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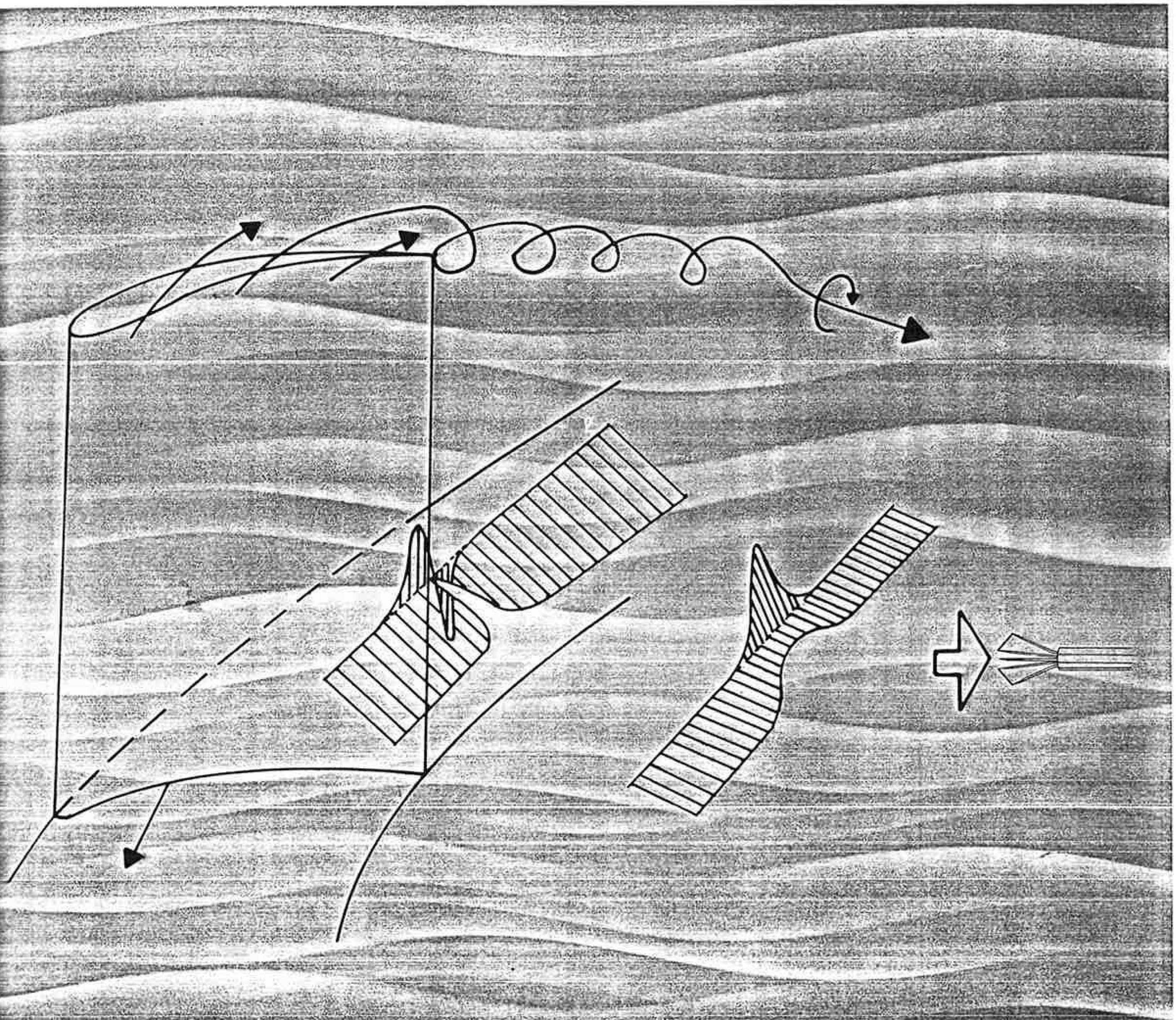

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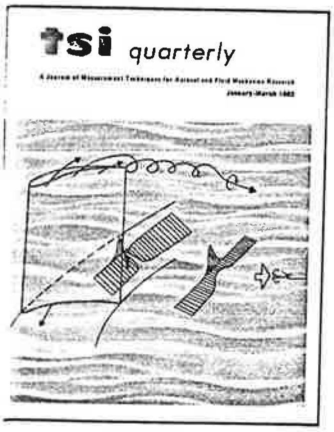

About the cover . . .

Artist's rendition of the wake behind a turbomachinery blade, and the three-sensor, hot-wire probe used to measure such turbulent flow fields. The paper in this issue discusses the measurement of three dimensional flow field using a three-sensor, hot-wire probe.

All the mean velocity components, turbulent stresses and intensities are derived from a single measurement using a three-sensor, hot-wire probe and ensemble-averaging technique. Extensive use of this technique by various investigators at The Pennsylvania State University is reported in references 29, 31, 34, 35, and 36. A review of both of these techniques is given in reference 16. Bennett[37, 38] employed the latter technique to measure wake from a turbomachinery rotor and propeller fan. All the Penn State investigators utilized a digital data processing technique.

Gaulier[39], Zimmerman and Abbott[40], and Moffatt et al.[41] have reported additional measurements using the three-sensor, hot-wire probe. The last two investigators utilized a custom built analog computer to solve the hot wire equations. Improvements in calibration and data processing procedures have recently been reported by Fabris[42], Davino[31], Gourdon et al.[43], Huffman[44], Acrivlellis[45], and Butler et al.[46]. The probe and the technique employed by Fabris[42] is capable of measuring the temperature as well as the three dimensional mean flow and turbulent quantities.

THREE SENSOR HOT WIRE PROBE

Typical three-sensor, hot-wire probe configurations employed by various investigators are shown in Figure 1. Some of these probes are commercially available from TSI and DISA. The probes (a) and (b) are commercially available. The probes (c), (e), and (f) were custom built by commercial companies and utilized in references 20, 23, and 33, respectively. The probe (d) was custom built by Fabris[42]. The probe (c) is a subminiature version suitable for measurements in thin boundary layers or in situations where the interference effects have to be small. The error due to spatial resolution is small. The wire diameter is 3 μm and the length to diameter ratio of this was equal to 300. Sensors in probe (c) are nearly perpendicular to each other inside a sphere of 1.3 mm diameter. The probes (a), (b), (c), (d), and (f) have three mutually perpendicular sensors consisting of wire or film. In probes (b), (c), and (f) the hot wires are mounted so that the direction of the flow is inside a cone of 70°. The probes are designed to avoid aerodynamic and thermal interference between wires. Two of the wires in configuration (e) are orthogonal to each other, while the third wire is at 45° to the plane containing wires (1) and (2). This probe was designed by Anand and Lakshminarayana[24] to measure the three dimensional flow field in a turbomachinery rotor passage. Sensors 1 and 2 are in the xy plane (Figure 1) and are orthogonal to each other. These wires sense mainly the axial and tangential components (or the velocity vector in the plane containing xy). Sensor 3 is at 45° to the xy plane. The elliptic cross section of the probe was adopted to avoid the aerodynamic interference during measurements close to the blade surface.

In wire (d)[42], the sensors numbered (1) and (2) are perpendicular to each other (forming a classical "x" wire probe in the x-y plane). Sensor 3 makes an angle of approximately 45° with the x and z axes and Sensor 4 is parallel to the z axis. The last sensor is used to sense temperature. Sensors 1 and 2 are primarily sensitive to velocity components in the x and y directions, and Sensor 3 is primarily sensitive to components in the x and z directions. The length of the (active) sensor was 2 mm and the diameter was 0.625 μm.

