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FLOW-DIRECTION MEASUREMENT WITH FIXED-POSITION PROBES

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SUMMARY

Because of space limitations and system complexity in many aeronautical applications, movable probes cannot be used to measure flow direction. This report presents correlations between measured fixed-probe pressures and airflow direction over a range of Reynolds number, Mach number, and flow angle. Flow direction is measurable to within about 1° over combinations of flow conditions in the range $1000 \leq Re \leq 40\,000$, $0.3 \leq M \leq 0.9$, $-30^{\circ} \leq \text{angle} \leq +30^{\circ}$.

INTRODUCTION

In all but the simplest experiments in fluid mechanics, a measurement of airflow direction is required along with airspeed. The latter is commonly derived from measured total and static pressures. Flow direction may then be determined from the indications of a pressure probe which has symmetrically oriented taps that are sensitive to flow direction.

There are two methods in which the probe may be used. The first and most direct method is to rotate the probe until the direction-sensing pressures are nulled, which means that the probe is alined with the flow. The aerodynamic center of the probe must be predetermined in a calibration tunnel.

In the second method, the probe is fixed and flow direction is determined from a correlation based on the relation between probe pressures and flow direction.

Recently, at the Lewis Research Center there has been renewed interest in flow-direction measurement with fixed-position probes. The areas of interest include V/STOL fan studies, jet-engine inlet distortion studies, and in-flight measurements on engine inlets.

There are several reasons for preferring fixed probes rather than rotatable ones. These reasons involve factors such as space limitations, system response, safety, complexity, and cost.

There are many reported works relating to the general subject of flow-direction measurement. Reference 1 has an extensive bibliography which includes several reports associated with flow-direction determination. However, the literature on flow-direction measurement with fixed probes (refs. 2 to 4) is limited in the range of Reynolds and Mach numbers.

The purpose of this report is to present correlations of two-dimensional and three-dimensional probe pressures against flow direction over a wide range of Reynolds and Mach numbers. Because it is desirable to obtain total and static pressure as well as flow direction with a single probe, correlations will also be presented based on these other pressures. The range of conditions investigated in this report are:

$$1000 \leq Re \leq 40\,000, \quad 0.3 \leq M \leq 0.9, \quad -30^{\circ} \leq \text{angle} \leq +30^{\circ}$$

This work is an extension of that of reference 5 in that it includes additional information on the flow-direction and static-pressure correlations.

PROBES AND TESTS

Flow-Direction Probes

Some considerations in designing flow-direction probes are the size and shape of the sensing element, the size and shape of the probe support, and the distance of the sensing element from the support.

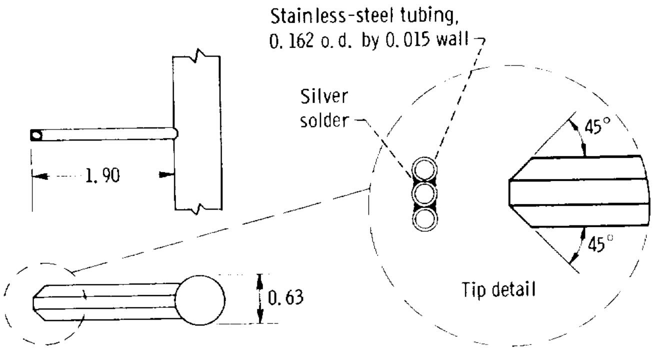
For flow-direction measurement in one plane, the sensing elements normally are two pressure taps on the surfaces of a wedge or cylinder, or two tubes whose inlets are angled to the flow direction. The corresponding elements for three-dimensional flows are the square pyramid, the hemisphere, and four tubes with angled inlets. All of these elements can be designed to provide adequate sensitivity except in low-pressure, low-velocity applications.

In order to minimize the flow-direction measurement errors when probing in a steep velocity gradient, the flow-direction sensing holes should be located close together to minimize the pressure difference caused by the velocity gradient.

