Correlation of Preston Tube Data with Laminar Skin Friction

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Nomenclature

$\bar{C}_f$ = nondimensional difference between theoretical and correlated skin friction coefficient $[(C_{f,t} - C_{f,c})/C_{f,t}]$
h = external height of face of flattened Pitot probe
$K_{\rm eff}$ = $(2Y_{\rm eff}/h)$
ΔP_p = difference in pressure between Preston tube and local static pressure
T^* = $\log_{10}(T'/T_e)$
T' = $T_e(0.55+0.035M_e^2)+0.45T_w$
U_p = velocity based on ΔP_p
U_τ = classical wall shear stress velocity, $(\tau_w/\rho_w)^{1/2}$
w = external width of a flattened Pitot probe
X^* = $\log_{10}(U_p Y_{\rm eff}/\nu_w)^2$
$Y_{\rm eff}$ = effective height of Preston tube above wall
Y^* = $\log_{10}(\tau_w Y_{\rm eff}/\rho_w \nu_w^2)$

Abstract

PRESTON tube data have been obtained on a sharp 10-deg cone in the NASA Ames 11 ft Transonic Wind Tunnel (TWT) over a Mach number range of 0.30-0.95 and at unit Reynolds numbers of 9.8, 13.1, and 16.4×10^6/m. The data obtained within laminar boundary layers have been correlated with the corresponding values of theoretical skin friction. The rms scatter of the skin friction coefficient about the correlation is of the order of 1%, which is comparable to the reported accuracy for calibrations of Preston tubes in incompressible pipe flow. In contrast to previous works on Preston tube/skin friction correlations, which are based on the physical height of the probe's face, this very satisfactory correlation for compressible boundary-layer flows is achieved by accounting for the effects of a variable "effective" height of the probe. The coefficients, which appear in the correlation, are dependent on the particular tunnel environment and probe aspect ratio. The general procedure can be used to define correlations for other wind tunnels.

Contents

Background

The work reported herein constitutes one step in the search for an improved procedure for calibrating the effects of noise on model tests in transonic wind tunnels. Earlier work by Treon et al.[1] suggested that a sharp-nose 10-deg cone could be useful in explaining differences between three transonic wind tunnel tests of the same C-5A aircraft model. Subsequently, a comprehensive series of tests were undertaken to measure free transition on a single cone in 23 wind tunnels and in flight. This cone was designated the AEDC Transition Cone and is a sharp-nose 10-deg cone with a highly polished surface and a traversing mechanism to move a miniature (0.025 cm high) Pitot probe along the surface. The basic purpose of the traversing probe is to detect the location of boundary-layer transition. Additional description of the cone can be found in Ref. 2.

As part of an effort to develop an improved method for correlating the effects of tunnel noise, it was decided to investigate the possibility of using the traversing Pitot probe data to derive a Preston tube correlation which might contain useful information on the tunnel environment. This synoptic reports the results of analyses of laminar boundary-layer data taken with the AEDC cone in the Ames 11 ft TWT. The subject data are from 19 different flow conditions which were selected from a Mach number range of 0.30-0.95 and freestream unit Reynolds numbers of 9.8, 13.1, and 16.4×10^6/m. Before presenting our Preston tube correlation based on these data, a very brief review of Preston tubes will help place our results in proper perspective.

Preston[3] utilized the classical law-of-the-wall similarity to derive the following form for a correlation between turbulent skin friction in incompressible pipe flow and pressure measured with a miniature Pitot probe resting on the inside wall,

$$y^* \equiv \log_{10}(\tau_w d^2/4\rho\nu^2) = A + B\log_{10}(\Delta P_p d^2/4\rho\nu^2) \equiv A + Bx^* \tag{1}$$

This correlation is also based on Preston's assumption that the characteristic distance from the wall is the height of the geometric center of a circular pitot probe above the wall, i.e., $d/2$. Later, MacMillan[4] and Granville[5] studied the effects of a variable "effective" height of Preston tubes. It is now known from dimensional analysis and experimental data that the effective height of a Pitot probe in contact with a surface is a function of $U_\tau h/\nu$ and aspect ratio w/h.

