Probe Systems for Static Pressure and Cross-Stream Turbulence Intensity

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A recent study of total-pressure probes for use in highly turbulent streams is extended herein by developing probe systems that measure time-averaged static or ambient pressure and turbulence intensity. Arrangements of tubular probes of circular and elliptical cross section are described that measure the pressure at orifices on the sides of the probes to obtain different responses to the cross-stream velocity fluctuations. When the measured data are combined to remove the effect of the presence of the probes on the local pressure, the time-averaged static pressure and the cross-stream components of turbulence intensity can be determined. If a system of total pressure tubes, as described in an accompanying paper, is added to the static pressure group to form a single cluster, redundant measurements are obtained that permit accuracy and consistency checks.

Nomenclature

H = stagnation pressure or total head
$\hat{i},\hat{j},\hat{k}$ = unit vectors in x,y,z directions
p = instantaneous value of static pressure
q = dynamic pressure, $\rho\bar{U}^2/2$
t = time
$\bar{U}$ = time-averaged velocity in stream direction
u = fluctuating part of velocity component in stream direction
V = instantaneous value of local velocity
v = fluctuating part of velocity component in lateral direction
w = fluctuating part of velocity component in vertical direction
x,y,z = distance in streamwise, lateral, and vertical directions, respectively
α = angle of pitch
β = yaw angle
ϵ = fineness ratio of ellipse, = major axis/minor axis
θ = meridian angle
ρ = air density

Subscripts

c = cylinder
circ = probe with circular cross section
e = based on entire instantaneous local velocity
orif = orifice
x = based on x component of velocity
y = ellipse aligned to measure lateral or y component of velocity
z = ellipse aligned to measure vertical or z component of velocity

Introduction

A PROBE shape is introduced in a companion paper[1] that makes it possible to measure directly, in highly turbulent streams, the time-averaged total pressure based on the static pressure and on the streamwise component of the velocity. If the time-averaged stagnation pressure at that locality is also measured with a shrouded probe or one with a conical indentation (so that it is based on the entire velocity vector), the sum of the squares of the cross-stream turbulence intensities may be found by subtracting the values. The stagnation pressure based on the streamwise component of velocity is needed along with the local time-averaged static pressure for the determination of the streamwise momentum, which is an important parameter used in the determination of the thrust of jets and augmentors. This paper presents a description of several probe systems that will theoretically provide the time-averaged static pressure in highly turbulent streams.

Prior to beginning the development of pressure probes that would perform satisfactorily in highly turbulent stream, a survey of the literature was made to find out what kinds of instruments were available for the measurement of pressure. It was found that turbulence can have a strong effect on measured static pressure and that, although a variety of devices was presented,[2-28] a satisfactory method was not available.

The works of Pitot, Prandtl and Tietjens,[2] Goldstein,[3] and Fage[4] have already been discussed in the companion paper.[1] In order to illustrate the kinds of static pressure probes presented in the literature, several are shown in Fig. 1. The uppermost probe, attributed to Prandtl and Tietjens,[2] measures the static pressure at the orifices in the side of the tube that makes it sensitive to crossflow. The remaining designs illustrated in Fig. 1 represent attempts to find shapes that were insensitive to flow angularity. The wedge-[5] and disk-shaped[2,11] probes are both based on the idea that they approximate a portion of a wall wherein the velocity component parallel to the wall does not cause a serious problem. Unfortunately, the lift distribution on these wing-like shapes varies considerably with the crossflow component perpendicular to the flat surfaces of the probe. On occasion, it is found that pressures are even affected by the mounting sting or tube because it modifies the Kutta condition on the circular plate. For these reasons, the errors at the orifices on the two flat surfaces of the probe do not usually compensate one another for even small angles of incidence. The use of a slender cone[22] with orifices on the conical surface spaced at several meridian angles assumes that flow angularity affects the pressures sensed on opposite sides of the cone in a way that provides automatic compensation. Flow across the circular cross section of the probe does, however, generate low pressures on both sides of the tube that are not compensatory. The rounded-square and the rounded-diamond probes that were designed by Smith and Bauer[18] are based on a sophisticated design technique that produced static probe shapes that perform satisfactorily up to angles of incidence of about 10 deg. The slotted sphere[27] is also a refined

