By using the data in Fig. 6 of Ref. 1, values of Re_{sL} (R_ℓ in Ref. 1) may be tabulated for constant $Re_{\infty c}$ (R_c in Ref. 1) or for constant $(U/\nu)_\infty$ inasmuch as aifroil chord c was constant and equal to 25 cm. Corresponding values of relative freestream turbulence intensity T' may be extracted from Fig. 7 of Ref. 1. It is then possible to plot Figs. 1 and 2. Figure 1 shows the expected decrease of Re_{sL} as T' increases at constant $(U/\nu)_\infty$. Figure 2, obtained by reading Re_{sL} for a constant T' in Fig. 1, reveals the strong Re/ℓ effect, and it is very similar in slope to that sometimes found in wind-tunnel data. Straight lines fitted to the points have an average slope of approximately 0.4. It is interesting to note that, within the range of these data, the influence of Re/ℓ is roughly double that of T' in magnitude and opposite in direction. Emphasis must be given to the limited range of the data because the rates of change seen in Figs. 1 and 2 are not expected to continue indefinitely.

There has been much speculation about the inadequately understood unit Reynolds number phenomenon. Interest principally focuses on the absent length that could eliminate the dimensional feature of U/ν or a frequency term that would make U^2/ν dimensionless. It seems possible that the particular character of the disturbance that causes transition in a given case is the product of the combination of environmental factors present. These include both freestream and surface factors. The unit Reynolds number, or something related thereto, apparently is one of the environmental factors that can influence the disturbance, its growth, or the receptivity of the boundary layer to destabilization. On the basis of prior work, the discovery of an Re/ℓ effect in transition of free shear layers should not be surprising. Because of the limited data, the demonstration is not as complete as one would prefer. However, the results shown are thought to make a convincing statement.

Conclusions

It is remarked in Ref. 1 that Re_{sL} seemed to increase with T', apparently because of some unknown influence related to changes in the chord Reynolds number. It is further stated that, for a given value of T', multiple values of Re_{sL} can occur, suggesting that some characteristics of the freestream other than the turbulence intensity has a substantial effect on Re_{sL}. After the present analysis of the same data, it seems that appropriate, albeit tentative conclusions are that 1) increasing turbulence intensity had the expected effect of decreasing Re_{sL} when $(U/\nu)_\infty$ was held constant; 2) a strong Re/ℓ effect was evident, increasing $(U/\nu)_\infty$ and causing Re_{sL} to increase for constant T', as is also found in many studies of the transition of bounded shear layers; 3) the Re/ℓ effect should not be neglected in efforts to characterize the laminar-to-turbulent transition of the shear layer over separation bubbles; and 4) more experimental data are obviously needed for better verification of these tentative conclusions.

Acknowledgment

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Effects of Pitot Probe Shape on Measurement of Flow Turbulence

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Introduction

THE high-frequency response of semiconductor strain gage-type pressure transducers makes them an attractive alternative for flow turbulence investigations when high-quality optical access is unavailable for laser anemometer equipment or when flow temperature or erosion problems are too severe for hot-wire anemometry. Their ability to follow fluctuations in the total pressure has brought them into common usage for aircraft compressor intake instrumentation. Steenken[1] demonstrated that the spatial resolution of high-frequency turbulence is determined by transducer diameter, with the smaller probes providing a more accurate representation of the auto-power spectra at high frequencies. Grande and Oates[2] compared the output of this type of transducer with the output from a hot-wire anemometer in wind tunnel flows and found that both signals had essentially the same normalized power spectral density at frequencies up to 25 kHz.

This Note describes some of the effects of enclosing this type of transducer with various tip housings to improve its response for mean and fluctuating pressure measurements. Measurements taken with these probes and with a hot film anemometer along the centerline of a freejet provided a relationship between the fluctuation levels of freestream velocity and total pressure.