In compressible flow, $K_{\rm eff}$ is expected to also be a function of Mach number. In fact, the work of Bradshaw and Unsworth[6] emphasizes the need for proper modeling of Mach number when selecting the functional form for a correlation. However, unlike the flat-plate data studied by these authors, the AEDC cone supplies only Preston tube pressures and is not instrumented to measure shear stress directly. Furthermore, this cone does not have static pressure orifices to measure surface pressure distribution since the cone is designed to detect free transition. These two facts required that we resort to theoretical calculations of the axisymmetric boundary layer. Thus, the inviscid conical flowfields were defined by using the computer code of Wu and Lock,[7] and the corresponding boundary layers were computed with a code developed by Crawford and Kays.[8]

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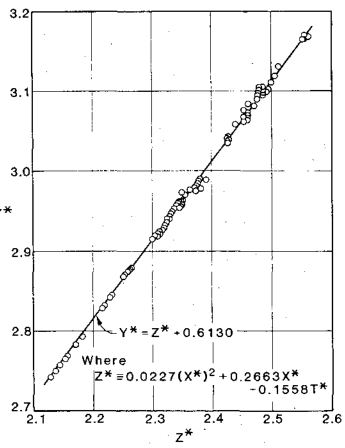

Fig. 1 Preston tube/laminar skin friction correlation based on a variable effective probe height.

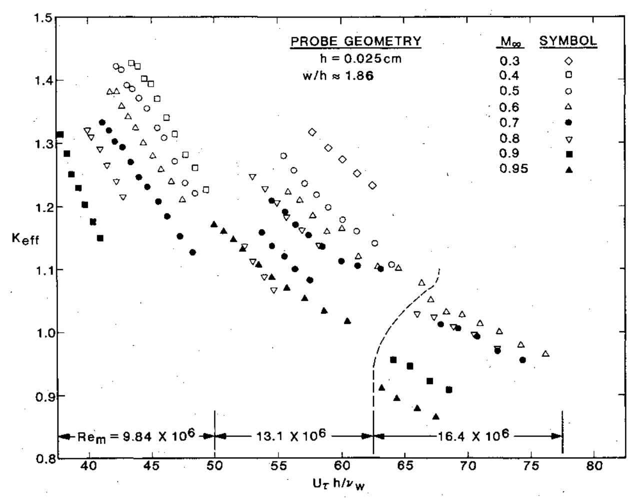

Fig. 2 Variation of effective height of probe.

Results

After preliminary studies of some simpler equations (see Ref. 2), the following equation was found to correlate Preston tube pressures and theoretical laminar skin friction satisfactorily,

$$Y^* = 0.0227(X^*)^2 + 0.2663X^* - 0.1558T^* + 0.6130$$

$$\text{for } 5.4 < X^* < 6.3 \text{ and } M_\infty < 1.0 \tag{2}$$

The nondimensional temperature parameter was introduced to account for departures of fluid temperatures from wall values. The numerical coefficients were determined by calculating Y^* and X^* at half-inch intervals along the cone's surface and then obtaining a least-squares fit to 132 data points. Equation (2) is shown in Fig. 1 with the corresponding data superimposed.

Calculation of Y^* and X^* requires values of Y_{eff}. The individual values of Y_{eff} were determined by finding the position within the theoretical laminar profiles at which the total pressure equals the measured Pitot pressures. The distribution of the resulting values of K_{eff} are presented in Fig. 2. It should be noted that these particular data are valid only for a probe with an aspect ratio of 1.9 and the Ames 11 ft TWT. Thus, the coefficients in Eq. (2) are *not* universal. The conclusion from this semiempirical data is that the effective height of a Preston tube does indeed vary with both Mach number and the classical parameter $U_\tau h/\nu_w$. In particular, the effective height decreases with increasing values of either. (This suggests an explanation as to why the correlations of Allen[9] remain valid even for probes with geometric height equal to 70% of the boundary-layer thickness.) The underlying common feature is that the *difference* in total pressure across the height of the probe's face increases as either of these two parameters increase.

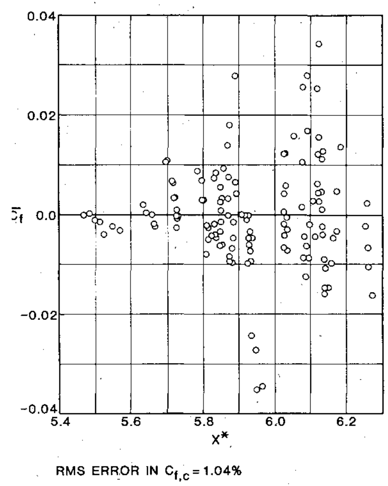

Fig. 3 Scatter of laminar skin friction about the final correlation for 11 ft TWT data.

Finally, one needs to know how accurately Eq. (2) correlates skin friction. The answer to this question is displayed in Fig. 3. The associated scatter is ±2%, and the rms error is 1.04% which is comparable to the accuracy reported for calibrations of Preston tubes in incompressible turbulent pipe flows. The amount of scatter is an order of magnitude less than that reported in Refs. 6 and 9 for compressible turbulent boundary layers.

Acknowledgments

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