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Effect of Reynolds Number and Mach Number on Flow Angularity Probe Sensitivity

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Summary

Preliminary calibrations were performed on nine flow angularity probes in the Langley 7- by 10-Foot High-Speed Tunnel (7 × 10 HST) and the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT). These probes will be used in surveying the test section flows of the National Transonic Facility (NTF). The probes used in this study have a pyramid head with five pressure orifices. The calibrations consisted of both isolated probe measurements and rake-mounted multiprobe measurements that covered a range of subsonic Mach numbers up to 0.90 and Reynolds numbers per foot up to 40×10^6.

The preliminary calibration in the 7 × 10 HST included testing the probes both individually and in a rake. The 0.3-m TCT calibration tested two probes singly at varying Reynolds numbers. The results from these tests include Mach number, Reynolds number, and rake-mounting effects.

The results of these tests showed probe sensitivity to be slightly affected by Mach number. At Reynolds numbers per foot above 10×10^6, the probe did not exhibit a Reynolds number sensitivity.

Introduction

As part of the calibration program planned for the National Transonic Facility (NTF), the distribution of mean flow angularity of the test section will be obtained by using nine five-hole, pyramid-head pressure probes and the associated data-analysis methods as described in references 1, 2, and 3. Pyramid-head probes have several advantages over conical or hemispherical probes because of their flat surfaces. The lower pressure gradient across these surfaces results in reduced sensitivity to orifice location, Reynolds number effects, compressibility effects, and roll alignment (ref. 1).

The calibration was conducted in two phases. First, the probes were calibrated in the Langley 7- by 10-Foot High-Speed Tunnel (7 × 10 HST), both individually and in the NTF multiprobe rake. The Mach number was varied between 0.4 and 0.9. Since this is an atmospheric facility, no Reynolds number control was available. The rake test investigated the effect of the flow field produced by the rake on probe sensitivity. Second, in order to determine Reynolds number and Mach number effects on the probe sensitivities, two of the probes were tested individually in the 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT). The Mach number range of 0.4 to 0.9 was repeated, and Reynolds numbers per foot up to 40×10^6 were run.

Since the magnitude of flow angularity in transonic test sections generally does not exceed 0.5°, the probe inclination angles for these calibrations were limited to ±4°.

Symbols

C_p	pressure coefficient, either $C_{p,12}$ or $C_{p,34}$
$C_{p,12}$	pressure coefficient for orifices 1 and 2 (see eq. (1))
$C_{p,34}$	pressure coefficient for orifices 3 and 4 (see eq. (2))
M	Mach number
P_T	tunnel total pressure, psi
P_1	pressure measured at orifice 1, psi
P_2	pressure measured at orifice 2, psi
P_3	pressure measured at orifice 3, psi
P_4	pressure measured at orifice 4, psi
R	Reynolds number per foot
α_p	angle of probe axis relative to horizontal, deg
α_f	angle of flow, deg
$\left\lvert \frac{\Delta C_p}{\text{deg}} \right\rvert_{\text{av}}$	probe sensitivity

Test Facilities

The 7 × 10 HST is a closed-circuit atmospheric tunnel with a rectangular unventilated test section. Its maximum Mach number capability is 0.90 (ref. 4), and the Mach number can be controlled to ±0.002. Models can be mounted on either a turntable on the sidewall or on the vertical sting support system. The tests reported herein were made from the support system.

The 0.3-m TCT is a closed circuit cryogenic pressure tunnel. Its test section is rectangular, 8 by 24 inches, with solid sidewalls and two longitudinal slots each in the top and bottom walls. It can operate over stagnation temperature and pressure ranges of 80 to 340 K and 17 to 88 psi, respectively. Tunnel temperature can be controlled to ±0.5 K and pressure can be held to ±0.05 psi. Subsonic Mach numbers up to 0.90 can be controlled to within ±0.002 (ref. 5).

Apparatus

Probes

Figure 1 is a drawing of a typical probe used in this test. The probe is designed with its tip

18.67 diameters ahead of the first flare so that the flow field induced by the flare does not interfere with the flow at the tip (ref. 1). The material used in constructing the probes was AMS 5737 H stainless steel (A286), which is compatible with the cryogenic environment of NTF (ref. 6). The probe tip was machined and the orifices drilled (0.02 inch diameter) to produce a high degree of symmetry of the angled surfaces and orifice locations. This tip was then soldered to the main body of the probe.

Rake

The rake used in this test is illustrated in figure 2. It is 5 feet wide with a 7-inch tip chord and holds nine probes at a spacing of 7 inches. The cross section of the rake is a wedge slab wedge with an included wedge angle of 15°. The maximum thickness of the cross section is 0.6 inch at the tips of the rake and 1.0 inch in the center. The rake is made of 18Ni-200 maraging steel, also compatible with the NTF environment (ref. 6).

Instrumentation

For the 7 × 10 HST calibrations, an inertial angle of incidence system (accelerometer) was installed at the base of the sting. For the rake test, an additional identical system was installed in the sting immediately downstream of the rake to eliminate sting bending effects. These accelerometers have an accuracy of ±0.02°. An inclinometer placed on a reference surface on the sting was used to determine zero angle of incidence.

In the 0.3-m TCT, angle of incidence is measured from one of two turntables mounted in the test section sidewalls. The angular position of the turntable is measured by an accelerometer. For this test, the base of the probe was mounted in a 1-inch-diameter cylinder which spanned the tunnel and joined the turntables. The cylinder was offset from the center of the turntable such that changing probe incidence angle left the probe tip on the tunnel centerline. This setup is illustrated in figure 3. To determine zero angle of incidence, an electrolytic bubble was mounted near the probe tip. The bubble levels relative to the horizon and is accurate to ±0.01°.

For pressure measurements, two different systems were utilized. In the 7 × 10 HST an electronically scanned pressure sensor (ESP) was used. This system allows pressures to be taken almost simultaneously. The quoted accuracy of these gauges is 0.25 percent of full scale. For this test, a 5-psi gauge was required and gave an error of ±0.01 psi.

In the 0.3-m TCT, barocells were used. Each orifice was hooked to a separate gauge so that simultaneous measurements could be taken. Accuracy of the barocells is 0.25 percent of reading.

Procedure

The procedure for calibrating probes outlined in reference 3 was used in this study. For a fixed free-stream Mach number, the probes were rolled three times in 90° increments. For each roll setting, the probes were swept through a range of angle of incidence. This process obtained upright and inverted runs for both sets of orifices. The calibration pressure coefficients $C_{p,12}$ and $C_{p,34}$ were obtained by using the following equations:

$$C_{p,12} = \frac{P_1 - P_2}{P_T - \frac{1}{4}(P_1 + P_2 + P_3 + P_4)} \tag{1}$$

$$C_{p,34} = \frac{P_3 - P_4}{P_T - \frac{1}{4}(P_1 + P_2 + P_3 + P_4)} \tag{2}$$

(See fig. 1 for orifice numbering scheme.) The use of $C_{p,12}$ or $C_{p,34}$ is determined by the pair of orifices in the pitch plane. Figure 4 illustrates how tunnel flow angularity and probe asymmetries would be reflected in a typical calibration plot. The point where the probe is aligned with the flow is represented by the intersection of the plots for the upright and inverted cases. The deviation of this point from the zero incidence axis indicates the deviation of the local tunnel flow from the reference axis. This local flow angle should be used as a correction when making additional angularity measurements of this position in the tunnel. If the intersection deviates from the axis at $C_p = 0$, a nonsymmetrical probe correction is indicated.

For the purpose of this study, the most important quantity was the slope of the plots, the probe sensitivity. This slope was assumed to be constant, a property of the probe at a given set of test conditions. It was believed that this slope, once determined, would be transferable to NTF. NTF calibration plots would be drawn by using one data point and the predetermined slope to draw a line through that data point. Consequently, only two data points would be needed to correct for tunnel flow angularity for a given condition. However, test results precluded this assumption, as discussed later.

7 × 10 HST

The first calibration was conducted in the 7 × 10 HST. It consisted of two parts: a single-probe calibration and a rake calibration. For the single-probe calibration, the nine probes were individually tested on a long, slender conical sting (fig. 5). The probes were swept through a range of angle of incidence from -4° to 4° in 1° increments. Between -1° and 1°, the probes were stepped in 0.5° increments. The probe was pitched while Mach number was held constant at settings of 0.4, 0.6, 0.8, and 0.9. Each probe required three 90° rolls to obtain upright and inverted information for both pairs of orifices. These rolls required that the probe be removed from the sting and remounted. The tolerance of the fit between the probe and probe holder gave an angle of incidence uncertainty of about 0.03°.

The rake calibration tested all nine probes at once. With the rake horizontal, orifices 3 and 4 were calibrated; with the rake vertical, orifices 1 and 2 were calibrated. Figure 6 shows this in more detail. To insure that the probes stayed at the same point in the flow, upright and inverted runs were obtained by rolling the probes individually instead of rolling the rake. The test procedures and conditions were the same as for the single-probe test with the exception that the highest Mach number was 0.85 rather than 0.9 because of flow blockage of the rake.

0.3-m TCT

The second calibration was conducted in the 0.3-m TCT. The two most symmetrical probes as indicated by the 7×10 HST results were tested over a range of Reynolds numbers to determine the effect on probe sensitivity. For each Reynolds number and Mach number, the angle of incidence was varied from -4° to 4° and the probe pressure readings recorded. The test Reynolds numbers per foot were 10×10^6, 20×10^6, and 40×10^6, as well as a low Reynolds number per foot (around 3×10^6) for comparison to 7×10 HST data. These Reynolds numbers were obtained by various combinations of temperature and pressure. In the 0.3-m TCT, only one pair of orifices was tested in order to reduce the time required for the test. Also the highest Mach number, 0.9, was dropped.

Results

Examination of the data resulting from these tests showed that the sensitivities were not affected by high Reynolds or Mach numbers. The rake was found to affect probe sensitivities only if placed in a plane where it could act as a lifting surface.

7×10 HST

Shown in figure 7 is a plot of sensitivity against Mach number for two different probes; these probes were chosen because calibration sensitivities for the rest of the probes are bracketed by the data shown in figure 7. As can be noted in this figure, the sensitivities for orifices 3 and 4 were very close to the sensitivities for orifices 1 and 2; this indicates probe symmetry. The data in this figure appear to show that the sensitivities are not significantly affected by Mach number. However, Reynolds number was varying with Mach number which may have influenced the data. The data in figure 8 show only a slight effect of Mach number on vertical offset (probe asymmetry effect) of the calibration line. Data for both the single probe and rake configurations are presented with the rake having no observable effect on vertical offset.

Figure 9 illustrates the tunnel flow angle as measured by two of the probes. This angle appears to be a function of Mach number. The scatter in the data is attributable to the accuracy in repositioning the probe axis relative to the probe-holder axis for both the upright and inverted runs. Even though the probe was positioned with set screws, it is unlikely that it was set to exactly the same angle each time.

Sensitivities measured for the probes mounted in the rake at Mach numbers 0.4, 0.6, 0.8, and 0.85 are presented in figure 10. There is a substantial difference between the sensitivities for the rake in the horizontal position (calibrating orifices 3 and 4) and in the vertical position (calibrating orifices 1 and 2). This difference is caused by the lift of the rake, which induces a flow angle at the probe tip that varies with angle of attack. Note, this lift is only present when the rake is oriented horizontally.

