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LOW-SPEED AIRSPEED CALIBRATION DATA FOR A SINGLE-ENGINE RESEARCH-SUPPORT AIRPLANE

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SUMMARY

A standard service airspeed system on a single-engine research-support airplane was calibrated by the trailing anemomenter method. The effects of flaps, power, sideslip, and lag were evaluated. The factory-supplied airspeed calibrations were not sufficiently accurate for high-accuracy flight research applications. The trailing anemometer airspeed calibration was conducted to provide the capability to use the research support airplane to perform pace aircraft airspeed calibrations.

INTRODUCTION

In many flight research situations, the need arises to conduct airspeed calibrations on uninstrumented aircraft. The most convenient method to use in this situation is the pace aircraft technique. By flying in formation with the uninstrumented, uncalibrated aircraft, the calibrated airspeed data from a pace aircraft can be used to provide airspeed position error information for the uncalibrated aircraft. The purpose of the present investigation was to provide an accurate airspeed calibration on a research support airplane which can be used for the pace calibration technique. The effects of flaps, power, sideslip, and pitot-static system lag were evaluated.

Although factory-supplied airspeed calibrations may be sufficiently accurate for operational use, there is a need, for research purposes, to determine airspeed precisely. For example, small errors in airspeed can produce significant differences in determining maximum lift coefficients.

The trailing anemometer used was developed by the staff of NASA Langley Research Center (ref. 1). A discussion of the accuracy of the system is given in references 2 and 3.

SYMBOLS

Except for airspeed, which is given in knots (1 knot = 0.514 m/sec), data are presented in the International System of Units (SI) with the equivalent values given parenthetically in U.S. Customary Units. (Factors relating the two systems of units in this paper are given in reference 4.)

C_L	Airplane lift coefficient, L/qS
h	Altitude, m (ft)
$\dot{h}$	Rate of change of altitude, m/s (ft/min), positive upward
K	Airspeed conversion constant, 0.514 m-sec^{-1} - knot^{-1} (1.688 ft-sec^{-1} - knot^{-1})
L	Lift, N (lb)
p	Freestream statio pressure, Pa (lb-ft^{-2})
q	Dynamic pressure, $\rho V^2/2$, Pa (lb-ft^{-2})
q_c	Impact pressure, (total pressure minus static pressure) Pa (lb-ft^{-2})
R	Gas constant for air, 287.05 J-kg^{-1} - $^oK^{-1}$ (1716.5 ft-lb - slug^{-1} - $^oR^{-1}$)
S	Wing planform area, m^2 (ft^2)
T	Absolute total temperature, ^oK (^oR)
V	True airspeed, knots
V_c	Calibrated airspeed, knots
V_i	Indicated airspeed, knots
α	angle of attack, deg
β	Sideslip angle, deg
Δh	Altitude position error, m (ft)
Δp	Static pressure position error, p' -p, Pa (lb-ft^{-2})
ΔV	Airspeed position error, knots
ΔV_I	Instrument scale error in airspeed indicator, knots
δ_f	Flap deflection, positive for trailing edge down
ρ	Air density, kg - m^{-3} (slugs-ft^{-3})

Subscripts:

o Standard sea-level conditions

A prime denotes a measured quantity which contains position error.

AIRPLANE AND INSTRUMENTATION

The airplane, figure 1, is a low-wing, retractable-gear, turboprop-driven, single-engine, two-place, military training aircraft. The airplane has a gross weight of 18.68 kN (4200 lb) and a wing area of 16.71 m^2 (180 ft^2). The service total pressure probe was mounted on the left wing at the 60-percent wing semispan location. The two static pressure orifices were located on either side of the fuselage aft of the cockpit canopy.

A calibrated, sensitive airspeed indicator was installed to permit indicated airspeed readings within ±0.5 knots. Ambient air temperature was measured with the standard, service outside air temperature probe within ±1.0 °C.

True airspeed was measured by an anemometer which was trailed outside the aircraft pressure influence field. The trailing anemometer was installed on the airplane as shown in figure 1. The deployment mechanism of the trailing anemometer system was attached to the bottom of the fuselage between the main landing gear. The anemometer has negligible shaft friction so that the anemometer propeller rotation speed is proportional to true airspeed without regard to air density (see ref. 1). A complete discussion of the anemometer system, installation, and operations is given in references 1, 2, and 3.

