The Lecture Contains:

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Piezoelectric Pressure Transducers

Instantaneous fluid pressure acting on a surface can be measured using pressure transducers. These consist of piezoelectric crystals that get charged when their faces are deformed. The electrical signal is suitably amplified before the local pressure is measured as voltage. Pressure transducers are primarily suitable for measurement of pressure fluctuations. Their operating characteristics deteriorate as the forcing frequency approaches zero. Pressure acting on a surface can also be estimated by installing strain gauges on it. This is accomplished by determining the change in resistance of the wire due to longitudinal strain. Fluid pressure can also be measured relative to atmospheric pressure using a capacitance pick-up. Here the differential pressure changes the capacitor spacing and hence the capacitance. When this element is placed in an electrical circuit the change in capacitance is observed as a change in output voltage. The pressure difference across the faces of the capacitor is developed commonly by a *pitot* or a *static* tube. Capacitor pick-ups vary significantly in construction depending on the method used to fabricate a capacitor element. This could be a thin metal diaphragm fixed on its boundary or a thin deformable layer on a semi-conductor substrate that forms a part of an amplifier circuit. Piezoelectric transducers are also used in `lift-drag-moment' balance that directly measures forces and moments on objects placed in wind tunnels. The design of the balance is usually complicated by the fact that elaborate mechanisms are needed to transmit the load to independent piezoelectric crystals.

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Static Tube

The static tube senses the local static pressure in the flow and is schematically shown in Figure 2.1.The holes on the periphery of the tube should be sufficiently far away from the tip facing the flow so that the effect of distortion of flow by the probe on the static pressure being measured is minimized. This distance L is preferably $10d$- $15d$, where d is the probe diameter

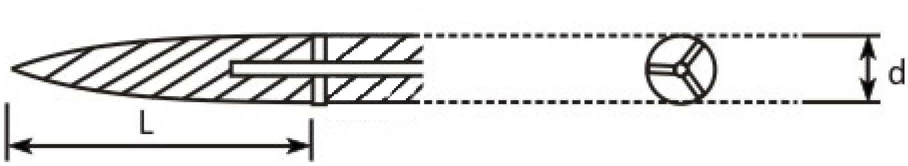

Figure 2.1: Static Tube.

The nose of a static tube is usually conical to streamline its surface and avoid flow separation. Three equally spaced holes are located on the periphery of the tube and the pressure recorded by the tube is an average over its circumference.

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Pitot Tube

A rapid way to measure gas velocity is to use a pitot tube inserted in flow. The pitot tube (also called a stagnation tube) consists of a thin tube held parallel to the flow and at the mouth of which fluid particles come to rest. This tube is typically of the size of a hypodermic needle and does not significantly alter the flow. In incompressible flow the pitot tube records the total pressure

$$p_t = p_s + \frac{1}{2}\,\rho\,u^2$$

A second probe with a tap whose axis is normal to the flow measures the static pressure p_s. The difference between p_t and p_s is a measure of velocity. This arrangement is shown in Figure 2.2

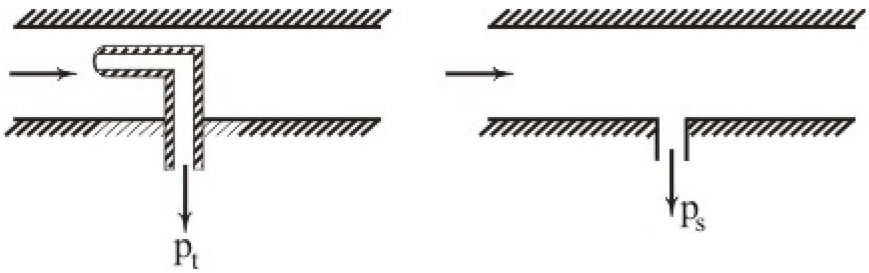

Figure 2.2: Total and Static Pressure Measurement.

