NASA Technical Memorandum 78535

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November 1978

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National Aeronautics and
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ON THE MEASUREMENT OF TURBULENT FLUCTUATIONS IN

HIGH-SPEED FLOWS USING HOT WIRES AND HOT FILMS

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SUMMARY

A hot wire has a limited life in high speed wind-tunnel flows because it is typically subjected to large dynamic loads. As a consequence hot films and modified hot wires are frequently used for turbulence measurements in such flows. However, the fluctuation sensitivities of such probes are reduced because of various factors, leading to erroneous results. This paper describes the results of tests on some sensors in both subsonic and supersonic boundary-layer flows. A simple technique to determine dynamic calibration correction factors for the sensitivities is also presented.

SYMBOLS

E	mean value of probe voltage
e	probe voltage
M	Mach number
Re	Reynolds number
S_{T_t}	probe sensitivity to total temperature
S_u	probe sensitivity to streamwise velocity
S_v	probe sensitivity to vertical velocity
S_ρ	probe sensitivity to density
T	temperature
u	streamwise velocity component
v	vertical velocity component
w	transverse velocity component

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y normal distance from wall

δ boundary-layer thickness

ψ probe yaw angle

ρ density

Subscripts:

e boundary-layer edge

t total

θ based on boundary-layer momentum thickness

Superscripts:

$(\ )'$ fluctuating value

$\overline{(\ )}$ time average value

$\langle(\ )\rangle$ root mean square

INTRODUCTION

The hot-wire anemometer is one of the most reliable tools available for the measurement of turbulent fluctuations in low-speed flows. Its use in transonic and supersonic flows, however, has met with only limited success, because the wire is subjected to high dynamic loads which lead to the problems of strain-gauging, vibration and breakage of the sensor. While the question of determining accurate sensitivity coefficients for the various fluctuations has been satisfactorily resolved for both transonic and supersonic flows (refs. 1 and 2), the mechanical strength of the wire continues to be the factor limiting its usefulness for fluctuation measurements in this regime.

Over the past few years, sensors for turbulence measurements have been developed that are more rugged than the hot wire and are capable of being used in high-speed flows (and other hostile environments such as flows with dirt and chemical impurities, flows of hot gases, water, and other liquids). Commercially available film sensors are an example. They are usually made by depositing a thin film of nickel or platinum on a suitably shaped quartz substrate. The film is then coated with a thin layer of quartz or alumina to protect the metal film from the environment. The common substrate shapes are cylinders, cones, and wedges.

Another probe that has been used in transonic and supersonic flows is the epoxy-backed hot wire (refs. 3 and 4). The usual hot-wire probe is modified by the application of a thin film of epoxy between the support prongs and the sensor. The epoxy hardens into a sheet that provides the sensor with greater mechanical strength.

Turbulence measurements have been obtained in heated hypersonic flows with the use of hot-wire sensors mounted on a ceramic wedge (ref. 5). The wire is spot welded onto steel supports, and the open space between the wire and the supports is filled with a high-temperature, alumina-based ceramic paste. The probe is then baked at high temperatures to provide good fusion between the wire and the ceramic wedge.

A crucial factor in the use of any of these probes is their calibration. The measurement of mean velocities is straightforward; it is possible to obtain a reliable static calibration for any of these probes and make accurate measurements of the mean field. However, the use of such probes for the measurement of turbulent fluctuations poses complex problems (refs. 6 and 7). An adequate high-frequency response can be obtained for these probes by the use of presently available constant temperature anemometers, but the response characteristics of these probes at low frequencies, unlike those of a hot wire, are markedly nonlinear. This is due to the heat conduction from the sensor to the substrate material, the influence of which is minimized in the case of hot wires by the use of large length to diameter ratios. The response is also a strong function of other factors such as sensor shape and probe Reynolds number. As a consequence, it is necessary to carry out a separate dynamic calibration for fluctuation measurements.

The purpose of the present study is to examine the dynamic calibrations of the hot film and modified hot wire probes described above so as to assess their suitability for use in some ongoing experiments for the measurement of turbulent fluctuations in compressible boundary layer flows.

CALIBRATION FOR FLUCTUATIONS

Several approaches have been suggested and used for the dynamic calibration of probes. One could, in principle, place the probe in a known oscillating flow and measure the probe response. However, this is difficult to achieve in practice. An alternative technique is to place the probe in a uniform flow, vibrate the sensor at known frequencies, and record the response. This method is limited to fairly low frequencies, and vibration of the probe stem and supports could affect the calibration. Other methods used include the calibration of the probe in a homogeneous flow field in which velocity fluctuations are generated by a grid or by the superposition of a monochromatic sound field (ref. 8). The drawback with such techniques is that they require the use of specialized equipment such as calibrating rigs, shakers, and the like. It was felt that a calibration procedure which did not require the use of such equipment would be very useful.

The usual procedure in making turbulence measurements with hot wires is to use fluctuation sensitivities obtained from the static calibration curves of the probe. For a probe held at an angle of yaw ψ in the x-y plane, e', the instantaneous fluctuating component of the probe output voltage is related to the velocity fluctuations u' and v' by an expression of the type

$$e' = \frac{\partial E}{\partial \bar{u}} u' + \frac{\partial E}{\partial \psi} \frac{v'}{\bar{u}}$$

and the sensitivities $S_u = \frac{\partial E}{\partial \bar{u}}$ and $S_v = \frac{1}{\bar{u}} \frac{\partial E}{\partial \psi}$ are determined from the static calibration curves of the probe. Sandborn (ref. 9) has discussed this procedure at length. For compressible flow, a probe responds to velocity, density, and temperature fluctuations (ref. 1), and its fluctuating output voltage may be expressed as

$$\frac{e'}{E} = S_\rho \frac{\rho'}{\bar{\rho}} + S_u \frac{u'}{\bar{u}} - S_{T_t} \frac{T_t'}{\bar{T}_t} + S_\psi \frac{v'}{\bar{u}}$$

where the sensitivity coefficients S_ρ, S_u and S_{T_t} are functions of the mean flow field and other system parameters. Details may be found in references 1 and 2.

The turbulence intensities $\langle u' \rangle$ and the Reynolds stresses $-\rho\overline{u'v'}$ are then deduced from a measurement of the RMS voltage fluctuations and their correlation and the static calibration curves.

