See Figure 8.)

The principle of operation of the liquid vortex flowmeter is based on a form of natural oscillation called vortex shedding. Studies of flow around immersed bodies indicate that flow patterns at high velocities generate a wake behind a cylinder or other nonstreamlined body. This wake is comprised of an orderly series of vorticies alternating in position about the centerline of the body. These vorticies create classic streak patterns described and analyzed by Von Karman in 1911. The alternating vorticies detach themselves from the boundary of the body and produce a zone of low pressure at the rear which shifts from side to side producing a variable side thrust. Over a range of Reynolds numbers, the frequency with which the vorticies are shed is linear with the incoming fluid velocity and therefore the frequency generated is directly related to the volumetric flow rate. Depending upon the meter diameter, the lower Reynolds number limits functioning at a velocity of 1 - 15 fps. A common example of the vortex shedding is a flag flying in the wind. The fabric of the flag positions itself between vortices and the vortices move along the flag causing it to wave or ripple.TThe flag does not wave regularly, because among other factors, the incoming flow pattern is nonconsistent and therefore the size of the vortices are nonuniform. The effect can also be seen in the flow around and behind a rock in the bed of a stream. Sensing techniques currently being used are front-face thermistors, central thermistors and external thermistors. (See Figure 9.)

LIGHT

The laser doppler anemometer (12) is a type of optical flowmeter utilizing the scattering of light. Applications to date have mainly concentrated on laminar flow studies or statistical properties of turbulence. However, instruments are now available which can continuously monitor a wide range of instantaneous velocities at specific points in a flow stream. The laser system provides spatial resolution an order of magnitude better than that of a hot-wire anemometer and offers directional sensitivity and easy measurement of two- and three-dimensional flows. In addition, the instrument does not disturb the flow; measures at a point and requires no calibration. It is therefore particularly useful for the study of flow stability, boundary layers, two-phase flow, and flow in narrow channels where the absence of physical contact and disturbance is important. Laser anemometers are also useful for flows which are too hostile for in-stream probes. Chief limitations are that the fluid medium must be transparent and contain suitable scattering particles.

In laser anemometry, a laser beam is used to sense the velocity of the flow. When the beam passes through the fluid flow, the light is scattered by particles in the fluid. The scattered light is interpreted by opto-electronic means to determine the flow velocity. (See Figure 10.) The scattered light from the moving particles is Doppler shifted. The Doppler frequency of the light f_d is related to the velocity by the vector equation:

$$f_D = \frac{1}{\lambda} \bar{V}\cdot(\hat{e}_s - \hat{e}_i)$$

where

$\hat{e}_s$, $\hat{e}_i$, unit vectors of the scattered and incident beams
λ, wavelength of laser light
$\bar{V}$, particle velocity vector

It can be seen from the f_D equation that the Doppler frequency is directly proportional to the particle velocity. (See Figure 11.)

The optics of the laser anemometer can be operated in several modes:

1. The <u>reference-beam mode</u> may be used to advantage when the concentration of scattering particles in the flow media is fairly high. The alignment tolerance necessary for the hetrodyning process is uncritical making this mode easy to use. (See Figure 12.)
2. The <u>differential mode</u>, using two incident beams of equal intensity (also known as the <u>fringe method</u> because the beams form a fringe pattern in the volume of intersection) is used where the intensity of scattering particles is low. In this case, scattered light can be picked up over a wide range since the differential Doppler frequency is independent of the direction of detection. (See Figure 13.)
3. The <u>differential-Doppler mode</u> on back-scattered light. Using the backscattering mode, the flow is measured from only one side which may be very useful. Even with high concentrations of scattering particles in the flow, this mode requires a powerful laser (1-5 watts). (See Figure 14.)