All these probes can be employed for the measurement of the three components of velocity, the three components of turbulent stresses, and the three components of Reynolds stresses

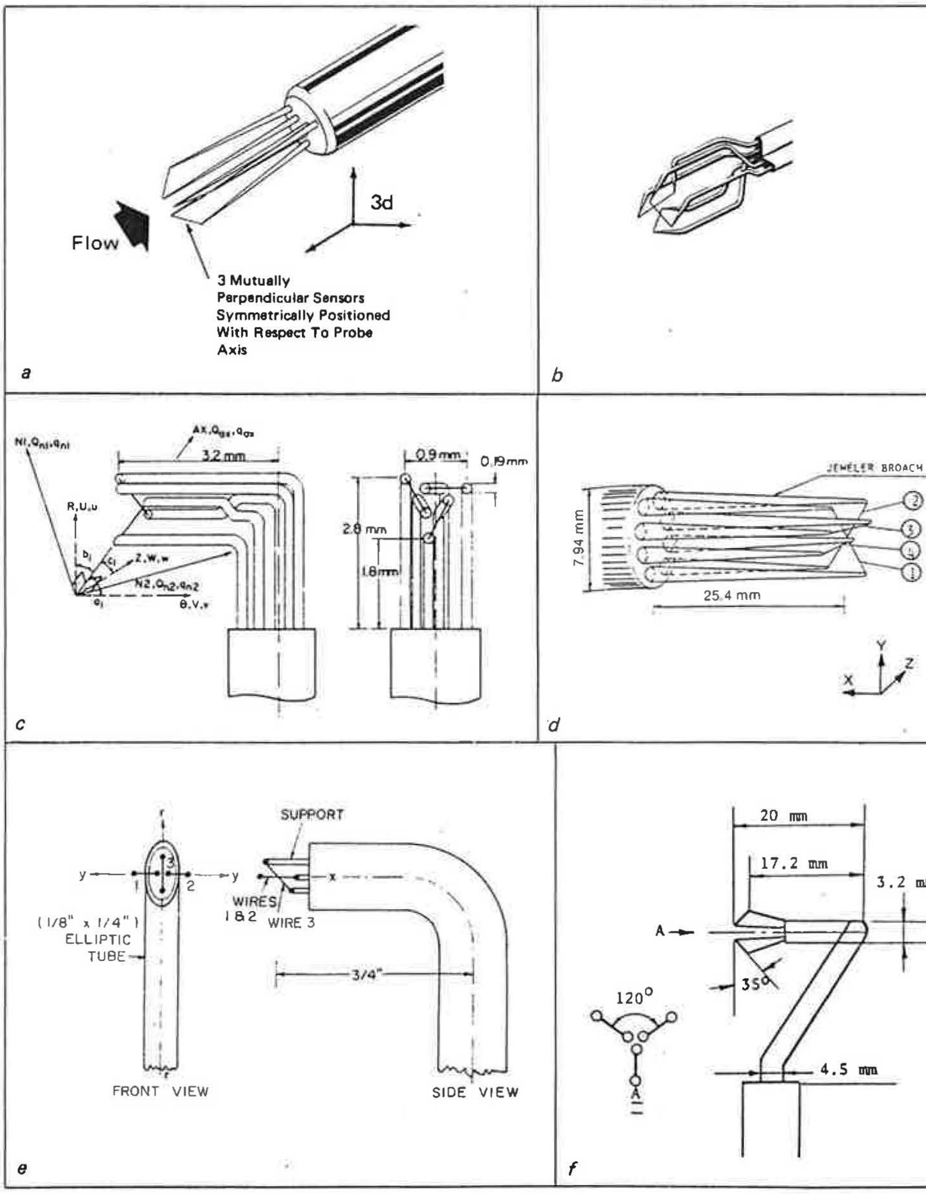

Figure 1. Typical Three-Sensor, Hot-Wire Probes

simultaneously. Probe (d) has the additional capability for the measurement of temperature.

HOT WIRE EQUATIONS

If the wires are orthogonal to each other, as shown in Figure 2, King's Law can be utilized to prove [47, 18] that for each wire

$$E_\ell^2 = A_\ell + B_\ell \; Q_\ell^{\,n_\ell} \qquad (1)$$

$$\frac{Q_\ell^2}{V^2} = \cos^2 \phi_\ell + k^2 \sin^2 \phi_\ell \qquad (2)$$

and

$$V^2 = \frac{Q_1^2 + Q_2^2 + Q_3^2}{2 + k^2} \qquad (3)$$

where ℓ denotes the wire (ℓ = 1, 2, and 3), A_ℓ, B_ℓ, and n_ℓ are calibration constants, Q_ℓ is the effective cooling velocity (instantaneous) sensed by each wire, V is the resultant velocity (instantaneous), ϕ_ℓ is the instantaneous angle between the resultant velocity vector and normal to the sensor (Figure 2). k is a factor that accounts for the deviation from the cosine law, its value can be derived from calibration at different inclinations[48] and is primarily dependent on the length-to-diameter ratio of the wire and the properties of the flow medium. If the flow is compressible, Q_ℓ should be replaced by ρQ_ℓ, where ρ is the fluid density. Q_ℓ can be derived from equation 1, V from equation 3, and ϕ_ℓ from equation 2 (Three equations for ℓ = 1, 2, 3). Knowing V and ϕ_ℓ (ϕ_1, ϕ_2, and ϕ_3), the velocity components can be determined in any chosen coordinate direction, provided the direction cosines between the wire directions and the coordinate directions are known. The direction cosines of the three-sensor, hot-wire probe direction (ℓ = 1, 2, 3) to the orthogonal reference frame should satisfy the equation

$$\sum_{k=1}^{3} a_{k\ell}^2 = 1 \qquad (4)$$

where $a_{k\ell}$ is the direction cosine of wire sensor direction ℓ to the reference coordinate k (x, y, z for the case shown in Figure 2). Techniques available for deriving the mean and turbulence quantities are similar to those for one and two sensor wires. This will be explained with reference to the non-orthogonal wires in the next section.

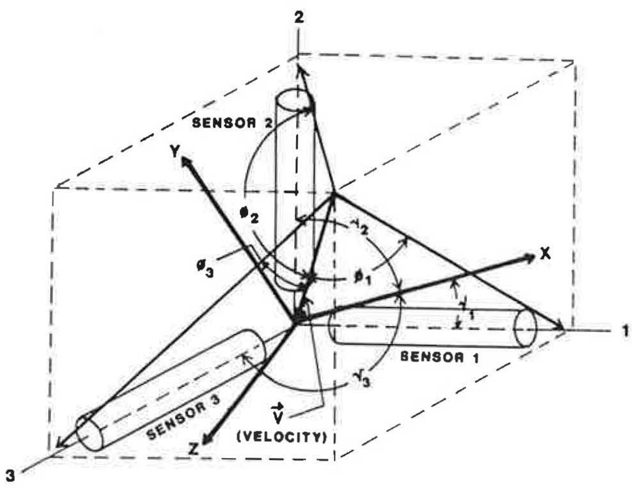

Figure 2a. Three Orthogonal Cylindrical Sensors

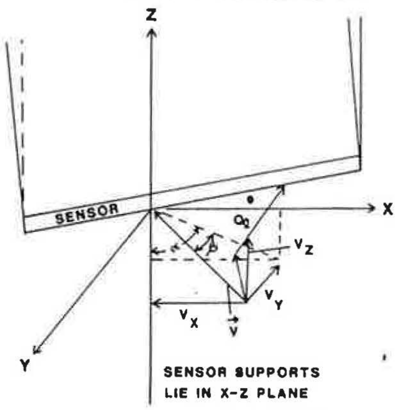

Figure 2b. Single Sensor Angle Definitions.

Figure 2. Geometry and Angle Definitions for Triple Sensor Probe.