It is generally accepted that accurate measurements of turbulent fluctuations may be obtained with a hot wire, using sensitivities derived from a static calibration. Young (ref. 10) has used this technique to make turbulence measurements in a fully developed, incompressible, steady channel flow, for which the Reynolds stress is directly proportional to the streamwise pressure gradient. Since the pressure gradient can be measured with a high degree of accuracy, an independent check on the measured Reynolds stress is available in this flow. Young showed that the Reynolds stress profile measured with hot wires accurately compares with the value obtained from the streamwise pressure gradient. He then argues that it is statistically unlikely that the u'v' product will be correct without the individual quantities u' and v' also being correct. Young also made measurements with various commercial film probes and showed that these probes yielded results consistently lower than the correct values. Based on this comparison he obtained calibration factors and equations for the different probes tested.

In the absence of an accurately measurable quantity which could serve to check the turbulence measurements, an alternative procedure is needed by which it would be possible to obtain either a correction factor to the measured turbulence quantity or an estimate of the error in the measurement due to the lack of a proper calibration.

DESCRIPTION OF EXPERIMENT

Most of the experiments were conducted in the Ames Pilot Channel, a description of which is available in reference 11. The boundary layer probed was 3 to 4 cm thick. The free-stream Mach number was varied from 0.2 to 0.6, and the corresponding Reynolds number based on momentum thickness ranged from 1.6×10^4 to 3.3×10^4.

The probes tested were a single 10 μm diameter Pt-10% Rh wire, 0.15 cm long, with an epoxy backing; a similar wire supported by a ceramic wedge; and two commercially available hot-film probes — one an alumina-coated film on a wedge formed in a 0.15 cm quartz rod and the other a film sensor deposited on a 0.05 mm diameter 0.1 cm long quartz rod. A similar epoxy-backed hot-wire probe and a commercially available dual-wedge hot-film probe were also tested in a supersonic boundary layer, at a nominal free-stream Mach number of 2.3. This experiment was carried out in the Ames High Reynolds Number Facility, described in reference 4. The boundary layer thickness was 4.7 cm, and the Reynolds number based on momentum thickness varied from 1.04×10^4 to 2.82×10^4.

Each probe was used to measure the streamwise turbulence intensity $\langle u' \rangle$ profile through the boundary layer, using fluctuation sensitivities obtained from its static calibration curve. The same measurement was also made with a 10 μm diameter 0.15 cm long, Pt-10% Rh, single hot-wire sensor, which served as a standard. The performance of each test probe was evaluated by obtaining the ratio of the turbulence intensities $\langle u' \rangle$ measured with the standard hot wire and the test probe at different locations within the boundary layer. This calls for dividing one measured quantity by another, a procedure in which uncertainties could increase as the measured quantities decrease. The comparison was therefore arbitrarily restricted to a region of the boundary layer for which $y/\delta < 0.6$, where the turbulence intensity was greater than 5%. A dynamic calibration correction factor was selected after examining the ratios so obtained.

RESULTS AND DISCUSSION

Figures 1 to 4 show the turbulence intensity ratios for the different test probes plotted against the position in the boundary layer for the subsonic tests. Figure 1 shows the results for the cylindrical film sensor. The values of turbulence intensity obtained with this probe are about 10% lower than the standard wire. The scatter in results obtained for different flow conditions is about ±5%. The ratios for the commercial wedge film probe are shown in figure 2. The fluctuating output from the wedge film is lower than that of the cylindrical film; as indicated by the higher values of the ratio obtained for the wedge. While the ratios obtained from these two sensors did not appear to be very sensitive to the imposed changes in flow parameters, the results for the ceramic wedge probe (fig. 3) show a large variation in the ratio, both with changes in flow conditions as well as in boundary layer position. In addition, the fluctuation intensities measured with this probe were a factor of three to six times lower than the standard probe values. While all the reasons for this kind of response are not clear, it was established that the frequency response of the probe was adequate for these flow conditions, and apparently thermal feedback problems resulted in the low fluctuation sensitivities. The ratios for the epoxy-backed probe (fig. 4) appear to be a weak function of Mach number and Reynolds number. However, the spread in the values is an order of magnitude smaller than for the ceramic wedge sensor.

Figure 5 shows the uncorrected turbulence intensity profiles obtained with the different probes at $M_e = 0.6$. Figure 6 shows the profiles obtained from the same measurements, but with a dynamic calibration correction factor applied to the sensitivity coefficients of each probe. The factor for each probe, chosen on the basis of the above comparisons, is indicated in figure 6. A correction for the ceramic-backed probe data was not attempted because of the large variation found.

The results for an epoxy-backed wire in the supersonic boundary layer are presented in figure 7. Here the ratios of the intensities appear to be a function of the probe Reynolds number. The range of probe Reynolds numbers (based on wire diameter) across the boundary layer varies from 10 to 20 for the lower Reynolds number flow condition and from 35 to 60 for the higher Reynolds number flow condition. Although a different but similarly constructed probe was tested in the subsonic boundary layer (fig. 4), the ratios of the intensities are of the same order as the supersonic results. However, the subsonic results did not indicate a clear Reynolds number trend. (The probe Reynolds number for the subsonic results varied from 30 to 100.)

The supersonic results were used to determine corrections to the sensitivity coefficients. The probe was used to measure turbulence profiles through adverse pressure gradient regions in the same wind tunnel (ref. 4). A single epoxy-backed probe remained intact after over 35 boundary-layer traverses.

The results for a dual-wedge film probe in the supersonic boundary layer are presented in figure 8. The wedge film results also appear to be a function of probe Reynolds number similar to the epoxy probe results. The results obtained in subsonic flow with a single-wedge film probe (fig. 2) were independent of Reynolds number, although the ratios of the intensities are of the same order as the supersonic results.

The present results verify that it is not sufficient that the usable frequency range of the probe (usually determined by spectrum analysis) be greater than the range of energy containing frequencies in the flow. Figure 9 compares the normalized $(\rho u)'$ spectra of the epoxy-backed probe and a dual-wedge film probe with the hot-wire in the Mach 2.3 boundary layer. The spikes seen in the hot-wire spectrum were in all probability associated with its vibrational modes. For frequencies below 500 Hz the spectra for the various probes are dissimilar due to the different heat conduction characteristics of each probe. All the probes exhibited a usable frequency range over 100 kHz, and subsequent data analysis indicated that less than 1% of the flow energy was contained in frequencies about 80 kHz. Even so, the other probes measured lower fluctuation magnitudes when compared with the hot-wire because of the incorrect determination of the probe sensitivity coefficient.