In order to analyze the effect of rake lift on the sensitivities, the subsonic vortex lattice method (VLM) described in reference 7 was used to determine the lift-induced flow angles for a Mach number of 0.4. The probe sensitivities were averaged for the rake vertical position, shown in figure 10(a) by the lower dashed line. This sensitivity value was then corrected for the induced angles across the span. The result is the upper dashed line which shows that the rake lift does account for the majority of the sensitivity difference. The difference between the theoretical curve and the experimental data reflects the sensitivity difference between the individual probes; that is, the character of the rake vertical curve is reflected in the rake horizontal curve.

If the rake is used in the vertical position to calibrate a tunnel, rake horizontal sensitivities should be applied to the yaw orifices because any yaw angle present will produce lift on the rake.

0.3-m TCT

Data from the two probes tested in the 0.3-m TCT are presented in figures 11 through 14. Figure 11 shows the effects of Mach number on the probe sensitivity at constant Reynolds number. At a Mach number of 0.6, the two different values shown for a Reynolds number per foot of 10×10^6 were obtained by using different combinations of temperature and pressure to achieve the desired Reynolds number. At this time no explanation for the difference is given, although differences in dynamic pressure may be a cause.

Figure 12 shows the effects of Reynolds number at constant Mach number. Above a Reynolds number per foot of 10×10^6, the curves change very little; below this value there is a substantial probe sensitivity to Reynolds number.

Vertical offset data for 0.3-m TCT showed a slight linear variation with Mach number or Reynolds number. (See figs. 13 and 14.) This result is consistent with results obtained in 7 × 10 HST as shown in figure 8.

Comparison of 7 × 10 HST and 0.3-m TCT Results

Figure 12 shows both 7 × 10 HST and 0.3-m TCT single-probe data. Extrapolating the 0.3-m TCT data to a Reynolds number equal to that of the 7 × 10 HST data yields sensitivities approximately 5 percent higher than the 7 × 10 HST results. This difference is equal to a 0.2° shift in angle of attack at 4°.

Part of the difference in the 7 × 10 HST and 0.3-m TCT sensitivities was due to the mounting systems. The probe support hardware used in the 0.3-m TCT test produced a flow angle at the tip of the probe. With the use of the subsonic VLM code of reference 7, it was found that the sidearms produced a flow angle of 0.008° at a probe angle of 4° and a Mach number of 0.4. The cylinder spanning the tunnel (fig. 3) also perturbed the flow at the probe tip. Because the cylinder was moved to an off-center position when the probe was pitched, the cylinder set up an imbalance in the flow through the tunnel ceiling and floor slots. In addition, the presence of the cylinder disturbed the flow at the probe tip location. These effects were studied by using the slotted tunnel interference predictor (STIPPAN) of reference 8 and FLO-36, a flow analysis code of reference 9. At an angle of incidence of 4° and a Mach number of 0.4, these effects combined to induce a flow angle of 0.080° at the probe tip. The total angle induced at the probe tip was 0.088°. The rest of the difference can possibly be attributed to Reynolds number effects or other tunnel differences.

Concluding Remarks

Nine pyramid-head pressure probes were calibrated both individually and in a rake in the Langley 7- by 10-Foot High-Speed Tunnel (7 × 10 HST) and individually in the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT) to determine Mach number, Reynolds number, and rake effects on probe sensitivities.

Mach number was found to have only a slight effect on probe sensitivity. Reynolds number per foot changes above 10×10^6 did not affect the sensitivities, but sensitivities decreased with decreasing Reynolds number per foot below 10×10^6. Using different values of pressure and temperature to set Reynolds number appears to have some effect on sensitivity. This effect needs to be studied further.

The probe rake, when oriented in the horizontal plane, generated lift when at an angle of attack and therefore induced higher probe sensitivities. These higher sensitivities should be used whenever flow angularity is being measured in a plane normal to the rake blade.

The differences in probe sensitivity observed by comparing 7 × 10 HST data with 0.3-m TCT data raises a question as to the usefulness of transferring calibration data from one tunnel to another. The probe sensitivity can be largely affected by factors such as the mounting arrangement and tunnel configuration. Therefore, a probe calibration done in one tunnel would need a large number of corrections applied to it before it could be used in a second tunnel. For this reason, it is presently anticipated that these probes will be calibrated in NTF.

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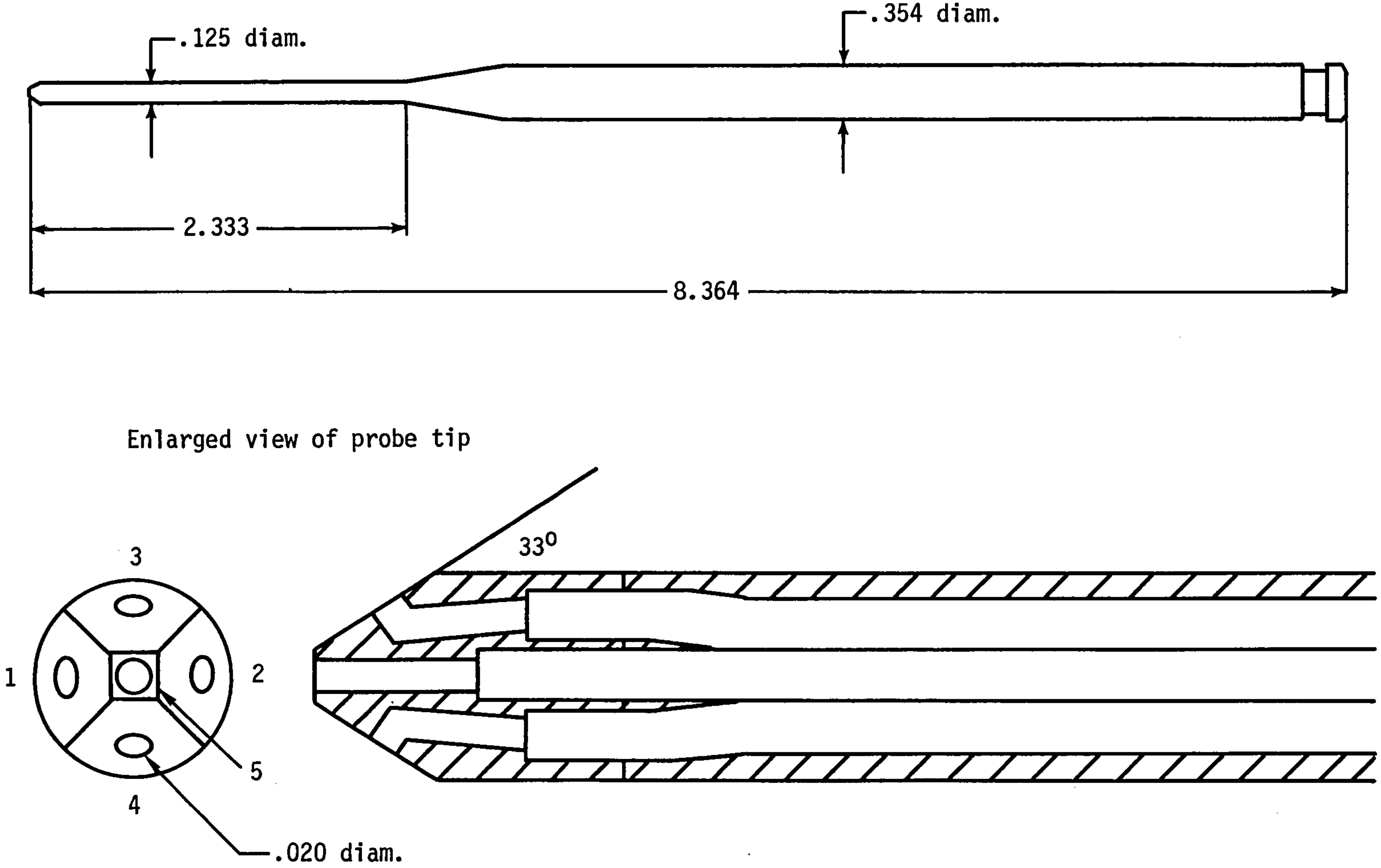

Figure 1. Five-hole pyramid-head flow angularity probe. Linear dimensions are in inches.

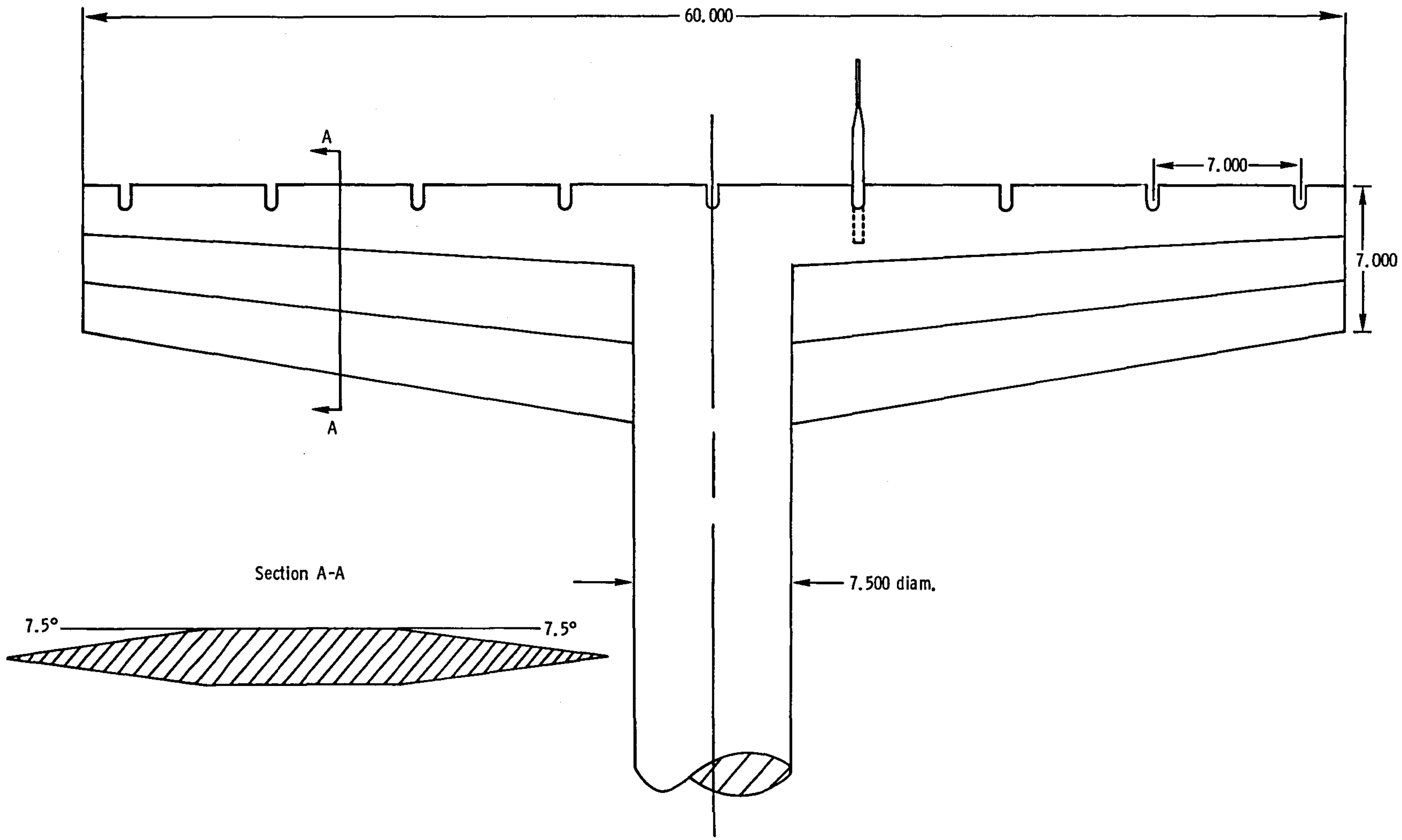

Figure 2. Rake geometry details. Linear dimensions are in inches.