If the wires are non-orthogonal, the angle between hot wire sensors can be obtained as follows:

$$\cos\theta_{\ell j} = \sum_{k=1}^{3} a_{\ell k}\, a_{jk} \qquad (5)$$

where $\theta_{\ell j}$ is the angle between sensors ℓ and j. Great care should be exercised in measuring these angles. Gorton and Lakshminarayana[20] measured the hot wire angles with respect to the RθZ coordinate system shown in Figure 1c using a microscope. The values of $a_{\ell k}$ for the probe illustrated in Figure 1c are shown in Table 1.

The relation between the effective cooling velocity (instantaneous) of the hot wire sensors and the velocity components in

		Wire Directions – ℓ		
	a_{ik}	1	2	3
Coordinate Directions (k)	R (1)	-0.62773	0.64357	-0.08108
	θ (2)	-0.46034	-0.51486	-0.64865
	Z (3)	0.62773	0.56634	-0.75676

Table 1. Direction Cosines of Wire Shown in Figure 1c with Respect to R, θ, Z System Shown (Gorton and Lakshminarayana[20])

three hot wire directions is then given by

$$Q_\ell^2 = \sum_{j=1}^{3} (k_\ell^2 \cos^2 \theta_{\ell j} + \sin^2 \theta_{\ell j})\, V_j^2 \qquad (6)$$

where V_j is the instantaneous velocity component in the direction of sensor j. By solving the three components in equation 6, the velocity components in three hot-wire sensor directions can be obtained. The components in the reference orthogonal frame are then given by

$$U_k = \sum_{j=1}^{3} a_{kj} V_j \qquad (7)$$

where U_k is the instantaneous velocity vector in the reference coordinate system. a_{kj} is the direction cosine between the coordinate direction k (k = 1, 2, 3) and the wire direction j (j = 1, 2, 3). These equations were employed in references 33 and 34. There are two methods of processing the data. One method is to carry out an analysis using an averaging procedure to derive expressions for the three components of mean velocity, turbulent stresses and intensities and relate these to the mean voltages and rms value of the fluctuating voltage. The other procedure is to resort to digital processing of the instantaneous data and to carry out a sampling technique to derive these quantities.

EXPRESSIONS FOR MEAN VELOCITY AND TURBULENT STRESSES

Gorton and Lakshminarayana[20, 21] carried out an analysis relating the mean and the RMS values of the fluctuating voltages from the hot wires to three mean velocity components and six stress components in an arbitrary coordinate system. A summary of this technique is given below and in reference 16.

In this analysis, the fluctuating and mean velocities are separated and the equations are simplified neglecting the second-order terms. The following equations (in matrix form) for the mean velocities and turbulence stresses relating them to the corresponding voltages are derived.

$$\{Q_{\ell n}\}_{(3,N)} = \{\alpha_{\ell i}\}_{(3,3)} \times \{U_{in}\}_{(3,N)} + \{\beta_{\ell ij}\}_{(3,3)} \times \left[\frac{U_{in}U_{jn}}{U_{1n}}\right]_{(3,N)} \qquad (8)$$

and equation 1 for this system is (assuming $n_\ell = 0.5$)

$$\{E_{\ell n}^2\}_{(3,N)} = \{E_{0\ell}^2\}_{(3,N)} + \{B_\ell(n)\}_{(3,1)} \times \{\sqrt{Q_{\ell n}}\}_{(3,N)} \qquad (9)$$

where subscripts ℓ, n, and i denote the wire, the observation point, and the velocity component in the reference coordinate system, respectively. U_{1n} is the principal component of mean flow velocity, which in the present coordinate system is in the streamwise direction. $\alpha_{\ell i}$ and $\beta_{\ell ij}$ are functions of direction cosines of the ℓth wire, which includes the correction factor for deviation from the Cosine Law. E_o is the output d c voltage at zero flow velocity. $E_{\ell n}$, $B_\ell(n)$ and $Q_{\ell n}$ are the measured values of voltage, local slope of the hot wire calibration curve, and effective mean cooling velocity, respectively, for the ℓth wire at nth observation point. U_i is the mean velocity component (e.g., U_r, U_θ, U_z). The coordinate system employed is shown in Figure 1c. The numbers in parentheses outside of a matrix represent its dimensions; e.g., $(Q_{\ell n})_{(3,N)}$ is a matrix with three rows and N columns. N is the total number of observation points in a measuring set. Indices i, j, ℓ can take values 1, 2, and 3. For ℓ = 1, α_{11}, α_{12}, α_{13} correspond to Gorton and Lakshminarayana's[20] terms a_5, a_6, a_7, respectively. Similarly, for ℓ = 1, $\beta_{122} = a_8$, $\beta_{133} = a_9$, and $\beta_{123} = a_{10}$, and all other values of $\beta_{\ell ij}$ are zero.

All of the six components of Reynolds stress tensor $(\overline{u_i u_j})$ at any point are obtained from the six measured values of the fluctuating voltage correlations $\overline{e_i e_j}$ and the three mean d-c voltages $\overline{E}_i$ (i, j = 1 to 3). The velocity correlations are related to fluctuating cooling velocities as follows:

$$\{\overline{q_{\ell n}\, q_{mn}}\}_{(6,N)} = \{\gamma_{\ell i}\gamma_{mj}\}_{(6,6)} \times \{\overline{u_{in}u_{jn}}\}_{(6,N)}$$

$$\gamma_{\ell i} = \left(\alpha_{\ell i} + \Gamma_{\ell ij}\frac{U_{in}}{U_{1n}}\right) \qquad (10)$$

where quantity $(\overline{q_{\ell m}\, q_{mn}})$ is the correlation between fluctuating cooling velocities of ℓth and mth wires at the nth observation point and is related to output ac and dc voltages as follows:

$$(\overline{q_{\ell n}\, q_{mn}}) = \frac{16\overline{E}_{\ell n}\,\overline{E}_{mn}}{B_\ell(n)B_m(n)} \qquad (11)$$

$$\sqrt{Q_{\ell n}\, Q_{mn}}\; (\overline{e_{\ell n}\, e_{mn}})$$

The coefficients $\alpha_{\ell i}$ and $\beta_{\ell ij}$ are the same as those occurring in equation 8 for mean effective cooling velocity Q. u is the fluctuating velocity, and u_{1n} is the mean velocity in the principal direction at the measuring point n. The superscript (—) denotes the time-averaged quantity. The coefficients $(\alpha_{\ell ij})$, for ℓ = 1 in Gorton and Lakshminarayana's[20, 21] notation are

$\Gamma_{122} = a_{11}$, $\Gamma_{133} = a_{12}$, $\Gamma_{123} = \Gamma_{132} = a_{13}$ $\Gamma_{222} = b_{11}$, $\Gamma_{233} = b_{12}$, $\Gamma_{223} = \Gamma_{232} = b_{13}$ $\Gamma_{322} = c_{11}$, $\Gamma_{333} = c_{12}$, $\Gamma_{323} = \Gamma_{332} = c_{13}$

Expressions for a_{11}, a_{12}, a_{13}, etc. are given in references 20 and 21. All other Γ values are zero. The quantities $\overline{E_{\ell n}}$, $B_\ell(n)$, and $Q_{\ell n}$, etc., are, respectively, mean dc voltage, slope, and mean effective cooling velocity of the ℓth wire at the nth data point and N is the total number of data points in a measuring set. The matrix equations 8-11 are solved successively using the known values of voltages and calibration data, by using the Newton-Raphson convergency scheme until the convergency criterion given below is reached.

$$\left| U_i^{(p)} - U_i^{(p-1)} \right| \le 0.005\, U_{Ref} \qquad (12)$$

where $U_i^{(p)}$ and $U_i^{(p-1)}$ are values of a mean velocity component U_i at pth and (p-1)th iteration, respectively, and U_{Ref} is some reference velocity.