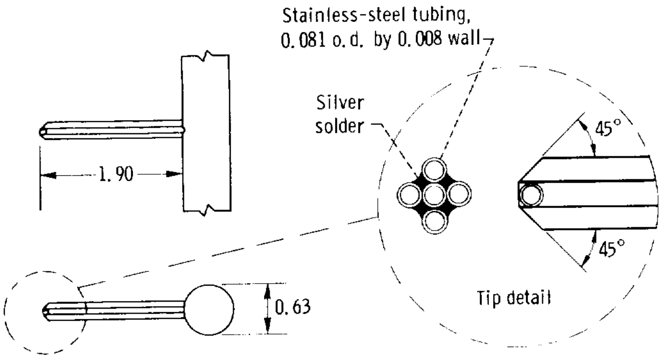
When flow-direction probes are used in a fixed position, they are often built in the form of a rake; that is, several elements are mounted on a single support which extends across the fluid stream. In order to minimize probe blockage, the frontal area of the probe support should be small, while still sufficient to maintain structural integrity. Although, a streamlined support would appear to be best, there are reasons for preferring a circular-cross-section support when the flow is not head on. A circular-cross-section support is itself unaffected by angle of attack. For subsonic flow, the presence of a noncircular-cross-section support may induce stronger angle-of-attack effects at the sensing element than the presence of a circular support; undesirable side forces on the support may also be greater.

Normally, a total-pressure tube is incorporated into the flow-direction probe, so that the probe is actually a combination probe. In order that the total-pressure indication be unaffected by the presence of the support when there is a transverse velocity gradient, the mouth of the total-pressure element should be at least 3 support thicknesses upstream of the support (ref. 6).

The scope of the work reported herein is limited in that a single probe design for two-dimensional flow and a single design for three-dimensional flow were tested. The two designs are shown in figure 1. The designs incorporate many of the features discussed above. The angled-tube design, with a total-pressure tube in the center of the tube cluster, is used for both the two- and three-dimensional probes. One three-dimensional and three two-dimensional probes were tested.



(a) Two-dimensional probe.



(b) Three-dimensional probe.

Figure 1. - Flow-direction probes. Dimensions are in centimeters.

Description of Tests

The characteristics of the probes were determined in the Lewis Instrument Research Branch small tunnel facility. This facility uses tunnels with test nozzles having throat sections about 8 centimeters in diameter. The flow in the nozzles and test regions is isentropic within the accuracy of the pressure and temperature measurements (0.05 percent or better). The axis of rotation of the probe passed through the probe tip, so that the tip of the sensing element remained at the same location for all angle-of-attack settings. The probe support extended entirely across the test nozzle exit. A more detailed description of the test apparatus and measuring system is given in reference 7. Tests were made at near ambient temperature.

Accuracy of Measurement

Probe position could be measured to $1/4^{\circ}$. Differential-pressure measurement errors, due principally to random fluctuations of the test-facility pressure and flow rate, were slightly larger than the readability (0.5 mm) of the water manometers used to measure differential pressures. The flow-direction error equivalent to these pressure-measurement errors was largest at the low ends of the Mach number and Reynolds number ranges, where density or velocity was correspondingly low. The equivalent flow-direction error was less than $1/2^{\circ}$ at the low ends of the ranges and several times smaller at the high ends of the ranges.

RESULTS AND DISCUSSION

The nomenclature used for flow orientation and the pressure tubes is shown in figure 2 for the three-dimensional probe. The same nomenclature applies for the two-dimensional probe except that p_3 and p_4 are absent.

Pressure differences will generally be expressed as a fraction of the difference between total pressure (as indicated by the central tube) and the average of the angled-tube pressures. When so expressed, the pressure differences will be termed ''normalized.''

Two-Dimensional Probe

Flow direction. - The variation in yaw angle with yaw pressure difference for a single two-dimensional probe is shown in figure 3, for the range $0.3 \leq M \leq 0.9$. The

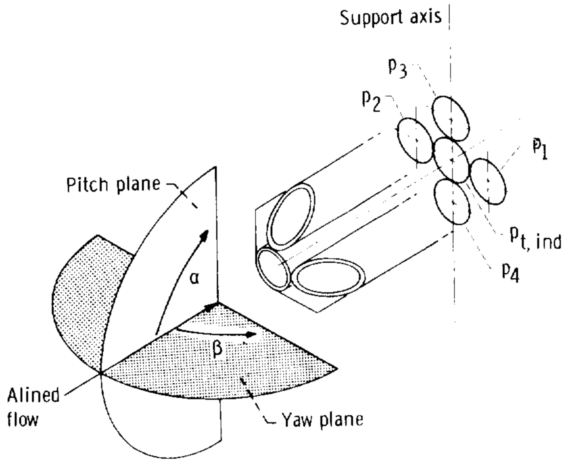


Figure 2. - Flow orientation and pressure tube nomenclature.

designations p_1 and p_2 indicate the pressures measured by the angled tubes. Pressure difference is expressed as a fraction of the impact pressure (the difference between total and static pressure).