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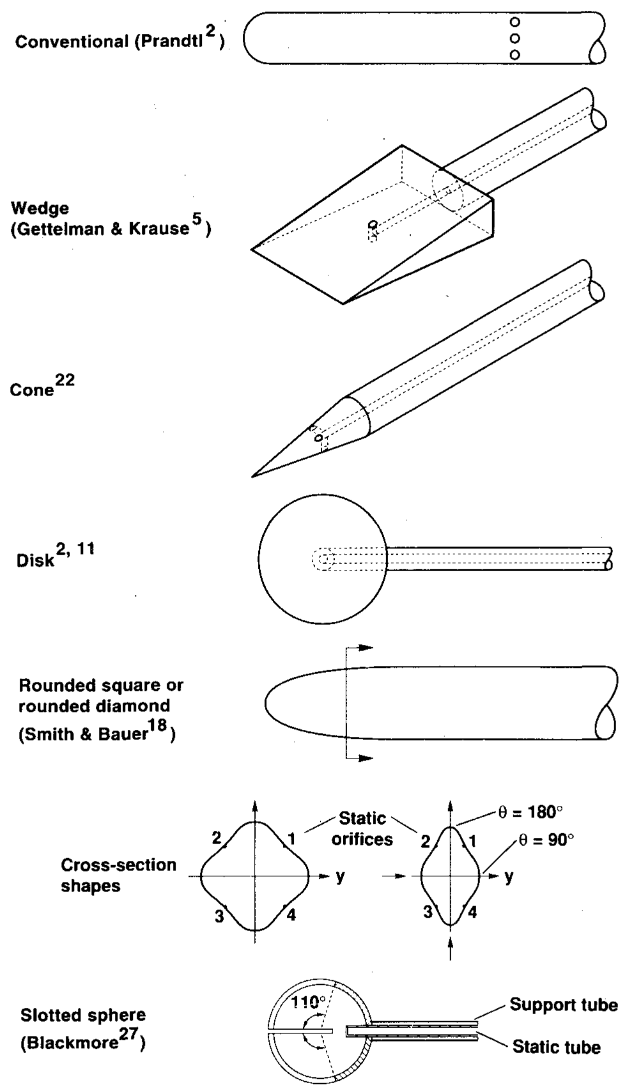

Fig. 1 Probe shapes used to measure static pressure.

effort that yields a static probe effective to flow angles around 20 deg. Unfortunately, the probes are not easy to construct. Furthermore, highly turbulent flowfields require a wider range of incidence angles if the interpretation of the probe measurements is to be unrestricted and uncomplicated.

It was the research of Becker and Brown[20] that prompted the development of a new probe shape[1] for the measurement of total head based on the streamwise component of the velocity. Their investigation provides a good example wherein measurements by a probe or probes were accepted and then interpreted by means of an analysis. Somewhat later, Cho and Becker[25] applied the same type of analysis as used by Becker and Brown[20] for the determination of time-averaged static pressure in a turbulent stream. In that study, the pressure measurement at a single pressure orifice on the side of a round tube is used to determine the time-averaged static pressure. Their methods do require assumptions as to the structure of the turbulence and as to its interaction with the probes used in the measurements.

The technique utilized in the present investigation employs several tubular probes of different cross section to amplify and separate out the various dynamic pressure components of highly turbulent streams. In the configurations presented here, two of the probes have elliptical cross sections to enhance the dynamic pressure associated with the two components of the cross-stream velocity fluctuations. Tubular probes of circular cross section are used to supplement these measurements to obtain enough information to solve for the time-averaged static pressure. In this way, combinations of the various probes can be assembled to produce the probe clusters, which provide an evaluation of the time-averaged static pressure and of the cross-stream components of the turbulence intensity. The present study is limited to subsonic flow wherein the effects of compressibility and viscosity are negligible.