The velocity components and shear stresses can be derived in any arbitrary coordinate system. A cylindrical coordinate system was used in references 20 and 21 and an intrinsic coordinate system was used in references 23 and 24. The computer program, reproduced in reference 21, incorporates many of the errors discussed later. This program was subsequently modified by Anand and Lakshminarayana[23, 24] and Ravindranath[26]. The latest computer program[26] incorporates corrections due to many of the errors. Among the most important corrections incorporated are:
(1) effect of change in the ambient fluid temperature during the course of the experiment and in calibration, included

at each step and for every data point, (2) spatial error, incorporated by interpolating measurements from adjacent points, (3) error due to deviation from the cosine law, (4) effect of change in slope B in the calibration curve. Local slope is used to alleviate this problem, and (5) in-site calibration was carried out to determine the value of E_0 at $Q = 0$. This value is used in a new calibration curve.

Gaulier[39] has recently suggested a three-term equation of the following type for the hot wire:

$$E^2 = A + BQ^n + CQ \qquad (13)$$

where C is an additional constant. Gaulier has provided hot wire equations assuming different values of k for each wire. This calibration equation can be easily incorporated in equations 8-11. The use of the computer program can be eliminated by designing an analog device to carry out some of the computations as was done by Zimmerman and Abbott[40] and Moffat et al.[41].

Hot wire equations employed by Moffatt et al.[41] are very similar to that of references 20 and 21 with the exception that the former authors allow for different values of k (which can be easily incorporated in equation 8 through the terms $\alpha_{\ell i}$ and $\beta_{\ell ij}$).

The velocity components in any other coordinate system can be derived using equation 7 and carrying out an averaging process (by writing $V_j = \overline{V_j} + v_j$, $U_i = \overline{U_i} + u_i$, etc.) For example, conversion from the hot wire coordinate system (1, 2, 3) to (x, y, z) leads to

$$\overline{u_x^2} = a_{11}^2\,\overline{u_1^2} + a_{12}^2\,\overline{u_2^2} + a_{13}^2\,\overline{u_3^2} + 2a_{11}a_{12}\,\overline{u_1u_2} + 2a_{11}a_{13}\,\overline{u_1u_3} + 2a_{12}a_{13}\,\overline{u_2u_3} \qquad (14)$$

where a_{12} stands for the direction cosine of the angle between wire 2 and the coordinate x (denoted by 1). Similarly, the velocity correlation is given by,

$$\overline{u_xu_y} = a_{11}a_{21}\,\overline{u_1^2} + a_{12}a_{22}\,\overline{u_2^2} + a_{13}a_{23}\,\overline{u_3^2} + (a_{12}a_{21} + a_{11}a_{22})\,\overline{u_2u_1} + (a_{13}a_{21} + a_{11}a_{23})\,\overline{u_3u_1} + (a_{13}a_{22} + a_{12}a_{23})\,\overline{u_2u_3} \qquad (15)$$

Thus, knowing the values of mean velocity components, turbulence intensities, and Reynolds stress components in any given direction (e.g., hot wire sensor directions), the components in any other coordinate directions can be determined from expressions such as equations 14 and 15.

Acrivlellis[15, 45] provided equations without neglecting higher order terms. This is accomplished by assuming $n = 0.5$ and squaring the hot wire response equation (1). The squared outputs (e.g., E_1^2, E_2^2, E_3^2, are utilized to calculate the mean velocity as well as the turbulence components in the flow field.

INSTRUMENTATION AND DATA PROCESSING

A typical instrumentation system used at The Pennsylvania State University for the three dimensional flow measurement in a turbomachinery rotor is shown in Figure 3. A three-sensor, hot-wire probe is used both in a stationary mode[18, 33-36] and in a rotating mode[20-32] to measure the three dimensional flow field inside a turbomachinery rotor (rotating three-sensor, hot-wire probe) and exit of a turbomachinery rotor (both rotating and stationary three-sensor, hot-wire probes). Details of the probe traversing and data transmission system for the rotating hot wire system are given in reference 30. The effect of rotation on hot wire response equations is found to be negligible[31, 49].

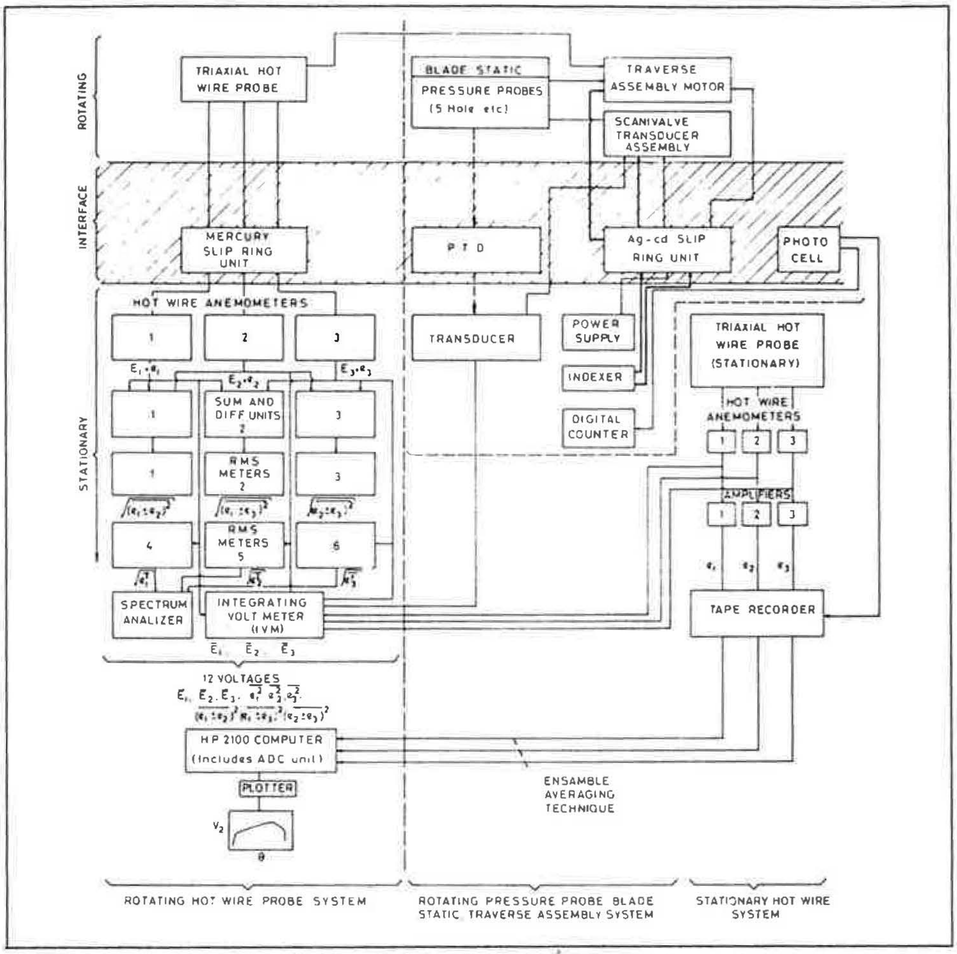

Figure 3. Schematic of Control and Instrumentation System for Rotating and Stationary Three-Sensor Hot-Wire Techniques, and Other Rotating Probes (Ref. 30).

A schematic of the instrumentation and control system used for the control of the probe traversing mechanism as well as scanivalve units, and for processing the signal from rotating and stationary three-sensor hot-wire probes is shown in Figure 3. The hot wire and other probes are traversed by the traversing mechanism, which has a step size of 0.09 degrees. The indexing device controls the forward and backward motion of the probe as well as the step size. The rotating hot-wire signal is processed through a three-channel hot-wire anemometer system, sum and difference circuits, and RMS meters. This will provide three mean voltages (E_1, E_2, E_3) and nine RMS values of fluctuating voltages($\overline{e_i^2}$, $\overline{(e_i \pm e_j)^2}$ —

$(i \neq j)$). These can be processed using the method described earlier, to derive three components of mean velocity and six components of Reynolds stresses (shear stress and normal intensity) in any chosen coordinate direction. The data can be processed through an online HP 2100 S computer and plotter, shown schematically in Figure 3, to derive the mean-velocity profile, etc. The spectrum analyzer is utilized to derive the energy spectrum of each component of turbulent stresses and intensities.

