The Lecture Contains:

Review of Probes and Transducers

Hot-wire Anemometry

A hot-wire anemometer measures local instantaneous velocity based on principles of heat transfer. However, it requires that the fluid itself be at a uniform temperature. It can be used to measure three components of velocity and velocity fluctuations arising in turbulent flow. This is possible because of the high speed of response of the hot-wire probe and the associated feedback circuit. A hot-wire probe is used in gas flows, while a hot-film is used for liquid flow. The hot-wire has a limitation that it is insensitive to the flow direction. Further, it has a non-linear input-output relationship which makes its sensitivity non-uniform over any velocity range. In particular, the sensitivity decreases with increasing velocity.

The hot-wire probe is a platinum-coated tungsten wire, typically of $5\ \mu m$ diameter and about 4 mm length, supported between highly conducting prongs (Figure 2.10). Tungsten has high temperature coefficient of resistance (i.e., resistance increases rapidly with temperature) and the platinum coating affords strength as well as protection against corrosion of the thin wire.

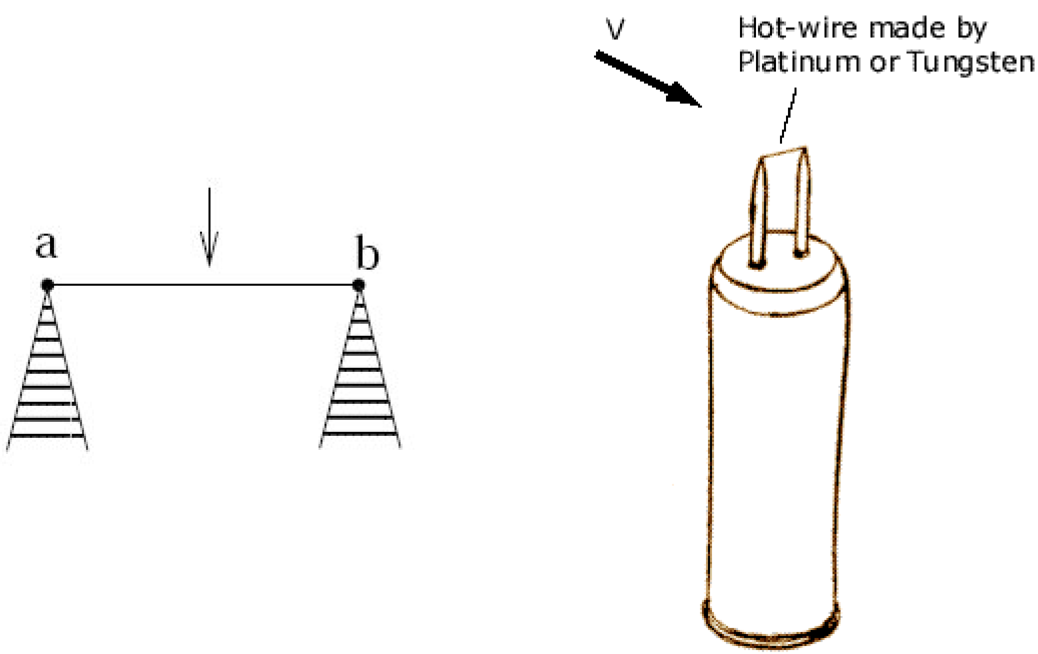

Figure 2.10: Schematic Drawing of a Hot-wire Probe.

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The wire ab is maintained at a constant temperature higher than that of the ambient, by passing a current through it. The flow past the probe cools it and momentarily reduces its temperature. The change in temperature results in a change in resistance of the wire ab. This is sensed by a feedback control circuit which passes more current through the wire to restore it to its original resistance and temperature. The excess voltage E required to maintain the wire temperature constant, when exposed to a flow, is a measure of the flow velocity u itself. This unique relationship between E and u must be obtained by calibration, i.e. E must be determined in a controlled experiment where u is precisely known. Typical calibration curves for hot-wire are shown in Figure 2.11 in which T_w and T_∞ denote the wire temperature and the local fluid temperature respectively. In a calibration experiment, it is common to keep T_w and T_∞ individually constant to generate each of the curves $1, 2, ...$