The main advantages of a laser Doppler anemometer are that it is unaffected by pressure, temperature and flow reversals, free from cross talk, and the output is linear. However, the medium must be transparent and it must contain scattering particles as previously mentioned. A number of laser Doppler anemometry parameters must usually be examined before the experimenter can get fully into his work. They are:

1. Budget
2. Experiment velocity range
3. Particle size
4. Particle concentration
5. Aperature and pinhole sizes
6. Laser power
7. Optical mode of operation
8. Type of signal processor required (tracker or counter type)
9. Photomultiplier - constant voltage or constant current operation
10. Estimate of velocity broadening (transit time)

CONCLUSION

The broad range of instruments covered in this paper inadvertently demonstrates that frequency response is a term which is open to interpretation. Within the fields of medical, scientific, and industrial research are included applciations where a fluid is considered turbulent if there are fluctuations as low as 0.1 cps.

The laser-Doppler anemometer has been in use for a relatively short time (eleven years) and has not yet begun to reach its fullest potential as an experimental tool. However, to date, it has proved to be the instrument which provides the widest frequency response with the best spatial resolution.

SYMBOLS

u	Velocity of flow
c	Velocity of sound in the liquid
θ	Angle of sonic beam
D	Inside pipe diameter
Δt	Difference between upstream and downstream transit times
Δf	Difference between the upstream and downstream frequencies
F_t	Frequency of the transmitted signal
α	Angle of attack
E	Electronic force in volts
B	Magnetic field in gauss
L	Electrode diameter in cm.

SYMBOLS (cont.)

g	Non-dimensional gain
a	Overheat ratio $(R-R_o)/R_o$
R	Resistance
s	Servo-amplifier transconductance
$\hat{e}_s$, $\hat{e}_i$	Unit vectors of the scattered and incident beams
λ	Wave length of laser light
$\overline{V}$	Particle velocity vector

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DISCUSSION

V. Goldschmidt, Purdue: Are you planning any unique new developments?

Humphrey: I would say that one of the major areas of development will be in the devoted mini-computer interface.