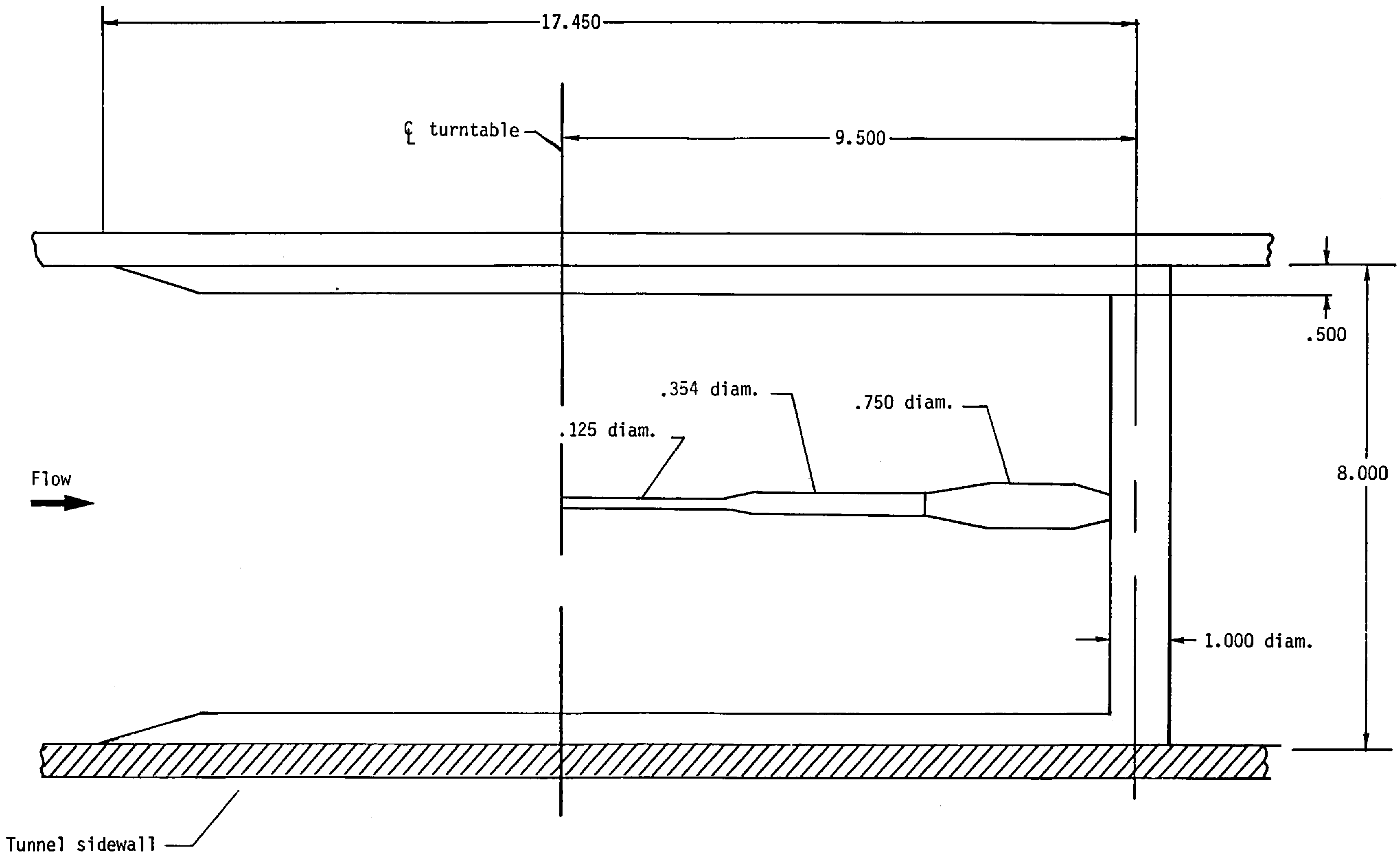

Figure 3. Test arrangement of 0.3-m TCT. Linear dimensions are in inches.

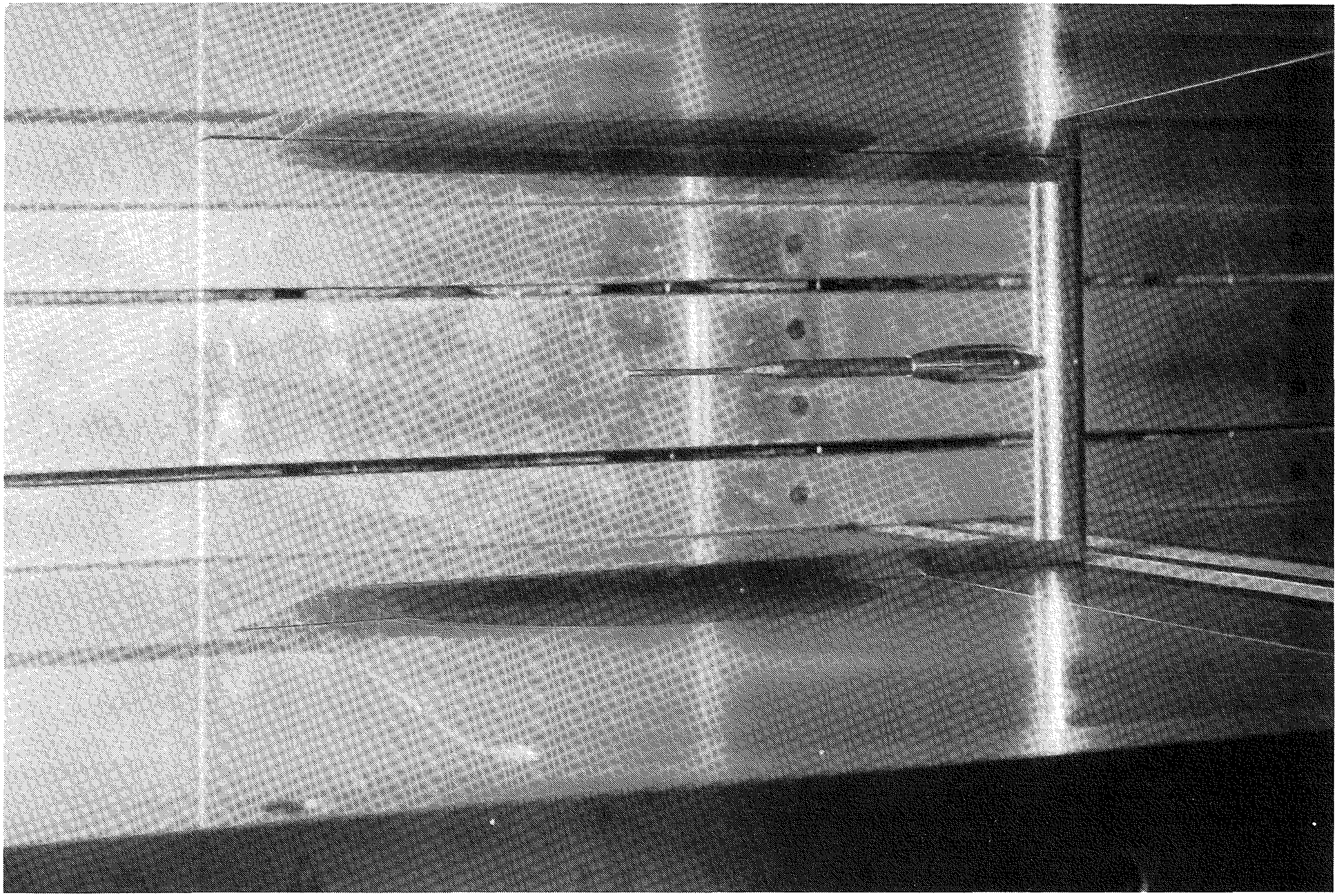

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Figure 3. Concluded.

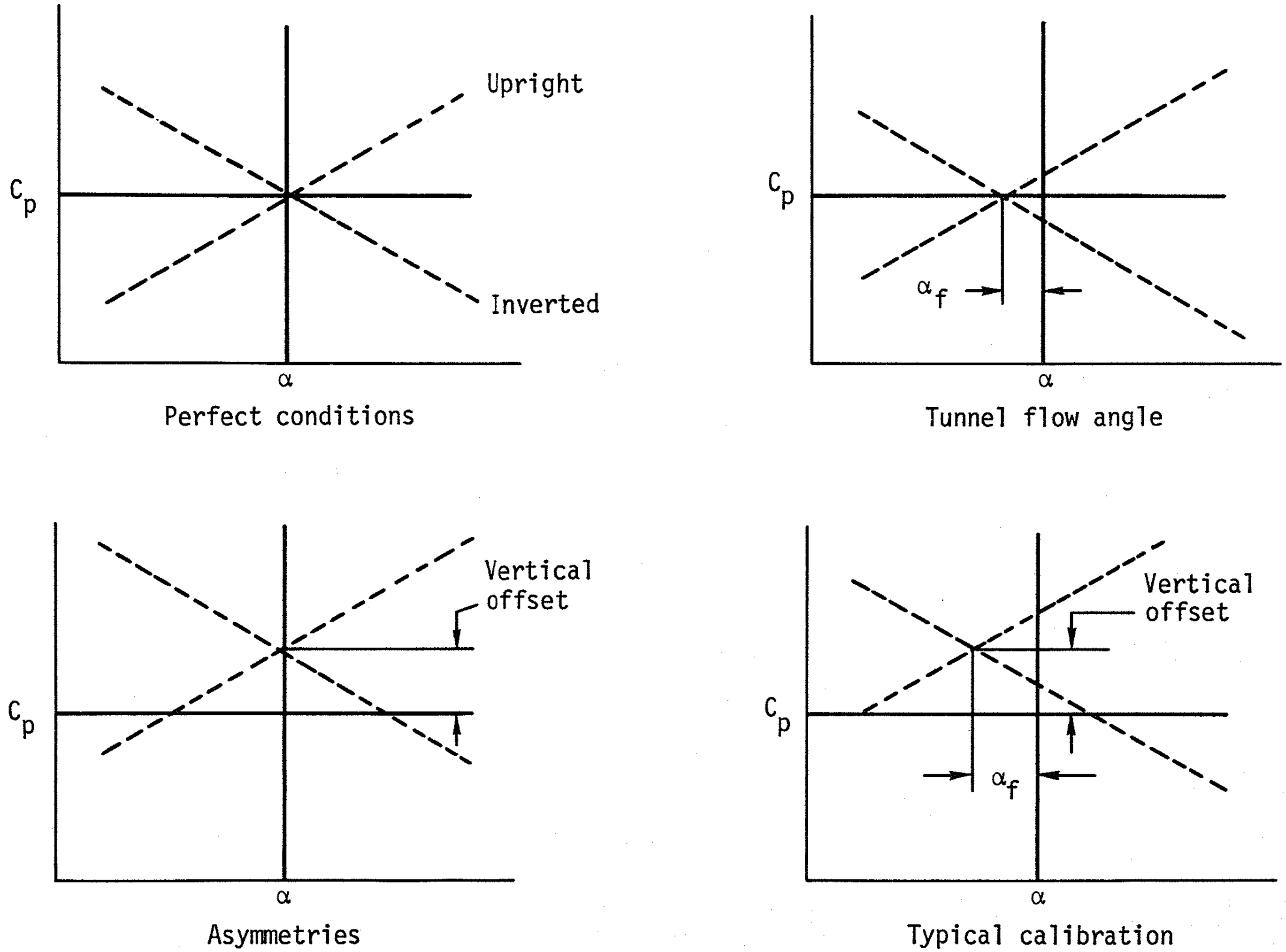

Figure 4. Calibration plots.