Experimental Approach

The experiments were conducted in a freejet from a 5.08-cm-diam nozzle with an 88.4 m/s mean velocity and a 0.2% turbulence intensity at the exit. The air supply was a 0.91-m square cross-section settling chamber pressurized by a centrifugal fan. A silicon diaphragm pressure transducer (Kulite model SCS-093-5), 2.36 mm in diameter and 25.4 mm long, was chosen as one of the smallest transducers to pro-

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vide both high-frequency response and mean pressure measurement capability. It was cemented to the end of a 20-cm-long tube that was mounted on a rotating support to allow variation of the probe angle of attack α at selected locations along the jet centerline. A strain gage power supply and signal conditioner were used for bridge excitation and signal amplification.

Preliminary measurements taken with the bare transducer located at the nozzle exit, showed a measured mean value 4% below the known stagnation pressure. The 0.76-mm-diam pressure sensing area of the transducer was large

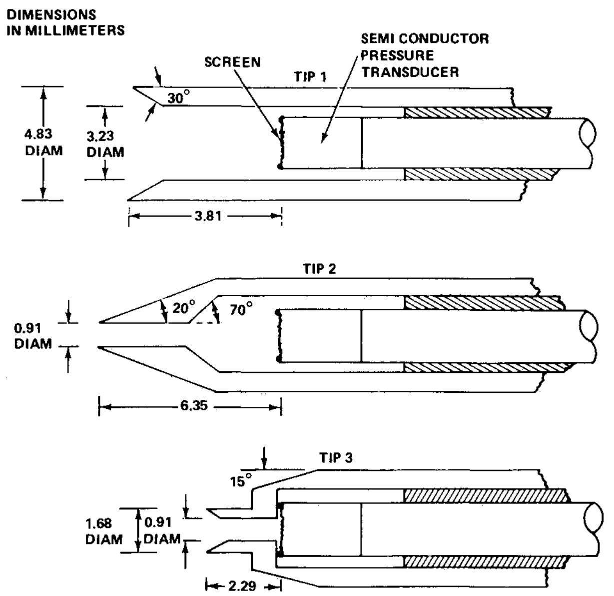

Fig. 1 Tip housings for total pressure probe.

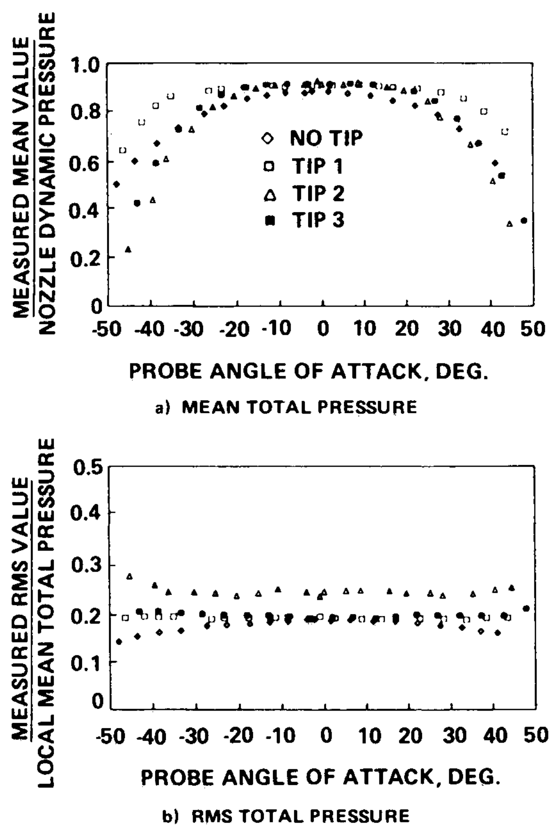

Fig. 2 Effects of probe inclination on signal response. Probe tip located on jet centerline six diameters from nozzle exit.

enough relative to its 2.36-mm o.d. to significantly lower the measured mean pressure. The three probe tips illustrated in Fig. 1 were designed to alleviate this problem and to provide better spatial resolution and/or less sensitivity to the probe inclination than with the bare transducer.