Since the fluctuating output obtained from such probes is lower than that from the standard hot-wire probe, some correction needs to be applied to the probe sensitivity coefficient. The probe response is a function of many parameters (e.g., the physical construction of the sensing element), its overall frequency response, the Mach number, probe Reynolds number, sensor overheat, and so on. The influence of all the factors is not easily quantifiable, hence the dynamic response of the probe must be examined in the flow in which measurements are to be made.

In this experiment, correction factors were determined for the $\langle u' \rangle$ sensitivity coefficients only. For the measurement of $\langle v' \rangle$, $\langle w' \rangle$, and the turbulent stresses with an epoxy-backed x-wire or a dual-wedge film probe, no absolute calibration is required, other than a relative measurement of the mean voltages to ensure that the two sensors are matched (i.e., have equal sensitivities). The probe (operated at a high overheat ratio to eliminate its sensitivity to total temperature fluctuations) is used to obtain only ratios of the fluctuating voltages and their sums and differences, and the correlation coefficient. In the measurement of these ratios the sensitivity coefficients cancel out. With a knowledge of the $\langle u' \rangle$ profile, the other turbulence quantities can then be computed.

CONCLUSION

It has been shown that the fluctuation sensitivity coefficients for hot-films and modified hot-wires that are frequently used for turbulence measurements in compressible flows need corrections in order that accurate measurements of the fluctuating velocities can be obtained. A simple procedure to obtain dynamic calibration correction factors has been described.

In the present work no attempt was made to accurately assess the effects of the various factors on the dynamic sensitivity of various probes in a systematic manner. A detailed investigation of these effects would be a valuable contribution for those attempting to obtain quantitative fluctuating measurements in compressible flow fields.

REFERENCES

1. Morkovin, M. W.: Fluctuations and Hot-wire Anemometry in Compressible Fluids. AGARDograph No. 24, Nov. 1956.

2. Horstman, C. C.; and Rose, W. C.: Hot-wire Anemometry in Transonic Flow. AIAA Journal, vol. 15, no. 3, March 1977, pp. 395-401.

3. Mateer, G. G.; Brosh, A.; and Viegas, J. R.: An Experimental and Numerical Investigation of Normal Shock-wave Turbulent Boundary Layer Interaction at M = 1.5. AIAA Paper 76-161, Jan. 1976.

4. Acharya, M.; Kussoy, M. I.; and Horstman, C. C.: Reynolds Number and Pressure Gradient Effects on Compressible Turbulent Boundary Layers. AIAA Paper 78-199, Jan. 1978.

5. Mikulla, V.; and Horstman, C. C.: Turbulence Stress Measurements in a Nonadiabatic Hypersonic Boundary Layer. AIAA Journal vol. 13, no. 12, Dec. 1975, pp. 1607-1613.

6. Bankoff, S. G.; and Roster, R. S.: Constant-temperature Film Anemometer as a Tool in Liquid Turbulence Measurements. Rev. Sci. Instr., vol. 33, Nov. 1962, pp. 1209-1212.

7. Bellhouse, B. J.; and Schultz, D. L.: The Determination of Fluctuating Velocity in Air with Heated Thin Film Gauges. J. Fluid Mech., vol. 29, part 2, Aug. 1967, pp. 289-296.

8. Bellhouse, B. J.; and Rasmussen, C. G.: Low Frequency Characteristics of Hot-Film Anemometers. DISA Information, no. 6, Feb. 1968, pp. 3-10.

9. Sandborn, V. A.: Resistance Temperature Transducers. Metrology Press, 1972.

10. Young, M. F.: Calibration of Hot-wires and Hot-Films for Velocity Fluctuations. Report TMC-3, Thermosciences Div., Mech. Eng. Dept., Stanford Univ., March 1976.