The stationary hot-wire probe technique utilizes an ensemble-averaging technique[17, 18]. This program is built into the HP 2100 S computer, thus enabling simultaneous processing of the data. The hot-wire data are sent through an amplifier and recorded on a magnetic tape. The signals are converted into digital values through the analog-digital conversion unit in the computer before activating the program to do the ensemble average of the signal. The samples are then processed to derive three components of velocity, six components of stresses, length scale, and spectrum using the HP 2100 S computer in the laboratory as explained in the next section.

'he HP 2100 S computer system consists of the main computer (32 K memory size), disk operating system, magnetic tape system, optical data recorder, ADC unit, teletype terminal, low- and high-speed optical terminal, electric printer, and digital plotter. All hot-wire data, from both rotating and stationary probes, can be processed online to derive the desired velocity and turbulence profiles across the passage and the wake.

There are essentially two techniques available for processing the data in a steady three dimensional flow field; digital and analog techniques. In the digital technique, equations 1-3 (orthogonal hot wire system) or 8-11 (non-orthogonal hot wire system) are solved using a digital computer as explained earlier. In the analog technique, employed by Moffatt et al[41] and Zimmerman and Abbott[40], an analog device is used to carry out these computations. These devices are commercially available. Use of a linearizer would greatly simplify the data processing.

DATA PROCESSING IN UNSTEADY (PERIODIC) THREE DIMENSIONAL FLOW

In many situations the flow is three dimensional as well as unsteady, with periodic as well as random components present. A typical example of this is turbomachinery (compressors, turbines, propellers, fans, windmills, helicopter rotor) blade wakes. The flow in these wakes is unsteady in a stationary frame of reference. Either a rotating three-sensor, hot-wire probe (as explained earlier) or a stationary hot wire with an ensemble averaging technique could be used to derive the spatial variation (blade to blade) of three dimensional mean and turbulent flow field. This technique was developed by Lakshminarayana and Poncet[18] and continuously modified by other investigators[29, 33, 34, 35]. A detailed review of these techniques is given in reference 16.

In this technique, the blade-to-blade flow is acquired using an analog signal enhancement[14] or digitized signals[18]. In both cases, a once-per-revolution signal is used to ensure conditional averages (time mean) for the same location relative to a specific blade. A brief discussion of the averaging method is followed by a description of the three sensor hot wire technique. The instantaneous signal from a hot wire can be decomposed into

$$U_i\,(t) = \overline{U}_i\,(t) + u(t) \qquad (16)$$

where $\overline{U}_i(t)$ is the signal obtained by periodically sampling the signal $U_i(t)$ of the ith wire with period $T(= 60/NB$, B = number of blades, N = rpm) and averaging,

$$\overline{U}_i\,(t) = \sum_{n=1}^{N} U_i\,(t + nT) \qquad (17)$$

since the contribution due to $u_i(t)$ as $N \to \infty$ is zero. $\overline{U}_i(t)$ and $u_i(t)$ can be separated by obtaining a reference signal from a photocell or an electromagnetic pulse generator at the blade passing frequency. This pulse can be used as a reference for determining the phase of the signal.

In the investigations carried out at Penn State[33-36, 29], the three-sensor, hot-wire probe was located downstream of a turbomachinery rotor such that the absolute mean velocity direction was inside the cone formed by the sensors. The angle between the probe axis and the rotor axis was noted. The fluctuating signals were amplified and memorized in a tape recorder and the dc voltages integrated in an integrating voltmeter. A one pulse per revolution signal from a photo cell on the rotor shaft was simultaneously recorded in one of the tape recorder channels to enable averaging by the PLEAT (phase locked ensemble averaging technique) method. A schematic of the instrumentation system used for these measurements is shown in Figure 3.

An analog-to-digital converter which was used could convert data in a form whereby each coded word contained a four-bit channel number, a six-bit identification number, a four-bit synchronization nibble, and a ten-bit integer data value. To adjust the digitized data to represent the characteristics of flow across one blade passage, only every (n + B)th wake (n = 0 to N) was saved. The value of N in this investigation varied from 80 to 200. A one spike per revolution signal peak was used to determine every $(n + B)^{th}$ wake. A sample input and output of this phase of data processing is shown in Figure 4.

The digitized electrical data (3 x N x 388 bits) corresponding to instantaneous voltages was converted to corresponding cooling velocities using King's equation (equation 1) with a varying exponent. The values of B_ℓ, n_ℓ, and A_ℓ were obtained from the calibration of each hot-wire sensor. In many instances, the exponent n_ℓ was varied for low, medium, and high fluid velocities. The equations 2, 5, 6, and 7 were used to get the instantaneous velocity from the three-sensor, hot-wire probe, whose three sensors are non-

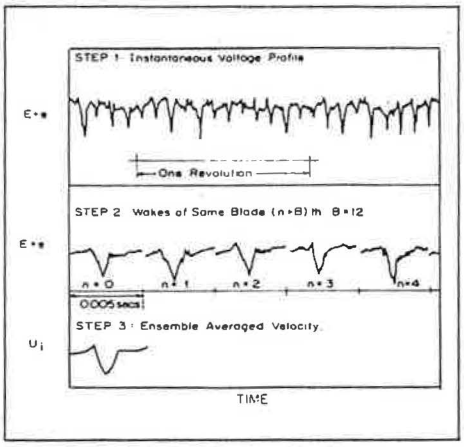

Figure 4. Procedure Involved in Phase-Locked Ensemble-Averaging Technique (PLEAT).

orthogonal. The direction cosines of the three sensor directions (k) to the reference orthogonal coordinates (i) were measured.

The processed data contain instantaneous velocity in three chosen coordinate directions sampled at M number of points (M = 50 in reference 18, 388 in reference 29) across the passage in N (N = 80 in reference 18, 200 in reference 34) number of consecutive signals of period ($2\pi/\Omega B$). Thus, the data belong, physically, to the same passage at different intervals of time. The ensemble average at any passage location $\theta = \theta_m$ is given by

$$\hat{U}_i(\theta_m) = \frac{1}{N} \sum_{n=1}^{N} U_{in}(\theta_m), \quad m = 1 \cdots M, \quad i = 1, 2, 3 \qquad (18)$$

where $U_{in}(\theta_m)$ represents the instantaneous velocity at the passage location θ_m ($m = 1 \cdots M$).

The turbulence intensity is given by

$$\overline{[u_i(\theta_m)]^2} = \sum_{n=1}^{N} \{[U_{in}(\theta_m) - \hat{U}_i(\theta_m)]^2\}/N \qquad (19)$$

and the velocity correlation at θ_m location is given by ($i \neq j$)

$$\overline{u_i u_j} = \sum_{n=1}^{N} [U_{in}(\theta_m) - \hat{U}_i(\theta_m)][U_{jn}(\theta_m) - \hat{U}_j(\theta_m)] / N \qquad (20)$$

where, i, j = 1, 2, 3 represent the coordinates of 1, 2, and 3, respectively.

The ensemble-averaged value ($\hat{U}_i$) approaches the time-averaged value,

$$\bar{U}_i = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} U_i dt \qquad (21)$$

for large values of N. The error involved in finite sampling is given by reference 17.

$$E\left[\frac{(\hat{U} - \bar{U})^2}{\bar{U}^2}\right] = \epsilon = \frac{T}{\sqrt{N}} \qquad (22)$$

where T is the turbulence intensity and E is the expected value. For example, with 10 percent turbulence intensity and N =120, the error in mean velocity is less than 1 percent.