The transducer sensitivity to temperature change was responsible for a second source of error in the mean total pressure measurements. With the amplifier gain set to provide a sensitivity of 496 Pa/V, the thermal effects on the dc level were noticeable even though the data were being taken in a jet having a total temperature only 10 K above the calibration temperature. This temperature difference provided a thermal offset of 0.2 V. Because the thermal response depends on the substrate temperature, which requires several minutes to reach equilibrium, this source of error in the mean total pressure measurements was suppressed by allowing the probe to reach thermal equilibrium in the flow, withdrawing it for rebalance, and then replacing it in the flow for measurement.

Figure 2a shows the variation of mean total pressure with probe inclination for the bare transducer and for the three tipe shapes when located 6 diameters from the nozzle exit. The symbol P_a represents the transducer reference pressure, which for this work was ambient. The measurements are shown normalized by the settling chamber pressure $(P_{sc} - P_a) = 4689$ Pa. The sharp-lipped, internally chambered design of tip 1 yields data that are almost insensitive to α for inclinations up to 25 deg. This design was included for reference only; its spatial resolution would have been inadequate for our planned experimental investigations. Corresponding data sets taken 16 diameters from the nozzle exit displayed essentially the same variation with α and the same progression with the tip shape as shown in Fig. 2a.

Measurements of transducer signal rms levels taken 6 diameters from the nozzle exit are shown in Fig. 2b. The

Table 1 Comparison of constants

Probe tip configuration	K	Standard deviation
No tip	1.123	0.027
Tip 1	1.114	0.034
Tip 3	1.127	0.035

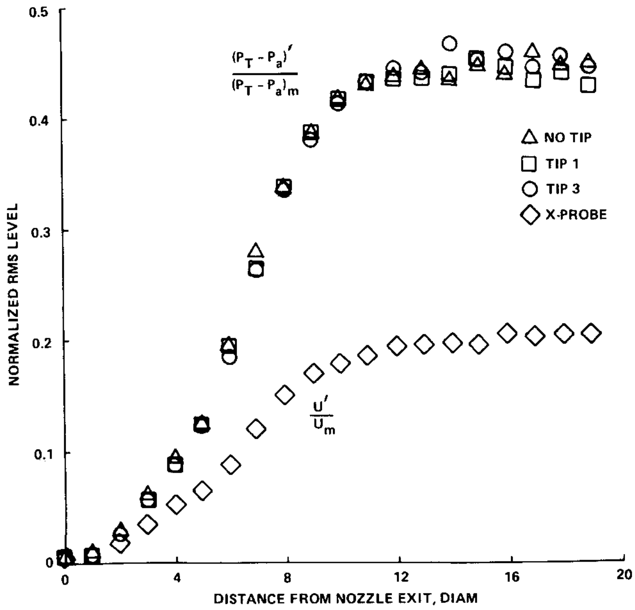

Fig. 3 Comparison of velocity and total pressure rms data taken along centerline of freejet.

rms data for each probe tip were normalized by the mean value of the total pressure measured with that probe tip at zero degrees probe inclination. The rms total pressure levels measured with probe tip 2 are considerably higher than those found for the three other tip configurations. Investigation of signal characteristics with a spectrum analyzer showed significant differences between the spectra for probe tip 2 and those found for the others. The spectra for tip 2 showed a predominate peak centered around 3 kHz and no frequency components above 5 kHz.

When probe tip 2 was moved forward on the support tube to provide a larger internal cavity, the spectra showed that the prominent peak dropped well below 3 kHz, indicating a dependence on cavity internal dimensions. The presence of turbulent fluctuations in the freestream flow appears to excite cavity oscillations in probe tip 2 that enhance the signal in a band of frequencies around 3 kHz but attenuate the high-frequency fluctuations that exist in the freestream flow. Parthasarathy, Massier, and Cuffel[3] found similar signal distortions using a piezoelectric crystal mounted inside a cavity in a pitot probe. They concluded from autocorrelations of the transducer signal that the cavity was acting as a tuned filter.