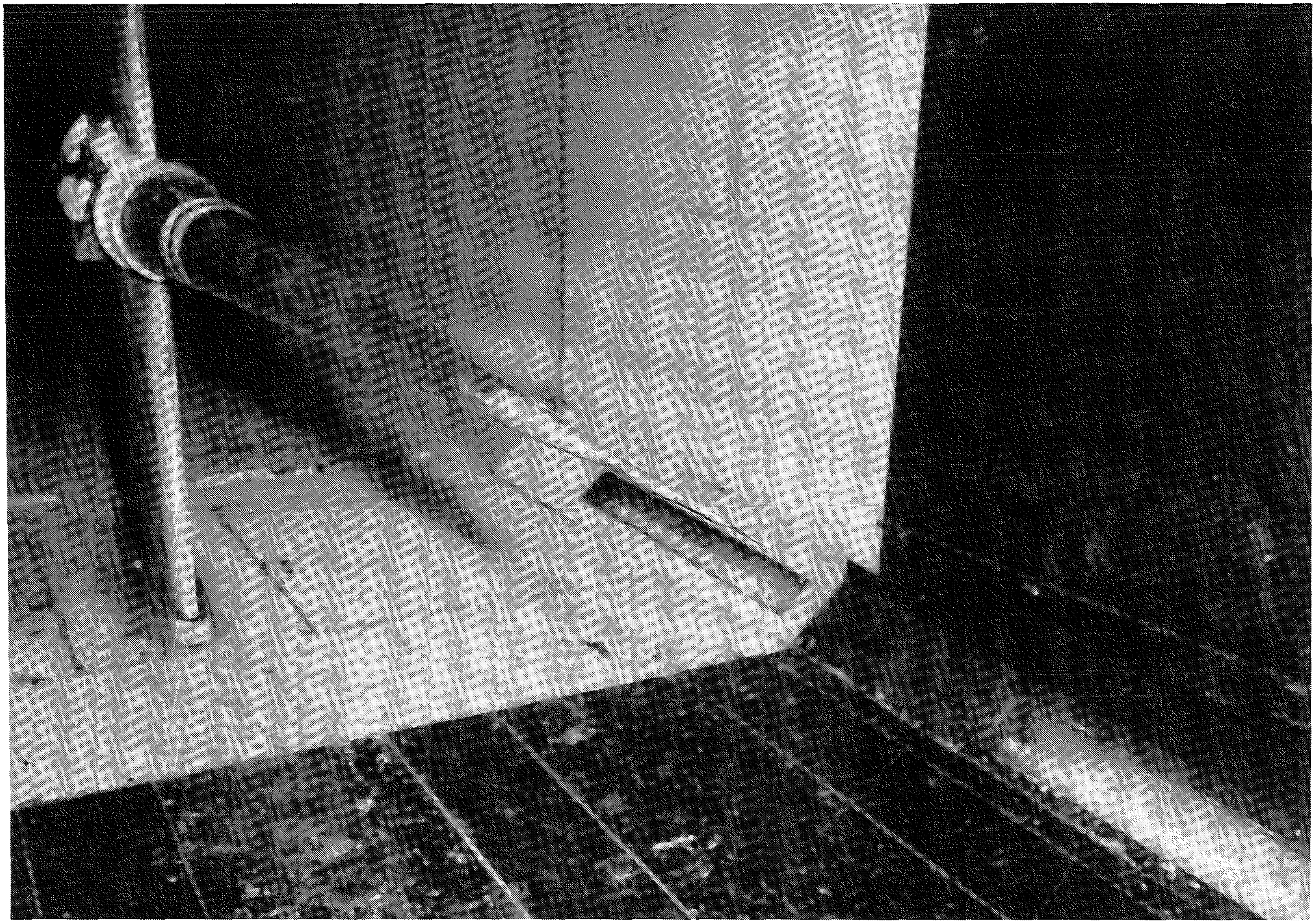

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Figure 5. Single-probe configuration in 7×10 HST.

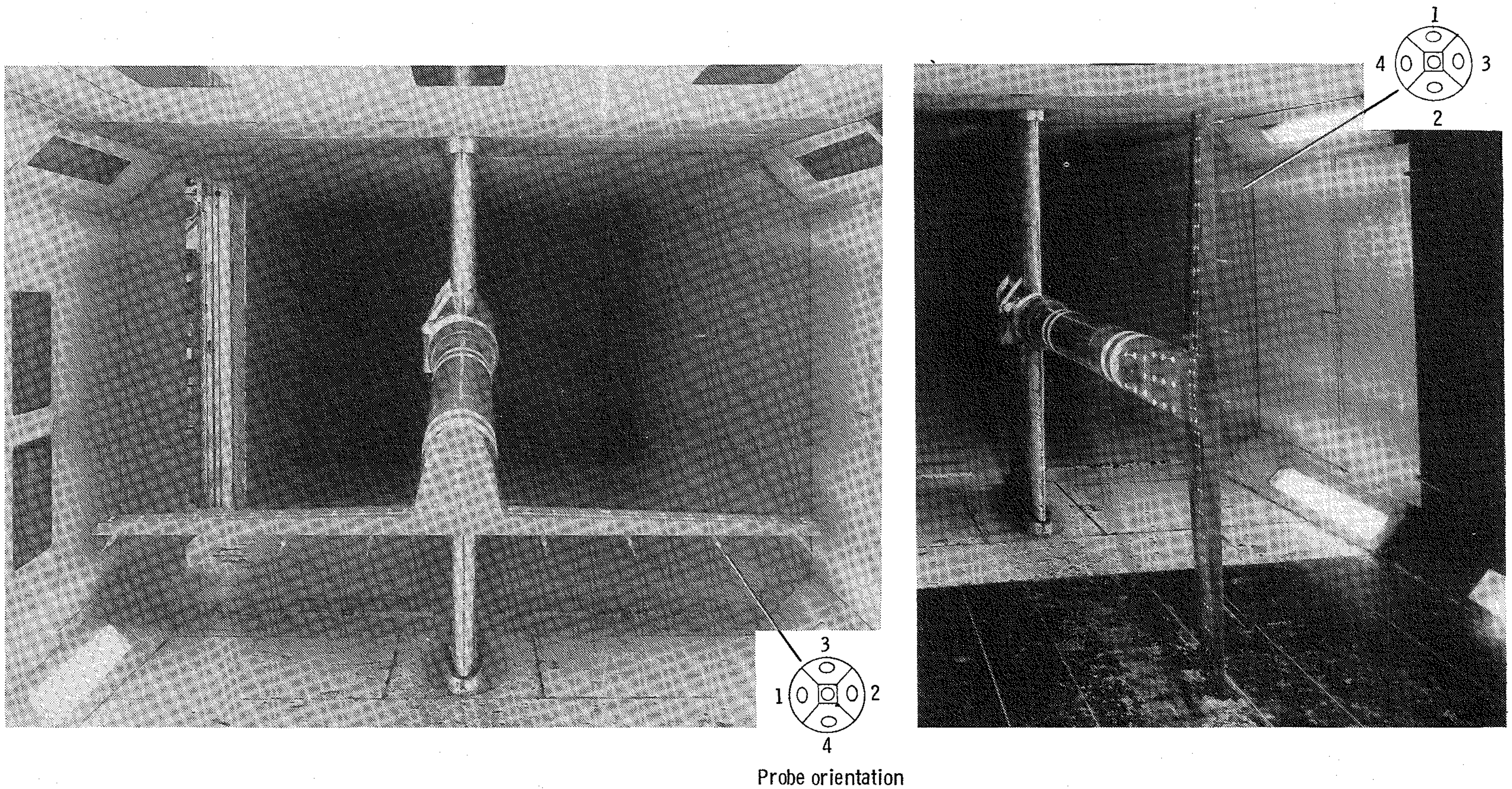

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Figure 6. Probe rake installation in 7 × 10 HST.

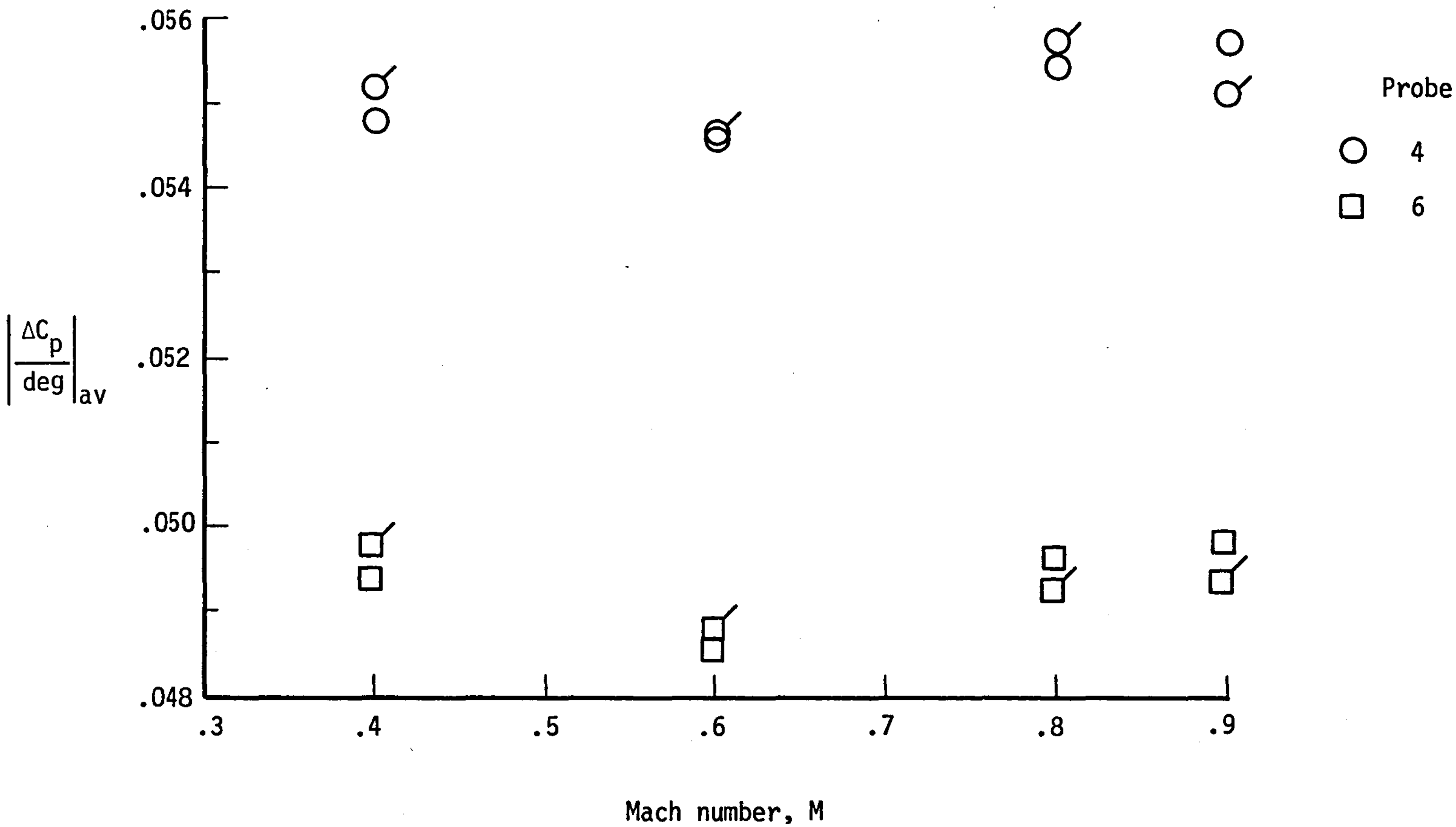


Figure 7. Mach number effects on probe sensitivities in 7 × 10 HST. Symbols without ticks are for orifices 3 and 4; symbols with ticks are for orifices 1 and 2.