The error in turbulence intensity, assuming the probability density of velocity is Gaussian, given by

$$\epsilon = \sqrt{2/N} \qquad (23)$$

The error associated with the hot-wire sensor and instrumentation is discussed in a later section. Equations 22 and 23 are errors associated with ensemble averaging alone.

Raj and Lakshminarayana[33] utilized a triple-sensor hot-wire and developed a computer program to derive three mean velocity components and six components of Reynolds stresses in an intrinsic (streamwise, principal normal, and radial directions) coordinate system, and reported extensive rotor wake data at several axial and radial stations. Reynolds and Lakshminarayana[29] modified these programs to include arbitrary wire geometry (e.g., non-orthogonal) corrections due to wire aging and temperature changes. They provided rotor wake data at various blade loadings. Hah[34] has adapted these programs to an online computer (Figure 3).

Bennett[37, 38] utilized some of these techniques to measure the flow at the exit of a compressor[37] and a propeller[38]. The data from the latter were acquired using a three-sensor, hot-wire probe at a rotor speed of 10,900 rpm. The data were analyzed using a Saicor correlator and probability analyzer with 2048 samples averaged for each time increment. He found that the k_ℓ factor is not constant, varying with both pitch and yaw angle. Hence, he employed a modified equation for the hot-wire/film equation given by

$$E^2 = A + F(\alpha) \sqrt{U}$$

where $F(\alpha)$ is a function of α, the angle between the total velocity vector (U) and the hot wire. Empirical values of $F(\alpha)$ versus α were used for each of the wires.

CALIBRATION TECHNIQUES

Each of the sensors in a three-sensor, hot-wire probe can be calibrated either individually or collectively. In the individual calibration, each wire is placed normal to a jet from a calibration tunnel and the voltage-velocity relationship is determined from equation 1. This involves evaluation of four constants (A_ℓ, B_ℓ, n_ℓ, k_ℓ) for each of these wires. The calibration data can be either curve fitted by a polynomial or approximated by a straight line in a logarithmic plot to determine these constants. The latter procedure was employed in reference 29. The calibration data can also be stored directly to evaluate these constants locally (at any given velocity) as was done in reference 20. The authors' experience indicates that the "collective" method of calibration is more accurate. In this technique, the three-sensor, hot-wire probe axis is aligned with the jet, and the angle that each of the wires makes with the jet is measured to calculate the direction cosines, a_{ik}. Knowing a_{ik}, the jet velocity can be decomposed into components normal to each wire. Using this information and the corresponding voltage for each wire, a calibration curve can be developed.

A typical calibration curve for the three-sensor, hot-wire probe employed by Reynolds and Lakshminarayana[29] is shown in Figure 5. Note the variation in

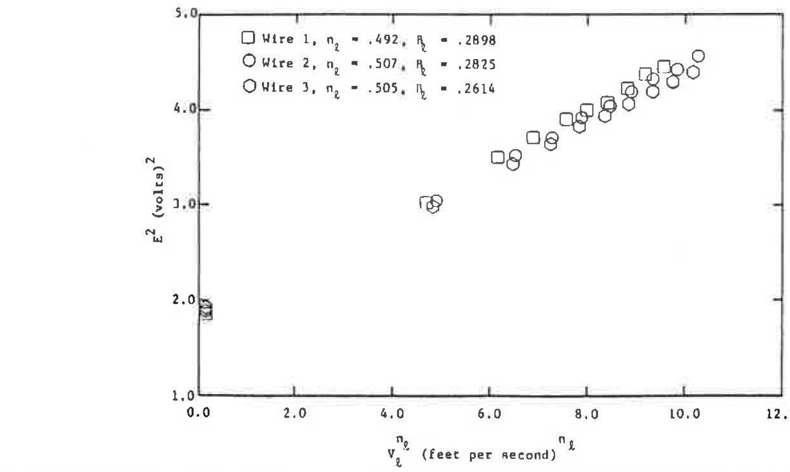

Figure 5. Typical set of calibration curves for three sensor probe.

the exponent n_ℓ and B_ℓ values for each of these wires. Variations in the calibration curve due to wire aging and ambient temperature changes were found by measuring the voltage at zero velocity, E_0, at the beginning and at the end of each experiment.

The three-sensor, hot-wire probe is sensitive to angles of yaw (α) and pitch (β) with reference to the probe axis (see Figure 2). Since the direction of the flow field is unknown in most situations, it is essential to design calibration techniques to evaluate errors due to yaw (α) and pitch angle (β). In any case, the velocity vector should be inside the cone formed by the sensors. A systematic investigation on this effect was carried out by Davino[31] and concluded that the response of a three-sensor, hot-wire probe to a varying incident velocity is different from that of a one-sensor, hot-wire probe. At large yaw and pitch angles, the response is subject to aerodynamic and thermal interference effects caused by the velocity components parallel to the wire and the wakes shed from adjoining sensors. In view of this, it is essential to calibrate the probe for changes in yaw (α) and pitch angles (β), and generate calibration curves (voltage versus velocity) at various values of α and β. The response equations (or curves) which incorporate these effects can then be included in the subsequent data reduction schemes. Details can be found in reference 31.

Fabris[42] concluded from the calibration tests that the widely used cosine law is valid up to $\alpha = \beta = 30^\circ$. Huffman[44] developed an automation calibration procedure which employs two sets of data — one at a variable velocity and fixed angle and a second at a fixed velocity and variable angle — and a numerical search program. This technique is useful in reducing the time involved in the calibration procedure, since for each probe at least 12 calibration constants (A_ℓ, B_ℓ, n_ℓ, k_ℓ) have to be determined at various velocities and pitch and yaw angles.

A recent paper by Butler and Wagner[46] provides a simpler method with improved accuracy over a wider range of flow angles. The probe is calibrated over a range of flow directions and velocity magnitudes and the resulting calibration data is least square fitted to quadratic polynomials, which are similar to hot wire response equations 1 and 2. This procedure is similar to Davino's[31]. The probe used and the response limits of the probe measured by Butler and Wagner are shown in Figure 6. It is evident that at ±30° pitch and yaw angles, the inaccuracy in velocity is about ±5 percent. This conclusion is similar to those of others.

Moffatt et al.[41] conclude from a detailed quantification test that the data from the commercially available unit (Figure 1b) is accurate to within ±3.5 percent as long as the velocity vector is within 30° of the probe axis, in a velocity gradient up to 1600 m/sec/m. Turbulence kinetic energy can be measured within 12 percent for α or β less than 18°. They anticipate miniaturization of the probe (Figure 1c) would improve the angular response characteristics.

ERRORS IN THREE-SENSOR HOT-WIRE MEASUREMENTS

In the case of measurements with a three-sensor hot-wire probe, the following sources of errors may occur: (1) inclination of the wire to the flow streamline (deviation from the Cosine Law), (2) geometry of prongs and probe body (inviscid flow and heat transfer effects), (3) finite distances between wires (spatial resolution of the probe), (4) finite dimensions of individual wires (ℓ/d, end effect, spatial resolution, etc.), (5) temporal resolution or thermal inertia of the wires, (6) aging, oxidation and contamination of the wires, (7) ambient temperature drift, (8) proximity of wire to the wall, (9) probe body vibration due to rotation and flow-induced excitation, (10) spurious signals from the power line (60 Hz) and blade-passing frequency,