Effect of Probe Design on Measured Pressure

Equations that describe the changes in pressure to be expected at orifices in the sides of probes of several different shapes will now be set up. The turbulent stream in which a measurement is to be made is assumed to have, at least locally, a direction that is, on the average, aligned with the x axis and whose time-averaged magnitude is given by

$$\bar{U} = \frac{1}{\Delta t} \int_0^{\Delta t} V \, \mathrm{d}t \tag{1}$$

where Δt is assumed to be a time interval sufficiently long that the magnitude of the averaged quantity does not change if Δt is increased, and V is the instantaneous velocity of the stream at the point in question. The components of the instantaneous values of the fluctuations of the velocity about this value due to the turbulence in the stream are labeled u, v, and w, which are taken to be aligned with the x, y, and z axes, respectively. If the velocity fluctuations vanish, the total head is given by the sum of the static pressure p and the dynamic pressure $(\rho/2)\bar{U}^2$ for the total head H, as given by Bernoulli's equation for incompressible flow $H = p + (\rho/2)\bar{U}^2$.

When the flowfield is turbulent, it is necessary to keep track of the various parts of the stream characteristics. For this purpose, a system of notation is used[1] to define and relate the various pressure magnitudes. The instantaneous total or entire stagnation pressure H_e is based on the local instantaneous static pressure p and the entire instantaneous local velocity V as given by

$$H_e = p + \frac{\rho}{2} V^2 = p + \frac{\rho}{2} [(\bar{U} + u)^2 + v^2 + w^2] \tag{2}$$

Similarly, the instantaneous value for the total head based on static pressure and the streamwise or x component of the velocity is given by

$$H_x = p + \frac{\rho}{2} (\bar{U} + u)^2 \tag{3}$$

The difference between the two time-averaged pressures expressed by Eqs. (2) and (3) eliminates the static pressure and the x component of velocity to yield[1]

$$(\bar{H}_e - \bar{H}_x)/q = (\overline{v^2} + \overline{w^2})/\bar{U}^2 \tag{4}$$

where $q = \rho\bar{U}^2/2$. That is, by use of the specially shaped probes described in Ref. 1, the difference between the time average of the two total head quantities in Eq. (4) yields the sum of the square of the two cross-stream turbulence intensities.

Similar arguments are now used to develop the relationships needed for a probe system that will provide enough information to obtain a reliable measurement of the time-averaged static pressure $\bar{p}$. The first step taken is to derive a theoretical expression for the response to flow incidence of a standard Prandtl pitot-static probe. Since the probe has a circular cross section and since the static pressure orifices are quite far from the nose of the probe (at least 5 diameters), the crossflow is approximated by two-dimensional time-dependent considerations. Consider first an estimate made of the effect of the presence of a tubular probe on the pressure by assuming that the flow over the cylinder is steady. Based on potential flow theory,[29] the static pressure on the cylinder is given by

$$H_e = p + \frac{\rho}{2} V^2 = p + \frac{\rho}{2} [(\bar{U} + u)^2 + (v^2 + w^2)(4 \sin^2\theta)] \tag{5}$$

The term containing ($4 \sin^2\theta$) adjusts the magnitude of the cross-stream velocity (and thereby the pressure) for the influence of the probe on the pressure at each of the orifices located at the meridian angle θ. The meridian angle θ is taken to be zero in the plane that contains the windward stagnation point. The difference between the local static pressure p and the pressure at a given orifice p_{orif} is found by substracting Eqs. (2) and (5). If the probe being used to measure the static pressure has a very large number of static orifices (so that the pressure is essentially monitored on a continuous basis with meridian angle), the average deviation of the measure static pressure from the actual value is found by integration with respect to θ around the probe to yield

$$(p_{\text{orif}} - p) = -\frac{\rho}{2}(v^2 + w^2) \tag{6}$$

The integration over θ is made before the time-averaging process because it is assumed in the present simple approach that the pressures at the orifices are in equilibrium at each instant of time. When the time average is taken and Eq. (4) is used, three measured pressures are related to the time-averaged static pressure by

$$\frac{(\bar{p}_{\text{orif}} - \bar{p})}{q} = -\frac{(\bar{v}^2 + \bar{w}^2)}{\bar{U}^2} = \frac{(\bar{H}_e - \bar{H}_x)}{q} \tag{7}$$