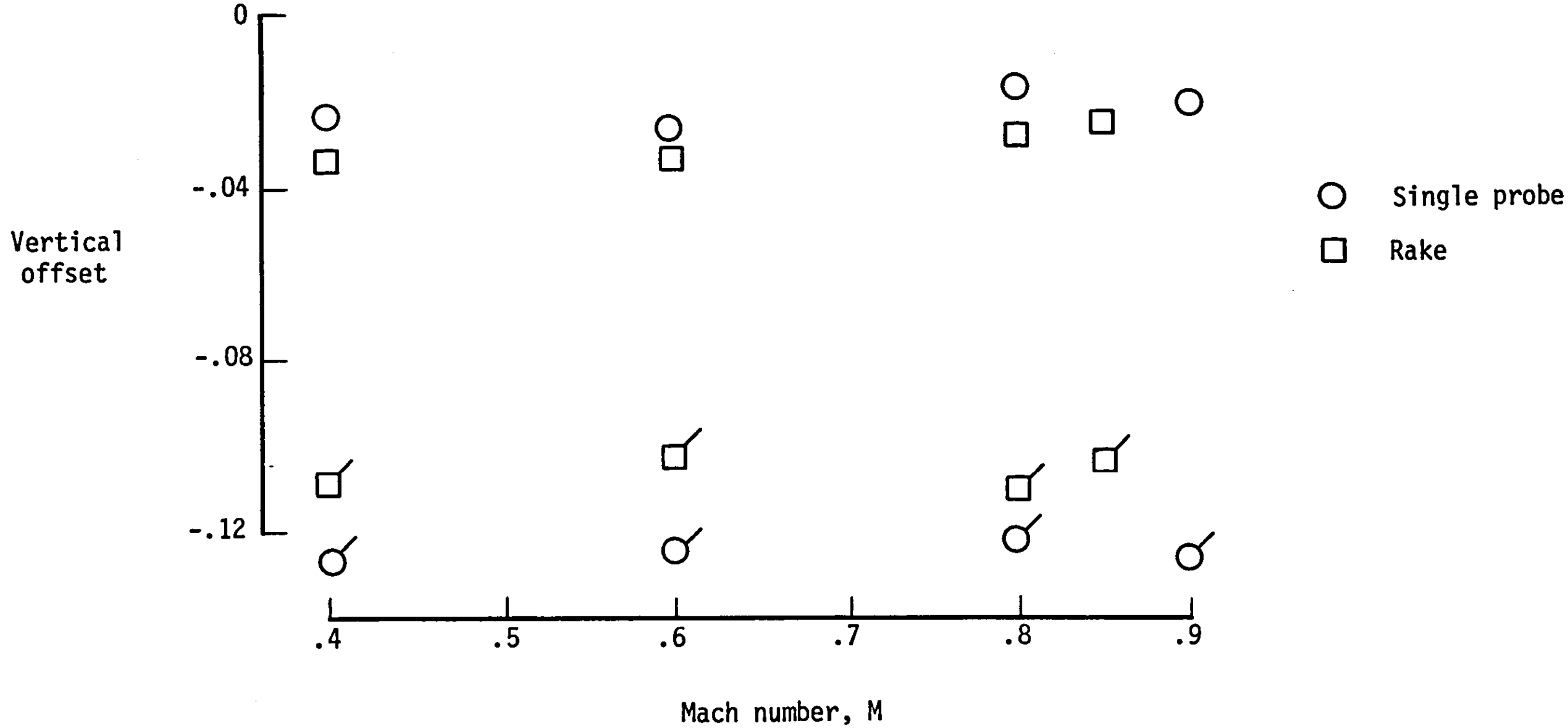


Figure 8. Mach number effects on calibration offsets in 7 × 10 HST. Probe 4; symbols without ticks are for orifices 3 and 4; symbols with ticks are for orifices 1 and 2.

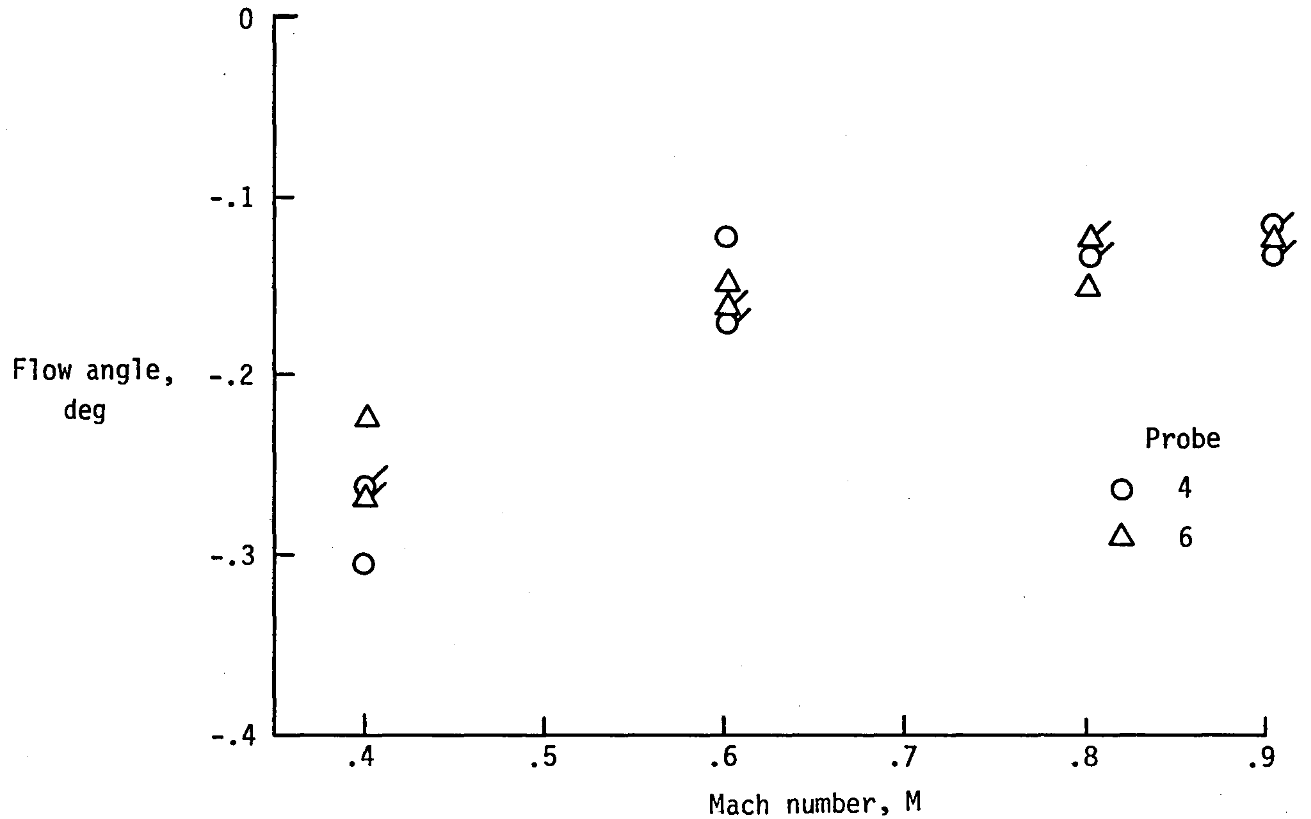
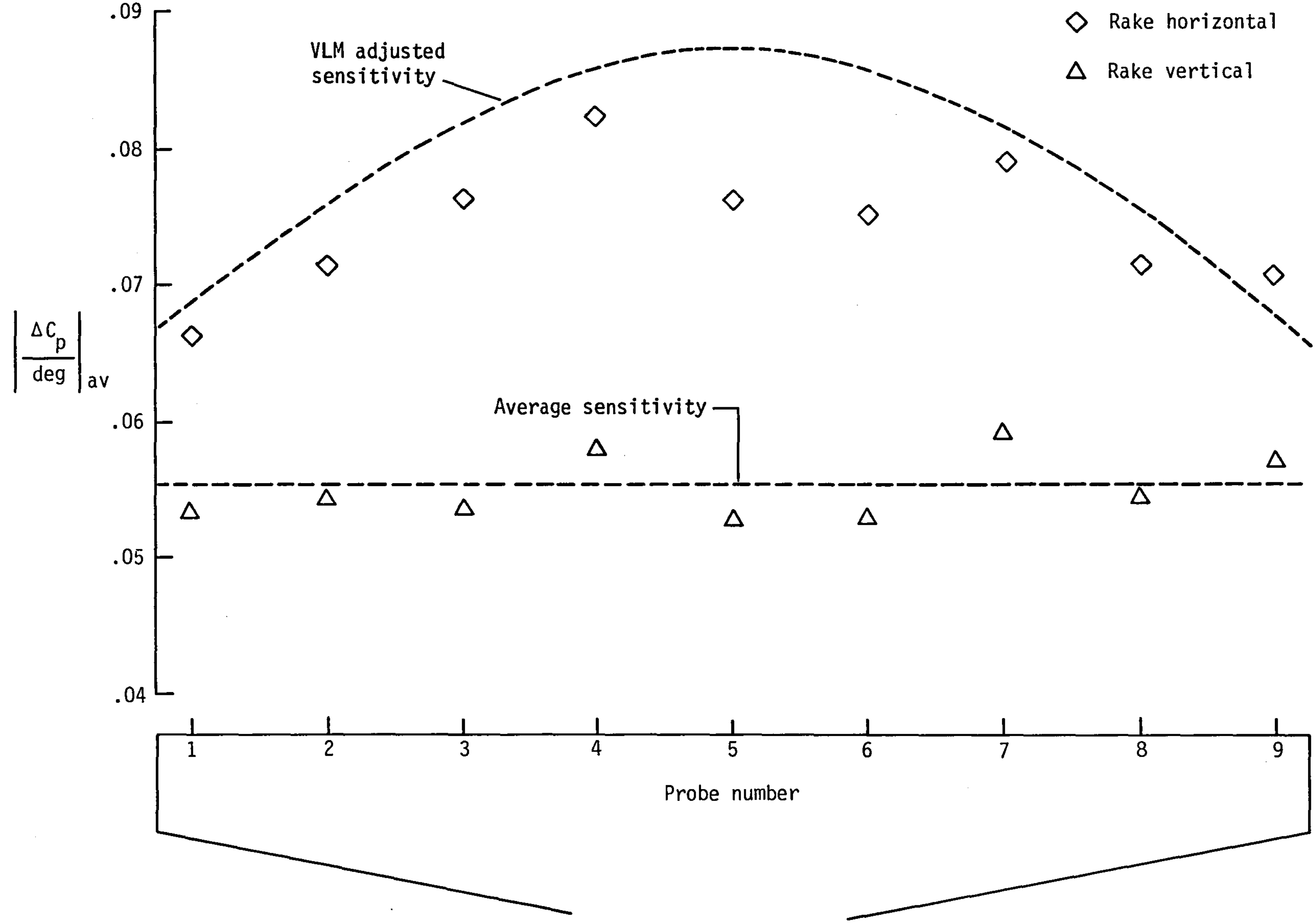
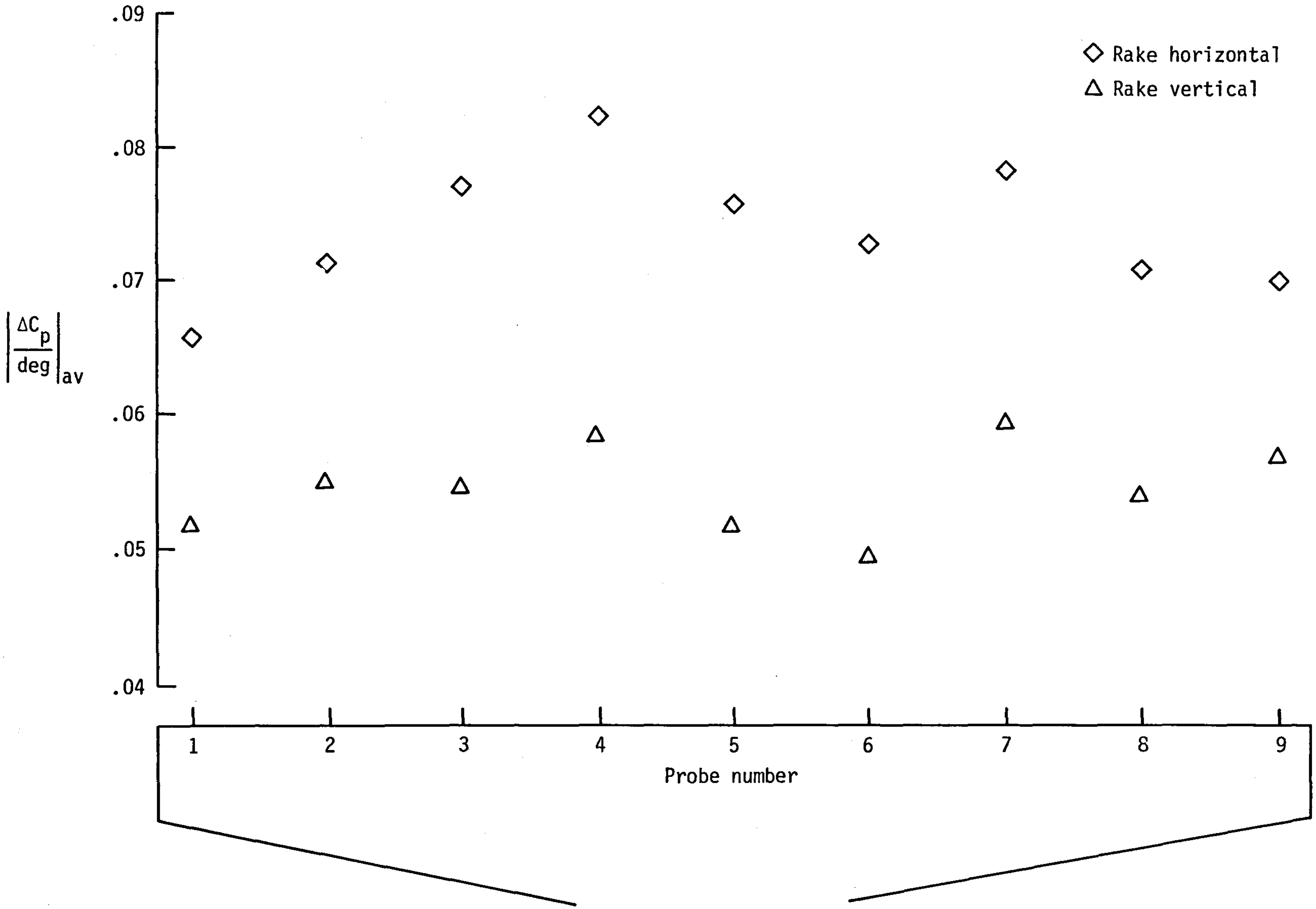