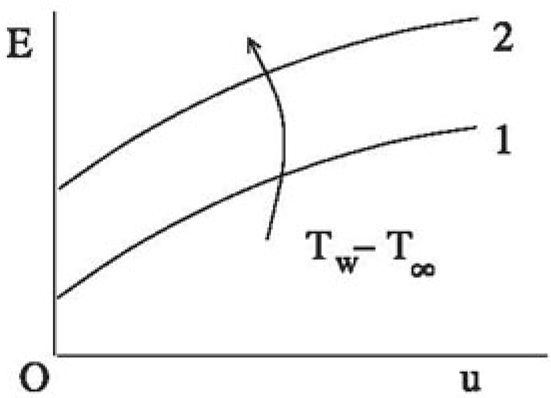

Figure 2.11: Calibration Curve of a Hot-wire Probe.

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Single-wire Measurement

When single hot-wire probe is kept in a flow of unknown velocity it produces a voltage E that can be converted into a velocity using the calibration curve. Velocity fluctuations u' manifest as voltage fluctuations e that can be recorded as the instantaneous signal $e(t)$ through a computer or as RMS value through a true-RMS voltmeter. If $u = f(E)$ is the calibration curve, the instantaneous velocity fluctuations are determined as

$$u'(t) = f(E + e(t)) - f(E)$$

where E is the mean voltage corresponding to a mean velocity u. The RMS value of the velocity fluctuations can be simply calculated as

$$u'_{RMS} = e_{RMS} \left.\frac{du}{dE}\right|_E = e_{RMS}\, f'(E)$$

Here f' is the derivative of the calibration curve calculated at the operating point (E, u) of the probe. This formula is based on a truncated Taylor's series expansion of the function f and is valid only for small values of e_{RMS}. Experiments show that it is valid for turbulence levels upto 10 percent. For larger turbulence levels it is more accurate to construct $u(t)$ pointwise, followed by $\bar{u}$, and $u'(t)$and determine u'_{RMS} using numerical integration of the u' signal.

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The hot-wire anemometer is a widely used transducer in velocity measurements and for this reason, salient features involved in its operation are discussed below:

1. Wire temperature is usually in the range 200- 250°C and is limited by the strength between the wire and the prongs. The corresponding wire resistances at room temperature and at $250^{\circ}C$ are 3.5 and 6.5 ohms, respectively. The ratio of these resistances, called the overheat ratio is between 1.5 and 2.

2. The hot wire output E is non-zero even when $u = 0$. This is because a non-zero current must flow through the wire to compensate for heat transfer to the prongs by conduction, buoyancy driven motion of the fluid around the wire and heat transfer by radiation.

3. Mode of operation of the hot-wire probe described above wherein it is kept at a constant temperature results in a constant temperature anemometer (CTA). It is possible to use the probe in a constant current mode (CCA) as well. In the CCA mode the change in resistance of the wire is measured by passing a small current $(= 1$ mA) through it and this change is related to the local velocity. It can be shown that a hot wire working in the CTA mode has a high frequency response $(> 10$ kHz) in comparison to the CCA mode $(< 100$ Hz). However, the CCA mode is useful in the measurement of local temperature and temperature fluctuations when the wire operates as a resistance thermometer.

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4. The calibration curve $u = f(E)$ is frequently written in the form

$$E^2 = E_0^2 + Bu^n$$

where E_0 is the value of E when $u = 0$. B and n are calibration constants that must be determined from the calibration data using a least squares procedure. The value of n is usually between 0.45 and 0.5. When u is not expected to be zero anywhere in the flow domain it is convenient to set $n = 0.45$ and treat B and E as curve-fitting parameters. The generalized least squares procedure for fitting the statistically smoothed data (E_i, u_i) through a function (E_i, u_i) with $a_j,\ j = 1, \dots N$ parameters is:

$$Minimize \quad ERR = \sum_{j=1}^{N} \ (u_i - f(E_i))^2 \ \ with \ \ respect \ \ to \ \ a_j, \ \ i.e.$$

$$\frac{\partial E_{rr}}{\partial a_j} = 0, j = 1, \dots N$$

This gives N equations for the N unknowns a_j. Depending on the form chosen for f, the N-simultaneous equations can be linear or non-linear. In the latter problem iterations will be required to solve for the a_j's.