For the trailing anemometer airspeed calibration method, the following variables were recorded manually from panel-mounted instruments under steady-state conditions: indicated airspeed, true airspeed from the anemometer, pressure altitude, and outside air temperature.

Static pressure and impact pressure were sensed by the pitot tube and static ports illustrated in figure 2. The static pressure orifices (figure 2a), one mounted on each side of the fuselage, were connected together inside the fuselage to minimize asymmetric effects of sideslip on static-pressure measurements. It is assumed that total pressure is measured with no errors caused by flow angularity (α and β), within the limits of the service pitot tube ($\alpha = \pm 10^{\circ}$). The standard service pitot-static system was not balanced. Thus, with changing airspeed or changing altitude, pneumatic lag will affect indicated airspeed and altitude. The calibration conducted with the trailing anemometer takes into account position error and flow angularity errors for the static pressure sensors (if any).

EXPERIMENTAL METHODS AND TESTS

Airspeed calibration data were taken at constant speed conditions for either constant or varying altitude, as indicated in table I. All data were gathered with the anemometer deployed with two wingspans of cable length. The true airspeed signal from the trailing anemometer was recorded by hand with visual averaging of the signal which varied by ±0.5 knots about the mean during these tests.

A total of 77 test runs were made, consisting of 34 flaps-up runs between 67 and 131 knots, and 43 flaps-down (δ_f = 100 percent) runs between 55 and 121 knots. The lowest speed point in each configuration was at the stall.

The effects of sideslip were evaluated by taking calibration data at two sideslip angles in each direction, left and right. The magnitude of wings-level sideslip angles was controlled by displacing the turn coordination ball from center in increments of 1/2 and 1-ball-width displacements. Data were gathered in sideslips with flaps up and flaps down.

The effect of power and the effect of pneumatic lag, individually, on airspeed calibrations can be large. Since the data herein were gathered manually, and since the pitot-static system used was not pneumatically balanced, it was not possible to conduct dynamic flight maneuvers which would allow the effects of power and lag to be separated. Thus, the data gathered during full-power climbs and throttle-idled descents include the effects of power and lag combined.

DATA REDUCTION

Two basic assumptions were made for this airspeed calibration method. First, for the low speeds used in these tests, the airflow was assumed to be incompressible. Second, it was assumed that all position error in the standard service airspeed system was static-pressure position error Δp due to the pressure influence field of the airplane. The static-pressure position error is the difference between the measured and the actual static pressure: $\Delta p = p' - p$. Actually, the Δp also included small flow angularity error in static pressure due to the characteristics of the fuselage flush-mounted static ports; but, since the entire airspeed system was being calibrated, this error was included as part of the static-pressure position error.

Because the center-of-gravity travel on this airplane was so small, no measurements were made of the effects of center-of-gravity position variations on position error.

Equations given in reference 2 show how pressure, temperature, density, and velocity relations have been combined to give the following expression for static-pressure position error using the trailing anemometer method:

$$\Delta p = \frac{(p' V^2 K^2/2RT') - q_c'}{1 + (V^2 K^2/2RT')}$$

This expression does not require measurement of freestream static pressure. Instead, the freestream state is established through measurement of true airspeed by the trailing anemometer. The measured impact pressure q_c' and the measured static pressure p' were sensed by the standard service pitot-static system. The total temperature T was sensed within ±1.0 °C by a standard outside air temperature probe mounted in the forward windscreem of the cockpit. It was assumed that T was equal to freestream temperature. The measured static pressure was then computed based on indicated pressure altitude.