The dark shaded band represents the scatter of results for a variation in pitch angle of 0° to $\pm 10^{\circ}$. The entire shaded band, which encloses about 350 data points, represents an extension of the pitch-angle range to $\pm 15^{\circ}$. The dark shaded band for pitch angles up to 10° includes Mach number, Reynolds number, and pitch-angle effects, whereas the scatter in the data between 10° and 15° pitch angle is due only to pitch-angle effect.

The slope of the mean of the shaded band is commonly called the flow-direction sensitivity. The value, at 0°, of 5 percent of impact pressure per degree of yaw misalinement, agrees with reported flow-direction sensitivities for other probes (refs. 6 and 8).

Although the slope appears symmetrical about the zero axis, in this case, it is generally desirable to calibrate for both positive and negative yaw angles, because any nonuniformity in probe geometry will result in a nonsymmetrical curve. Complete symmetry cannot always be built into such very small probes.

One of the shortcomings of a plot such as figure 3 is that the stream total and static pressures (p_t and p_s) are required in order to determine the flow direction. This shortcoming can be eliminated by representing the yaw pressure difference in normalized form, which involves only measured quantities, as shown in figure 4. The term

$$p_{t,ind} - \frac{1}{2}(p_1 + p_2)$$

is about one-half of the impact pressure for the probe of figure 1(a). An interesting feature of this method of presenting the calibration is that the scatter of the data is less than that of figure 3. At a yaw angle of 20°, the total spread of the shaded band is 2°,

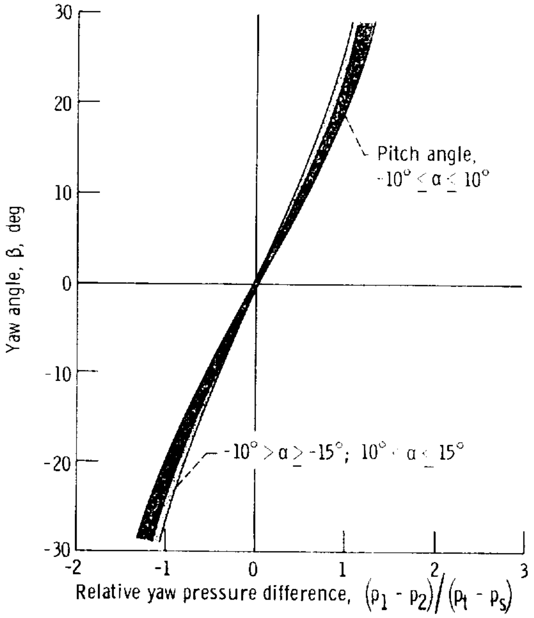


Figure 3. - Variation in relative yaw pressure difference with yaw angle for two-dimensional probe. Mach number range, 0.3 to 0.9; Reynolds number range, 3.5×10^3 to 3.7×10^4.

or ±5 percent. This is an improvement by a factor of 3 over the results of figure 3.

Many probes (18 rakes with a total of 54 flow-direction elements) of a design similar to that of figure 1(a) were routinely calibrated. The combined sensitivity plots for all 54 elements had a shaded band whose extremes were different from those of figure 4 by about 15 percent of the value of the normalized yaw pressure difference.

The sensitivity of the normalized yaw pressure difference to both Mach and Reynolds numbers is shown in figure 5. The characteristic length used for the Reynolds number is the outside diameter of the pressure tubes at the probe tip. The greater scatter in the data at the lower Mach numbers is due to increasing inaccuracy of pressure-difference measurements at the lower velocities. Figure 5 shows that at $\alpha = 0^\circ$, $\beta = 14.4^\circ$, the normalized yaw pressure difference is constant over the range of Mach and Reynolds numbers tested. However, there is a Reynolds-number effect on yaw pressure difference for $\alpha = 0^\circ$, $\beta = 30^\circ$. This change is probably due to Mach number change, because the Reynolds number is above the viscous range. The increased width of the scatter band at high yaw angles in figure 4 also reflects this change.