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In applications where p_s can vary substantially from one location to another, p_t and p_s must be measured close to each other. This is accomplished using a pitot static tube (Figure 2.3). A probe with a spherical head in which five holes are present at right angles to it is used in the measurement of three dimensional velocity field (Figure 2.4). This is sometimes called a five-hole probe and can be used as follows: The probe is rotated along two independent axes till pressure p_a becomes equal to p_b and $p_{a'}$ equal to $p_{b'}$, i.e., the manometer shows a null reading for the pairs of holes (a, b) and (a', b'). Under these conditions p_c is the stagnation pressure of the flow and the probe axis is parallel to the flow direction. In applications where the probe cannot be rotated, it is common to calibrate $(p_a - p_b)$ and $(p_{a'} - p_{b'})$ as functions of the magnitude of $p_{c'}$, local flow velocity and two angles. Calibration charts for prescribed probe dimensions and hole locations are available and need not be repeatedly generated. A simpler route is to employ the potential flow solution for flow over the surface of the sphere, namely

$$\frac{p_0 - p}{\frac{1}{2}\rho\, U^2} = 1 - \frac{9}{4}\, sin^2\, \beta$$

where β is angular position of the point under consideration from the flow axis and p_0 is the stagnation pressure.

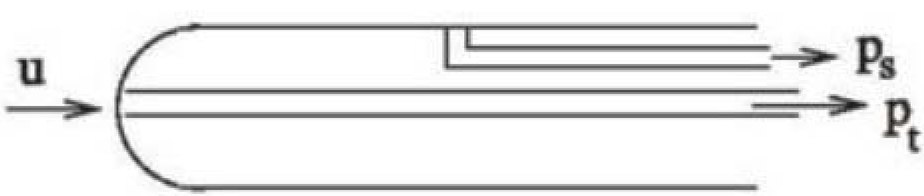

Figure 2.3: Pitot-Static Tube.

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Referring to Figure 2.5, we can determine

$$\beta_h: \quad \frac{p_a - p_b}{2p_c - p_a - p_b} = \frac{\sin 2\alpha}{1 - \cos 2\alpha} \quad \tan\ 2\beta_h$$

$$U_h: \quad \frac{p_a - p_b}{\frac{1}{2}\rho U_h^2} = \frac{9}{4} \quad \sin 2\alpha \quad \sin\ 2\beta_h$$

$$\beta_v: \quad \frac{p_{a'} - p_{b'}}{2p_c - p_{a'} - p_{b'}} = \frac{\sin 2\alpha}{1 - \cos 2\alpha} \quad \tan\ 2\beta_v$$

$$U_v: \quad \frac{p_{a'} - p_{b'}}{\frac{1}{2}\rho U_v^2} = \frac{9}{4} \quad \sin 2\alpha \quad \sin\ 2\beta_v$$

the above equation, holes a' and b'can be used to determine β_v and U_v.

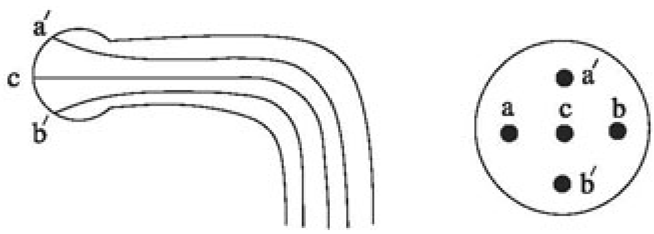

Figure 2.4: 5-hole Probe.

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The effective velocity vector $U(=U_h/\sin\gamma$ can now be determined using geometrical relations implied in Figure 2.5. [With reference to Figure 2.5, note that arc *acb* falls in the x- y plane; arc *a'cb'* is in the x- z plane; the x axis is the probe axis; γ is the flow direction; and $\beta$is the position of any point on the spherical probe surface with respect to the flow direction.]

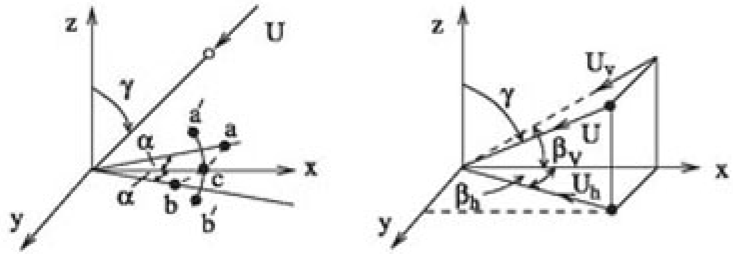

Figure 2.5: Vector Decomposition of Total Velocity U.

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Manometers

Pressure difference $p_t - p_s$ can be measured using a manometer. Different kinds of manometers are available. A U-tube manometer (Figure 2.6) uses a secondary fluid such as mercury, water or non-volatile oil. Each limb of the manometer is exposed to either p_t or p_s. When the liquid levels reach equilibrium, velocity is calculated as

$$\frac{1}{2}\rho u^2 = p_t - p_s = (\rho_l - \rho)\ gh$$

where ρ_l is the manometric liquid density.

