NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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COMPARISON OF AIRSPEED CALIBRATIONS EVALUATED BY THE ACCELEROMETER AND RADAR METHODS

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SUMMARY

A calibration of the pitot-static airspeed installation on a jet fighter airplane was made to compare the accelerometer method of determining static-pressure error with the radar method. The radar method makes use of measurements of static pressure recorded in the airplane and of geometric height as determined by recording radar-phototheodolite equipment on the ground. In the accelerometer method, free-stream static pressure is computed from measurements of pressure, measurements of temperature, and changes in geometric height determined by integrations of accelerometers carried by the airplane. The tests included shallow dives up to a Mach number of about 0.80 with pull-ups of about 4, 3, and 2g normal acceleration.

The results of the tests indicated that, for vertical plane maneuvers, the accelerometer method may be used as an alternate to the radar method. Although the accelerometer method requires airplane instrumentation of fairly high precision, this equipment may be more generally available than the radar equipment.

INTRODUCTION

Calibration of the pitot-static installation is necessary for accurate determination of aircraft speed. Airspeed-calibration procedures that have proved useful at low altitudes and low airspeeds, such as those described in reference 1, are not suitable for airspeed calibration in maneuvers at high altitudes and high airspeeds. Two methods that are suitable for use under these conditions are the radar method and the accelerometer method described in references 2 and 3, respectively.

In the radar method, geometric altitude is used as a reference for comparing atmospheric pressure determined with the static-pressure installation under conditions for which the calibration is known with static pressures measured in maneuvers for which the calibration is desired. Geometric altitude is computed from measurements of range and elevation angle with radar-phototheodolite equipment. This method has been used successfully by the National Advisory Committee for Aeronautics for several years. However, the necessary equipment and trained radar personnel are not generally available.

The accelerometer method was suggested in reference 3 as an alternate method for calibrating airspeed installations with the idea that the required instrumentation, although of high precision, may be more generally available than the radar equipment. The accelerometer method, which is restricted to vertical plane maneuvers, makes use of initial vertical velocity and the change in geometric altitude determined by integrating the vertical component of acceleration. By starting the calibration under conditions for which the static-pressure error, and hence the free-stream static pressure, is known, the free-stream static pressure at any other time may be determined from a relation of the change in geometric altitude, measured temperature, and measured static pressure. In the tests reported herein the initial vertical velocity was determined by a procedure which involved the use of a sensitive pressure recorder and accelerometers. This procedure, which is different from that described in reference 3, also provided a flight determination of the zero reading of the normal accelerometer.

Although the accelerometer method was presented in detail in reference 3, no experimental results were included. An airspeed calibration has since been made on a fighter-type airplane up to a Mach number of about 0.8 by both the radar and accelerometer methods. The purpose of this paper is to compare the results of the calibrations by the two methods.

SYMBOLS

p	free-stream static pressure
p_T	free-stream total pressure
p_m	indicated free-stream static pressure
p_a	free-stream static pressure computed from equation (1) by using values of temperature and altitude computed from accelerometer measurements
p_r	free-stream static pressure computed from equation (1) by using values of temperature and altitude determined by radar

q_c'	indicated impact pressure $\left(p_t - p_m\right)$
n	constant derived in reference 3 (taken as 0.286 in this paper)
R	gas constant
t	time
h	altitude
M	free-stream Mach number
M'	indicated free-stream Mach number
T	free-stream temperature, absolute units
T_m	measured temperature, absolute units
T'	temperature $\left(\frac{T_m}{1 + \frac{\gamma - 1}{2} KM'^2}\right)$
K	temperature recovery factor $\left(\frac{T_m - T}{0.2M^2 T}\right)$
a_x	longitudinal acceleration, positive forward along x-axis
a_z	normal acceleration, positive upward along z-axis
a_v	vertical acceleration, positive upward along vertical of earth (obtained by equation (3))
g	acceleration due to gravity
v	vertical velocity
γ	ratio of specific heats (1.4)
θ	attitude angle, positive below horizon

Subscripts:

0	beginning of level-flight run or shallow dive preceding calibration
1	beginning of evaluation of maneuver

EQUIPMENT

The jet-powered fighter airplane used for the calibration tests was equipped with a pitot-static tube mounted on a boom about 1 fuselage maximum diameter ahead of the fuselage nose. A resistance-type free-stream thermometer equipped with two radiation shields was mounted about 2/3 fuselage maximum diameter ahead of the nose on the airspeed boom. The thermometer had a recovery factor very nearly 1.0 and a time lag of about 1/10 second for the altitude and speed range at which the tests were made. The thermometer and pitot-static head are shown mounted on the boom in figure 1.