Total pressure. - In order to determine the true stream total pressure from measured probes pressures, a calibration such as that shown in figure 6 is required. The normalized difference between indicated and true total pressure is plotted against the normalized yaw pressure difference. Again, the dark band represents results for pitch angles up to ±10° while the entire shaded band is for a pitch-angle range of ±15°. The

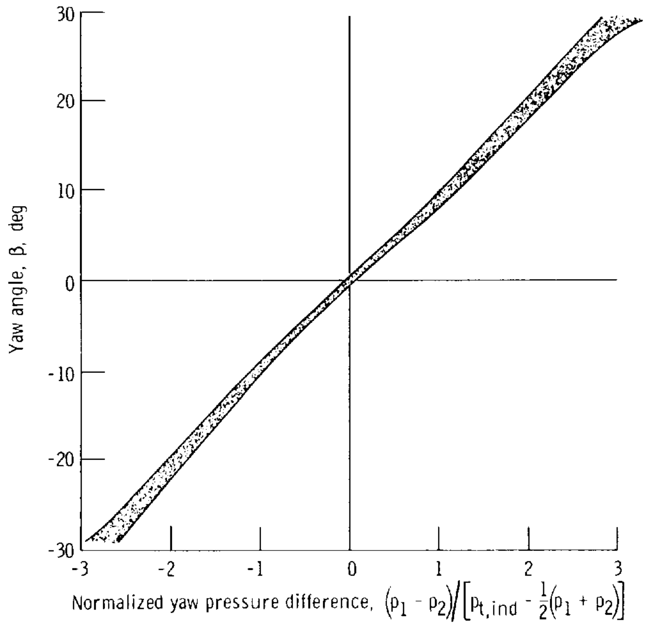


Figure 4. - Variation in yaw pressure difference with yaw angle for two-dimensional probe. Mach number range, 0.3 to 0.9; Reynolds number range, 3.5×10^3 to 3.7×10^4; pitch angle, -15° to 15°.

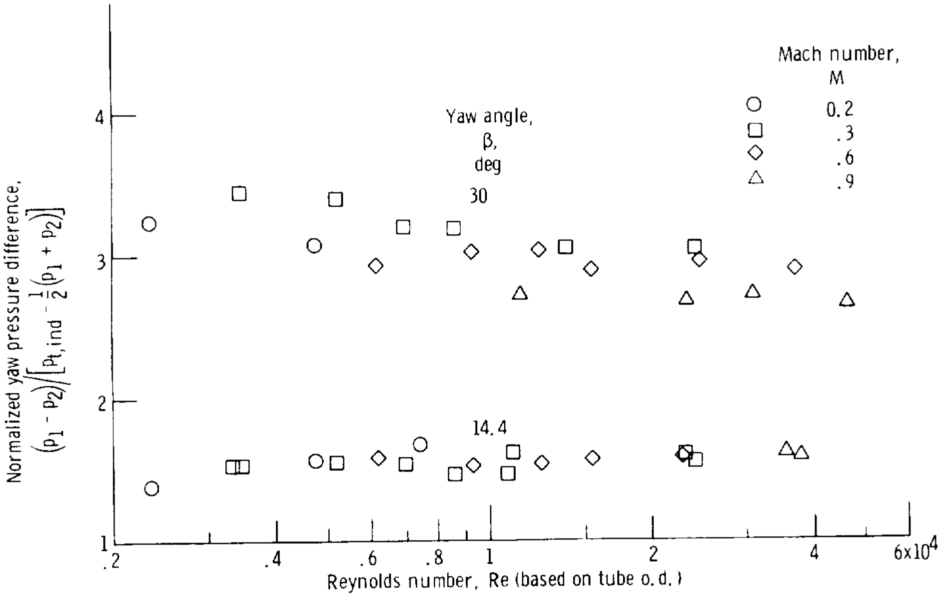


Figure 5. - Variation in yaw pressure difference with Reynolds number for two-dimensional probe. Mach number range, 0.2 to 0.9; pitch angle, 0°.