The measured impact pressure q_c' was determined indirectly from indicated airspeed, V_i. As defined in reference 6, indicated airspeed contains both instrument and position errors. For the present tests, a calibrated, sensitive airspeed indicator was used to determine indicated airspeed. The instrument error ΔV_I for this indicator was calibrated and is presented in figure 3 and the indicated airspeed containing only position error is given by the relation:

$$V_i = \text{Indicator reading} - \Delta V_I$$

By removing the instrument error from indicated airspeed, V_i, the following relations apply:

$$q_c' = \frac{(V_i K)^2 \rho_o}{2}$$

The static-pressure position error, $\left(\frac{\Delta p}{q_c'}\right)$, was then used to determine the following:

(a) Calibrated airspeed:

$$V_c = V_i \sqrt{1 + \left(\frac{\Delta p}{q_c'}\right)}$$

(b) Impact pressure:

$$q_c = q_c' + \Delta p$$

(c) Static pressure:

$$p = p' - \Delta p$$

(d) Airspeed position error:

$$\Delta V = V_c - V_i$$

As illustrated in figure 3, there is a random difference shown between laboratory measured points for increasing and decreasing pressures, therefore the average value was used as ΔV_I during data reduction. It can be seen that the accuracy of the indicated airspeed from this sensitive, mechanical airspeed indicator is poorer than the accuracy of the true airspeed from the trailing anemometer (±0.5 knots, see ref. 3). To achieve comparability between the accuracy of true airspeed and indicated airspeed measurements and for convenience in static pressure measurement, an electronic digital display of measured impact and measured static pressure sensed by electronic pressure transducers should be used. The service altimeter used was not calibrated for instrument error; however, the allowable manufacturing scale tolerance for the type of altimeter used is equivalent to an error of the order of 0.5 percent of the pressure at the static port (approximately ±190 Pa [±4 lb/ft^2]). This altimeter tolerance produces an insignificant error in airspeed calibration data when using the trailing anemometer technique.

A position-error correction for the indicated altitude can be computed using the equation

$$\text{(g)} \quad \Delta h = h - h' = RT \ \ell n \left(\frac{p + \Delta p}{p}\right)$$

This correction should be added to the instrument-error calibration for the altimeter used (not given in this paper).

RESULTS AND DISCUSSIONS

Figures 4 to 6 present the variation of static-pressure position error $\Delta p/q_c'$ with trimmed airplane lift coefficient, C_L. It is important to note that in future use of the present data for pace airspeed calibrations, angle of attack data is desirable to permit accurate determination of C_L. Without knowledge of α, indicated airspeed, V_i is used to compute C_L at the test weight. This biased value of C_L is then used to read position error $\Delta p/q_c'$, from the appropriate figure. Note, however, that if the correction to V_i is very large, C_L can be recomputed with the corrected V_i. This will produce an iterated value of $\Delta p/q_c'$. For operational use of the data presented herein, the initial value of $\Delta p/q_c'$ obtained from the indicated airspeed will generally be sufficiently accurate.

At faster airspeeds, since C_L changes very little with small airspeed changes and since V_i contains relatively little position error, this procedure yields negligible errors in C_L and, therefore, in $\Delta p/q_c'$. However, at slower speeds, where C_L changes a lot with small airspeed changes, and since V_i contains a relatively larger position error, the biases in C_L and in $\Delta p/q_c'$ will be larger. To eliminate this error, provision for measuring angle of attack would allow precise determination of C_L, and, hence, position error, $\Delta p/q_c'$. The data presented herein for very high angles of attack are uncertain due to the accuracy limit ($\alpha = \pm 10^\circ$) of the total pressure sensor (service pitot tube). Since the precise load flow angles at the pitot tube are not known, it would be desirable to install a total head probe which maintains a high level of accuracy over a wide range of flow angularity.

The effect of flap setting on the position errors is presented in figure 4. As illustrated by these data and by data from reference 7, flap deflection produces large changes in position error when static pressure is measured by vents mounted on the rear section of the fuselage. These changes are caused in part by the effects of the fuselage, wings, flaps, horizontal tail, propeller slipstream, and angle of attack differences for a given lift coefficient as the flap is deflected. At speeds slower than V_i = 80 knots (at gross weight $C_L > 1.0$) the effect of flap deflection on position error was appreciable. At speeds faster than $V_i = 80$ knots, the effects of flaps on position error is very small.

The effects of power and pneumatic lag, combined, are illustrated in figure 5 for two flap settings. The power effects on position error can be large (see references 3 and 7), as can be the effects of lag in an unbalanced airspeed system. No effort was made in this investigation to separate the effects of these two variables. To accurately calibrate the effects of power on airspeed calibrations, the effect of lag must be removed by computation or the airspeed system must be pneumatically balanced.