11. Acharya, M.: Effects of Compressibility on Boundary Layer Turbulence. AIAA Paper 76-334, July 1976.

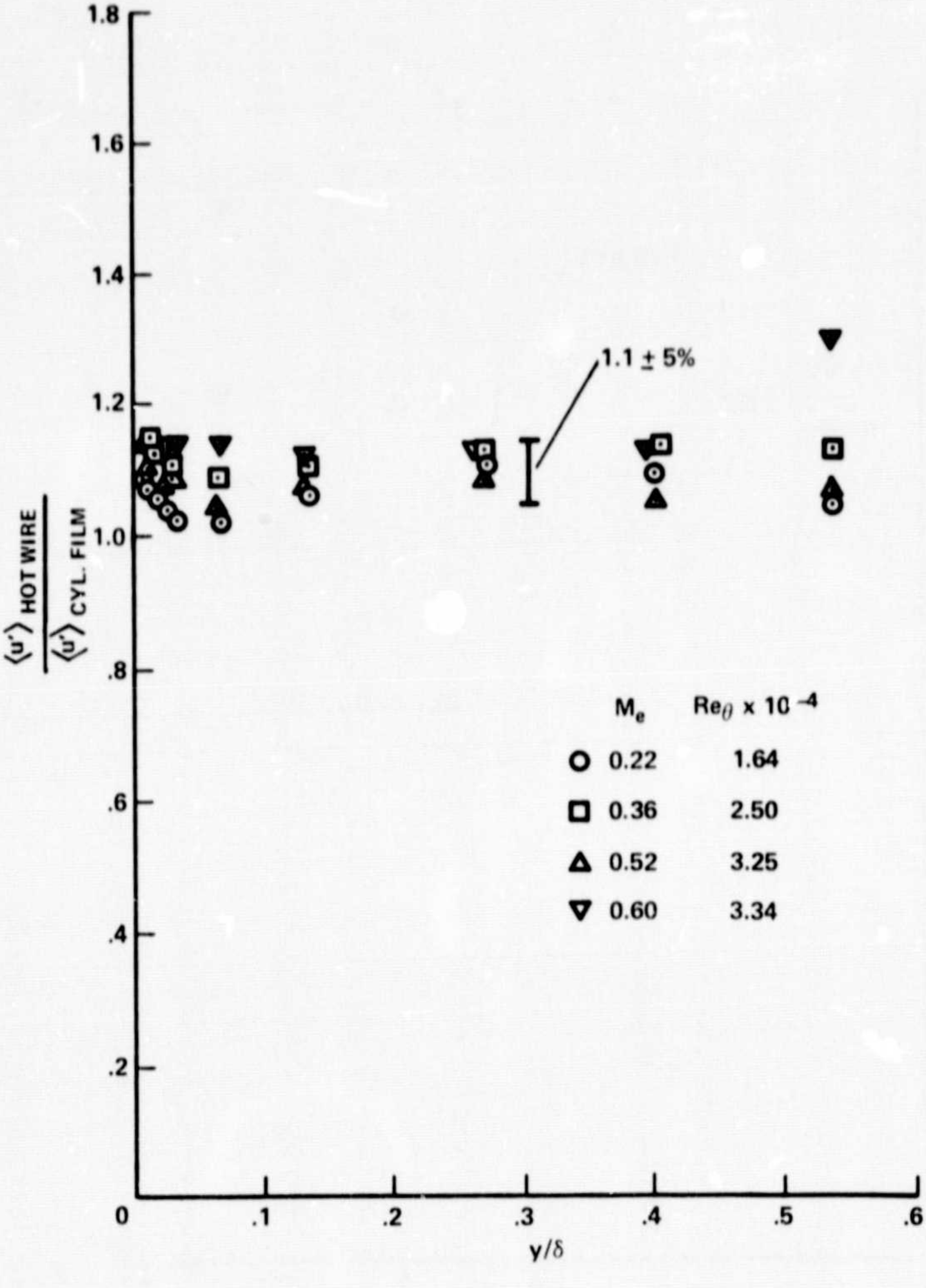

Figure 1.- Cylindrical film probe.

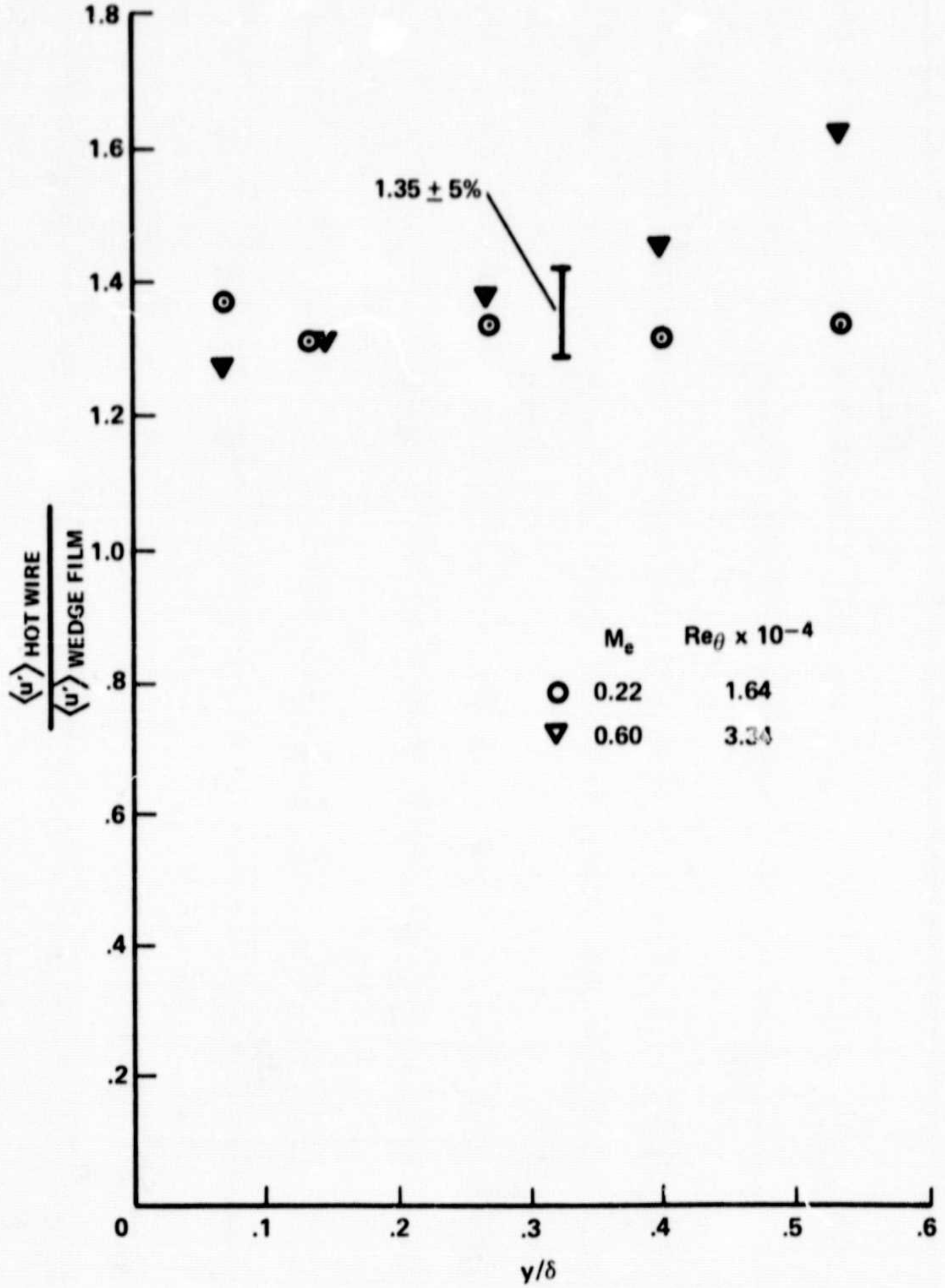

Figure 2.- Wedge film probe.