The instruments installed in the airplane and the range of each instrument are as follows:

Thermometer	-40° to 40° F
Static-pressure recorder	95 to 422 inches of water
Impact-pressure recorder	30 to 84 inches of water
Normal accelerometer	0 to 2g
Normal accelerometer	2 to 4g
Longitudinal accelerometer	-0.5 to 0.2g
Sun camera	30°

All of these instruments recorded the measurements continuously on films which were synchronized by a $\frac{1}{10}$-second timer. An identification code, which synchronized the radar measurements with the measurements taken in the airplane, was transmitted to the ground radar station by the aircraft radio.

The sun camera was mounted in the airplane below an opening in the skin ahead of the pilot's canopy. The camera was designed to record continuously the attitude of the airplane relative to the sun. A simple sundial, shown in figure 2, was installed to aid the pilot in maintaining the lateral axis of the airplane normal to the rays of the sun.

The time of the start or end of a test was determined by means of an ordinary watch checked against time obtained from radio station WWV operated by the National Bureau of Standards.

The radar-phototheodolite ground equipment was the same as that described in reference 2.

ACCURACY OF RECORDING EQUIPMENT

The recording equipment was, in general, specially built to give the high degree of accuracy required by the accelerometer method. Much care was taken in the calibration of the instruments and in the reading of the film.

A flight test was made prior to the airspeed-calibration tests to check the measurements of free-stream temperature by using two thermometers and recording galvanometers of the same design. The recorders indicated an occasional difference in temperature of no more than $\frac{1}{2}^{\circ}$ F. The errors in temperature resulting from lag in the thermometer varied with the rate of change of measured temperature. The average error was only about -0.1° F in the dives; therefore, no corrections were applied since the errors were considered negligible.

The static-pressure recorder had a reading accuracy of about ± 0.05 inch of water. A calibration of the static-pressure recorder with increasing and then decreasing pressure indicated a hysteresis loop of about ± 0.5 inch of water. The accuracy of the static-pressure recorder, however, is believed to be better than this value indicates since the diaphragm was put in a rested state by applying and releasing a suction of about 350 inches of water several times immmediately before flight and since the static-pressure recorder was calibrated immediately after flight by using a pressure-time sequence approximating the flight tests. The static-pressure recorder is believed to have precision satisfactory for use in place of a statoscope (recommended in reference 3) for measuring small changes in static pressure required in the determination of initial vertical velocity as described in the appendix.

The impact-pressure recorder had an accuracy greater than about ± 0.1 inch of water. The accuracy of the recorder is well within the precision required by the accelerometer method since impact pressure affects only the ratio of static-pressure error to impact pressure, the determination of Mach number M', and the temperature T'.

The time lag in the static-pressure line connected to the static-pressure recorder was estimated to be 0.05 second for the altitude of the tests. Since this time lag corresponded to a lag in static pressure of less than 0.1 inch of water or $0.001 \ q_c'$ for the maximum rate of change of static pressure occurring in the maneuvers, no correction was applied. The time lag in the total-pressure line was estimated to be 0.03 second. The effect of the lag in the total- and static-pressure lines on impact pressure was negligible.

A calibration of the normal accelerometer indicated effects of longitudinal acceleration and of temperature for which corrections were applied. Consistent errors in normal acceleration due to zero shift in the instrument are believed to be eliminated by use of the method described in the appendix. The normal accelerometer had a constant uncertainty of about ±0.2 percent of the change of normal acceleration from 1g. Uncertainty of the longitudinal accelerometer zero is believed to be about ±0.002g.

The sun camera had a reading accuracy of about 0.07° and its setting relative to the axes of the accelerometers could be measured to within about 0.2°. Although the solar time was determined to within 5 seconds, the time was taken at the midpoint of each maneuver since the resulting error in the elevation angle of the sun at the beginning and end of the maneuver was estimated to be small (less than 0.1°).