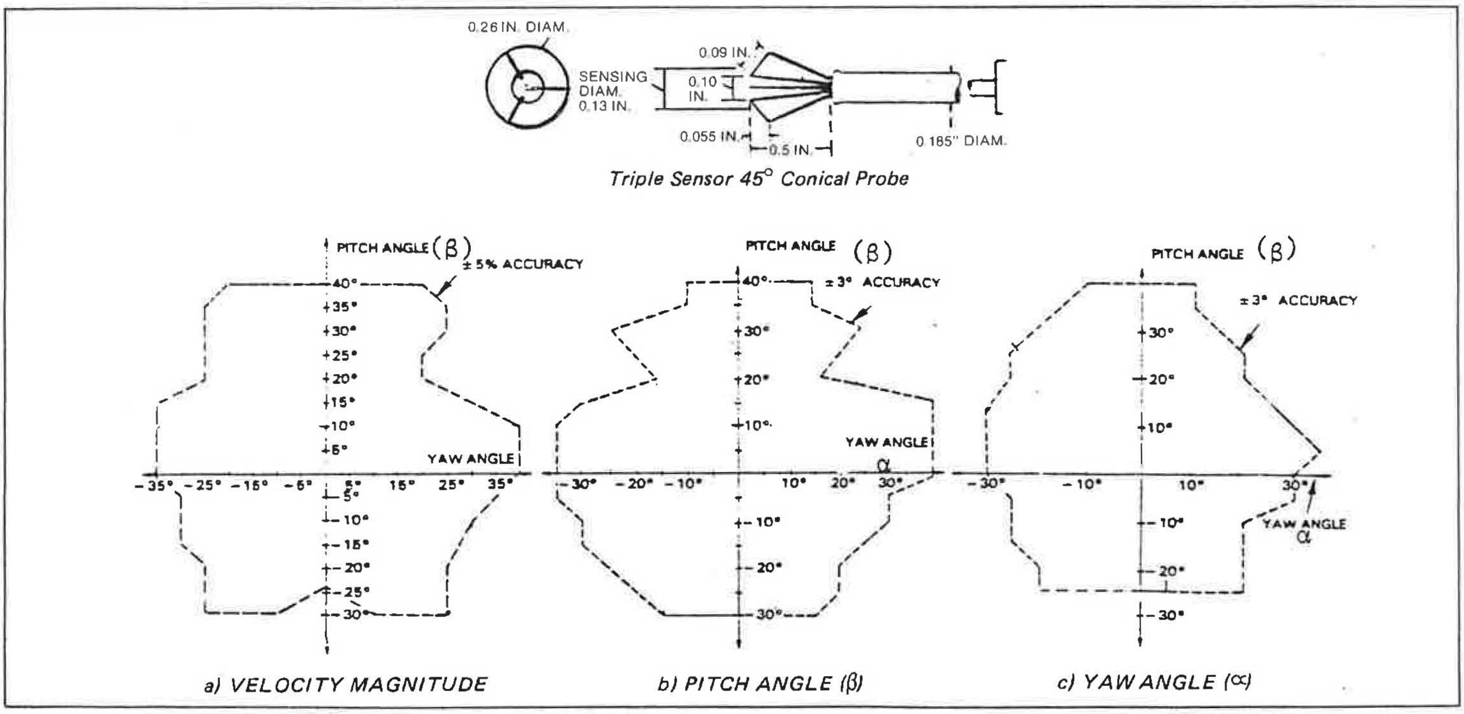

Figure 6. Accuracy of Solutions for Steady State Calibration Data (Ref. 46).

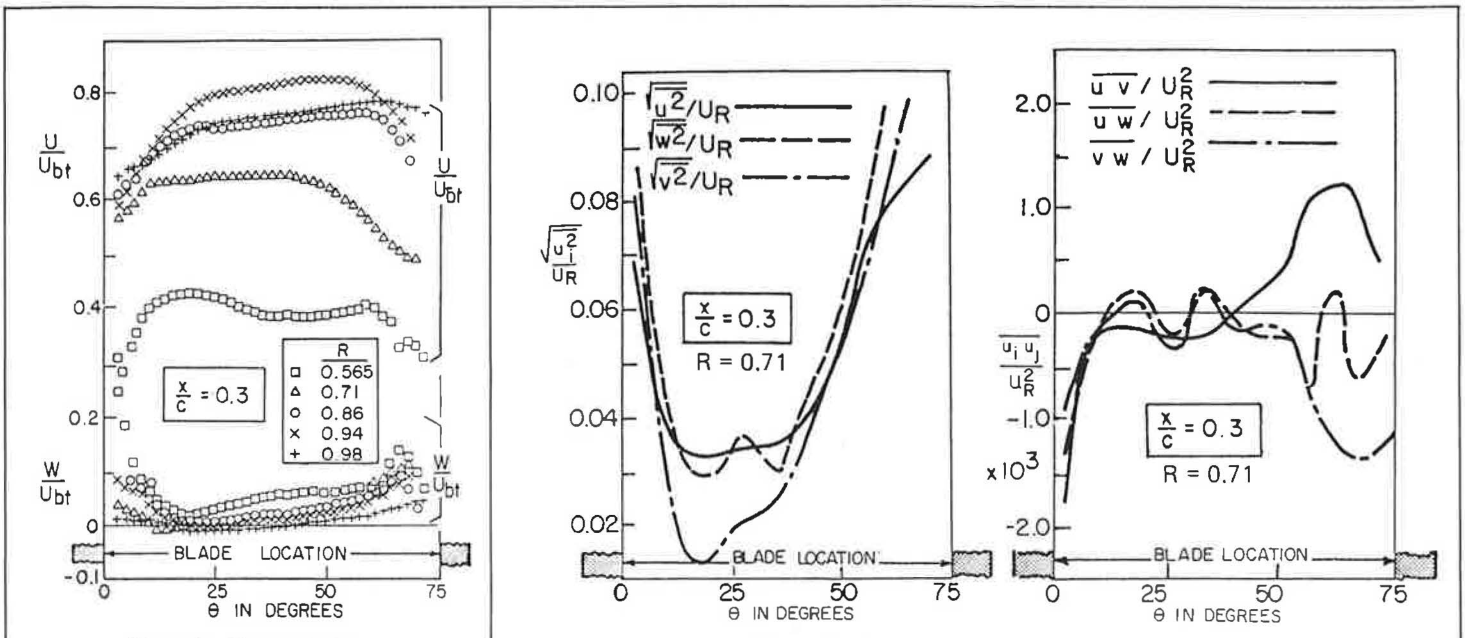

Figure 7a. Mean velocity.

Figure 7b. Turbulence Intensity and Stresses.

Figure 7. Distribution of Mean Velocities, Turbulence Intensities, and Shear Stresses Inside Rocket Pump Inducer (R is the non-dimensionalized radius, θ is the angular position measured from the blade) (Ref. 23).

(11) finite sampling time, (12) measurement of wire angles with respect to the reference coordinate system, and (13) mis-alignment of the probe with respect to the reference axis.

Errors (1, 7) and (8) are eliminated by using correction factors from available hot-wire literature and by calibrating the probe for pitch and yaw angle as well as wall vicinity effects. The probe and sensor errors (2-6) are minimized by proper selection of the probe dimensions, support needles, and sensors. Error (9) is eliminated by proper clamping, and error (10) is minimized by reducing the number of ground loops to a minimum. Error (11) is inherent and can only be reduced by increasing the sampling time. Errors (12) and (13) depend on the accuracy of the angle-measuring equipment and aligning devices, respectively.

A detailed discussion of the methods of estimating and minimizing the above-mentioned errors, and methods of correcting the data are described in Anand and Lakshminarayana[24]. Most of the important errors have been incorporated in the rotating three-sensor hot-wire[26] and the stationary three-sensor hot-wire[33] data reduction computer programs. A brief discussion of many of these errors are given in earlier sections.

One of the major sources of errors occurs in the measurement of large gradient in mean velocity as well as turbulence quantities due to spatial resolution of the probe. This can be minimized by utilizing a subminiature sensor such as the one shown in Figure 1c, where the distance between active portions of the wire is less than 0.5 mm. An estimate of the error due to this source can be made by assuming a local structure and spectrum of turbulence as was done in reference 24. The error in cross correlation is determined by the maximum eddy size the probe can correlate because of the finite distance between wires.

The above list of errors does not include those arising from the data processing.