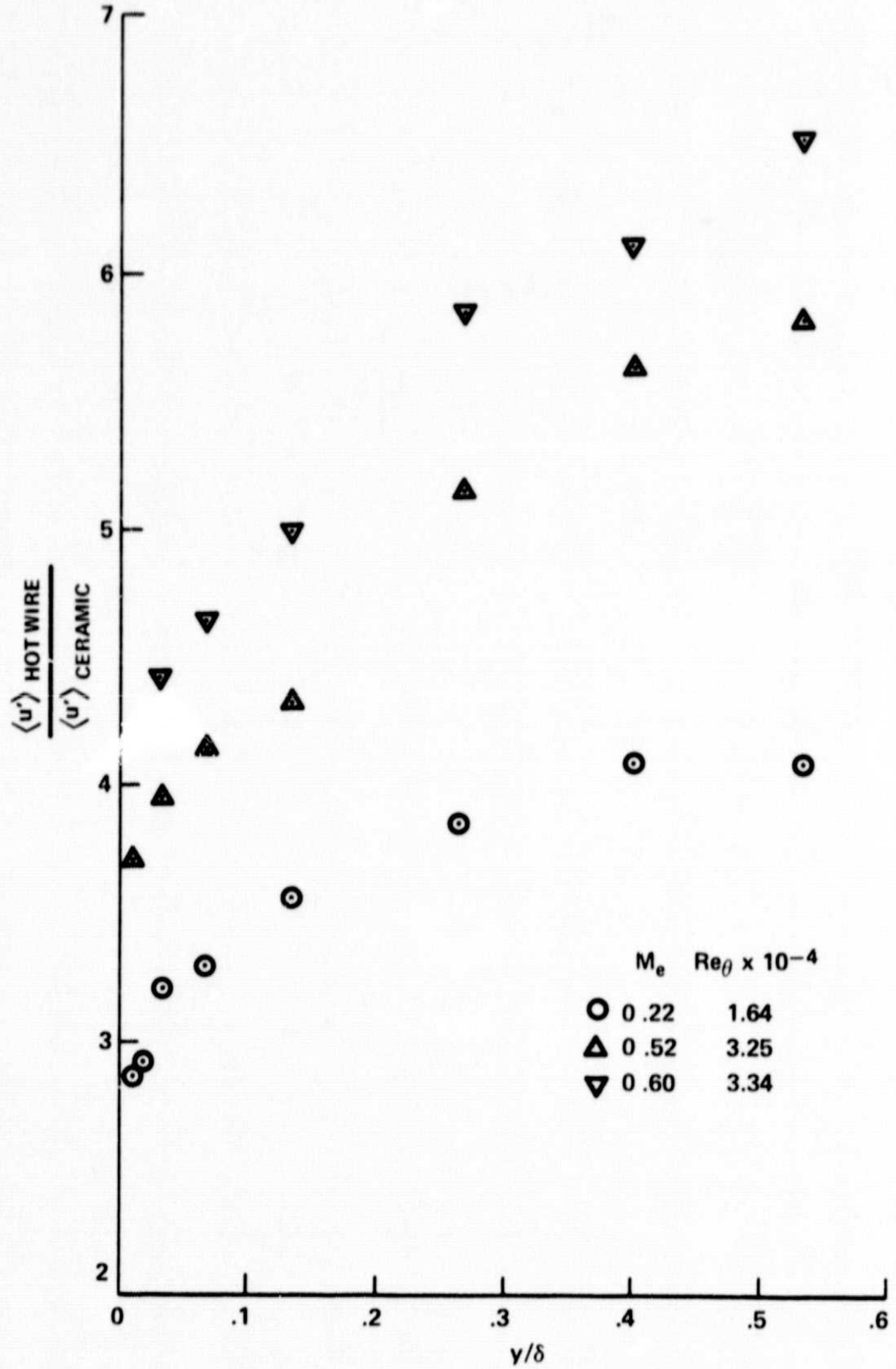

Figure 3.- Ceramic backed probe.

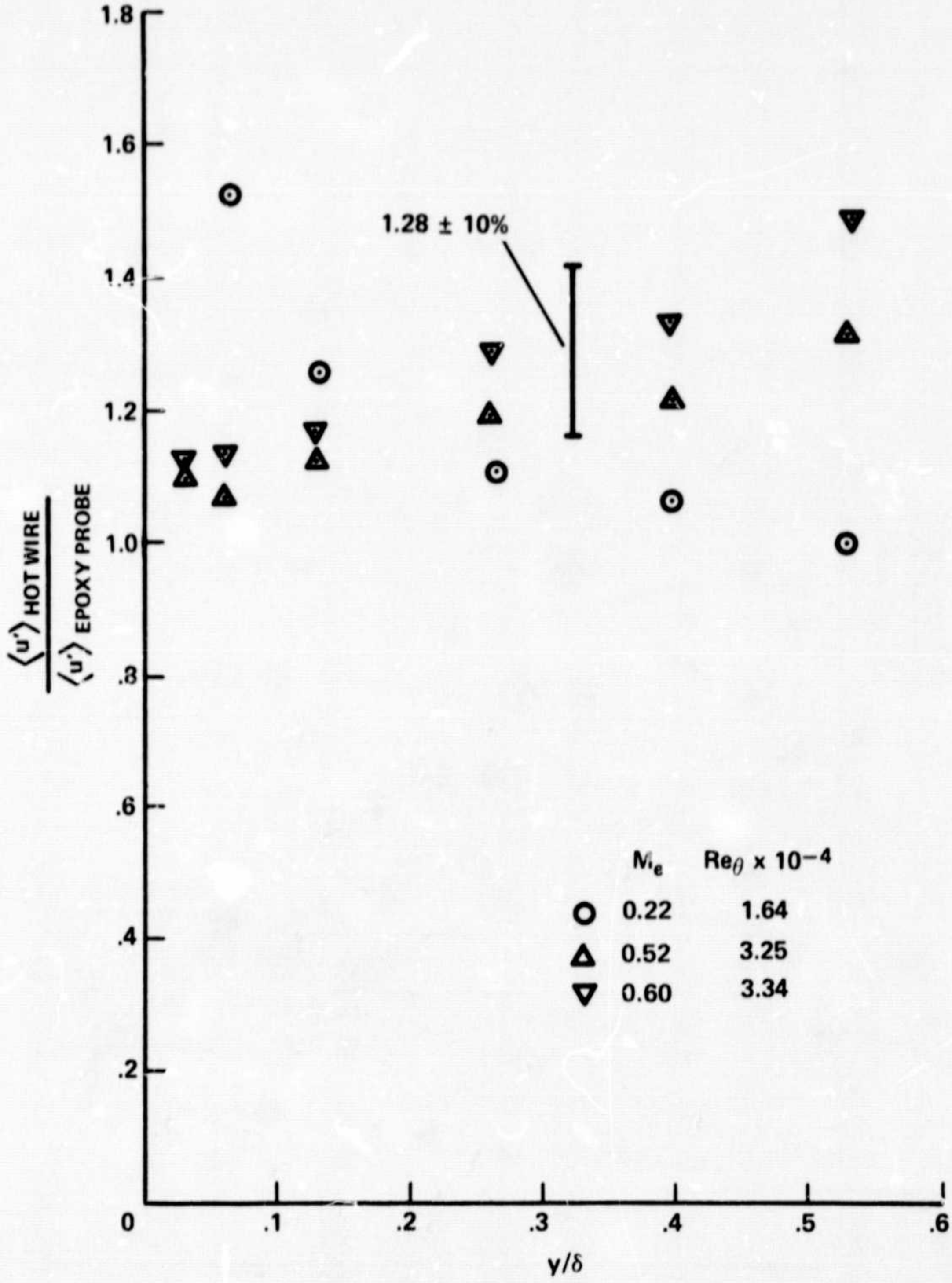

Figure 4.- Epoxy backed probe.