FLIGHT TESTS

The tests consisted of three shallow dives from an altitude of 31,000 feet to an altitude of about 26,000 feet. Two dives of about $\frac{1}{2}$-minute duration covered a Mach number range from about 0.60 to 0.80 with 2 and 4g pull-ups, and the third dive of about $1\frac{3}{4}$-minutes duration covered a range of Mach numbers from about 0.40 to 0.80 with a 3g pull-up. Prior to each of the short dives, a survey of atmospheric pressure for the radar method was made in a climb at an airplane Mach number of about 0.45 and records were taken about every 500 feet between altitudes of 23,000 and 31,000 feet. Continuous measurements were made during the dives and pull-ups. Radar-phototheodolite equipment was not used for the third dive. The pilot attempted to hold the lateral axis of the airplane normal to the sun's rays through the use of the sundial.

METHOD

The calibration of the airspeed installation by the radar method was made, surveys of atmospheric pressure being used, as described in reference 2. Free-stream static pressure was determined in the surveys by using the static-pressure error determined in previous tests with a trailing airspeed head up to a Mach number of about 0.40. The surveys were made at a Mach number of about 0.45; therefore, extrapolation of the static-pressure error obtained from the tests with trailing airspeed head for the approximate Mach number range from 0.40 to 0.45 was necessary.

The data for the accelerometer method were evaluated by using the following equations as given in reference 3:

$$\left(\frac{p}{p_1}\right)^n = 1 - n\int_{h_1}^{h}\left(\frac{p_m}{p_1}\right)^n \frac{dh}{RT'} \tag{1}$$

where

$$dh = \left(v_1 + \int_{t_1}^{t} a_v\, dt\right)dt \tag{2}$$

and

$$a_v = a_z \cos\theta - a_x \sin\theta - g \tag{3}$$

For the purpose of evaluation, the dives were divided into two parts. Data from the first part of each dive were used to determine the vertical velocity v_1 at the beginning of the last part of the dive as described in the appendix. The static-pressure error was evaluated only for the last part of the dive.

The static-pressure error determined for corresponding flight conditions from results obtained with the trailing airspeed head and the radar method was used in computing the vertical velocity v_1 from data taken during the first 12 seconds of dive 1, the first 13 seconds of dive 2, and the first 45 seconds of dive 3.

The free-stream static pressure p_1 in equation (1) was obtained from the static pressure measured at the beginning of the last part of the dives by using the static-pressure error as determined from the calibration by the radar method. Since the results of the radar calibration were obtained from Mach numbers of 0.57 to 0.78, the results of dive 3 were evaluated by the accelerometer method starting at the time at which a Mach number of 0.57 was attained (57 sec from end of maneuver).

By using vertical velocity v_1 and static pressure p_1 thus determined, the static-pressure error was evaluated for the last 22, 24, and 57 seconds of dives 1, 2, and 3, respectively.

RESULTS AND DISCUSSION

The results of the calibrations by both methods are presented as plots of $\frac{p_m - p}{q_c'}$ against indicated Mach number M' in figure 3. The static-pressure error determined by the accelerometer method for dives 1 and 2 and subsequent pull-outs was nearly constant at about 2.5 percent of impact pressure with very little scatter of data over the range of Mach numbers used in the evaluation (0.65 to 0.78). The results of dive 3, evaluated over a much larger time interval and Mach number range (0.57 to 0.78), agreed closely with the results of the other dives up to the start of the pull-out, after which the results for dive 3 showed a few points that were lower than the average for the other dives by as much as 1 percent of impact pressure. Because of the absence of similar effects in pull-outs following dives 1 and 2, this deviation is not considered to be the effect of airplane lift coefficient on the calibration. The deviation is, however, within the accuracy accepted for most calibrations. Uncertainties of the airspeed calibration, due to the estimated errors of several sources, varied from zero near the beginning of dive 3 to maximum values near the end of the dive. These maximum values are shown in table I. Since the calculations for two of the sources were necessarily probable errors and for the remaining sources were necessarily nominal maximum possible errors, no attempt was made to compare the data with any combination of these uncertainties.