The data for climbs presented in figure 5 were gathered in full-throttle climbs at a density altitude of 4115 m (12,500 ft), which yields about 90-percent of maximum rated sea level power. Indicated rate of climb varied between 3.81 - 9.73 m/sec (750 - 1900 ft/min), depending on airspeed. The descent data presented in figure 5 were gathered with throttle idled, yielding descent rates of 7.62 - 13.21 m/sec (1500 - 2600 ft/min). Note that for a given lift coefficient, the deflected flap during the climbing and descending maneuvers makes the position error $(\Delta p/q_c')$ considerably more negative.

The effects of sideslip on position error are presented in figure 6 for two flap deflections. Flaps up or down, the effect of sideslip is symmetric; that is, left and right sideslips produced nearly identical position errors. This behavior was expected due to the design of the static pressure system which connects pressure vents on both sides of the fuselage. For the two sideslip angles tested, there appears to be very little effect of magnitude of sideslip on magnitude of position error induced by sideslipping. Converted to airspeed corrections, ΔV, these errors are as large as 4 knots.

The results of these tests suggest that, even though the static system utilizes symmetric, joined static vents on eigher side of the fuselage, sideslipping should be avoided when using this research support airplane for the pace airspeed calibration method.

Figure 7 illustrates the differences between flight manual data (ref. 5) and flight-test results presented herein. The large differences are likely due to the inherent inaccuracy of the ground course method of airspeed calibration (especially at low speeds) used to produce the factory-supplied calibration.

As discussed in reference 3, the trailing anemometer method gives more precision at low speeds than calibration methods which depend on measurement of static pressure to establish position error. The differences between the two sets of airspeed calibration data were as large as 7 knots at low speeds, but vary depending on speed and flap deflection. It is reiterated here that the accuracy of the total head at high angles of attack is uncertain, and may affect the high C_L data presented herein.

SUMMARY OF RESULTS

The standard, service airspeed system on a single-engine research support airplane was calibrated using the trailing anemometer method. The results of the tests indicated that:

1. Appreciable position errors exist in the standard service airspeed system and the accuracy of the factory-supplied calibrations is insufficient for highly accurate flight research applications. The differences between the factory-supplied and trailing anemometer measured airspeed calibrations were as large as 7 knots, near stall speed with flaps deflected. (Note that the angle of attack limit for accuracy of the total pressure probe is $\alpha \leq \pm 10^{\circ}$. Thus the accuracy of the position error data presented at very high C_L is uncertain.)

2. At speeds slower than 80 knots (at gross weight $C_L > 1.0$), the effect of flap deflection on position error was appreciable, and must be accounted for during pace airspeed calibrations.

3. Even though the standard service static-pressure system utilizes symmetric, joined static vents on either side of the fuselage, sideslip-induced position errors were as large as 4 knots. Sideslipping should be avoided when using this research support airplane in the pace airspeed calibration method.

4. The combined effects of power and pneumatic lag on position error are very large, producing airspeed position error corrections as large as 8 knots. To minimize the position error corrections during the use of this airplane in the pace airspeed calibration method, maneuvers involving any rate of change of altitude should be done with flaps retracted. Even in this case, the magnitude of the power-effect contribution to the position error is unknown.

5. The accuracy of airspeed calibrations conducted using the present data and pace aircraft could be improved by the following changes:

(a) Provide calibrated angle of attack data on the aircraft to permit the data to be presented as a function of α.

(b) Provide electronic digital readouts for indicated static and dynamic pressure (p' and q_c') directly from pressure transducers to eliminate the airspeed instrument scale error.

(c) Provide a balanced pitot-static pressure measuring system to permit accurate calibration of the effects of power on position error.

(d) Calibrate high α range with total head tube insensitive to large α variations.