Figure 9. Summary of centerline angularity data in 7×10 HST. Symbols without ticks are for orifices 3 and 4; symbols with ticks are for orifices 1 and 2.



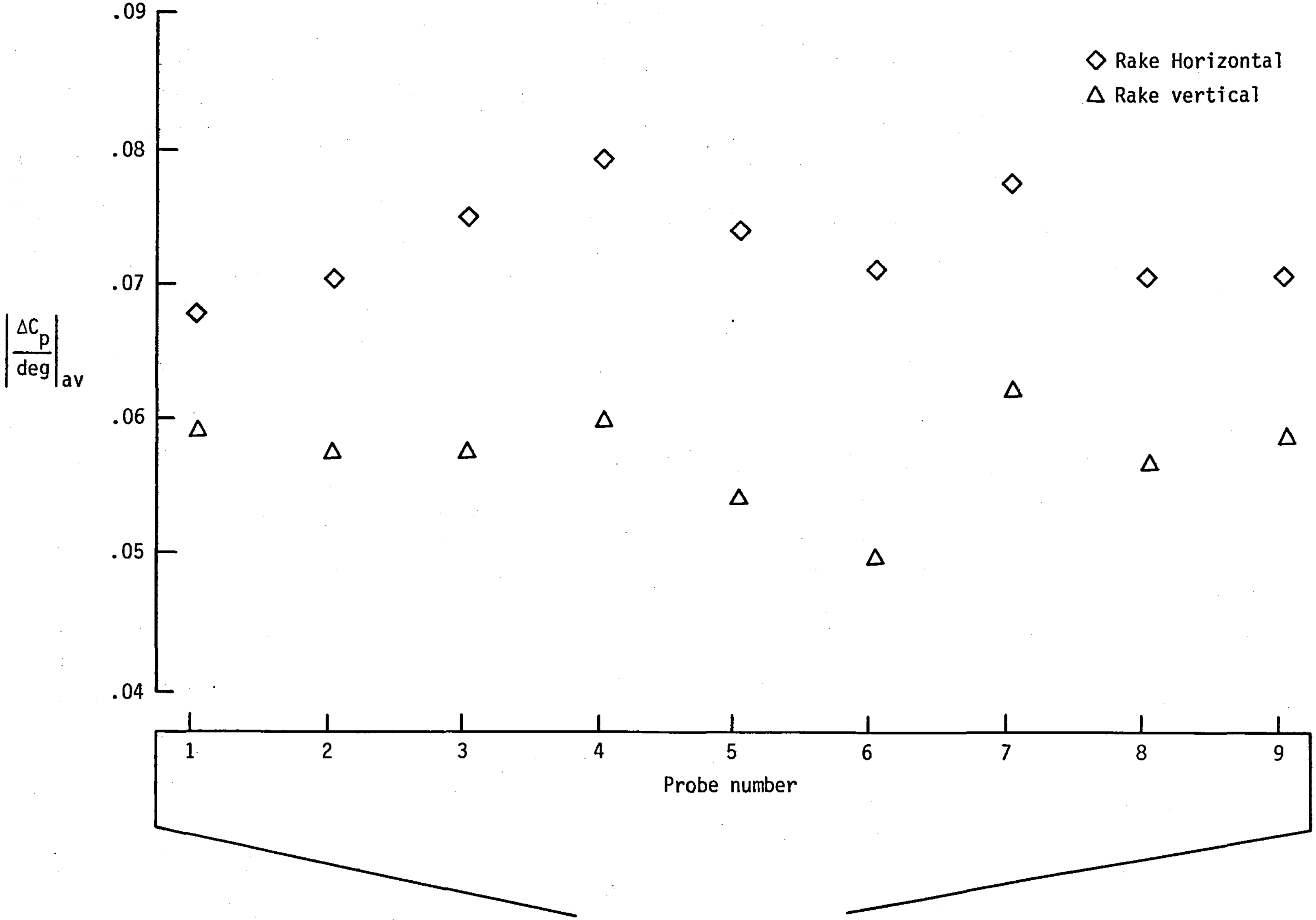
(a) $M = 0.4$.

Figure 10. Rake-mounted probe sensitivities in 7×10 HST.



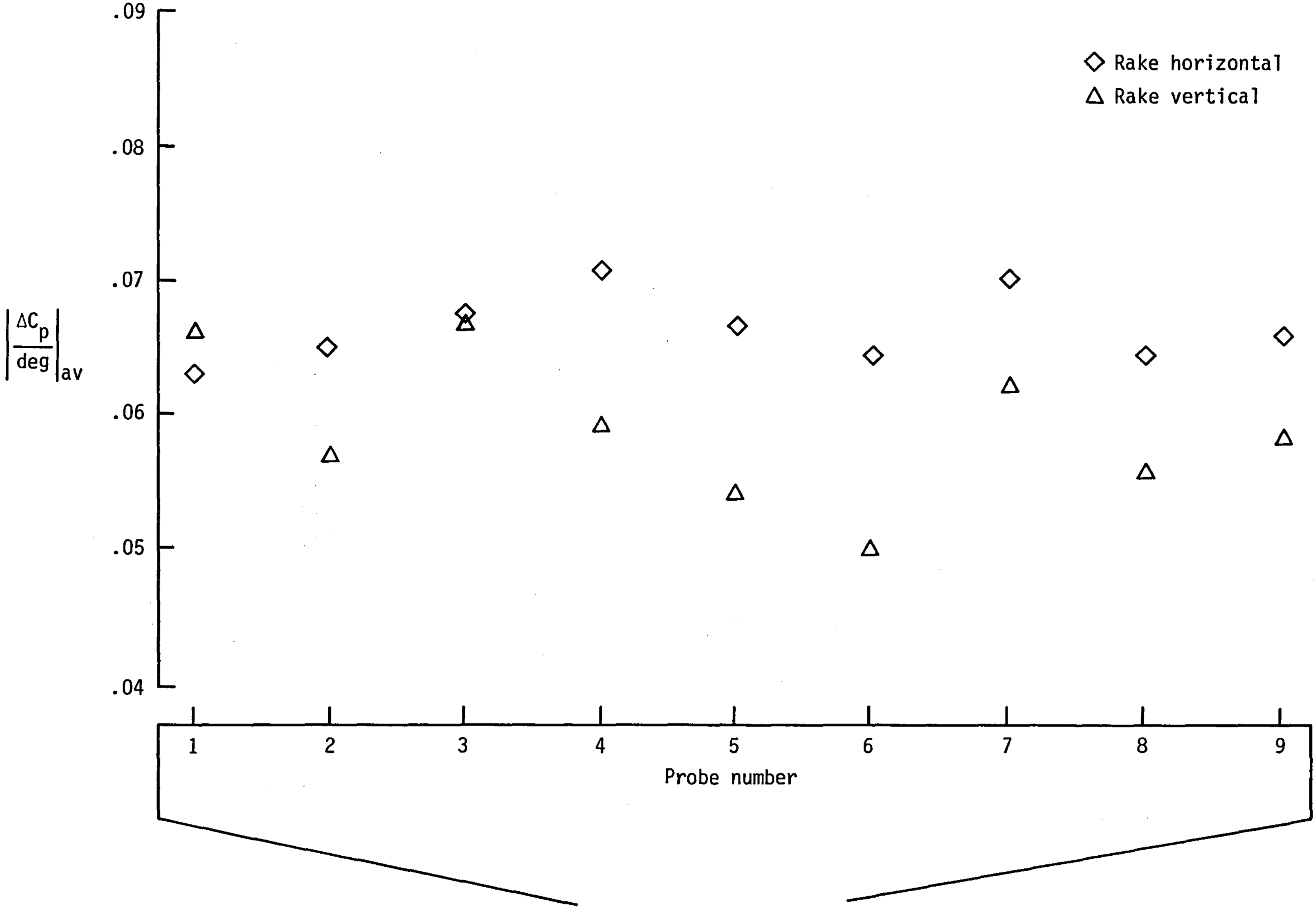
(b) $M = 0.6$.