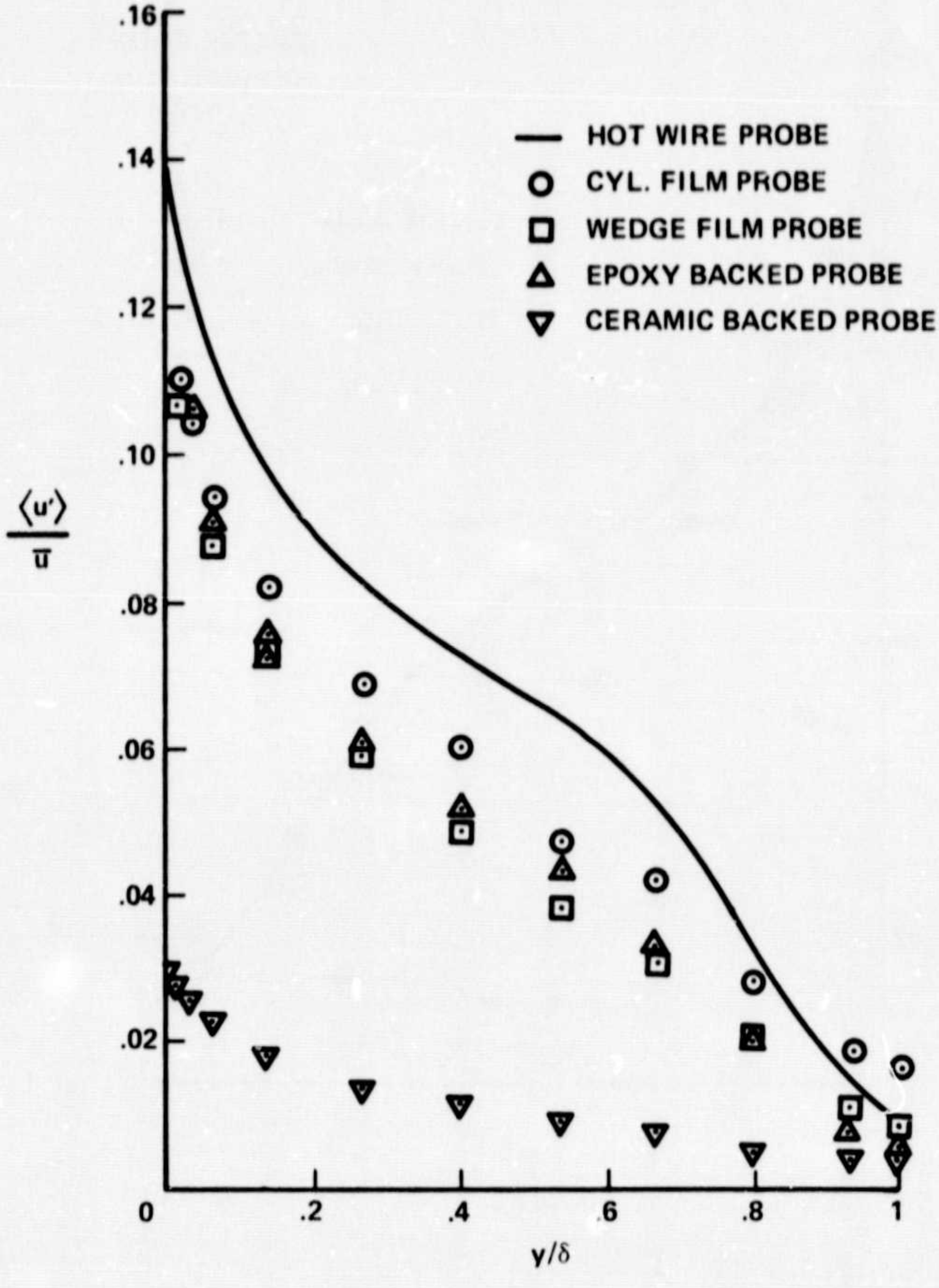

Figure 5.- Measured intensities at M_e = 0.6.