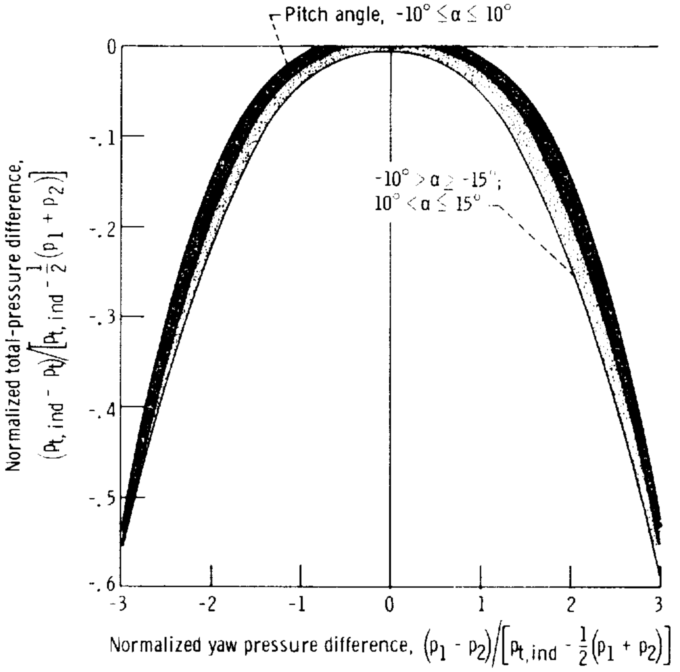


Figure 6. - Variation in total-pressure difference with yaw pressure difference for two-dimensional probe. Mach number range, 0.3 to 0.9; Reynolds number range, 3.5×10^3 to 3.7×10^4.

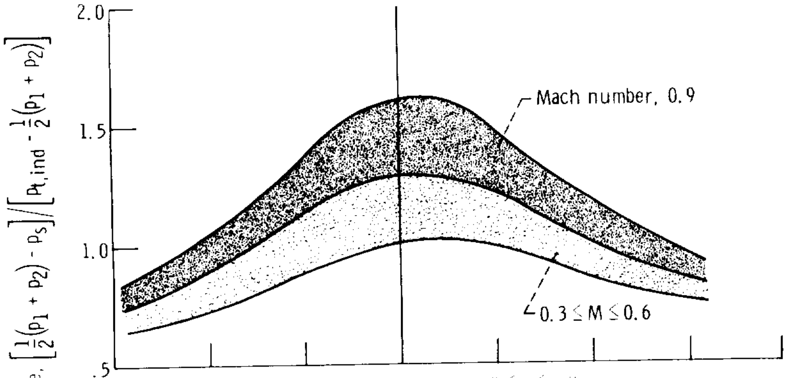
shape of the figure is typical of flow-direction characteristics of total-pressure tubes. Square-ended tubes typically indicate true total pressure up to about 10° of misalinement, and then show a rapidly increasing defect for greater misalinement. This small defect in the light shaded band at zero yaw pressure difference is due to the fact that this band represents pitch angles beyond 10°.

Static pressure. - The ability to which the two-dimensional probe can be used to determine stream static pressure is illustrated in figure 7, which shows the variation in the normalized static-pressure difference

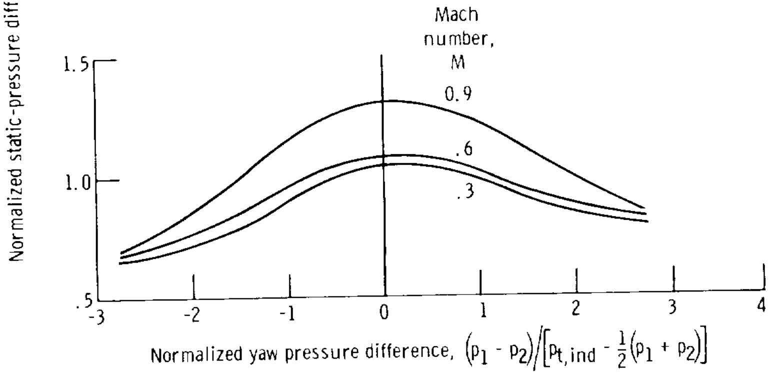
$$\frac{\frac{1}{2}(p_1 + p_2) - p_s}{p_{t,ind} - \frac{1}{2}(p_1 + p_2)}$$

with the normalized yaw pressure difference

$$\frac{p_1 - p_2}{p_{t,ind} - \frac{1}{2}(p_1 + p_2)}$$



(a) Pitch angle, $-10^\circ \leq \alpha \leq 10^\circ$.



(b) Pitch angle, $\alpha = 0$.

Figure 7. - Variation in static-pressure difference with yaw pressure difference for two-dimensional probe. Reynolds number range, 3.5×10^3 to 3.7×10^4.

The ordinate level of the shaded band of figure 7(a) confirms that the average of the p_1 and p_2 flow-direction tubes is a pressure which is about halfway between stream total and stream static pressure. Most of the band width is due to the range of pitch angles covered. The light shaded band represents the scatter of results for the range $0.3 \leq M \leq 0.6$. The entire shaded band represents an extension of the Mach number range to 0.9.