Figure 10. Continued.



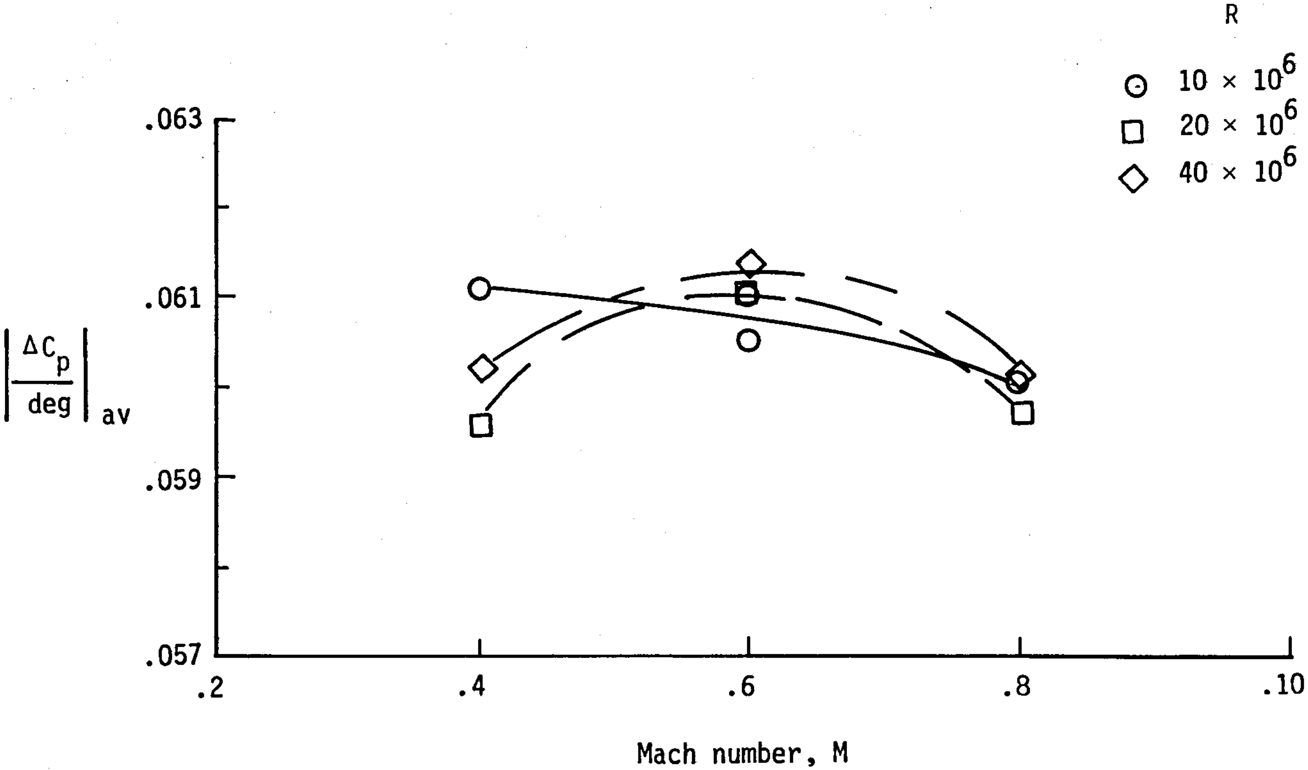
(c) $M = 0.8$.

Figure 10. Continued.



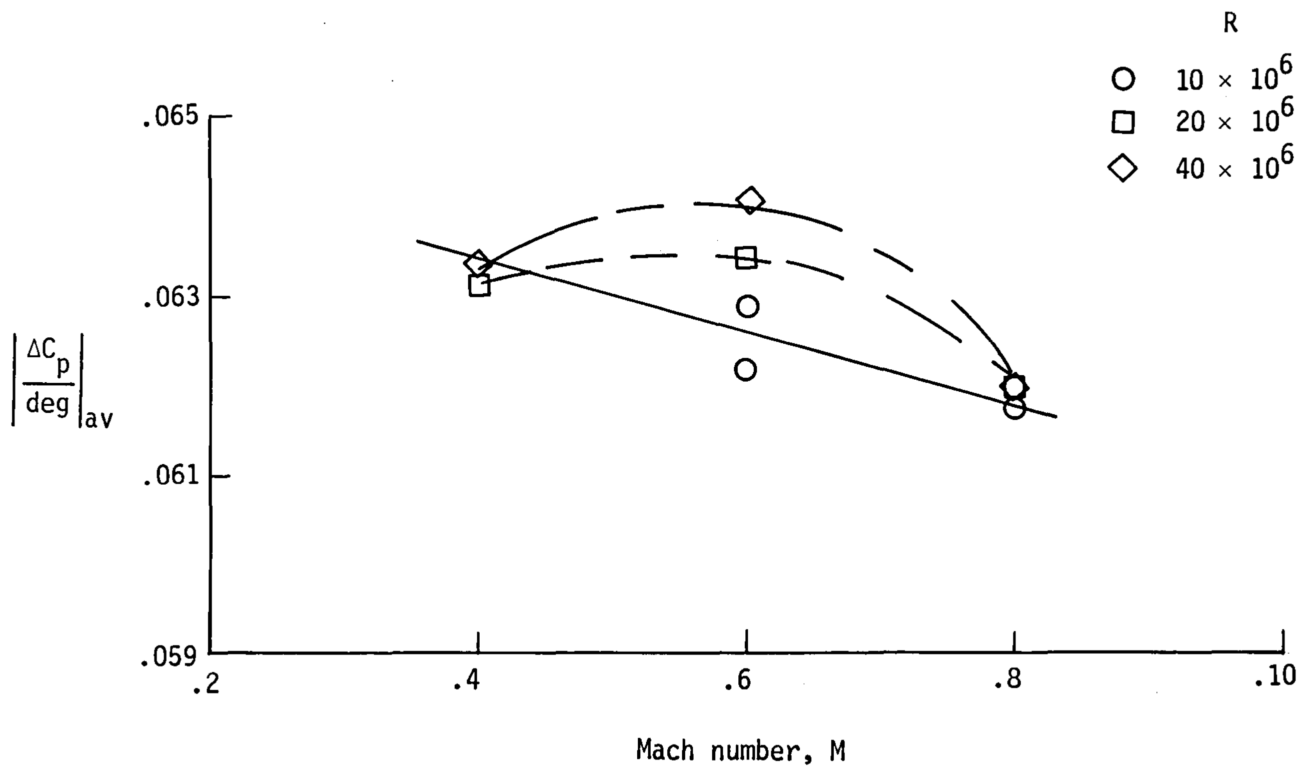
(d) $M = 0.85$.

Figure 10. Concluded.



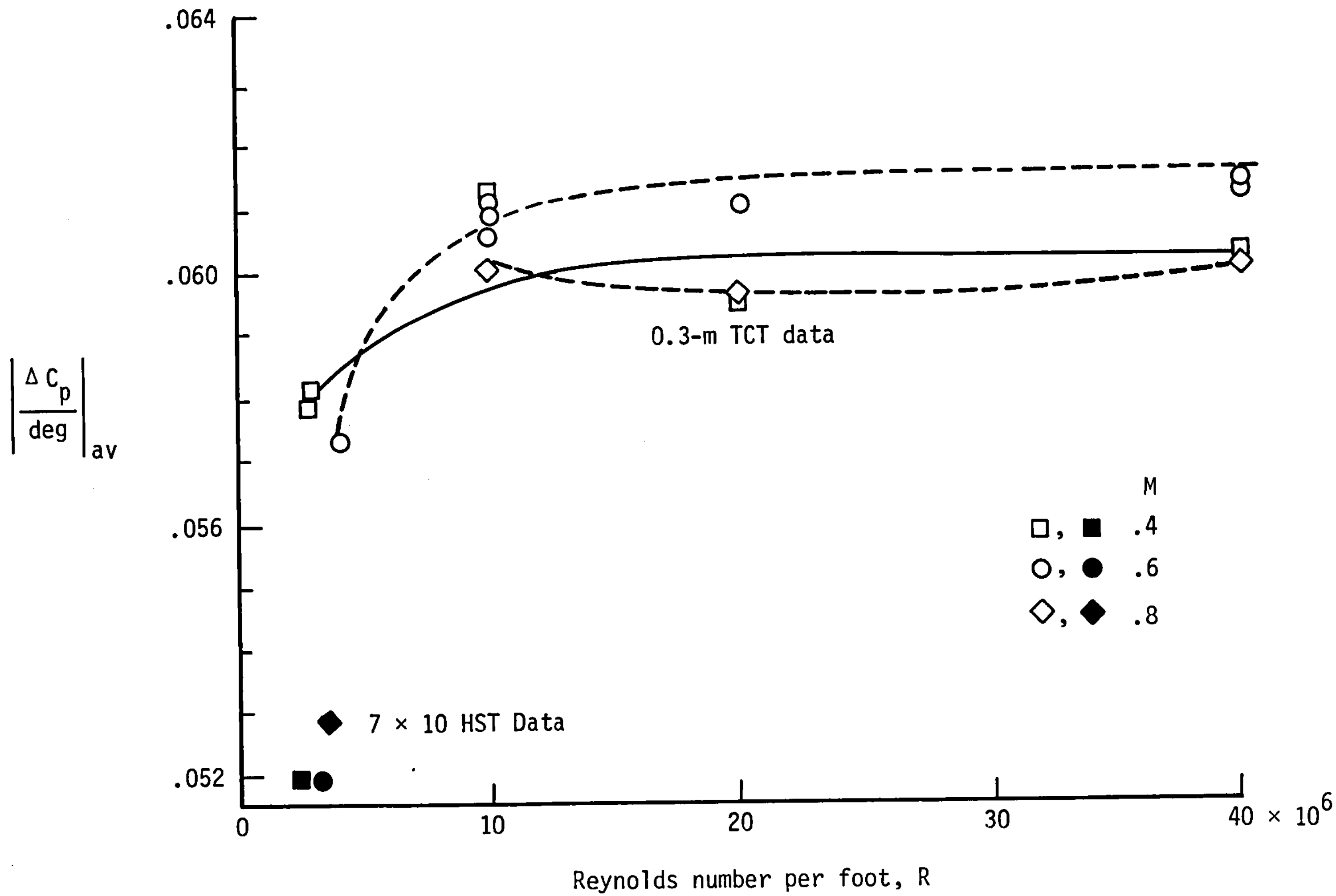
(a) Probe 8.

Figure 11. Mach number effects in 0.3-m TCT.