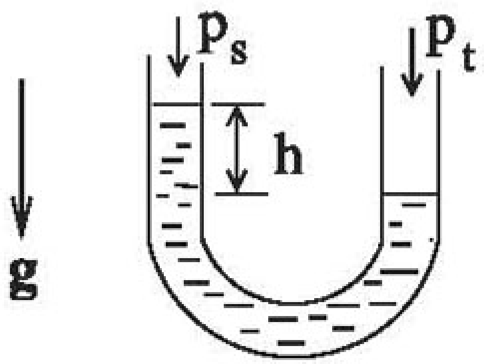

Figure 2.6: U-Tube Manometer.

Module 2: Review of Probes and Transducers

Lecture 7: Pressure measurement

When air is the working fluid in which pressure measurements are carried out, $p_t - p_s$ is small and considerable error can occur in the measurement of h with a U-tube manometer. In such instances one can use an inclined tube manometer that amplifies h by a factor of $1/\sin\theta$. This arrangement is shown in Figure 2.7.

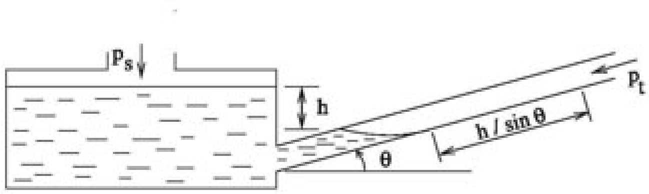

Figure 2.7: Inclined-Tube Manometer.

Module 2: Review of Probes and Transducers

Lecture 7: Pressure measurement

The pressure difference $p_t - p_s$ can also be measured on a digital manometer which uses a pressure transducer such as a capacitance pick-up. An electronic circuit can be used to extract the velocity of the fluid as well by calculating $\sqrt{2(p_t - p_s)/\rho}$ at a reference density (normally at 20°C). The advantages of using a digital manometer are:

1. Convenience in making an observation

2. Possibility of obtaining an analog/digital output in proportion to the instantaneous pressure

3. Time-averaging the pressure output to obtain a mean value.

Velocity Measurement Using Pitot Tubes

Pitot tubes (and pitot static tubes) are commonly used for velocity measurement in a wide variety of flow situations due to their simple construction and low cost. Although their application is primarily meant for laminar incompressible flows at high velocities, measurements can be made in turbulent or compressible flows with some modifications.

For flows with low-level of turbulence the mean velocity is directly related to the mean pressure difference in exactly the same way as in laminar flows. It is due to the fact that the time-averaged pitot tube reading is unaffected by turbulence levels upto 10 $\%$; this result can be seen as follows.

The instantaneous pressure difference is

$$\Delta p(t) = p_t - p_s$$
$$= \frac{1}{2}\rho(u(t))^2$$
$$= \frac{1}{2}\rho(\bar{u} + u')^2$$
$$= \frac{1}{2}\rho(\bar{u}^2 + u'^2 + 2\bar{u}u')$$

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Hence the time averaged pressure difference is

$$\overline{\Delta p} = 12\rho(\bar{u}^2 + \overline{u'^2})$$

as $\bar{u}' = 0$. This can be further written as

$$\overline{\Delta p} = \frac{1}{2}\rho\,\bar{u}^2\left(1 + \bar{u}'^2/u^2\right)$$

For turbulence levels as large as 10%, $\bar{u}'/u = 0.1$ but the error in pressure measurement is $\bar{u}'^2/\bar{u}^2 = 0.01$, i.e. 1%. On the other hand it can be shown that the instantaneous pressure fluctuations relate to velocity fluctuations as

$$\frac{(p_t)_{RMS}}{\rho\bar{u}^2} = \frac{u'_{RMS}}{\bar{u}}$$

Hence the pitot tube can be used for measurements of the velocity fluctuations in turbulent flows, as well, via measurement of total pressure fluctuations. As discussed in Lecture 10 Transient and Frequency Response (Example 2), pitot tubes have strong attenuation characteristics and an accurate determination of $(p_t)_{RMS}$ is a source of difficulty. The attenuation is quite high at higher frequencies. Hence, if the velocity spectrum does not contain high frequency components, the measurement of velocity fluctuations can still be carried out.