Because of the relatively large uncertainties associated with the scatter band of figure 7, it is better to make an independent measurement of static pressure in applications where the velocity must be accurately determined. This independent static-pressure determination can be made either with a wall static-pressure tap in applications where the static pressure is constant across the stream, or with a properly designed static-pressure probe in applications where gradients exist. However, in an application of almost fixed pitch angle, the width of the scatter band of figure 7(a) can be reduced to an acceptably small level, particularly for $0.3 < M < 0.6$. Figure 7(b) is a plot of the static-pressure difference for a pitch angle of 0°.

Three-Dimensional Probe

It was shown in the previous sections that the two-dimensional probe is adequate for flow-direction determination when the flow direction in the nonmeasuring plane is known to within $\pm 15^{\circ}$. For applications exceeding the above limit, or when the flow direction is completely undefined, a three-dimensional probe is required.

Flow direction. - Figure 8 is a flow-direction map for the three-dimensional probe of figure 1(b) at a Mach number of 0.6. The normalized yaw pressure difference is plotted against the normalized pitch pressure difference over a range of flow angles from -30° to $+30^{\circ}$ in both the pitch and yaw directions. Each intersection on the grid of figure 8 represents a calibration point; there are 49 in all for the 10° increment grid. In an ideal situation, the grid would consist of straight horizontal and vertical lines and the quadrants would be symmetrical. The nonlinearity and nonsymmetry of the grid are due to the fact that the angled tubes at the tip of the probe cannot be fabricated with perfect symmetry.

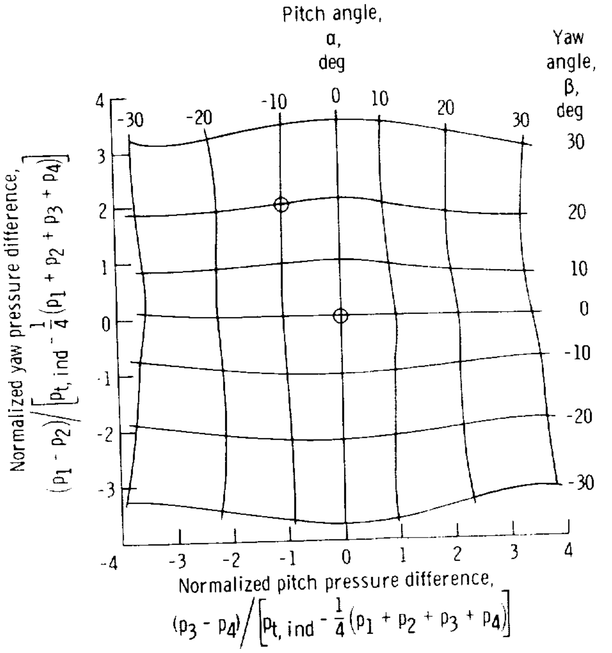
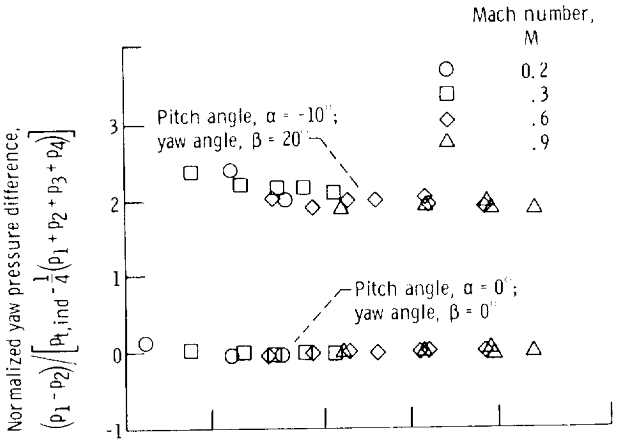
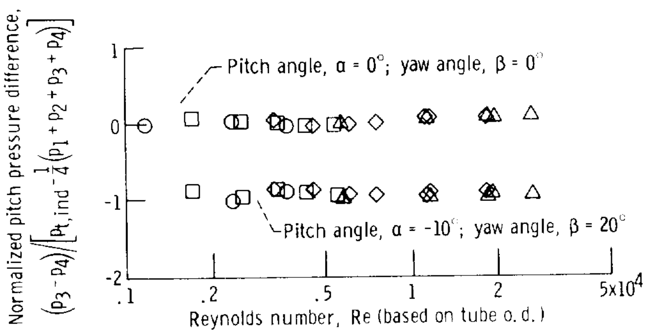


Figure 8. - Pressure difference map for three-dimensional probe. Mach number, 0.6; Reynolds number, 1×10^{4}.

