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Influence of Probe Geometry on Pitot-Probe Displacement in Supersonic Turbulent Flow

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Nomenclature

D = pitot probe outside diameter
M_e = boundary-layer edge Mach number
R_θ = Reynolds number based on momentum thickness
u = streamwise velocity
u_e = streamwise velocity at boundary-layer edge
y = normal coordinate
α = angle between probe and support shaft (see Fig. 1)
δ = boundary-layer total thickness
θ = boundary-layer momentum thickness
θ_0 = boundary-layer momentum thickness for $D=0$

IN a recent *AIAA Journal* Note,[1] Wilson compared the pitot probe interference experiments of Allen[2] with those of Wilson and Young,[3] and concluded that the reason the results of these two experiments did not agree was differences in probe-tip and support geometries. Allen's experiment was conducted with flat-ended probes supported by a shaft of circular cross-section (configuration C of Fig. 1), whereas Wilson and Young's experiment was conducted with beveled probes supported by a thin, diamond-shaped shaft, similar to configuration E of Fig. 1. Both were conducted in turbulent boundary layers on the sidewall of supersonic wind-tunnels.

The probe interference effects obtained in these two experiments are illustrated in Fig. 2 in which velocity profiles measured at similar test conditions are compared. The effects of probe size in Allen's data are much larger than those in Wilson and Young's data; hence the pitot probe displacement effects are correspondingly larger.

In an attempt to analyze these geometric effects, the present author has conducted a further experiment in which the six probe configurations shown in Fig. 1 were tested at the flow conditions of the Ref. 2 experiment. A small flattened probe, used to measure reference profiles, a beveled probe, and a flat-ended probe were tested with both circular- and diamond-shape support shafts so that the effects of probe tip and support geometry could be separated. The objective of this Note is to report the results of these further tests.

The velocity profiles obtained with all six configurations are presented in Fig. 3, which shows that probe support shape had a negligible effect on the measured profiles. Oil-flow photographs of these configurations revealed that the interference region of the circular support shaft, although more extensive than that of the diamond shaft, was nevertheless well downstream of the probe tip. Hence the differences between the results of Refs. 2 and 3 do not appear to be caused by the support shaft. On the other hand, they do not appear to be

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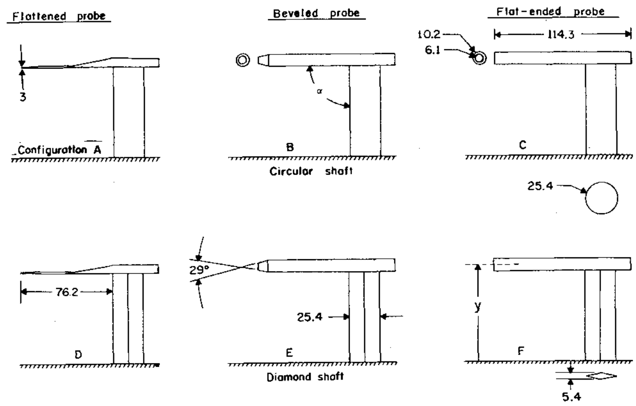

Fig. 1 Probe sketches. (All dimensions in mm.)

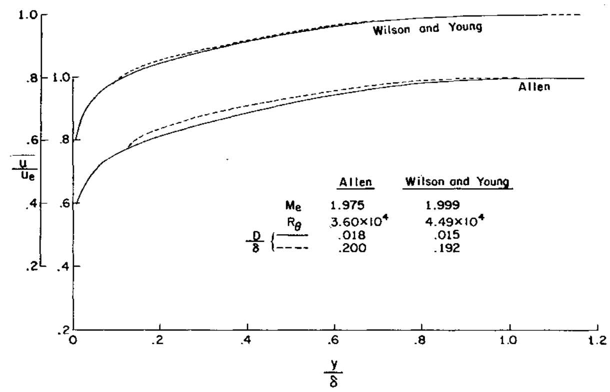

Fig. 2 Comparison of Refs. 2 and 3 probe interference results.

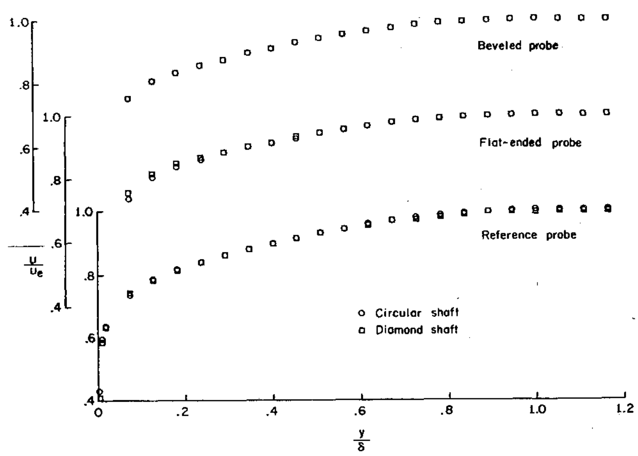

Fig. 3 Effect of support-shaft geometry on measured profiles.