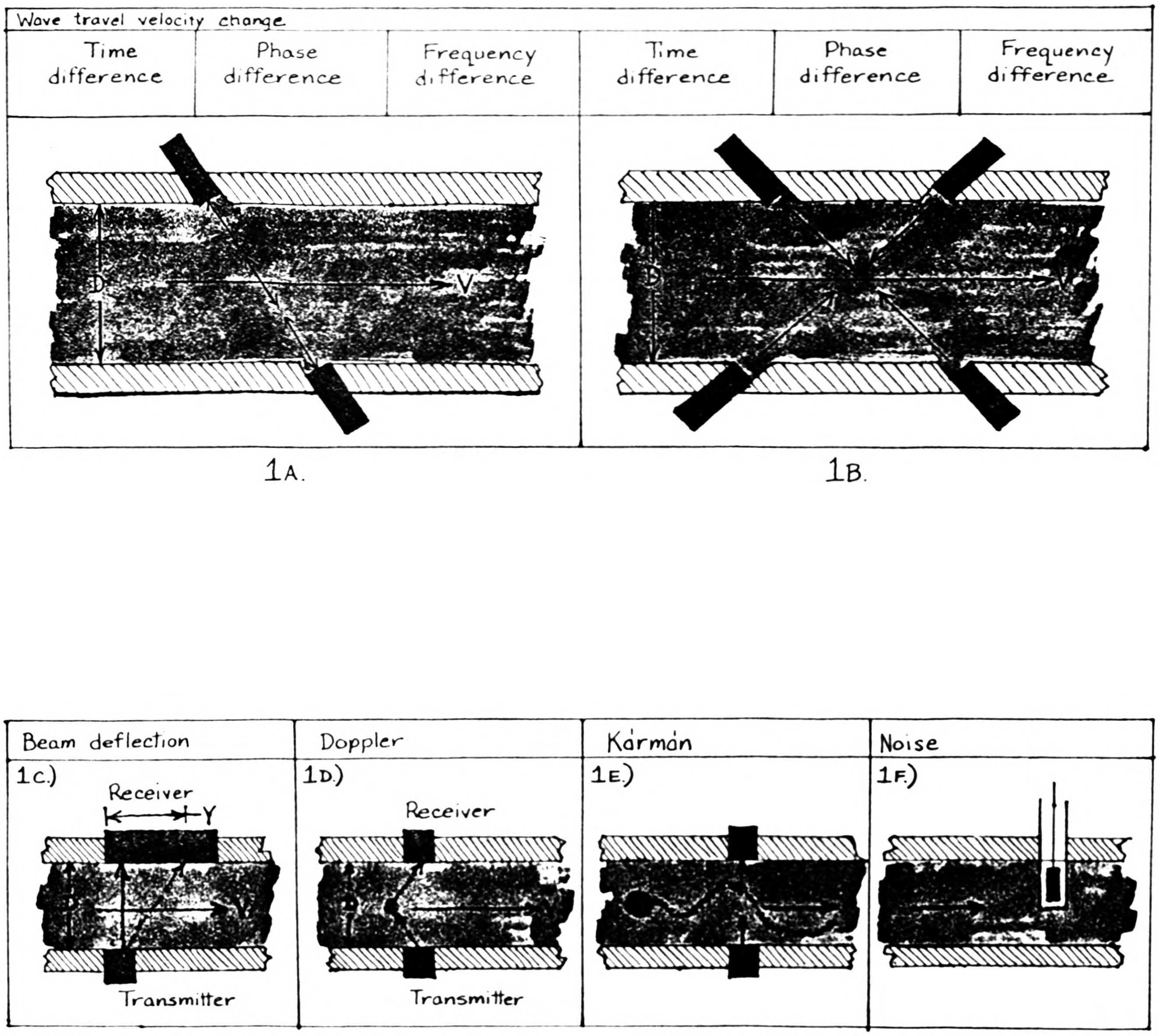
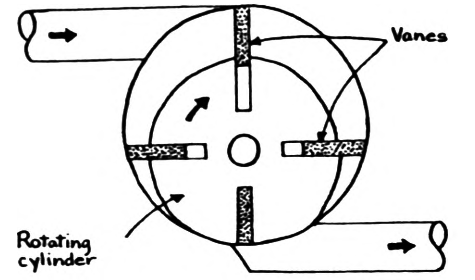
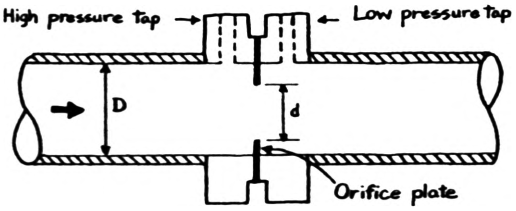

Wave travel velocity change
Time difference
Phase difference
Frequency difference
Time difference
Phase difference
Frequency difference
D
V
1A.
1B.
Beam deflection
Doppler
Kármán
Noise
1c.)
Receiver
Y
Transmitter
1D.)
Receiver
Transmitter
1E.)
1F.)