TYPICAL DATA

It is beyond the scope of this paper to discuss various data acquired from a three-sensor probe. This can be found in references 17 through 49. Some typical data from the Penn State effort is given in this section.

Typical data[23] from a three-sensor, hot-wire probe (Figure 1e) rotating inside a rocket pump inducer passage (3 ft. diameter, 4 blades, 450 rpm, tested in air) is shown in Figure 7. The data acquisition system was similar to the one shown in Figure 3. About 50 data points at each axial and radial location of the passage were acquired. The blade-to-blade distribution of the streamwise velocity (U), radial velocity (W), streamwise turbulence intensity ($\sqrt{\overline{u^2}}/U_R$), radial turbulence intensity ($\sqrt{\overline{w^2}}/U_R$), normal turbulence intensity($\sqrt{\overline{v^2}}/U_R$), and the corresponding three components of velocity correlations ($\overline{uv}/U^2{}_R$, $\overline{vw}/U^2{}_R$, $\overline{uw}/U^2{}_R$) are shown in Figure 7. The normalizing factors are U_{bt} (blade tip speed) for the velocities and U_R (local total relative velocity of the flow) for the turbulence quantities. R is the non-dimensionalized radius (R = 1 at the tip), θ is the angular position measured from the blade and x is the distance from the leading edge normalized by blade chord. Development of boundary layer on the blades and large turbulence intensities and stresses near the blade surface is clearly evident. Perhaps the most important observation is the fact that the radial turbulence intensities are higher than the streamwise intensities near the blade surfaces. This is caused by the presence of coriolis forces. Data such as these have provided valuable information on the flow structure inside turbomachinery rotor passages (references 20-25, 30-32).

Typical data[36] obtained from a stationary three-sensor, hot-wire probe at the exit of an axial flow compressor rotor is shown in Figure 8. A three-sensor probe similar to the one shown in Figure 1c was employed in this program. The data was taken near the end wall region of a compressor rotor[30] of 3 ft. diameter, 21 blades, operated at 1066 rpm. The ensemble averaging technique was utilized to derive the rotor wake profiles in this region. For the sake of brevity, only the mean velocity profiles are shown. The blade-to-blade flow has 300 data points across one passage (S). R = 1 represents tip of the blade and R = 0.5 denotes the hub of the rotor. The mean velocities in the steamwise (U/U_0), principal normal (V/U_0) and radial (W/U_0) directions at 2.1 percent of the chordwise distance from the blade (Z = 0.021) trailing edge are shown in Figure 8. Y is the tangential distance from the wake center and U_0 is the maximum streamwise velocity. The presence of large radial velocities inside the rotor wake as well as the rapid increase in the wake width near the tip is clearly evident from this plot. Data such as this one has provided invaluable information on the structure of flow and wake downstream of a rotor[25-31, 33-38]. Such information is essential for the aerodynamic and acoustic analysis, design, and performance improvement of turbomachinery used in aircraft and marine transportation and other industrial applications.

CONCLUDING REMARKS

The three-sensor, hot-wire probe is invaluable for the measurement of three dimensional flow and turbulence field in fluid mechanics. Even though it has some disadvantages (finite size, aerodynamic interference, etc.), the disadvantages are outweighed by the advantages and usefulness of such a probe.

Some of the improvements that can be carried out to increase the accuracy of the three-sensor hot-wire technique are as follows: (1) improved calibration technique to include the effects of yaw and pitch angle as well as the vicinity of a wall, (2) inclusion of corrections for the nonuniform temperature distribution along the wire and probe interference effects, (3) decrease in the error due to spatial resolution by miniaturization or other means, and (4) online data (digital) processing in real time.

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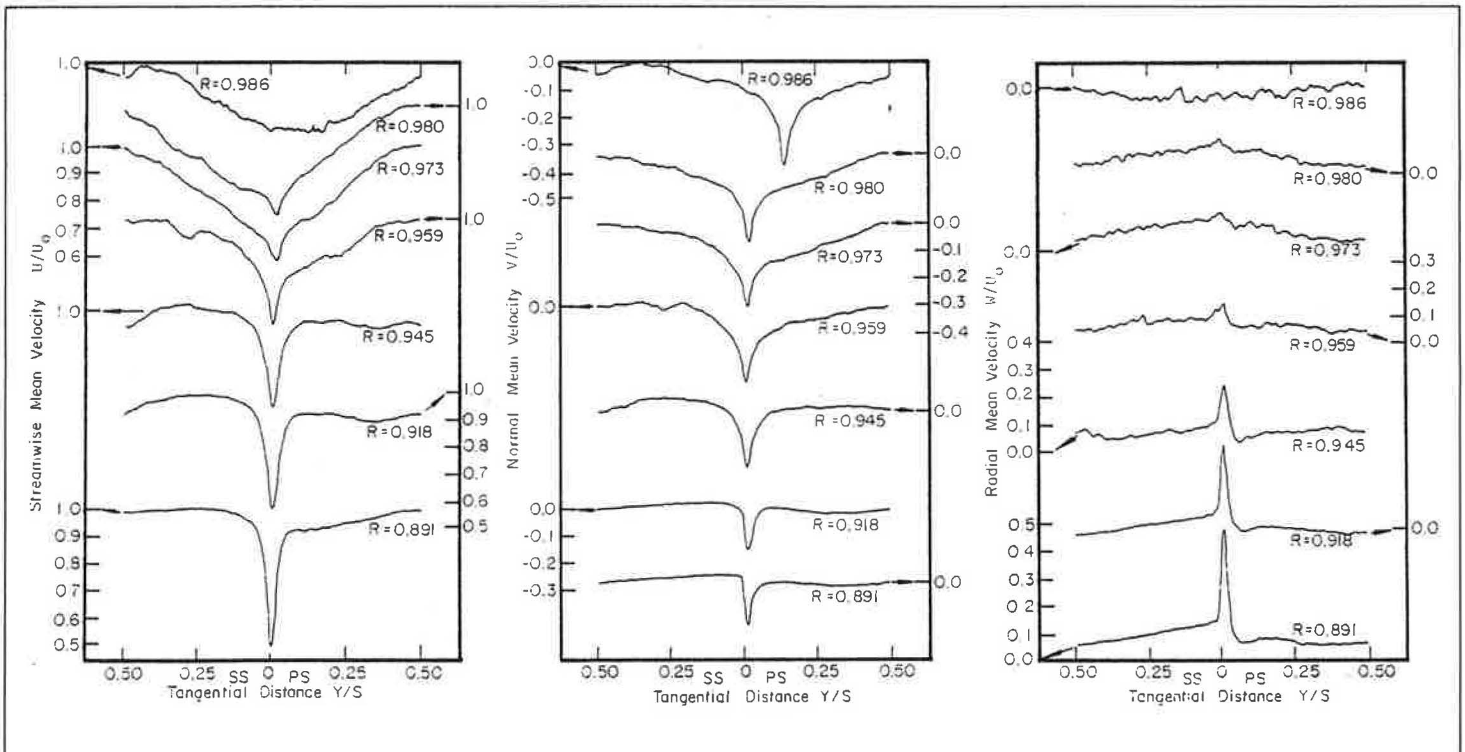

Figure 8. Distribution of Mean Velocity in the Wake and Exit Flow in the End Wall Regions of an Axial Flow Compressor (Ref. 36).

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*27th International Gas Turbine Conference and Exhibit	April 18-22, 1982	London, U.K.
American Industrial Hygiene Conference	June 8-10, 1982	Cincinnati, Ohio
Computational Fluid Mechanics & Heat Transfer	June 14-16, 1982	Pennsylvania St. Univ. University Park, PA
Turbulence Models for Computational Fluid Dynamics	June 21-23, 1982	Pennsylvania St. Univ. University Park, PA
International Symposium on Applications of Laser-Doppler Anemometry to Fluid Mechanics	July 5-7, 1982	Lisbon, Portugal
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