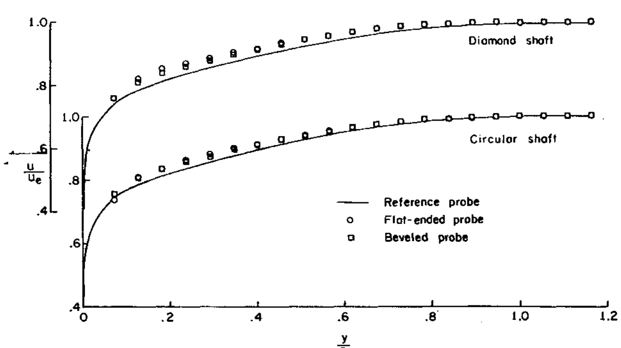

Fig. 4 Effect of probe-tip geometry on measured profiles.

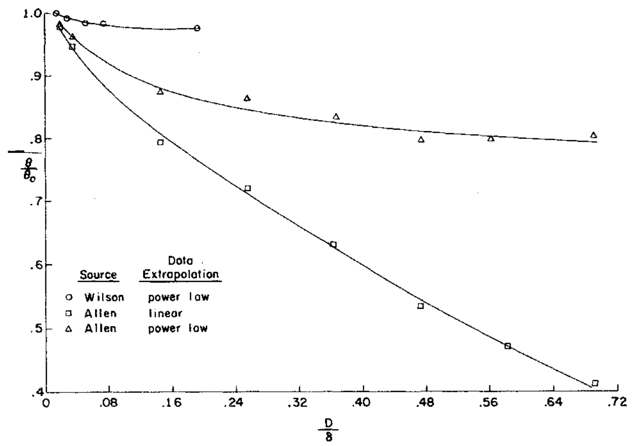

Fig. 5 Effect of probe size on experimental momentum thicknesses.

caused by probe-tip geometry, as can be seen in Fig. 4 in which the data of Fig. 3 have been replotted to isolate the effects of probe tip.

In an attempt to discover what were the true causes of the divergent results, the present author performed three additional checks: 1) the probe of configuration A was made structurally rigid and tested to see if it had been deflecting under airload; 2) configuration F was run at several values of α to see if the small angle-of-attack difference between the probes of Refs. 2 and 3 caused the interference results to differ; and 3) configurations A and C were tested in another wind tunnel to see if the present results were caused by some anomaly in the original test setup. Neither of these three further checks made any significant difference in the measured results.

To illustrate the difference in the results obtained in these two experiments, Fig. 4 of Wilson's Note[1] showed the effects of probe size on the momentum thickness calculated from the measured profiles of the two experiments. The values of the momentum thickness for large probe data, however, depend on the type of data extrapolation used between the wall and $D/2$. The momentum thickness comparison in Wilson's Note was made between data in which these extrapolations were not the same: Wilson and Young used a power-law extrapolation whereas Allen, who was attempting to show the errors that would occur if large probes were used in conjunction with standard data integration procedures, used a linear extrapolation.

In order to make the momentum thickness comparisons based on a similar data integration procedure, Allen's momentum thicknesses have been recalculated assuming a power-law extrapolation, and the results are shown in Fig. 5. The recalculated momentum thicknesses show much less effect of probe size. However, the effects are still larger than those shown in Wilson and Young's data, as would be expected from the fact that Allen's velocity profiles contained larger probe interference effects than those of Wilson and Young.

In summary, the author finds it frustrating not to be able to establish the reason for the differences between the pitot-probe interference results of Refs. 2 and 3; however, he feels that the additional data reported herein have shown that the differences are not caused by differences in the probe-tip and support geometrics as stated by Wilson.[1]

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Numerical Procedure for Analyzing Langmuir Probe Data

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Nomenclature

A = probe collection area, m^2
B_1 = primary electron current intercept, amp
B_2 = primary electron current slope, av^{-1}
B_3 = $I_{sat} \exp(-\phi_p/T_m)$, amp
B_4 = $1/T_m$, ev^{-1}
B_i^0 = initial estimates of the parameters $B_i (i=1,4)$
i_p = primary electron current at plasma potential, amp
I = probe electron current, amp
I_{sat} = Maxwellian electron saturation current, amp
m_e = electron mass, kg
n_m = Maxwellian electron number density, m^{-3}
n_p = primary electron number density, m^{-3}
q = electronic charge, C
T_m = Maxwellian electron temperature, ev
V = probe potential, volt
δB_i = corrections to the estimates of the parameters $B_i (i=1,4)$
ζ_p = primary electron energy, ev
ϕ_p = plasma potential, volt

Introduction

THE analysis of Langmuir probe data obtained in electron bombardment ion thrusters that use mercury as the propellant is complicated by the presence of two distinct groups of plasma electrons. One group has a Maxwellian energy distribution function with a temperature of approximately 5 ev, and the other group has an isotropic monoenergetic distribution function with an energy of approximately 30 ev. This latter group is sometimes referred to as a "primary" electron group. Although the two-group theory is only an approximation, it does have a physical basis and has been verified by experiment.[1,2]

If the plasma contains only Maxwellian electrons the analysis of Langmuir probe data is straightforward since the current to an infinite planar probe varies exponentially with probe voltage in the retarding field region (probe voltage less than plasma potential), and remains constant in the accelerating field region (probe voltage greater than plasma potential). Experimentally there is a slight variation in probe current with probe voltage beyond the plasma potential and this phenomenon is attributed to an increase in the dimensions of the plasma sheath surrounding the probe. The graphical procedure used in analyzing probe data when only Maxwellian electrons are present in the plasma consists of plotting the logarithm of the probe current as a function of probe voltage. This results in a curve which can be approximated by two straight line segments which intersect at the plasma potential. The slope of the straight line approximation in the retarding field region determines the electron temperature and the

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