Use of Cylindrical Hot Films in Unsteady Flows

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Introduction

THE use of hot-wire or hot-film probes for absolute velocity measurements in unsteady flows has significantly increased the accuracy of the results compared with those acquired using pneumatic measurements. The inability of pneumatic instrumentation to account for the effects of the unsteadiness renders even the mean measurements questionable in many instances.[1] Assuming that the reduced frequency response and somewhat higher signal-to-noise ratio of films pose no difficulties, the user has, until now, been faced with a dilemma in deciding between hot films and hot wires. The hot-film sensors are much less susceptible to breakage and have much more repeatable calibrations over a period of time; the hot-wire sensors, on the other hand, have a reduced sensitivity to the velocity component parallel to the sensor and thus better fit the standard empirical calibrations recommended by probe manufacturers.

This Note discusses the typical technique as well as an improved one for using hot films in unsteady flows. The inaccuracies associated with the most common technique for accounting for velocity angle sensitivity are detailed. In addition, an improved formulation is outlined and documented in terms of accuracy. The result is an improved procedure for making velocity measurements in flows for which accuracy is the dominant consideration rather than frequency response.

Discussion

The hot-film sensors described herein were used in an experimental program to measure the periodic wakes behind a model compressor.[2] Three sensors were arranged in such a configuration as to be at about 45 deg to the mean flow direction with sensitivities to all three velocity components (Fig. 1). The probes were built by Thermo-Systems, Inc. (TSI) using their −10 sensors (0.001 in. diam, 0.040 in. long). The probes were used in conjunction with a Thermo-Systems 1050 Constant Temperature Anemometer.

The calibration of the sensors was performed in a low-turbulence tunnel having provision for accurately varying the pitch and yaw angles (α and β of Fig. 1) relative to the uniform tunnel flow. The tunnel cross section was 12 × 20 in.; as such, there was no interaction of the probe with the tunnel boundary layers for any orientation. The calibration as a function of velocity magnitude followed the typical relation

$$I_w^2 R_w / (R_w - R_c) = A + B U_{tot}^{1/2} \tag{1}$$

where I_w is the wire current, R_w the wire operating resistance, R_c the wire unheated resistance, and U_{tot} the total velocity.

The calibration of the probe for angle sensitivity revealed a limitation on accuracy for angles greater than ±5 deg. The usual, recommended form for this sensitivity is given by

$$B = B_0 (U_\perp^2 + K^2 U_\parallel^2)^{1/4} / U_{tot}^{1/2} \tag{2}$$

where B is defined in Eq. (1), B_o is independent of angle, $U_\perp$ is the velocity component perpendicular to the sensor, $U_\parallel$ is the velocity component parallel to the sensor, and K is an empirical constant. For the present experiments, a value of

$$K = 0.4 \pm 0.1 \tag{3}$$

was found to best fit the calibration data; this value agreed well with the value recommended by the manufacturer.

The accuracy of the probe calibrations then was tested by acquiring data in a steady flow at known combinations of pitch and yaw angle. The results are compared with the known or true values in Fig. 2. Figure 2a displays the total velocity error as a function of true pitch angle α_T and true yaw angle β_T. Figure 2b shows pitch angle error $\Delta\alpha$ and yaw angle error $\Delta\beta$ as a function of α_T and β_T. Note that errors were as high as 8% in total velocity and 20 deg in angle for large values of pitch and yaw angle. After careful analysis, it was determined that the empirical coefficient K in Eq. (2) was not sufficiently constant over the range of pitch and yaw angle calibrated. In this regard, conclusions from the present study agree with previously published results.[3]

The conclusions from Fig. 2 are particularly relevant to the use of hot-film sensors in rotating machinery. Although the increased reliability of such sensors is attractive, the decreased accuracy represents a severe limitation. Typical variations in flow angle behind a compressor, for example, might be ±10 deg or more. The errors, from Fig. 2, associated with this variation severely limit the use of such measurements for calculation of performance.

A new formulation (labeled the F formulation[2]) has allowed greater accuracies using hot-film sensors. As an

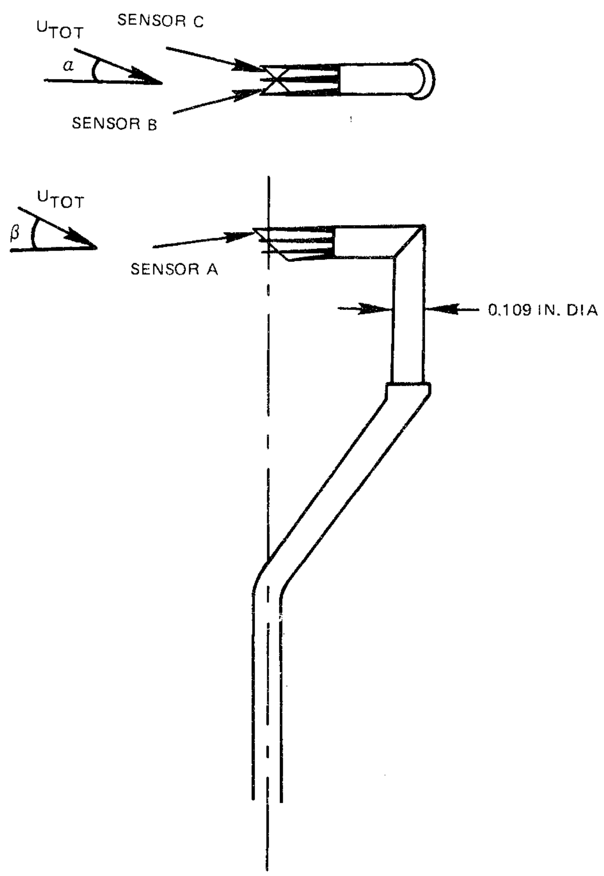

Fig. 1 Three-sensor hot-film probe.