A map such as figure 8 requires a rather tedious calibration. The 10° increments represent a minimum number of calibration points for a useful grid. A 5° increment would be more desirable, but would involve over 150 calibration points.



(a) Yaw pressure difference.



(b) Pitch pressure difference.

Figure 9. - Variation of yaw and pitch pressure differences with Reynolds number for three-dimensional probe.

The two circled calibration points ($\alpha = 0$, $\beta = 0$ and $\alpha = -10^{\circ}$, $\beta = 20^{\circ}$), in figure 8 were run over a range of Mach and Reynolds numbers; the results are shown in figure 9. Figure 9(a) is normalized yaw pressure difference against Reynolds number, while figure 9(b) is normalized pitch pressure difference against Reynolds number. The lowest Reynolds number in figure 9 is about half that in figure 5 because of the smaller tube size of the three-dimensional probe.

From figure 9 it can be seen that there are no Mach or Reynolds number effects for $\alpha = 0^{\circ}$, $\beta = 0^{\circ}$. However, there is a small change in the pitch and yaw pressure differences for $\alpha = -10^{\circ}$, $\beta = 20^{\circ}$ over the range of Mach and Reynolds numbers covered. This change is probably due to Mach number change, because the Reynolds number is above the viscous range. This change corresponds to a total change in pitch angle α of 1.5° at a level of -10° and a total change in yaw angle β of 3° at a level of 20°. These values represent a total change in flow direction of 15 percent for the range

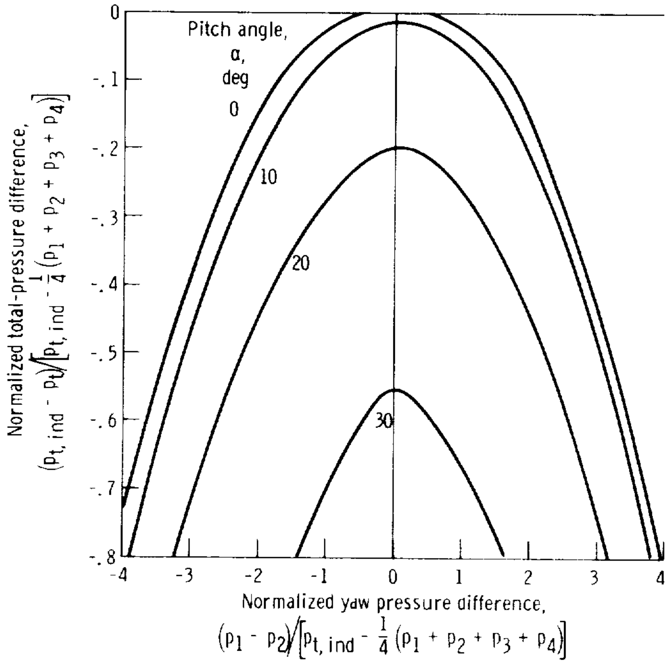


Figure 10. - Variation in total pressure difference with yaw pressure difference for three-dimensional probe. Mach number, 0.6; Reynolds number, 1×10^4.

$0.2 \leq M \leq 0.9$ and $1000 \leq Re \leq 20\,000$. For applications where the range of Mach and Reynolds number is small, it is sufficient to obtain a calibration map such as that of figure 8 at some midrange value. However, if the probe is to be used over ranges such as those of figure 9, several maps may be required.

Total pressure. - Figure 10 shows the variation in normalized total-pressure difference with normalized yaw pressure difference, for the three-dimensional probe, for pitch and yaw angles up to 30°. The results are similar to those of figure 6 for the two-dimensional probe except that the total-pressure defect begins to become appreciable at smaller misalinement angles. The lines of constant pitch angle represent the average for positive and negative values of pitch angle. For example, at a normalized yaw difference of zero and a pitch angle of 20°, the value of normalized total-pressure difference can vary ±10 percent of the value indicated in figure 10 depending on whether the pitch angle is positive or negative. Such random deviation is also due to the fact that the probe tip cannot be made perfectly symmetrical.

Static pressure. - The general comments stated about static-pressure measurement for the two-dimensional probe also apply to the three-dimensional probe. Again, the level of the pressure sensed by the angled tubes is about halfway between stream total and static pressures. One advantage of the three-dimensional probe for static-pressure measurement is that static pressure is obtainable because both pitch and yaw angles are known.