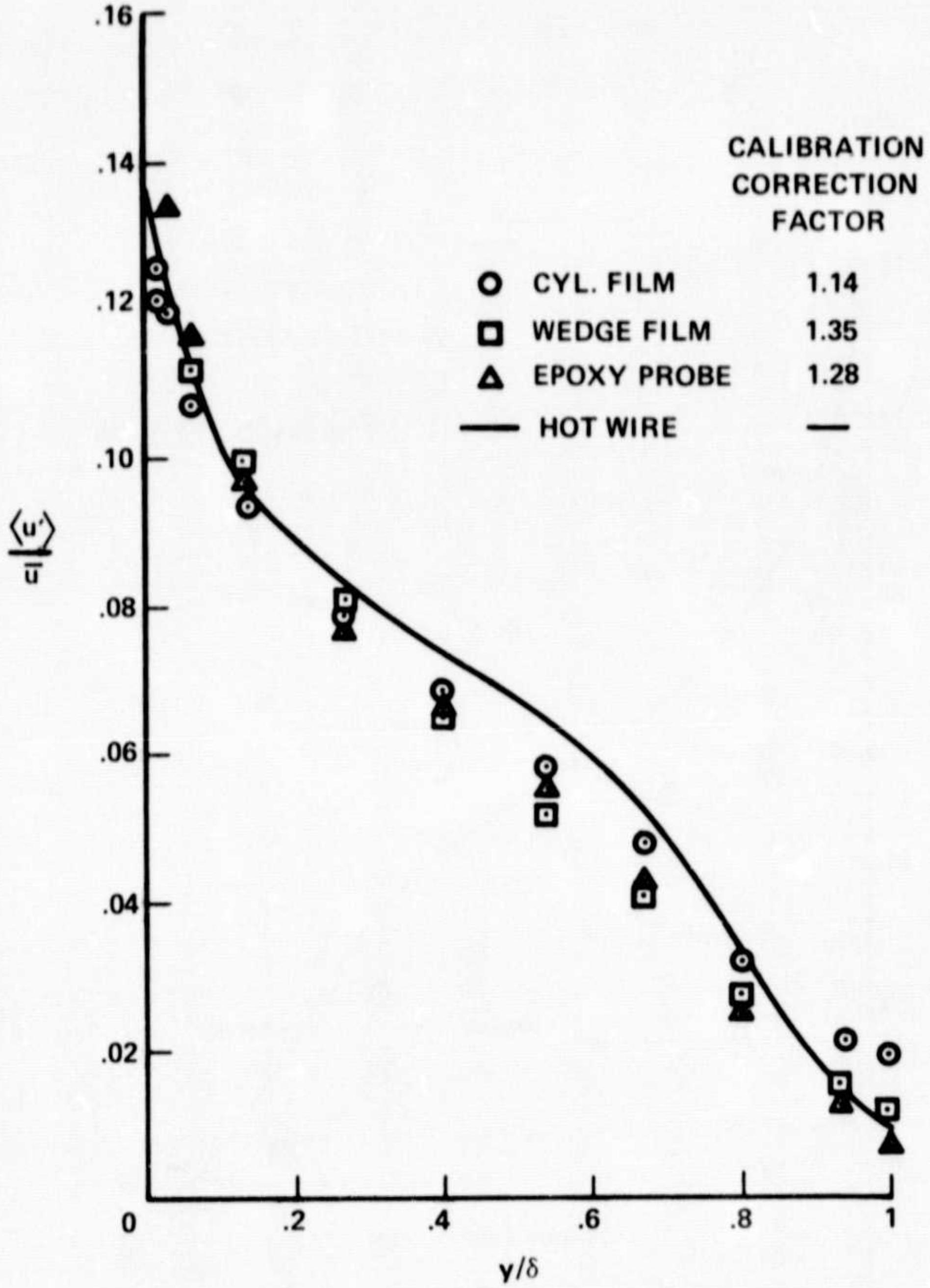

Figure 6.- Corrected intensities M_e = 0.6.

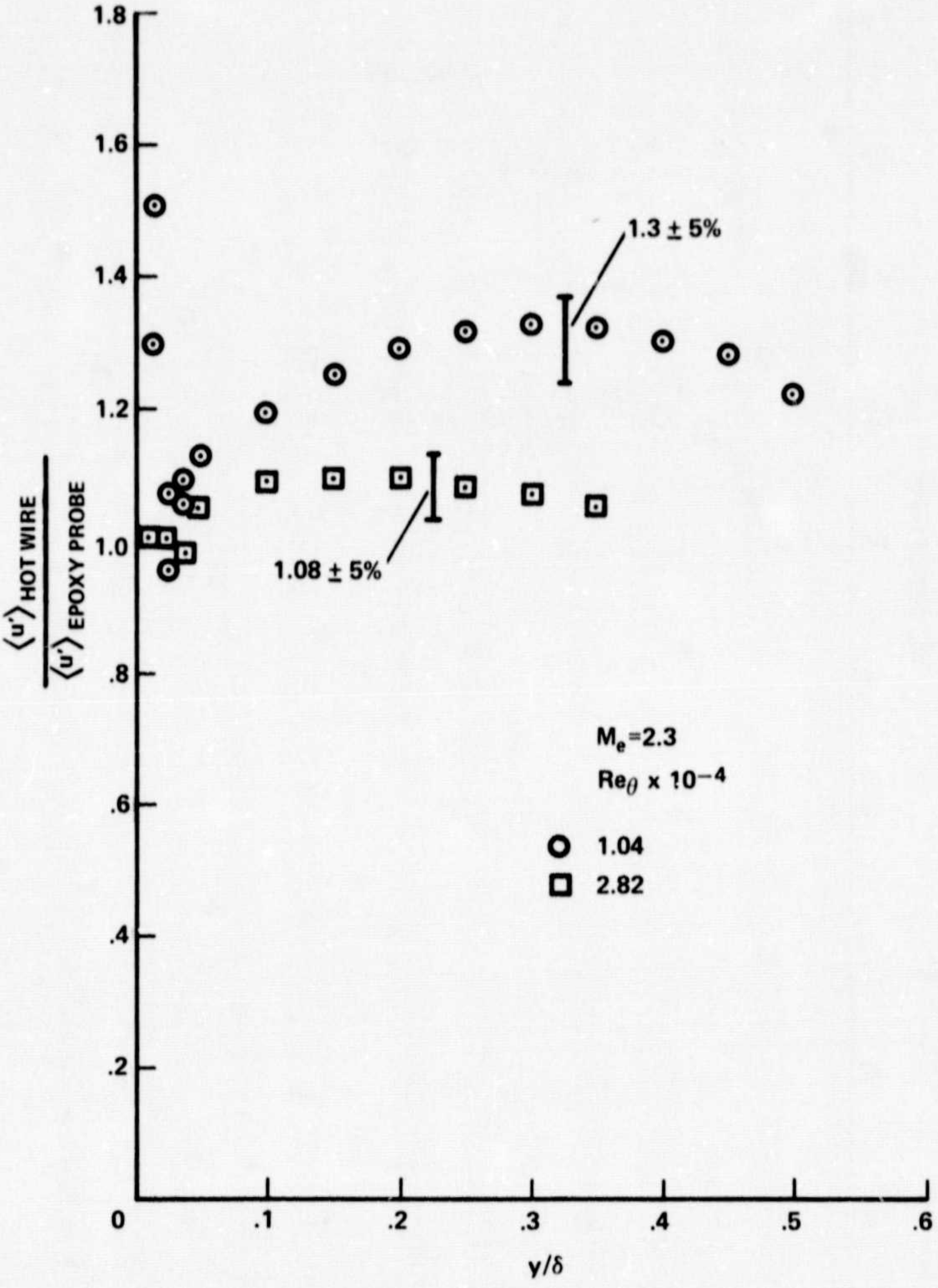

Figure 7.- Epoxy backed probe, supersonic flow.