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TABLE I.- AIRSPEED CALIBRATION TEST CONDITIONS (LANDING GEAR RETRACTED)

Flaps	Power	V_i (kts)	β	$\dot{h}$ (m/sec)
0%	Level flight	68 to 130	0°	0
100%	Level flight	55 to 120	0°	0
0%	Level flight	90, 120	±1/2; ±1 ball	0
100%	Level flight	90, 120	±1/2; ±1 ball	0
0%	Full throttle (≈90% power)	67 to 131	0°	+5.59 to +9.73
100%	Full throttle (≈90% power)	55 to 120	0°	+3.81 to +7.62
0%	Throttle idled	80 to 130	0°	-9.14 to -11.18
100%	Throttle idled	61 to 121	0°	-7.62 to -13.21

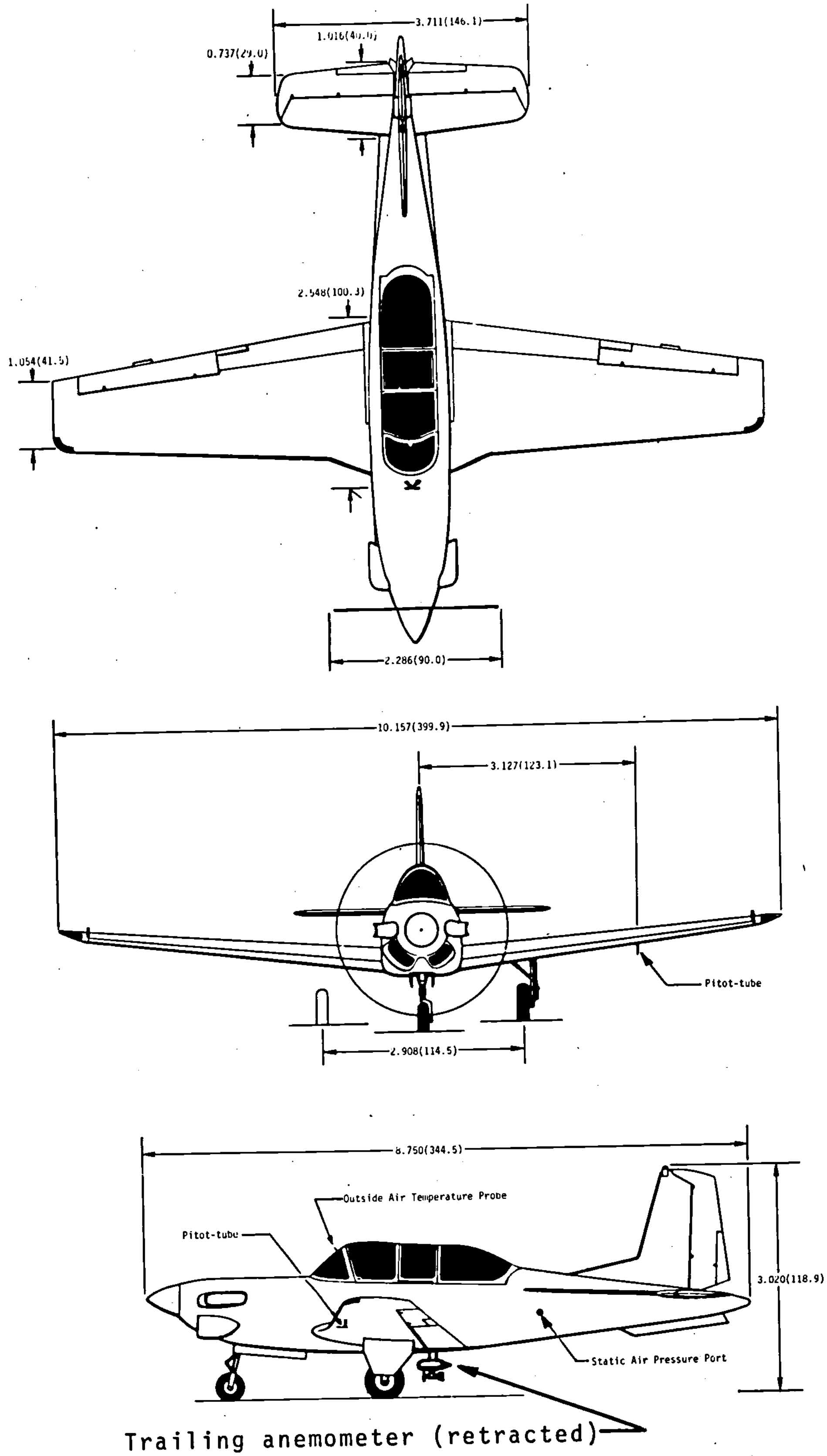
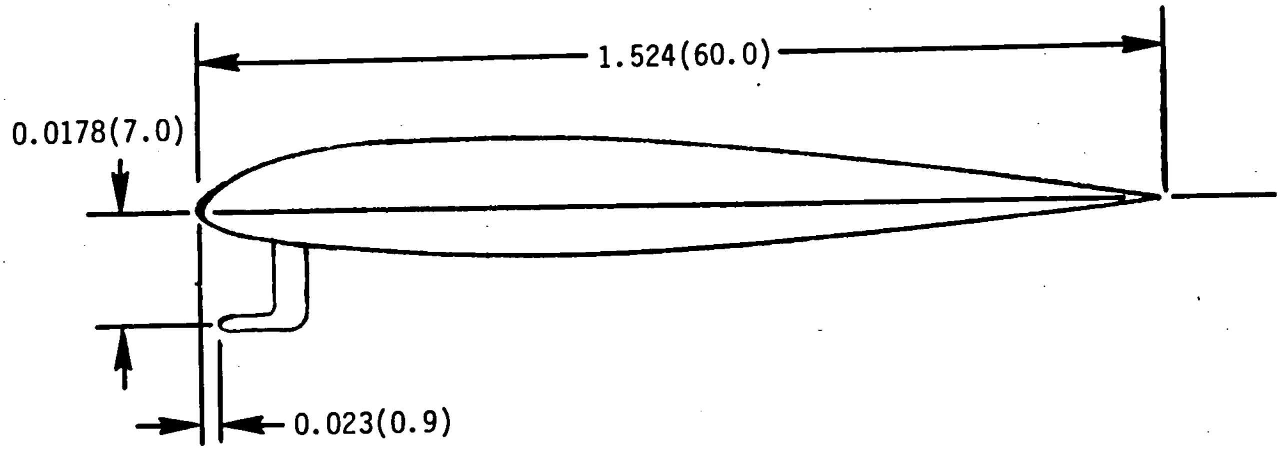
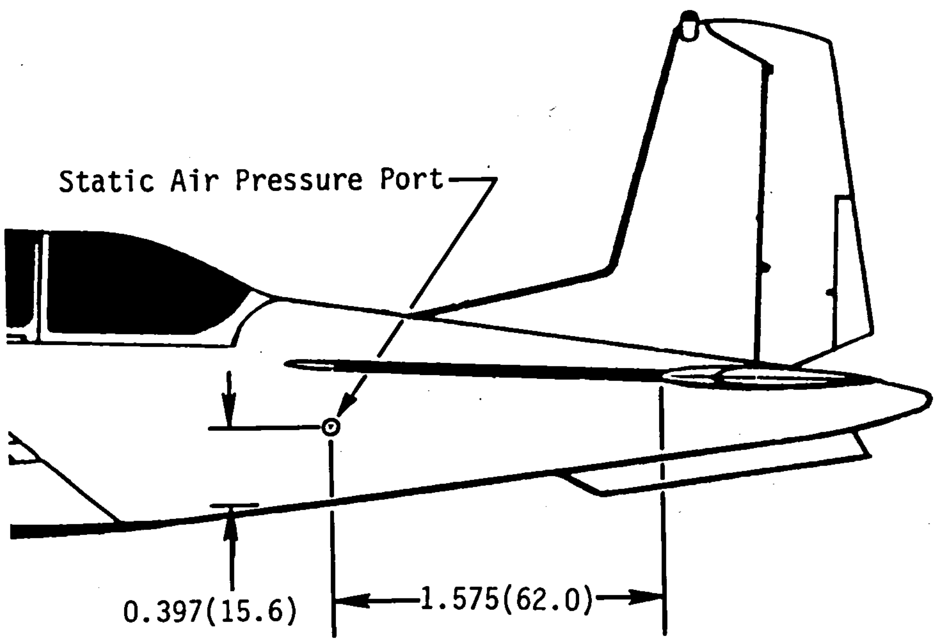


Figure 1.- Threeview of NASA 510 T-34C Research support airplane. Dimensions in m (inches).