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5. Since hot-wire is based on heat transfer principles the calibration curve changes if either the wire temperature or the ambient temperature is altered. If the velocity is large (> 3 m/s in air), heat transfer from the wire is primarily due to forced convection and hence for a given velocity the heat transfer coefficient h is independent of the temperature difference $\Delta T = T_w - T_\infty$. At smaller velocities additional heat transfer mechanism such as conduction to the prongs and free convection become important. When h is independent of ΔT, changes in T_∞ can be accounted for by changing T_w to keep ΔT and hence the calibration curve unchanged. Since the wire resistance R and T_w are related as

$$R_w = R_o \left(1 + \alpha \left(T_w - T_o\right)\right)$$

adjustments in T_w can be made by a suitable setting of the operating resistance R_w. For tungsten the value of α is about 3.6×10^{-3}/°C.

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Two-wire Measurement

Two wires are needed for two and three wires for measuring three components of velocity respectively. Here we discuss a two-wire probe, also called a crossed wire or an X-probe (Figure 2.12).

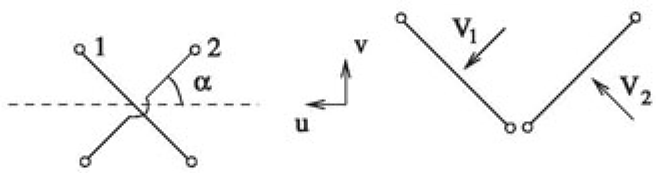

Figure 2.12: Schematic Drawing of a X-wire Probe.

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The angle α is chosen so that the probe has the greatest sensitivity under the desired operating conditions. However, commercial probes use $\alpha = 45°$. Such probes are most sensitive in measuring isotropic turbulence for which $u' = v'$. Let u and v be the Cartesian components of velocity and V_1 and V_2 be the effective velocities sensed by the wires. The voltage outputs E_1 and E_2 of wires 1 and 2 will correspond to the effective velocities V_1 and V_2 respectively. One can calibrate wires 1 and 2 individually in uniform parallel flow and generate the calibration curves $V_1 = f_1(E)$ and $V_2 = f_2(E_2)$ for each of them. This is schematically in Figure 2.13.

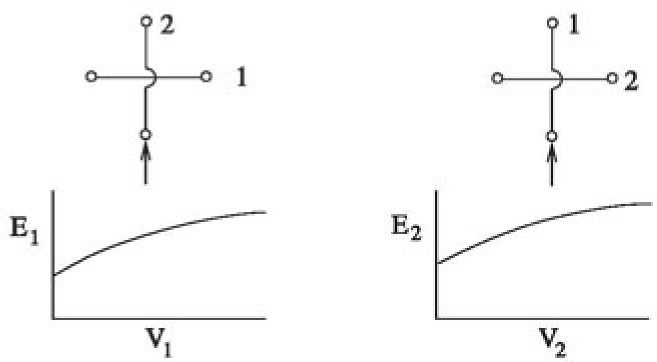

Figure 2.13: Calibration Arrangement for X-probe.

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It is most convenient from the view point of data reduction that the functions f_1 and f_2 be close to each other, i.e. wires 1 and 2 be identical and their overheat ratios should also be equal. The measurement of E_1 and E_2 directly gives the values of V_1 and V_2 through the calibration curves. These can be related to u and v as follows.

For wire 1, the normal velocity component is $(u\ \cos\alpha\ -\ v\ \sin\alpha)$ and the longitudinal velocity component is $(u\ \sin\alpha\ +\ v\cos\alpha)$. The heat transfer coefficient associated with each velocity component is different. Hence the effective velocity V_1 that accounts for cooling represented by the voltage E_1 is written as

$$V_1^2 = (u\ \cos\alpha - v\ \sin\alpha)^2 + K_T^2\ (u\ \sin\alpha + v\ \cos\alpha)^2$$

where K_T is the ratio of heat transfer coefficients in parallel flow to cross-flow past a cylinder under attached flow conditions (i.e., Re based on wire diameter < 40). The commonly used value of K_T is $0.2.$ Similarly, for the second wire

$$V_2^2 = (u\ \sin\alpha + v\ \cos\alpha)^2 + K_T^2\ (u\ \cos\alpha - v\ \sin\alpha)^2$$