Interestingly, the same expression applies to probes that have four static orifices spaced at 90-deg intervals around the tube being used as the static probe regardless of the meridian angle of the oncoming crossflow direction. Hence, 4, 8, or 12 orifices equally spaced around the probe all yield the same result as given by Eq. (7).

It is desirable that measurements be made of the static pressure by different means so that redundant values can be obtained. One way to obtain more measurements in the turbulent stream is to design the probe so that it emphasizes a component of the crossflow. As mentioned previously, the approach used here introduces tubes of different cross sections to emphasize by a predictable amount the crossflow dynamic pressures in order to make them easier to measure. Hence, one element of an alternate probe system consists of a tube of elliptical cross section that has its major axis perpendicular to the y axis. That probe then amplifies the pressure variations due to velocity fluctuations in the y direction. Similarly, a tube

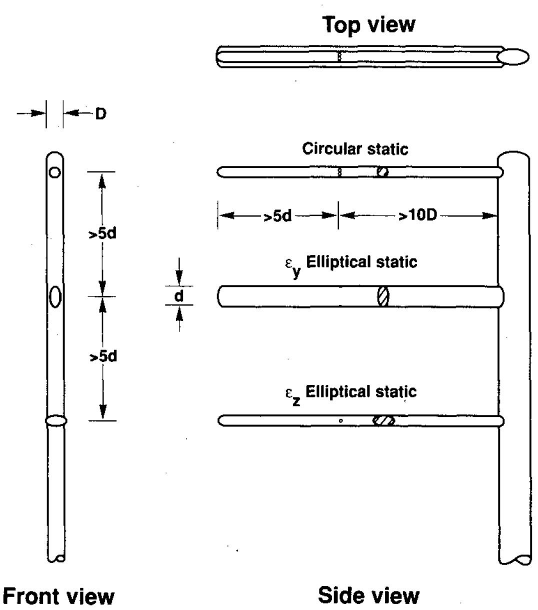

Fig. 2 Probe system for determining static pressure composed of two tubes of elliptical and one of circular cross section arranged to emphasize the cross components of turbulence.

of elliptical cross section placed so that it has its major axis perpendicular to the z axis emphasizes pressure variations due to velocity fluctuations in the z direction (see Fig. 2). In order that each elliptically shaped probe does in fact emphasize or amplify its particular component of the crossflow, static pressure orifices are located only at the two extremities of the major axis at about 5 major axis lengths from the nose of the probe. Since the amount of amplification is governed by the fineness or axis ratio (major/minor axis), it should probably be over 2 and not much larger than 4. Figures in this range will provide ample enhancement but will not be so large that extensive flow separation occurs on the leeward side of the probe. Orifices located elsewhere, such as at the ends of the minor axis, provide a pressure signature that amplifies the pressure fluctuations by only a small amount.

Based on steady inviscid flow around a tube of elliptical cross section, the pressure p_y at orifices located on the two extremities of the elliptic tube used to measure fluctuations in the velocity along the y axis is related to the instantaneous velocity at those orifices by Bernoulli's equation. Subtraction of Bernoulli's equation for the flow in the absence of the probe yields an expression for the pressure at the orifices located at the ends of the major axis as

$$(p_y - p) = \frac{\rho}{2}[V^2 - (\bar{U} + u)^2 - v^2(1 + \epsilon_y)^2]$$

where p is the instantaneous local static pressure. After combination of terms and time averaging, the foregoing equation may be written as

$$\frac{(\bar{p}_y - \bar{p})}{q} = \frac{(\bar{v}^2 + \bar{w}^2)}{\bar{U}^2} - \frac{\bar{v}^2}{\bar{U}^2}(1 + \epsilon_y)^2 \tag{8}$$

where ϵ_y is the axis ratio of the elliptical tube used to measure the y component of the turbulence. In this case, the major axis of the ellipse is assumed to be aligned with the vertical or z axis in order to emphasize the lateral component of the fluctuating velocity.