FIGURE 1



ROTARY VANE



ORIFICE PLATE

FIGURE 2

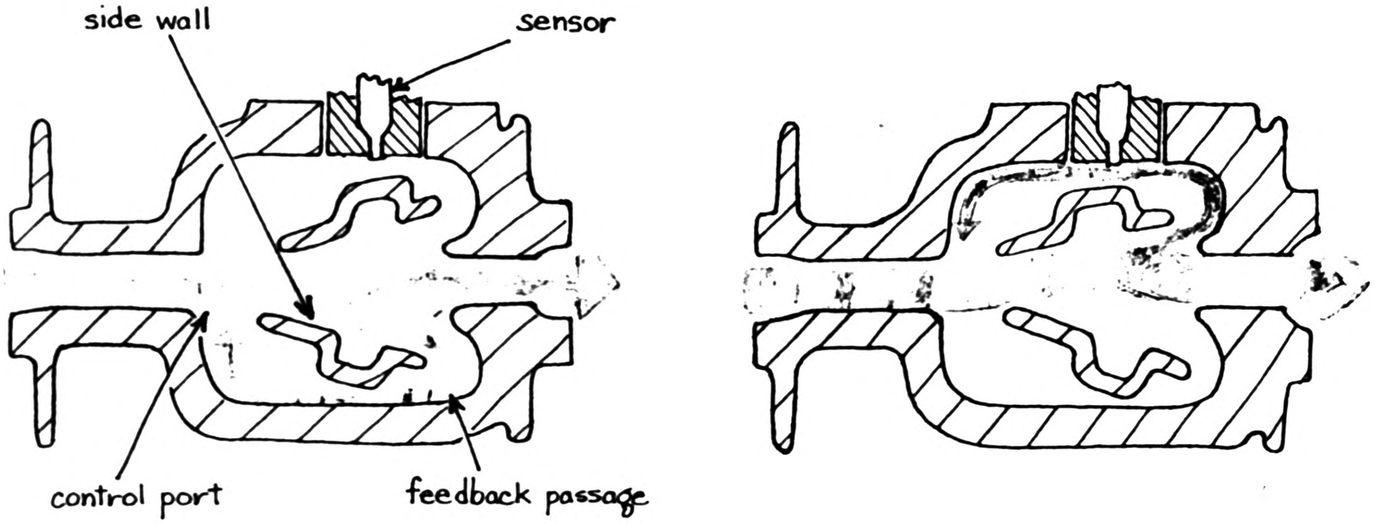


FIGURE 3

Operating Principle of Aerodynamic Turbulence Gauge

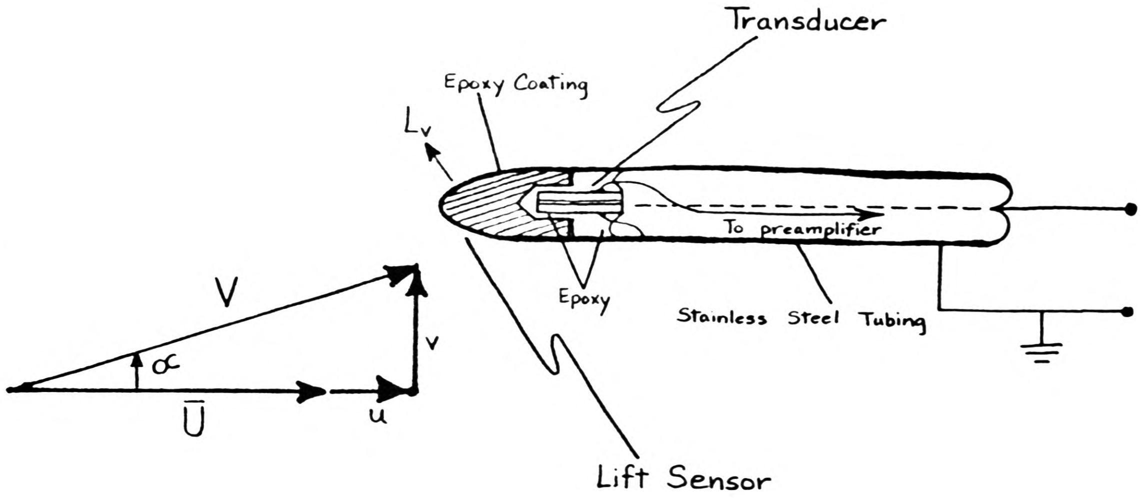


FIGURE 4

Measurement of mean flow velocity by electromagnetic induction.