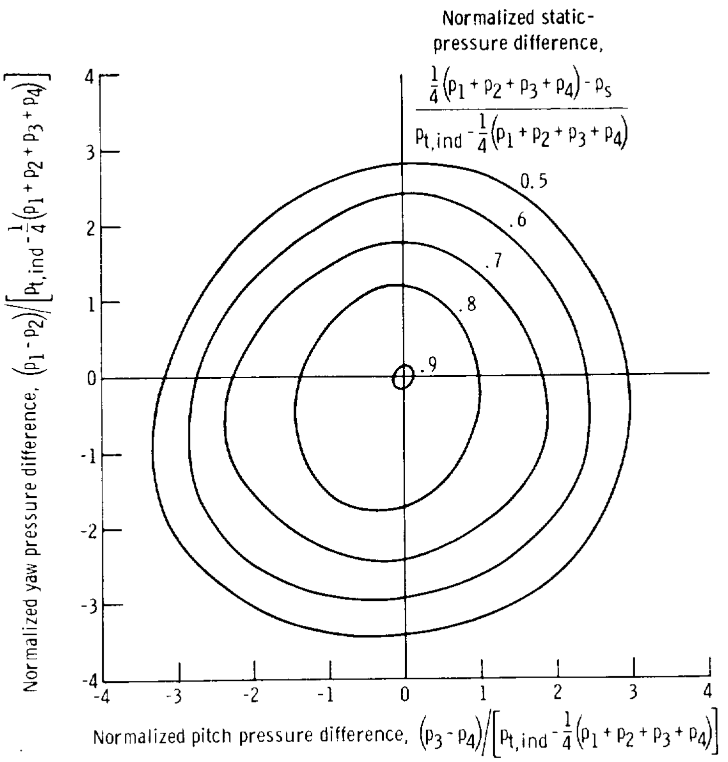


Figure 11. - Static-pressure difference map for three-dimensional probe. Mach number, 0.6; Reynolds number, 1×10^4.

The uncertainty in static-pressure measurement associated with flow direction uncertainty can be eliminated with a contour map such as figure 11. The coordinates are the same as figure 8 except that the contour lines are lines of constant normalized static-pressure differences

$$\frac{\frac{1}{4}(p_1+p_2+p_3+p_4)-p_s}{p_{t,ind}-\frac{1}{4}(p_1+p_2+p_3+p_4)}$$

Figure 11 also involves an extensive calibration. In addition, an undesirable feature of such a static-pressure contour map is that it changes considerably at the higher Mach numbers. For example, the normalized static-pressure difference for the point $\alpha = -10^0$, $\beta = 20^0$ changes over 30 percent as Mach number changes from 0.6 to 0.9. Therefore, several contour maps would be require in order to obtain static pressure over such a range of Mach numbers.

CONCLUDING REMARKS

This report has presented some of the features of flow-direction measurement with fixed-position, two- and three-dimensional probes. Only a single type of probe design was checked experimentally. The type consisted of clustered tubes, with the flow-direction tubes cut off at 45°. The range of flow conditions were $0.3 \leq M \leq 0.9$, $1000 \leq Re \leq 40\,000$.

Flow direction is measurable to within about 1° over most combinations of flow conditions in the above range. However, in order to obtain such accuracies, each probe may require an individual calibration. For example among 54 probes fabricated at the same time by the same mechanic, to drawings that were the same except for support design, the deviation of angle sensitivity of any one probe from the mean slope of figure 4 was about 15 percent. Therefore, the probe characteristics presented in this report serve as a guide rather than as universal calibrations.

If flow direction is known to vary no more than 15° in one of two orthogonal directions, the two-dimensional probe should be used rather than the three-dimensional probe. An advantage is that a smaller supporting strut may be used, which minimizes blockage. If flow direction may vary more than 15° in both yaw and pitch, the three-dimensional probe is necessary, with the attendant increase in the number of calibration points.

Both the two- and three-dimensional probes can be used to obtain an adequate measurement of total pressure. The total pressure indicated by the central tube of the tube cluster also permits normalization of the data in a manner that reduces random scatter.

The angled tubes may be used to obtain an approximate value of static pressure. However, where an accurate value of static pressure is required, either a wall static-pressure tap (when there is no pressure profile) or a properly designed static-pressure probe should be used.

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National Aeronautics and Space Administration,
Cleveland, Ohio, August 15, 1969
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