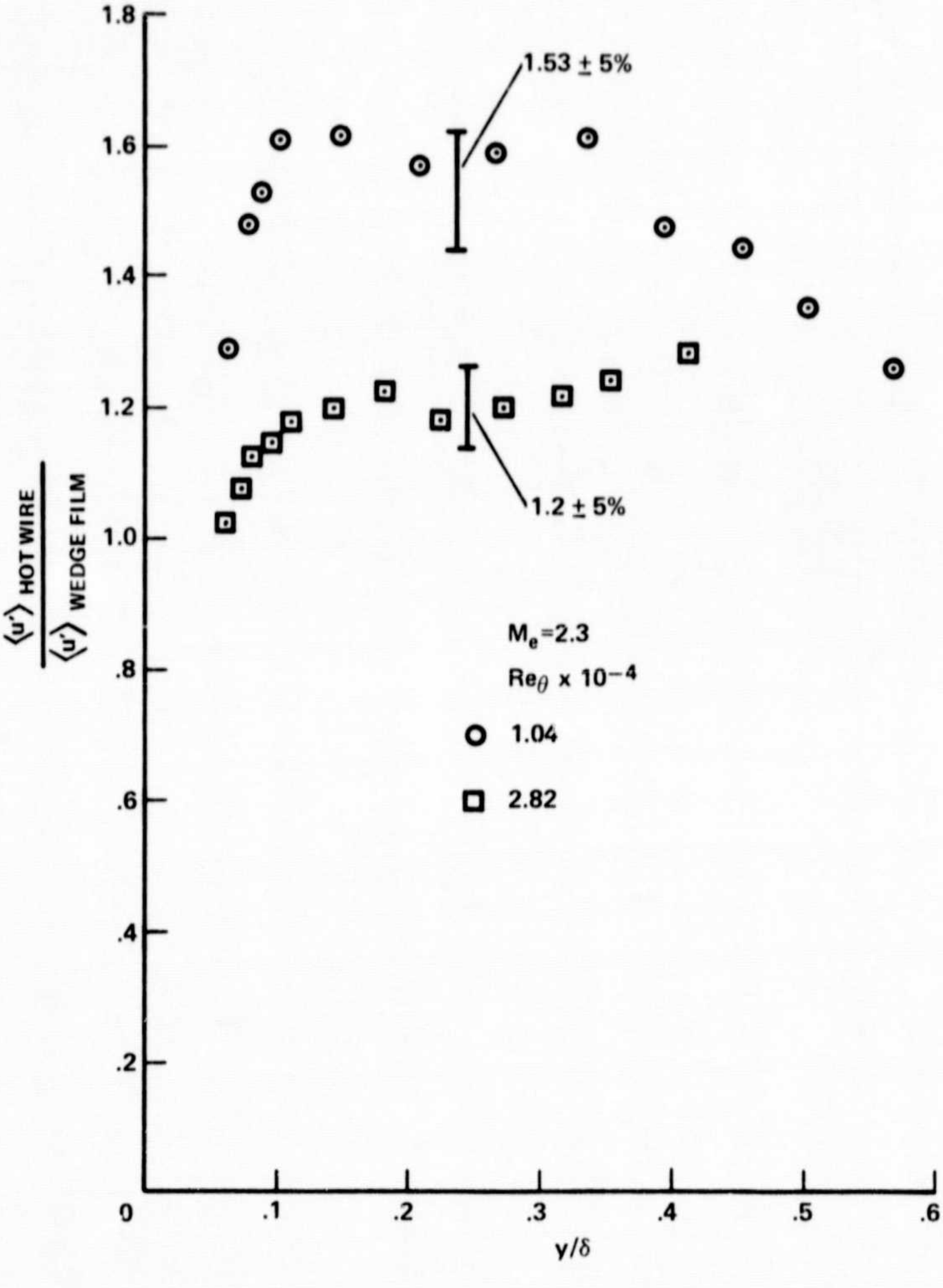

Figure 8.- Dual wedge film probe, supersonic flow.

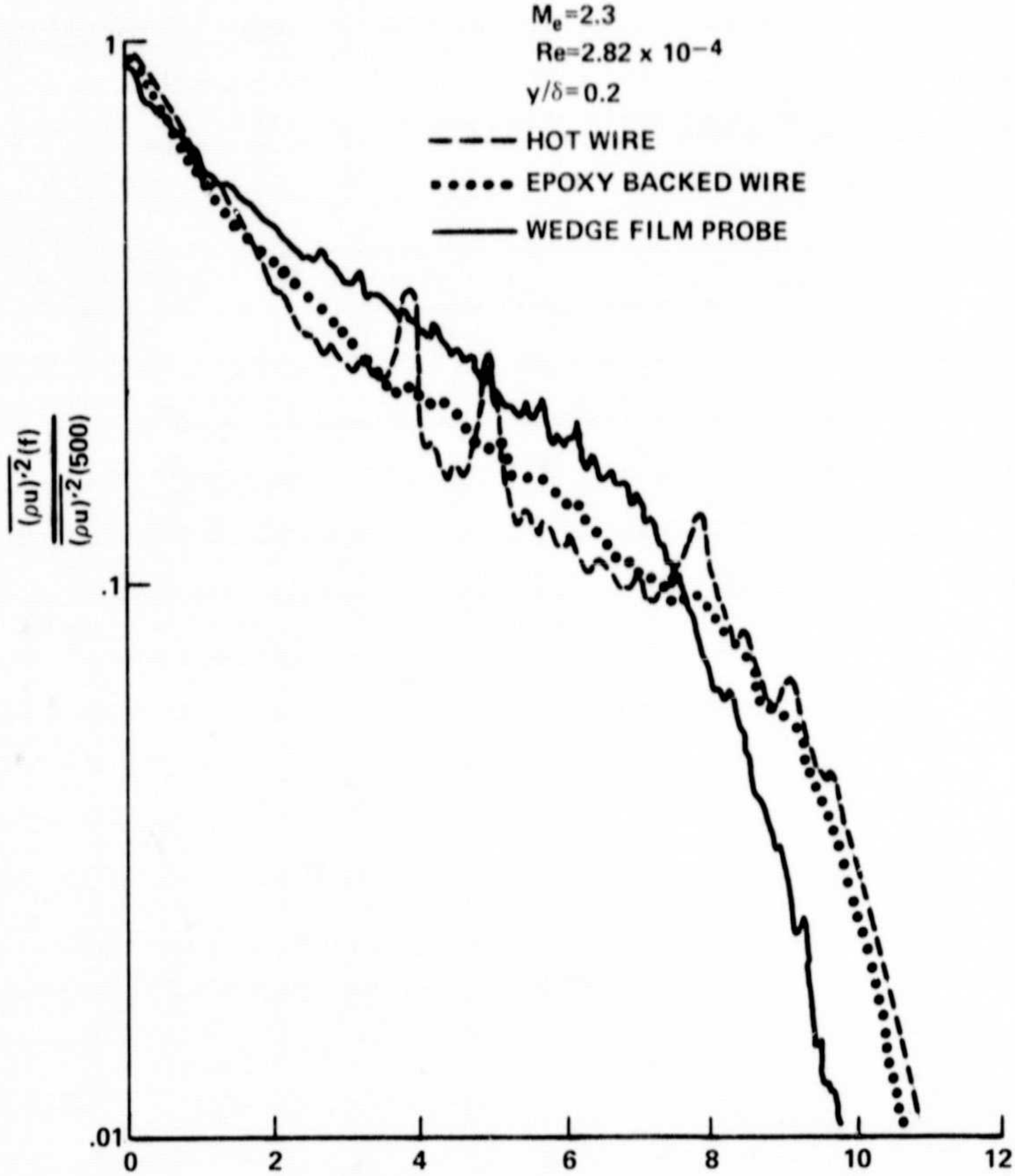

Figure 9.- Normalized spectra.