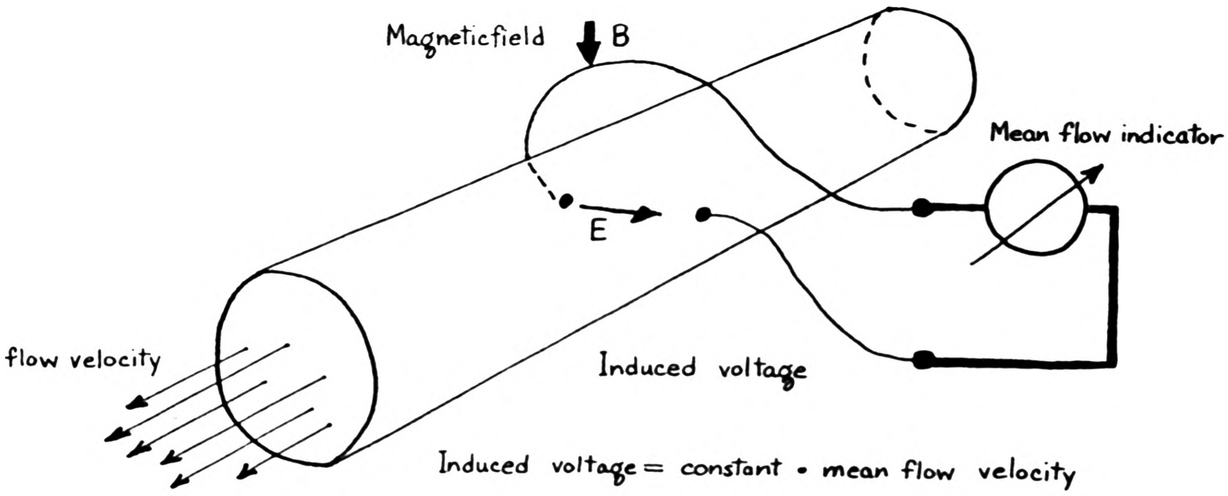


FIGURE 5

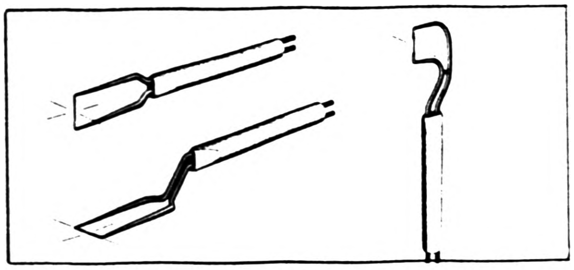


Figure 6c.

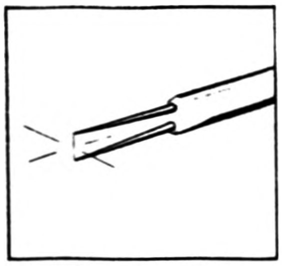
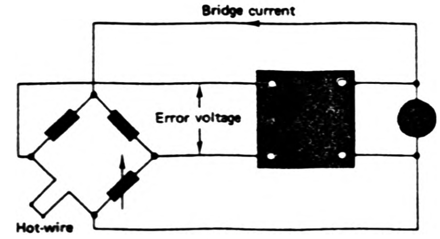


Figure 6a.



Principle of Constant-temperature Anemometer.

Figure 7.