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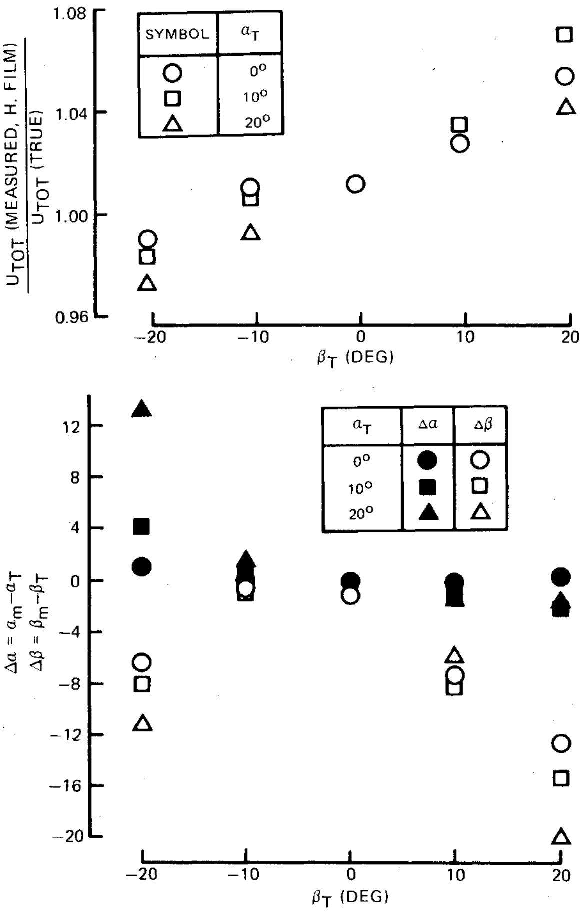

Fig. 2 Errors with K^2 formulation.

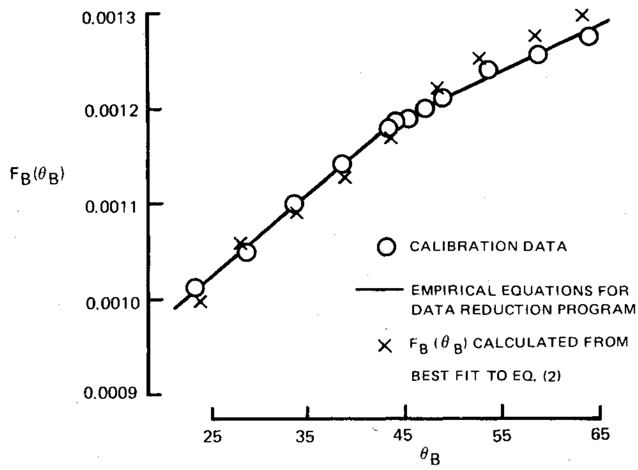

Fig. 3 Typical hot-film F calibration.

alternative to the angle-sensitivity formulation of Eq. (2), the velocity coefficient B of Eq. (1) is expressed by

$$B = B_0 F(\theta_i) \tag{4}$$

where the angle e_i is defined by

$$\cos\theta_i = (\hat{e}_i \cdot U_{tot})/U_{tot} \tag{5}$$

with $\hat{e}_i$ the unit vector in the direction parallel to the individual sensor, and U_{tot} the total velocity vector. One advantage of this type of formulation is simplified definition of angle relative to the previous use of two angles, α and β. The use of the angles $\theta_i - i = 1,2,3$ for the probe configuration of Fig. 1 was found to collapse the calibration data for α and β to a single curve for all sensors.

An example of such a calibration is given in Fig. 3 for the B sensor of Fig. 1. Note that, for these calibration data, the empirical equations used to describe the results represented the data to an accuracy of 0.5% or better. Although not shown, the calibrations $F_i(\theta_i)$ for all three sensors (Fig. 1) on all probes calibrated had calibrations similar to that of Fig. 3. A two-regime using straight lines permitted a simplified representation within the data reduction program. The specific calibration curve showing F vs θ_i would not be expected to be universally applicable and would depend on the particular sensor configuration employed. Since the value of $F_i(\theta_i)$ is used, and not the slope of the curve, the discontinuity in shape shown in Fig. 3 is of no relevance to the data reduction.

The change in slope probably is associated with the response of the hot-film sensors at large angles and directly related to the previously mentioned variability in value of constant K in Eq. (2). The step change in slope simplifies the data reduction procedure. Since no mechanism is readily apparent, one would expect a continuous change in slope between the two regions of constant slope. To emphasize the value of this new F formulation, the equivalent expression for $F_i(\theta_i)$ based upon the best fit of the data to Eq. (2) with constant K value is also shown on Fig. 3. To be sure, as an alternative to the F formulation, one could input a $K(\theta_i)$ expression into the data reduction as well; consideration of this alternative led to the conclusion that such a technique was unnecessarily complicated compared to the technique actually used.

Using the *same* data of Fig. 2 but with the new formulation, the results showed agreement to within less than 1% in total velocity and less than 1 deg in pitch or yaw angle (i.e., velocity direction). These accuracies, over a range of ±20 deg in flow direction, significantly increase the accuracy of subsequent calculations of performance in rotating machinery. As such, the technique represents an improvement in measurement techniques for unsteady flows for which accuracy is a more important requirement than frequency response.

References

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Supersonic Flow over a Deep Cavity for a Laser Application

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FLOW disturbances generated by a supersonic flow over a deep three-dimensional alcove were studied experimentally. The cavity geometry under study is shown schematically in Fig. 1. The alcove has a cross section 14-cm wide and 40-cm in the flow direction (L) with an adjustable

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