Similarly, the w component of turbulence is emphasized in a pressure measurement made by use of a tube of elliptical cross section, which has its major axis oriented in the horizontal plane along the y axis. The corresponding time-averaged static pressure at the orifices located at the two extremities of the major axis is given by

$$\frac{(\bar{p}_z - \bar{p})}{q} = \frac{(\bar{v}^2 + \bar{w}^2)}{\bar{U}^2} - \frac{\bar{w}^2}{\bar{U}^2}(1 + \epsilon_z)^2 \tag{9}$$

where ϵ_z is the fineness ratio of the elliptical tube with its major axis perpendicular to the z axis. It is noted that the pressures at the orifices on the major axis of the two elliptic tubes are enhanced by the square of the product of the cross-stream velocity component and the ellipticity of the tube.

Before leaving this section, it should be pointed out that Eqs. (8) and (9) also apply to a probe setup wherein the elliptic tubes have their minor axes perpendicular to the velocity components being considered. If such an arrangement of probes is used, the pressure sensed at orifices located on the extremities of the minor axis is only slightly perturbed by the ellipsoidal shape; i.e., $\epsilon < 1$. The primary contribution to the pressure at the orifices is then given approximately by the impact pressure of the other transverse component of velocity fluctuations; set ϵ_y and ϵ_z equal to zero in Eqs. (8) and (9). Although such an arrangement presents another way for making measurements for the determination of the time-averaged static pressure, location of the orifices on the ends of the major axis is to be preferred because that configuration enhances the pressure fluctuations so that they become more significant and, therefore, easier to measure. Also, pressure orifices located at the downwind or leeward ends of the minor axis are much more likely to be influenced appreciably by flow separation effects than orifices located at the ends of the major axis.

Arrangements of Probes for Determining Static Pressure

By use of equations derived in the previous section, several probe systems are now described that gather enough information to determine the time-averaged static pressure in a turbulent stream. Some simpler probe groups could also be assembled but they would not provide enough information to solve for all of the flowfield characteristics needed in the determination. In the various arrangements to be discussed, it is assumed that the turbulence in the flowfield is homogenous over a region large enough to envelop the probe system and that the gradients are small enough that the flowfield characteristics do not change appreciably across the largest distance between probes. If such is the case, each probe in a given system encounters (when averaged over time) an equivalent flowfield even though the individual probes may be experiencing a different eddy at a given instant of time. It is also assumed that the flow around one probe does not measurably affect the flowfield in the vicinity of the orifices of any other probe in the system. If the stream is repeatable over a sufficiently long period of time, the probes could also be traversed individually along the same path through the stream at different times to obtain the needed data. Hence, variations in pressure at the orifices of the various probes may not be synchronized because their spacing is larger than some of the eddy sizes (or they were in the same part of the flowfield at a different time), but the time-averaged pressures each yield a representative value for the local flowfield. When the elements in the flowfield associated with the velocity fluctuations, or the eddies, are smaller than a probe diameter, the pressure signals impressed at the various orifices will respond in a way that is not represented by the equations presented here. Nevertheless, the tubular probes will pick up the pressure variations of the eddies that are on the order of the probe diameter or larger, which usually includes the most energetic part of the turbulence. When the data are used for engineering purposes or for comparison with other data, the foregoing shortcomings should be kept in mind.