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For $\alpha = 45^\circ$ the expressions for V_1 and V_2 reduce to

$$V_1^2 = \frac{1}{2}\left[(u-v)^2 + K_T^2\,(u+v)^2\right]$$

$$V_2^2 = \frac{1}{2}\left[(u+v)^2 + K_T^2\,(u-v)^2\right]$$

Extracting explicit expressions for u and v from these equations is difficult. However, for the limiting case of $|u| >> |v|$ and neglecting terms of order K_T^4 in the binomial expansion of a square root the following relations can be derived:

$$\bar{u} = \frac{\bar{V}_1 + \bar{V}_2}{\sqrt{2}}\,(1 - 2K_T^2)$$

$$\bar{v} = \bar{V}_2 - \bar{V}_1\sqrt{2}\,(1 - 2K_T^2)$$

Here the bar denotes the time-averaged value of the appropriate velocity component.

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The two components of velocity fluctuations are determined as follows. Let e_1 and e_2 be the RMS voltages of fluctuations sensed by wires 1 and 2 respectively. The effective velocity fluctuations that the voltages correspond to are given by

$$v'_1 = \left.\frac{dV}{dE}\right|_1 e_1$$

$$v'_2 = \left.\frac{dV}{dE}\right|_2 e_2$$

where the derivatives are calculated from the calibration curves of wires 1 and 2. These equations can be interpreted for instantaneous voltages and velocities, or in terms of RMS values
Since K_T^2 $(=0.04)$ is small it can be set equal to zero for calculations of the turbulence levels. Hence

$$u(t) = \frac{V_1(t) + V_2(t)}{2} \quad and \quad v(t) = \frac{V_2(t) - V_1(t)}{2}$$

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This can be written as

$$u'_{RMS} = \frac{1}{2}\,(v'_1 + v'_2)_{RMS} \; and \; v'_{RMS} = \frac{1}{2}\,(v'_2 - v'_1)_{RMS}$$

where $v'_1(t) = V_1(t) - \bar{V}_1$ and $v'_2(t) = V_2(t) - \bar{V}_2$.

Similarly the Reynolds stress component $\overline{-u'v'}$ can be determined as

$$\overline{-u'v'} = -\frac{1}{2}\,\overline{(v'_1 + v'_2)\,(v'_2 - v'_1)}$$

Once the signals $v_1(t)$ and $v_2(t)$ are available over an identical time interval, quantities such as $(\quad)_{RMS}$ can be determined by numerical integration.

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The calculation of turbulence quantities can be greatly simplified if the two wires are identical and have the same overheat ratio. Then the wire sensitivities are also nearly equal; let K be the representative value of the wire sensitivities and defined as

$$K = \frac{1}{2}\left[\left.\frac{dV}{dE}\right|_1 + \left.\frac{dV}{dE}\right|_2\right]$$

The turbulence quantities can now be obtained as

$$u'_{RMS} = \frac{1}{2} K \,(e_1 + e_2)_{RMS}$$

$$v'_{RMS} = \frac{1}{2} K \,(e_2 - e_1)_{RMS}$$

$$\overline{-u'v'} = -\ \frac{1}{2}\ K^2\overline{(e_1\ +\ e_2)\ (e_2\ -\ e_1)}$$

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These formulas require that the signals $e_1(t)$ and $e_2(t)$ be simultaneously collected by a computer. In modern instruments it is possible to add and substract instantaneous signals e_1 and e_2. The correlation between two signals must be obtained on special correlation meters. Since true-RMS voltmeters are commonly available, the cross-correlation term can also be determined as

$$\overline{-u'v'} = \frac{1}{2}K^2\overline{(e_1^2 - e_2^2)}$$

$$= \frac{1}{2}K^2\,(e_{1\,RMS}^2 - e_{2\,RMS}^2)$$

provided the two terms on the right hand side are not very close to each other.