The static-pressure error as determined by the radar method increased from about 2.5 percent of impact pressure at a Mach number of 0.57 to a little over 3.0 percent at a Mach number of 0.78. The scatter of about ±0.5 percent at the low Mach numbers and ±0.2 percent at the high Mach numbers is about 1/2 the maximum possible scatter due to inaccuracies of measuring static pressure and height by radar (±45 feet slant range and ±0.2 mil elevation angle). On the basis of the faired data, the results of the radar-method calibration show the greatest difference (0.5 percent) from the accelerometer-method calibration at the high Mach numbers. Differences of this magnitude have been noted between two tests for a radar calibration in reference 2, although in the present tests there was no consistent difference between the two successive dives. It should be noted that the maximum uncertainty in the accelerometer method, due to the estimated possible error in static pressure (shown in table I), is about the same magnitude.

The calibration, as determined by both the radar and accelerometer methods, is typical of nose-boom installations inasmuch as there was little effect of either Mach number or lift coefficient over the ranges covered in these tests.

As the result of experience gained with evaluating the data for the accelerometer method, some improvements in the test procedures and reduction of data outlined in reference 3 were apparent. The initial vertical velocity may be determined as discussed in the appendix. The accuracy of the determination of the initial vertical velocity could be improved if a run, in perhaps steady level flight at a speed for which the airspeed calibration is known, is made for an appreciable length of time immediately prior to, and continuous with, the calibration maneuver. The time for the calibration maneuver should be as short as possible since the error in static pressure due to errors in the initial vertical velocity and in vertical acceleration will increase with time. A short time for the calibration maneuver may require a steep dive and hence a sun camera covering a wider range of attitude angles.

CONCLUDING REMARKS

A calibration of the pitot-static airspeed installation on a jet fighter airplane was made to compare the accelerometer method of determining static-pressure error with the radar method. The tests included shallow dives up to a Mach number of about 0.80 with pull-ups of about 4, 3, and 2g normal acceleration.

The calibrations of the dives by the two methods are typical of a nose-boom installation inasmuch as there was little effect of either Mach number or lift coefficient over the ranges covered in these tests. The static-pressure error as determined by the radar method increased from about 2.5 percent of impact pressure at a Mach number of 0.57 to a little over 3.0 percent at a Mach number of 0.78. The static-pressure error determined by the accelerometer method was nearly constant at about 2.5 percent of impact pressure over the same Mach number range.

From the results of the tests it appears that, for vertical plane maneuvers, the accelerometer method may be used as an alternate to the radar method. Although the accelerometer method requires airplane instrumentation of high precision, this equipment may be more generally available than the radar equipment.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., September 28, 1951

APPENDIX

DETERMINATION OF INITIAL VERTICAL VELOCITY AND ZERO SHIFT IN A NORMAL ACCELEROMETER

If a run in level flight or a shallow dive is made prior to, and continuous with, the calibration maneuver, the initial vertical velocity v_o at the start of this run may be determined from integrations of the accelerometer measurements and change in geometric height computed from pressure and temperature measurements by using the equation

$$-\int_{p_o}^{p} \frac{RT}{p}\, dp = v_o t + \int_0^t \int_0^t a_v \, dt\, dt \tag{4}$$

This method of determining vertical velocity v_o, however, may introduce errors due to errors in vertical acceleration. An appreciable source of error in the airspeed calibration by the accelerometer method may be the zero shift of the normal accelerometer. This error can be corrected at the same time that v_o is determined. The vertical acceleration may be written as

$$a_v = a_v' + \Delta a_v \tag{5}$$

where a_v' is indicated vertical acceleration and Δa_v is a constant error in vertical acceleration. In level flight or a shallow dive

$$\Delta a_v \approx \Delta a_z \tag{6}$$

Equation (4) may therefore be rewritten as

$$-\int_{p_o}^{p} \frac{RT}{p}\, dp - \int_0^t \int_0^t a_v' dt\, dt = v_o t + \Delta a_z \frac{t^2}{2} \tag{7}$$

A solution of this equation which contains two unknowns, v_o and Δa_z, may be determined by satisfying the equation over two time intervals. A better approach is to use the method of least squares with a large number of time intervals.