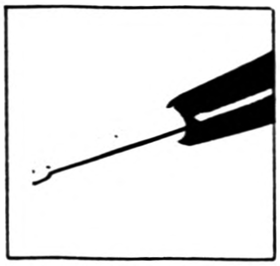
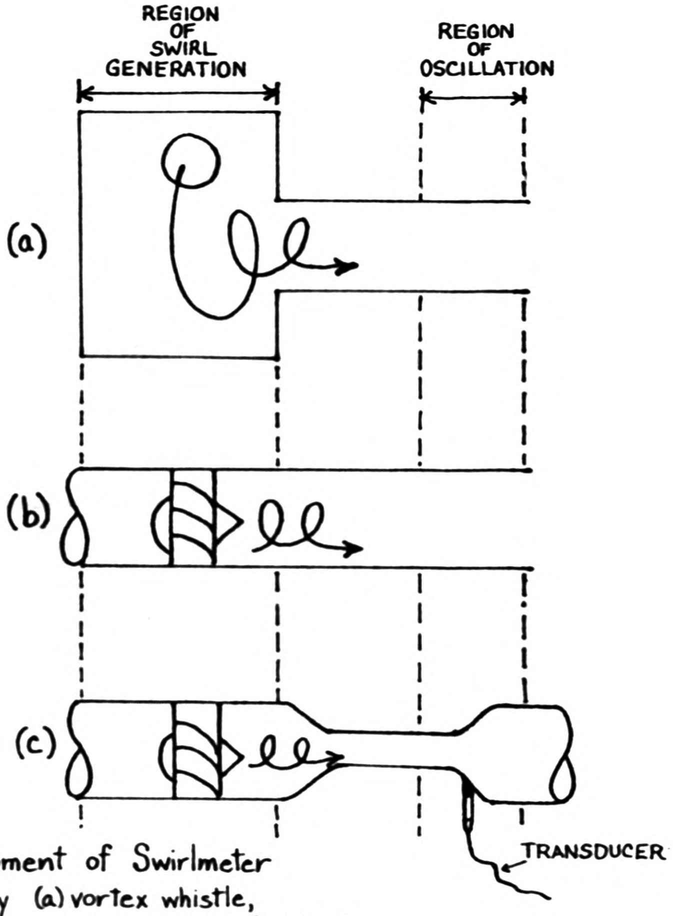
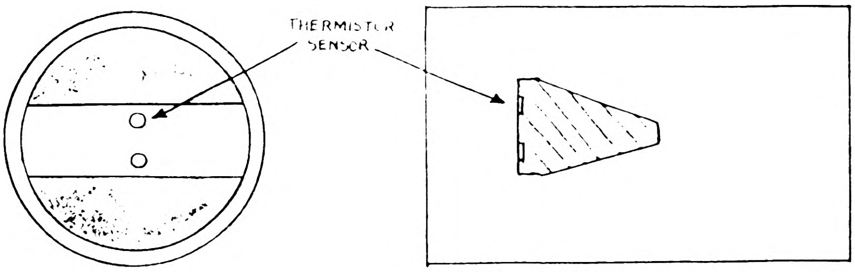


Figure 6b.

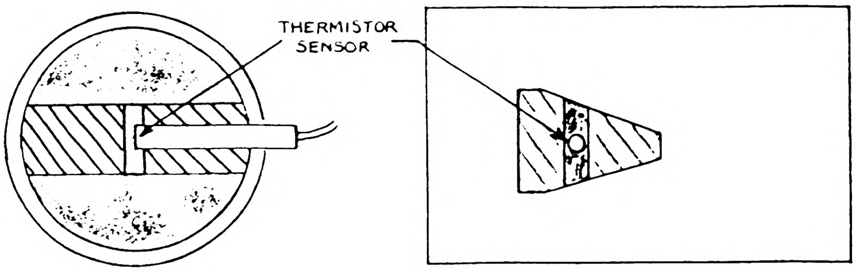


Development of Swirlmeter geometry (a) vortex whistle, (b) modified vortex whistle, (c) Swirlmeter