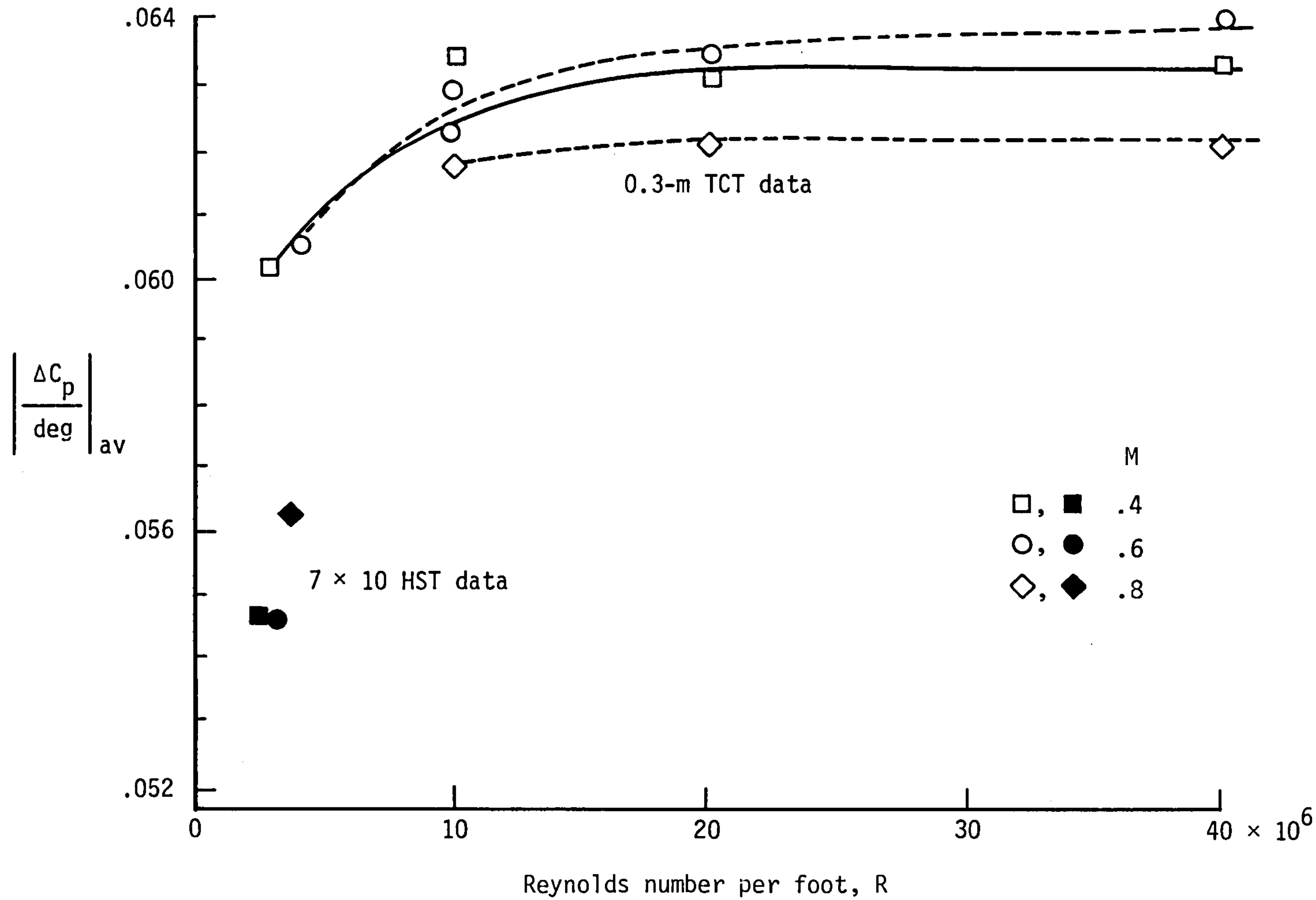
(b) Probe 9.

Figure 11. Concluded.



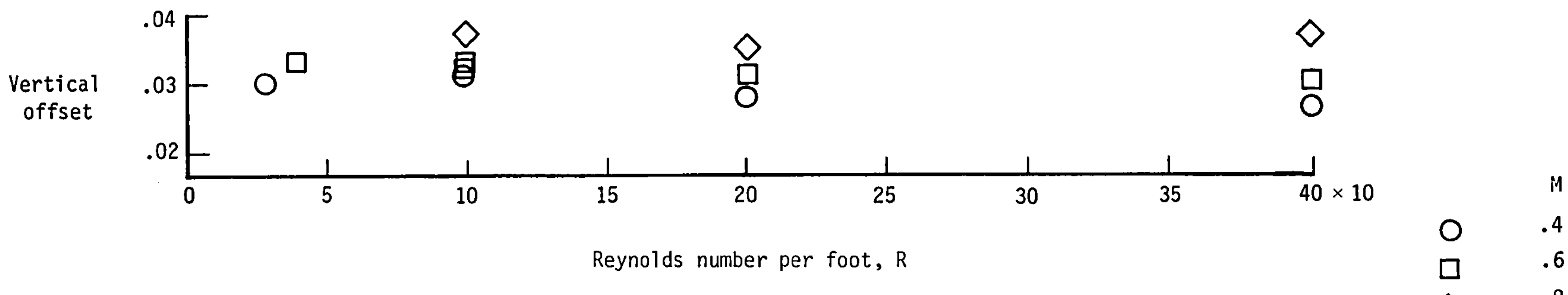
(a) Probe 8.

Figure 12. Reynolds number effect on probe sensitivity.

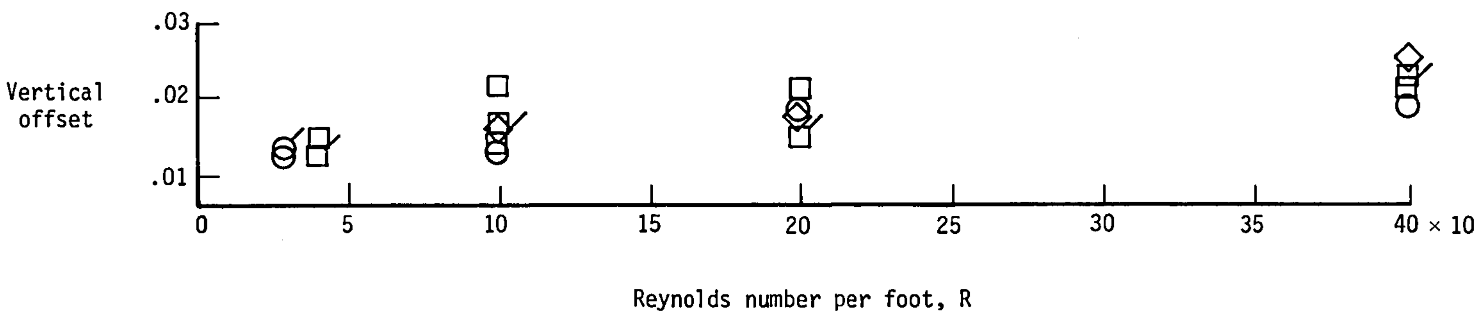


(b) Probe 9.

Figure 12. Concluded.

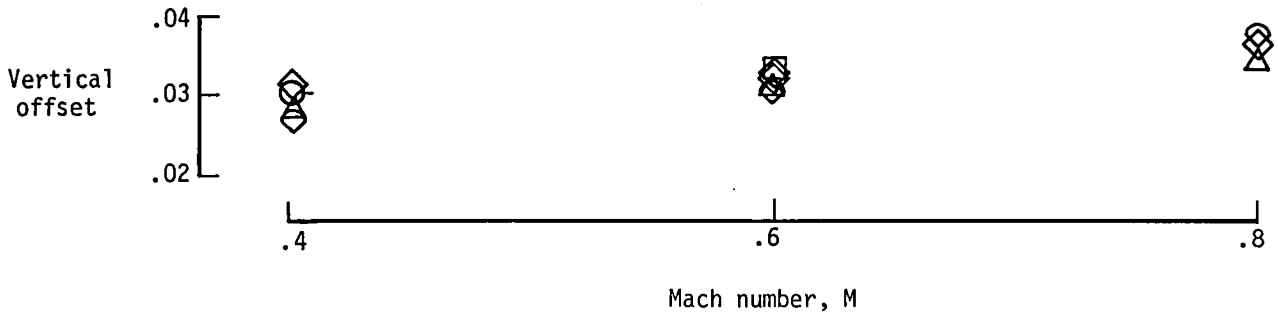


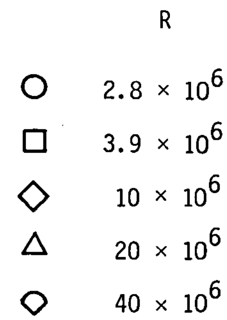
(a) Probe 9.



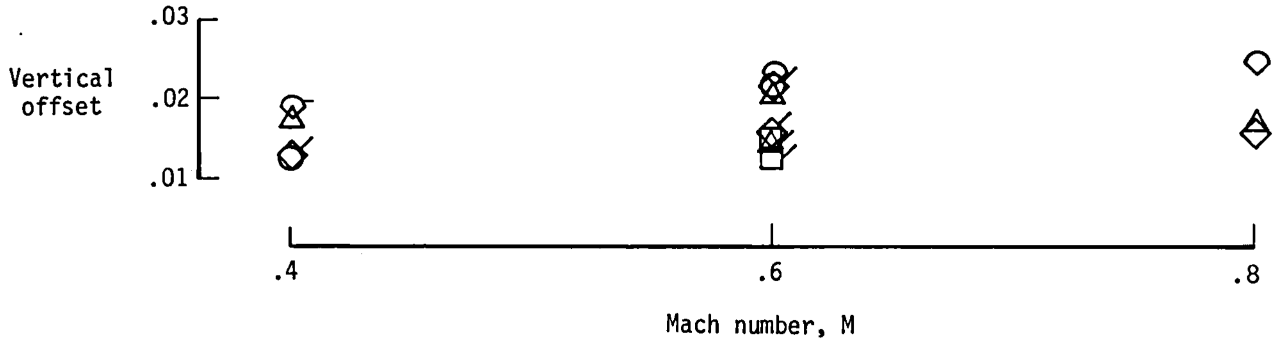
(b) Probe 8. Symbols with ticks are for second run.

Figure 13. Reynolds number effect on vertical offset in 0.3-m TCT.





(a) Probe 9.



(b) Probe 8. Symbols with ticks are for second run.

Figure 14. Mach number effects on vertical offset in 0.3-m TCT.

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15. Supplementary Notes

16. Abstract

Preliminary calibrations were performed on nine flow angularity probes in the Langley 7- by 10-Foot High-Speed Tunnel (7×10 HST) and the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT). These probes will be used in surveying the test section flows of the National Transonic Facility (NTF). The probes used in this study have a pyramid head with five pressure orifices. The calibrations consisted of both isolated probe measurements and rake-mounted multiprobe measurements that covered a range of subsonic Mach numbers up to 0.90 and Reynolds numbers per foot up to 40×10^6. The preliminary calibration in the 7×10 HST included testing the probes both individually and in a rake. The 0.3-m TCT calibration tested two probes singly at varying Reynolds numbers. The results from these tests include Mach number, Reynolds number, and rake-mounting effects. The results of these tests showed probe sensitivity to be slightly affected by Mach number. At Reynolds numbers per foot above 10×10^6, the probe did not exhibit a Reynolds number sensitivity.

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