Once v_o $\left(\text{and } \Delta a_z\right)$ is determined, the vertical velocity v_1 at the start of the calibration maneuver may be determined as

$$v_1 = v_o + \int_0^{t_1} a_v \, dt \qquad (8)$$

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TABLE I

ESTIMATED ERRORS IN AIRSPEED CALIBRATION NEAR THE END OF DIVE 3 DUE TO VARIOUS SOURCES OF CONSTANT ERROR IN THE EVALUATION BY THE ACCELEROMETER METHOD

Source	Source error	Error in airspeed calibration (percent impact pressure)
Initial velocity v_o determined by least-square method	±0.09 ft/sec (probable error)	±0.04 (probable)
Zero of normal accelerometer determined by least-square method	±0.0053 ft/sec^2 (probable error)	±.21 (probable)
Sensitivity of the normal accelerometer	$\pm 0.002 \left(a_z - g\right)$	±.11
Zero of longitudinal accelerometer	±0.064 ft/sec^2	∓.08
Attitude angle	$\pm 0.2^\circ$	∓.02
Temperature	$\pm \frac{1}{2}^\circ$ F	±.25
Static pressure	$\pm \frac{1}{4}$ in. of water	∓.46

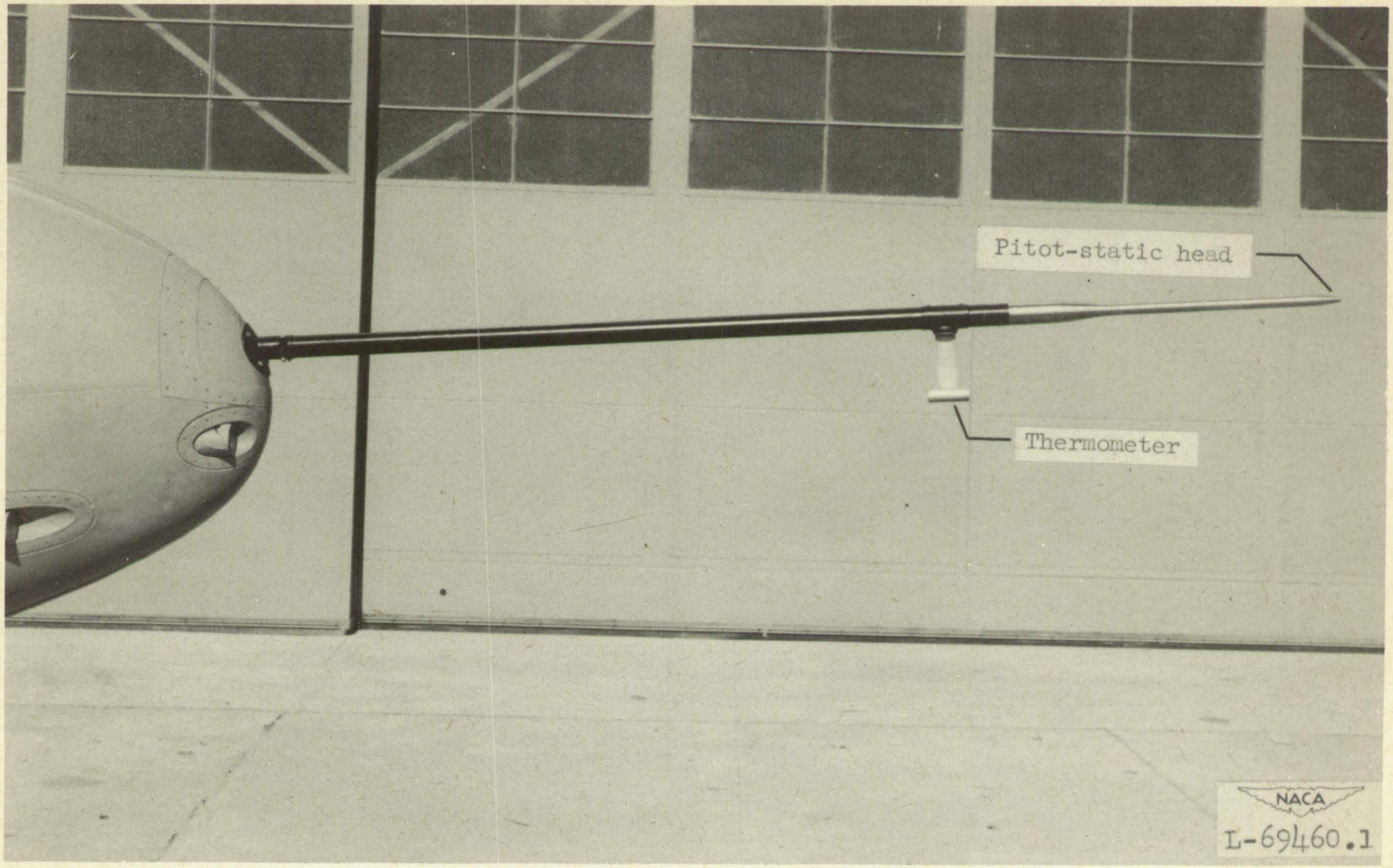
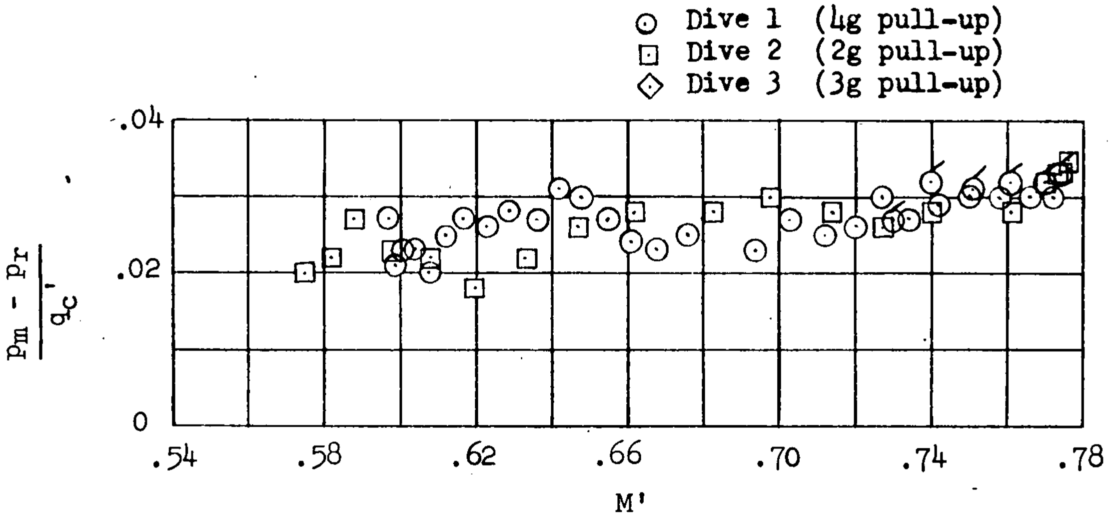
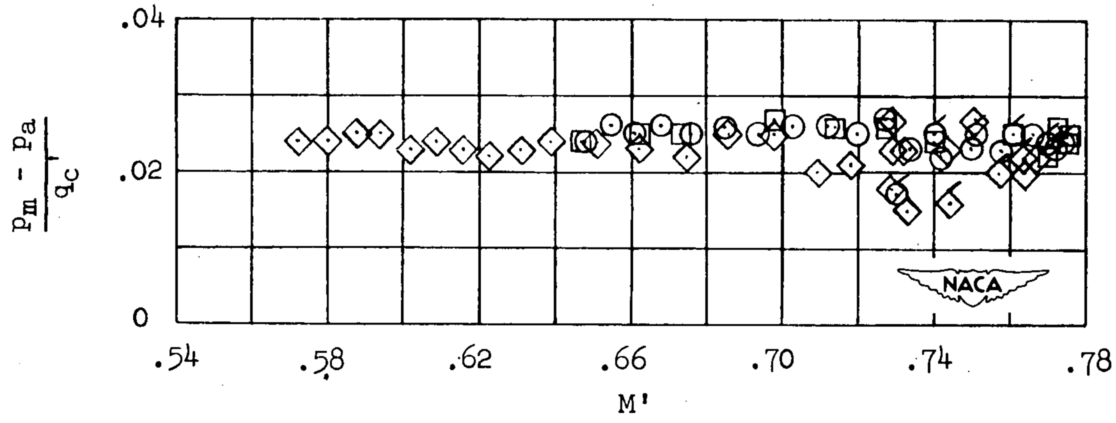


Figure 1.- Pitot-static head and thermometer mounted on the fuselage nose boom.

Figure 2.- Sundial used by the pilot as an aid in alining the airplane with the sun.



(a) Radar method.



(b) Accelerometer method.

Figure 3.- Airspeed calibration as evaluated by the radar and accelerometer methods. Flagged symbols are in the pull-out where $a_z \geqq 2g$.