FIGURE 8



FRONT TECHNIQUE



CENTRAL TECHNIQUE

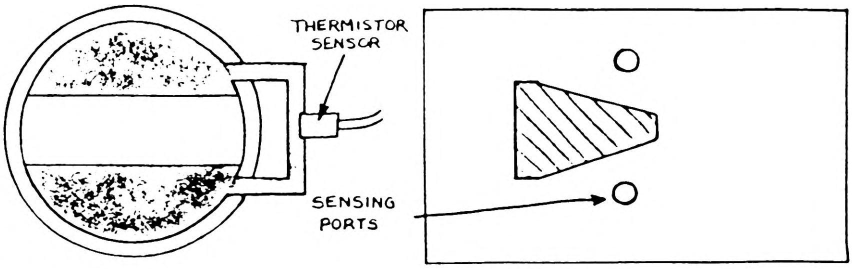


FIGURE 9

EXTERNAL TECHNIQUE

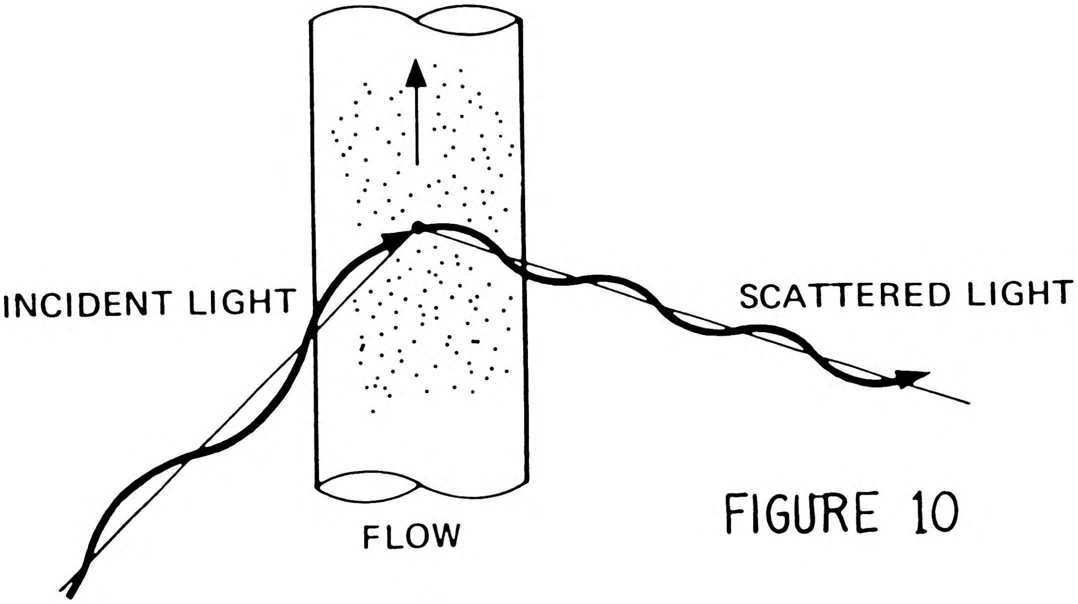


FIGURE 10

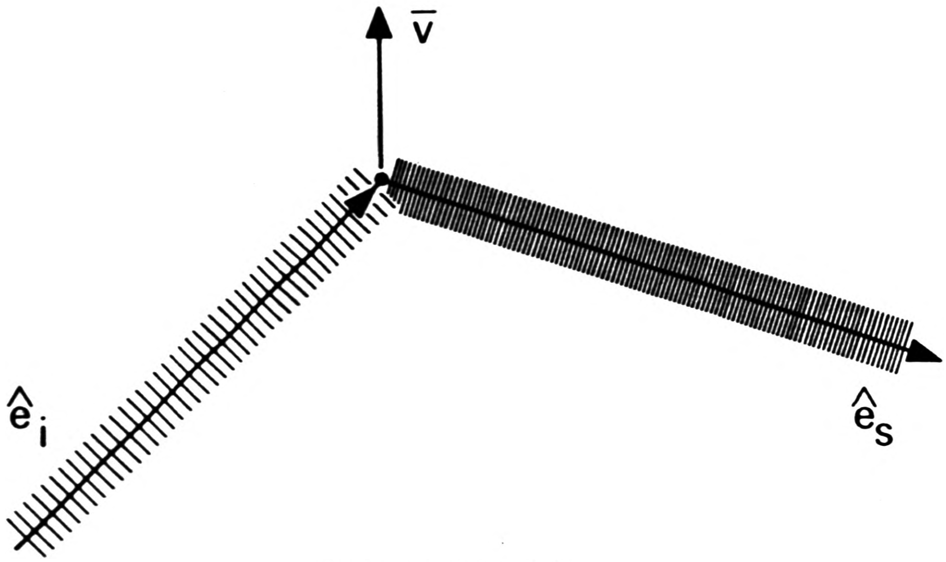
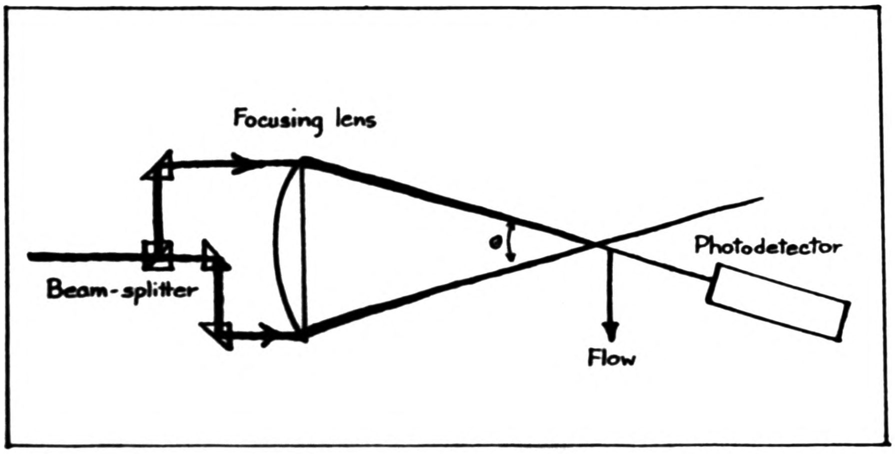