Insertion into a turbulent stream of a single tubular probe of circular or elliptical cross section yields information on the static pressure at that location. However, the fluctuating crossflow over the probe due to turbulence reduces the pressure at the orifices by an amount that depends on the cross-sectional shape of the probe and on the magnitude of the crossflow velocity [Eqs. (7–9)]. Since the characteristics of the crossflow velocity fluctuations are not known, additional information is needed to find the time-averaged static pressure. As mentioned previously, the method proposed here for obtaining the needed information is to insert additional probes into the flowfield in the vicinity of the point of interest until enough information is available to solve for the flowfield characteristics. The quantities in Eqs. (7–9) that are to be measured so that the time-averaged static pressure can be determined is used as a basis for placing the various probe shapes into a given cluster.

The first probe system that produces enough information to determine the time-averaged static pressure consists of an assembly of one circular and two elliptical tubes aligned with the time-averaged stream direction (Fig. 2). The pressure orifices in all three probes are assumed to be located in the sides of the tubes at the same streamwise station and at the same distance from the nose of each probe. As described in the previous section, one of the tubes of elliptical cross section has its major axis perpendicular to the y axis and the other to the z axis. Pressure measurements at the orifices in the sides of the probes then relate to the cross-stream turbulence components and to the time-averaged static pressure by Eqs. (7–9). When Eqs. (7–9) are combined to eliminate the cross-stream turbulence intensities, an equation for the time-averaged static pressure in terms of measured quantities is found as

$$\frac{\bar{p}}{q}=\left[\frac{\bar{p}_{\text{orif}}}{q}\left(1-\frac{1}{(1+\epsilon_y)^2}-\frac{1}{(1+\epsilon_z)^2}\right)-\frac{\bar{p}_y}{q(1+\epsilon_y)^2}-\frac{\bar{p}_z}{q(1+\epsilon_z)^2}\right]\bigg/\left[\left(1-\frac{2}{(1+\epsilon_y)^2}-\frac{2}{(1+\epsilon_z)^2}\right)\right] \tag{10a}$$

When the same size of elliptical tubing is used for the two probes, which will usually be the case, $\epsilon_y=\epsilon_z=\epsilon$, Eq. (10a) can be simplified and rewritten as

$$\frac{\bar{p}}{q}=\{\bar{p}_y+\bar{p}_z+\bar{p}_{\text{orif}}[2-(1+\epsilon)^2]\}/\{q[4-(1+\epsilon)^2]\} \tag{10b}$$

Although not indicated in Eqs. (10a) and 10b), the pressures will usually be measured relative to a reference pressure. It should also be noted that the static pressure becomes singular when the fineness ratio of the elliptical tubes approaches 1. This simply calls attention to the fact that all of the time-averaged static pressure measurements become equal if the ellipticity of the probes vanishes so that all three tubes are of circular cross section.

Once the time-averaged static pressure is known, the separate values for the cross-stream turbulence can be found from Eqs. (7) and (8) as

$$\frac{\bar{v}^2}{\bar{U}^2}=\frac{2\bar{p}-\bar{p}_{\text{orif}}-\bar{p}_y}{q(1+\epsilon_y)^2} \tag{11}$$

Similarly, the expression for turbulence intensity in the z direction is given by

$$\frac{\bar{w}^2}{\bar{U}^2}=\frac{2\bar{p}-\bar{p}_{\text{orif}}-\bar{p}_z}{q(1+\epsilon_z)^2} \tag{12}$$

A method by which the other component of turbulence intensity $\bar{u}^2/\bar{U}^2$ could be measured was not found because $\bar{U}$ and $\bar{u}$ appear to be intimately coupled in any pressure measurement. However, if the fluid mechanisms generating the turbulence are not specifically oriented toward certain components $\bar{u}^2/\bar{U}^2$ could be assumed to be equal to $\bar{v}^2/\bar{U}^2$ or $\bar{w}^2/\bar{U}^2$ or to an average of the two.