The rms levels found for the other probe tip configurations were all quite close and relatively independent of the probe inclination. In order to investigate the relationship between fluctuations in velocity and total pressure, measurements were taken along the jet centerline with three probe tip configurations (except tip 2) and a hot-film X probe. These data are shown in Fig. 3, with the rms values of total pressure and velocity normalized by their respective mean values.

Analysis of Signal Fluctuations

If the static pressure in the jet is equal to ambient, then for incompressible flow conditions the mean total pressure measured with respect to ambient can be interpreted as the dynamic pressure. The mean values of total pressure and velocity are assumed to be related by

$$(P_t - P_a)_m = Q_m = 0.5\rho U_m^2$$

Let the instantaneous values of velocity and dynamic pressure be given by

$$U = U_m + u, \qquad Q = Q_m + q$$

where the rms values are

$$u' = \sqrt{\overline{u^2}}, \qquad q' = \sqrt{\overline{q^2}}$$

The expression for U can be squared to obtain

$$U^2 = U_m^2 + 2uU_m + u^2$$

The term $2uU_m$ averages to zero and hence represents a component of fluctuation with no mean value. If we assumed that the instantaneous values U and Q are related by

$$Q \doteq 0.5\rho U^2$$

then the fluctuating component of dynamic pressure can be expressed in terms of velocity fluctuations

$$q = 0.5\rho(2uU_m + u^2)$$

and the rms value is given by

$$\frac{q'}{Q_m} = \sqrt{4\frac{\overline{u^2}}{U_m^2} + 4\frac{\overline{u^3}}{U_m^3} + \frac{\overline{u^4}}{U_m^4}}$$

The first term on the right is dominant. The second would be zero for a symmetric velocity distribution function, and for low-turbulence intensity the last term can be neglected. Then the fluctuations in dynamic pressure and velocity can be related by

$$\frac{q'}{Q_m} = \frac{2u'}{U_m} \tag{1}$$

An expression similar to Eq. (1) was presented by Nagamatsu, Sheer, and Bigelow.[4] They compared measurements taken in a freejet (with a piezoelectric transducer in a total pressure probe) with freejet data obtained by other investigators using hot-wire probes.

The measured total pressure signal cannot exactly represent the freestream dynamic pressure. Our hot-film X probe measured fluctuations of the axial velocity component in terms of heat transfer from 0.025-mm-diam cylinders in a probe that is designed to minimize flow disturbance. By contrast, the total pressure probe stagnates the flow on a flat surface to measure the force on a small surface-mounted strain gage and should be expected to show some response to transverse velocity fluctuations. Becker and Brown[5] investigated the effects of probe tip shape and yaw angle on total pressure measurements in a freejet using a remotely mounted pressure transducer. Their work showed that differential pressure measurements made with two separate probes having dissimilar tip geometry can be used to find the mean square level of turbulent velocity fluctuations transverse to the flow.

We have chosen to use an empirical relation between rms values of total pressure and velocity based on Eq. (1):

$$\frac{(P_T - P_a)'}{(P_T - P_a)_m} = 2K\frac{u'}{U_m} \tag{2}$$

where K has been evaluated from the data in Fig. 3. Values of K for a particular tip configuration were found at each axial location by comparison with the hot film data taken at the same location. Close to the nozzle exit, K was less than 1 and showed a strong variation with distance from the exit Z. However, for $6 \leq Z/D \leq 19$, we found that the values of K were almost independent of Z and essentially the same for all three probe tip configurations. Each value of K listed represents an average of fourteen measurements that were taken along the jet centerline.

Concluding Remarks

Signal fluctuations from a pressure transducer housed in a pitot probe can be used to determine the magnitude of freestream velocity fluctuations in a turbulent, incompressible flow. An empirical constant required to establish this relationship was found to be almost independent of the probe tip shape, provided that resonance cavity conditions were avoided in the tip design. This constant was found to be valid over a wide range of probe angles of attack and freestream turbulence intensity.

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