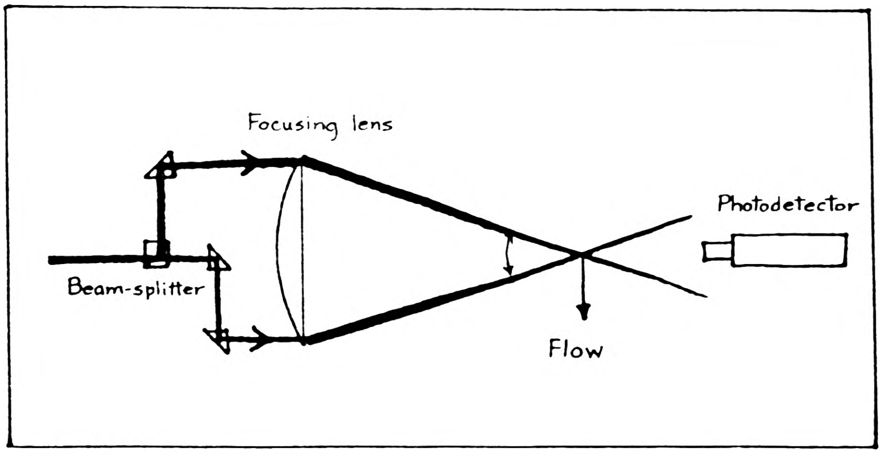


FIGURE 11



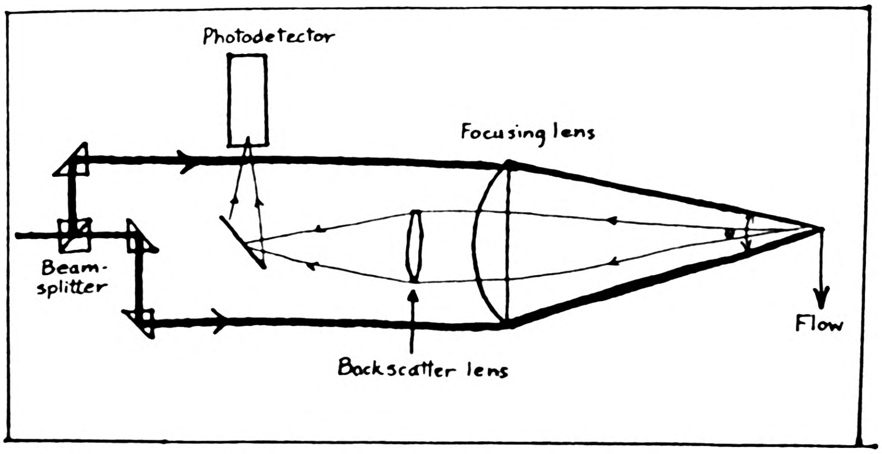
Reference Beam Mode

FIGURE 12



Differential Doppler Mode - forward scatter

FIGURE 13



Differential Doppler Mode - backscatter

FIGURE 14