Figure 2 presents an arrangement wherein the circular tube is on top of two tubes of elliptical cross section. In fact, the circular tube could have been placed in the center or on the bottom of the arrangement. It seems that any disposition is

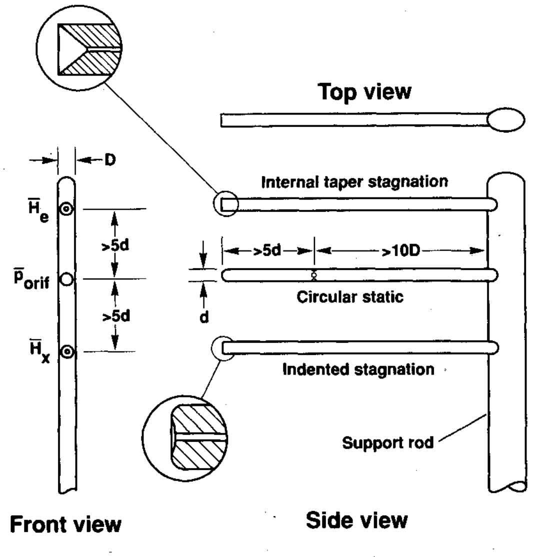

Fig. 3 Probe system for determining static pressure composed of one tube of circular cross section and two stagnation probes for the time-averaged static pressure and the sum of the squares of the cross-stream components of turbulence.

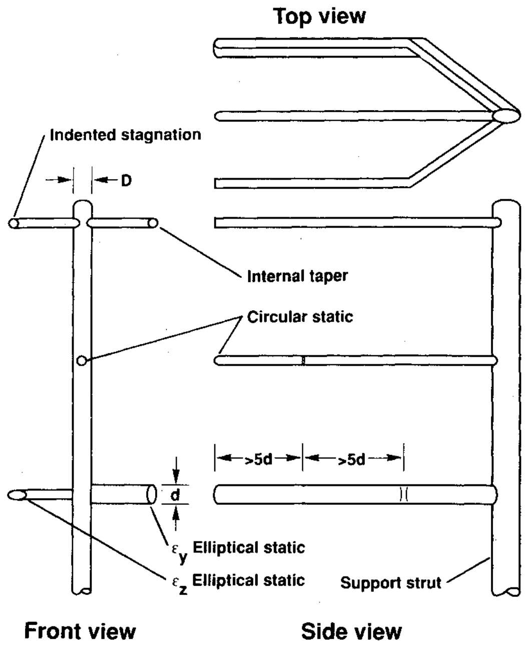

Fig. 4 Probe system for determining static pressure composed of two tubes of elliptical, one of circular cross section, and two stagnation probes assembled to provide redundant values for the time-averaged static pressure and the cross-stream components of turbulence.

acceptable as long as the wakes of the various probes do not pass over a tube near its orifice locations.

Since the foregoing relationships are quite idealized, it seems prudent to determine the static pressure by several techniques to find out how well they agree. In order to accomplish a redundant measurement for the static pressure, a second probe configuration is formed by combining the total head probes described in Ref. 1 [see Eq. (4)] with a static pressure probe of circular cross section (Fig. 3). Such a three-probe configuration provides a measurement of $\bar{p}_{\text{orif}}$, $\bar{H}_e$, and $\bar{H}_x$ so that a determination can be made of $\bar{p}$ by means of Eq. (7) as

$$\frac{\bar{p}}{q} = \frac{\bar{p}_{\text{orif}} + \bar{H}_e - \bar{H}_x}{q} \tag{13}$$

A third arrangement of probes can be assembled by combining the configurations in Figs. 2 and 3 so that a complete set of the measurements being discussed here is obtained. The probe system so constructed consists of the two stagnation probes of Ref. 1, a static probe of circular cross section, and two static probes of elliptical cross section (Fig. 4). The time-averaged pressures measured at the various orifices can then be used in Eqs. (10–13) to determine redundant values for the time-averaged static pressure and the cross-stream turbulence components. As a bonus, the two time-averaged stagnation pressures would also be available. The bulk of the five-probe system and its sensors is a disadvantage but the redundant feature of the system is believed to more than outweigh this handicap. Although the configuration shown in Fig. 4 uses a rectangular system, other arrangements, such as linear or circular, for the various probes are also permissible as long as the flowfields of the various probes do not interfere with one another and they cluster near the point where a measurement is desired. As an alternative, if test time is available, the probes may be traversed through the stream separately to obtain the data along the same path and the results then combined.