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A pitot tube is insensitive to misalignment with the flow direction for yaw angles upto 15°.

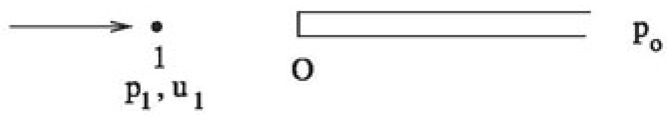

Figure 2.8: Pitot Tube Placed in a Flow.

Pitot tubes can also be used for measuring velocity in compressible gas flows. Let 1 be the far field and 0 be the mouth of the pitot tube (Figure 2.8). It is required to measure velocity at point 1. Under incompressible flow conditions Bernoulli equation can be used between points 1 and 0 to yield

$$\frac{p_1}{\rho} + \frac{u_1^2}{2} = \frac{p_0}{\rho}$$

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Hence

$$\frac{\rho u_1^2}{2} = p_0 - p_1$$

as given earlier. In compressible flows with Mach number M < 1, Bernoulli equation is written as

$$\int \frac{dp}{\rho} + \frac{u^2}{2} = constant$$

The integral can be evaluated by assuming ideal gas behaviour and a reversible adiabatic process that brings the fluid particles to rest at point 0 (i.e., p/ρ^{γ}= constant). It can be shown that

$$\left(\frac{u_1}{c_1}\right)^2 = \frac{2}{\gamma-1}\left[\left(\frac{p_0}{p_1}\right)^{(\gamma-1)/\gamma} - 1\right]$$

where γ is the ratio of specific heats, c_1 is the speed of sound equal to $\sqrt{\rho R T_1}$, R is the specific gas constant (=287 J/kg K for air) and T_1 the absolute temperature of the fluid at point 1. Pressure p_0 is the stagnation pressure recorded by the pitot tube.

If M_1 is greater than unity, a bow shock will form ahead of the pitot tube as sketched in Figure 2.9. In ideal gases M_1>1 if $p_0/p_1 > 1.893$, the critical pressure ratio. The velocity at point 1 is then determined by relating it first to point 2 by the Rankine-Hugoniot conditions and then to 0 using reversible adiabatic equations given above. This is possible because the flow beyond the shock (at point 2 and 0) is subsonic. The pressure ratio in this case can be shown to be

$$\frac{p_0}{p_1} = \frac{1-\gamma+2\gamma M_1^2}{\gamma+1}\left(\frac{(\gamma+1)^2 \ M_1^2}{4\gamma M_1^2-2(\gamma-1)}\right)^{\gamma/\gamma-1}$$

Such calculations are best carried out using normal shock and isentropic gas tables.

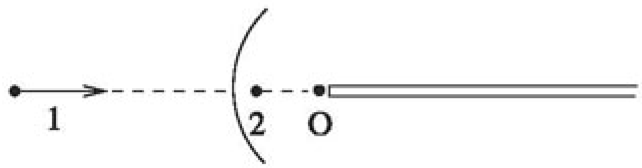

Figure 2.9: Pitot Tube Measurement when M>1 .

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While using a pitot tube for low speed measurement, two important sources of errors must be kept in mind: (i) low Reynolds number error and (ii) wall proximity error. At small values of Re, the fluid particles anticipate the presence of the probe wall and will have sufficient time to go around it. The curvature of the flow path and the divergence of the streamline accelerate the fluid locally and will reduce the static pressure below the free stream value. Hence $(p_t - p_s)$(measured) will be larger than the true value. Let C_p be the correction factor to the measured pressure difference. Typical values of C_p as a function of Re based on pitot tube diameter for a blunt-nosed pitot tube are given in Table 1

Table 1: Correction Factor for a Pitot Probe at Low Reynolds Numbers

Re	5.000	10.000	20.000	40.00	60.00
C_p	0.746	0.909	0.975	1.00	1.00

For $Re > 40$, C_p is nearly unity and no correction is required. For $Re < 5$ the correction factor is quite small and the uncertainty in its value limits the utility of the pitot tube.

The second source of error arises from the proximity of a wall. The distortion of the streamlines near the probe-wall region affects the local static pressure distribution as discussed earlier and it leads to the measurement of an incorrect velocity. Correction factors for this source of error are not readily available and accounting for the wall effect remains a challenge at this time.

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