The foregoing analysis is based on rather idealized flowfield approximations. Discussions are presented in textbooks such as Schlichting[17] and Lamb[29] on the effect of both inviscid and viscous flow over oscillating cylinders. These results indicate that the time-averaged inviscid values are not affected greatly by the oscillations themselves. However, it may be that viscosity would bring about flow separation on the leeward side of the probes that may cause the foregoing equations to become less accurate for the larger eddy sizes even when time averages are taken.

Design Aspects of Probe Systems for Static Pressure

Good probe design dictates that several guidelines be followed to ensure that the tubular probes provide the measurements desired. First, the probes should have their axes or centerlines aligned with the time-averaged direction of the oncoming stream. If they are not, the measured pressures will have a steady-state component induced by the steady cross-flow velocity. The probes should also be long enough that the static pressure orifices in the sides of the tubes are located at least 5 diameters (or major axis lengths) from the nose of the probe and at least 10 rod diameters from the rod that supports the entire probe system. In addition, the probes should be spaced around the point where measurements are desired at 5 or more diameters apart so that the pressure field of one probe does not produce a measurable pressure change at any other probe in the system. The probe and support rod surfaces should be smoothly streamlined so that flow separation or other flow disturbances are not produced as the stream flows over the nose, cylindrical afterbody, and support rod of the tubular probe system. The orifices in the sides of the tubes should have smooth openings into the duct that passes through the length of the probe to pressure sensing elements that yield quantitative values for the pressure. The orifice diameter should not be more than about 10% of the minor dimension of the probe in order to avoid pressure influences from the other parts of the probe shape. As mentioned previously, the axis ratio of the elliptical tubes should be at least 2 and probably not much over 4 to ensure that enough velocity enhancement occurs and yet that excessive flow separation on the downwind side of the tube does not occur.

Since the foregoing relationships for the pressure at the orifices in the differently shaped tubes were derived by assuming inviscid flow, deviations from the ideal flow may be encountered in a test situation. In an effort to explore how deviations from the ideal will affect the measured quantities, three solutions presented in the literature[17,29] for the flowfield about circular cylinders were examined in an effort to estimate, at least in part, the time-dependent and viscous changes in performance that might affect the measured quantities. It is concluded that, although instantaneous deviations in pressure will certainly occur, the time average of the pressures at the various orifices eliminates the viscous contributions to pressure. From these results, it is also noted that, since the pressure field around a probe responds rapidly to changes in the oncoming velocity, the probe measurements probably include the contributions of eddy sizes as small as 1 probe diameter.

Concluding Remarks

Probe systems that have the capability to measure the static pressure and cross-stream turbulence intensities in highly turbulent streams have been described. The designs are based on idealized equations for the flow around the probes. The probe systems provide a means for determining the total and static pressures in a highly turbulent stream that uses only pressure measuring devices. As such, the installation is simple, inexpensive, and easy to operate. It should be kept in mind that the results measured with the foregoing probe systems provide gross measurements and should not be used as high fidelity instruments for diagnosing details of the stream. They do satisfy the objectives of the study by providing information needed for engineering estimates for the time-averaged static pressure, the streamwise velocity, and momentum balances for thrust.

Several tube cross-sectional shapes and tube arrangements have been considered in this paper. These are not the only ones that can provide reliable pressure measurements in unsteady or turbulent streams. The elliptical shapes were chosen in order to emphasize a particular component of the fluctuating flowfield and because a simple relationship exists for the velocity field over elliptic cylinders. All of the configurations considered require that the probe axes are aligned with the time-averaged stream direction. Any misalignment will be interpreted by the probes as a velocity fluctuation along that coordinate axis. Each assembly should be designed to minimize both mutual probe interference and physical probe size.

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