(b).- Pitot tube



(a).- Static ports (one on each side of fuselage)

Figure 2.- Standard service pitot-static system on research support airplane. Dimensions in m (inches).

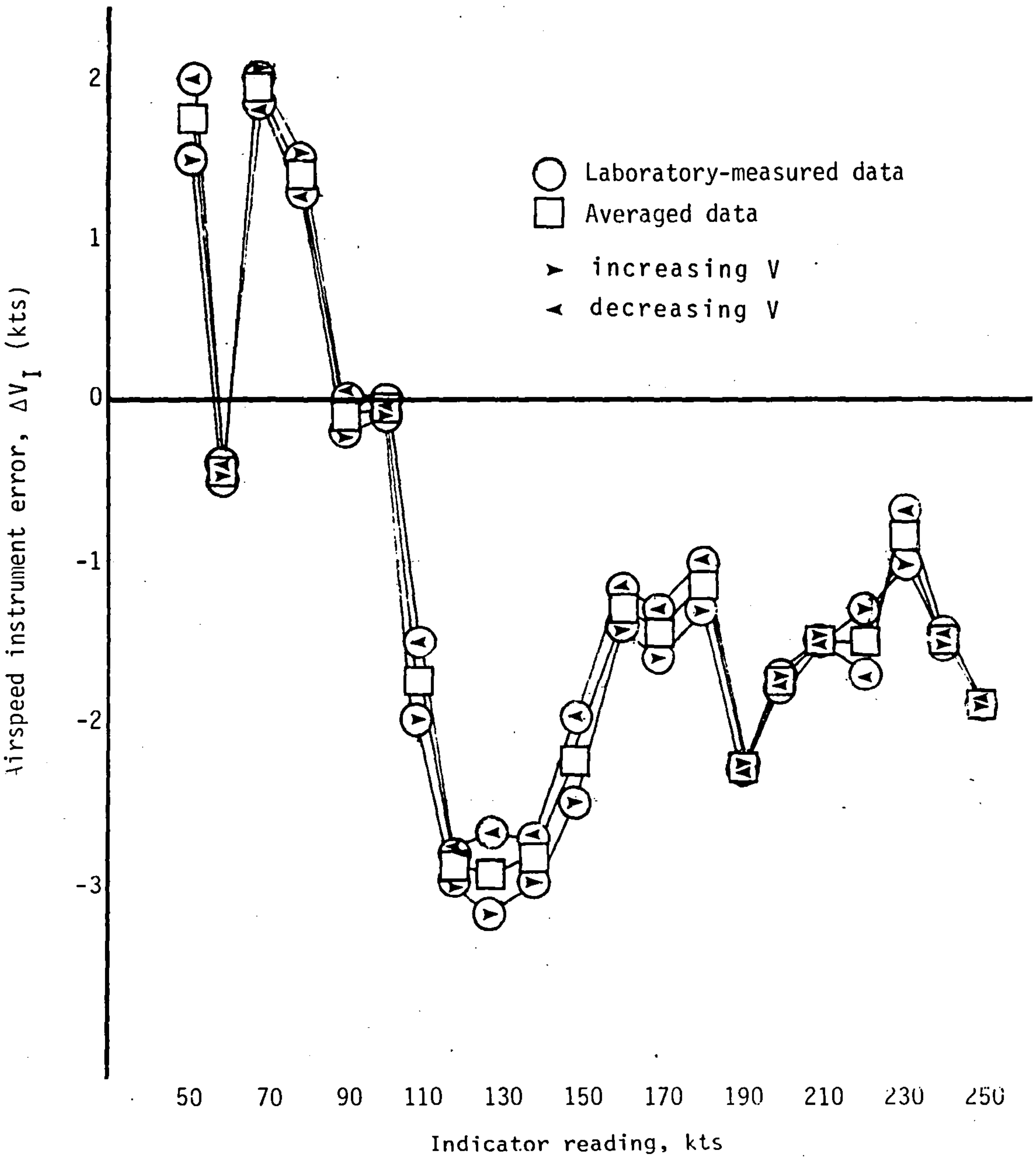


Figure 3.- Instrument scale error for sensitive airspeed indicator in research support airplane (arrows indicate increasing and decreasing speeds during calibration).

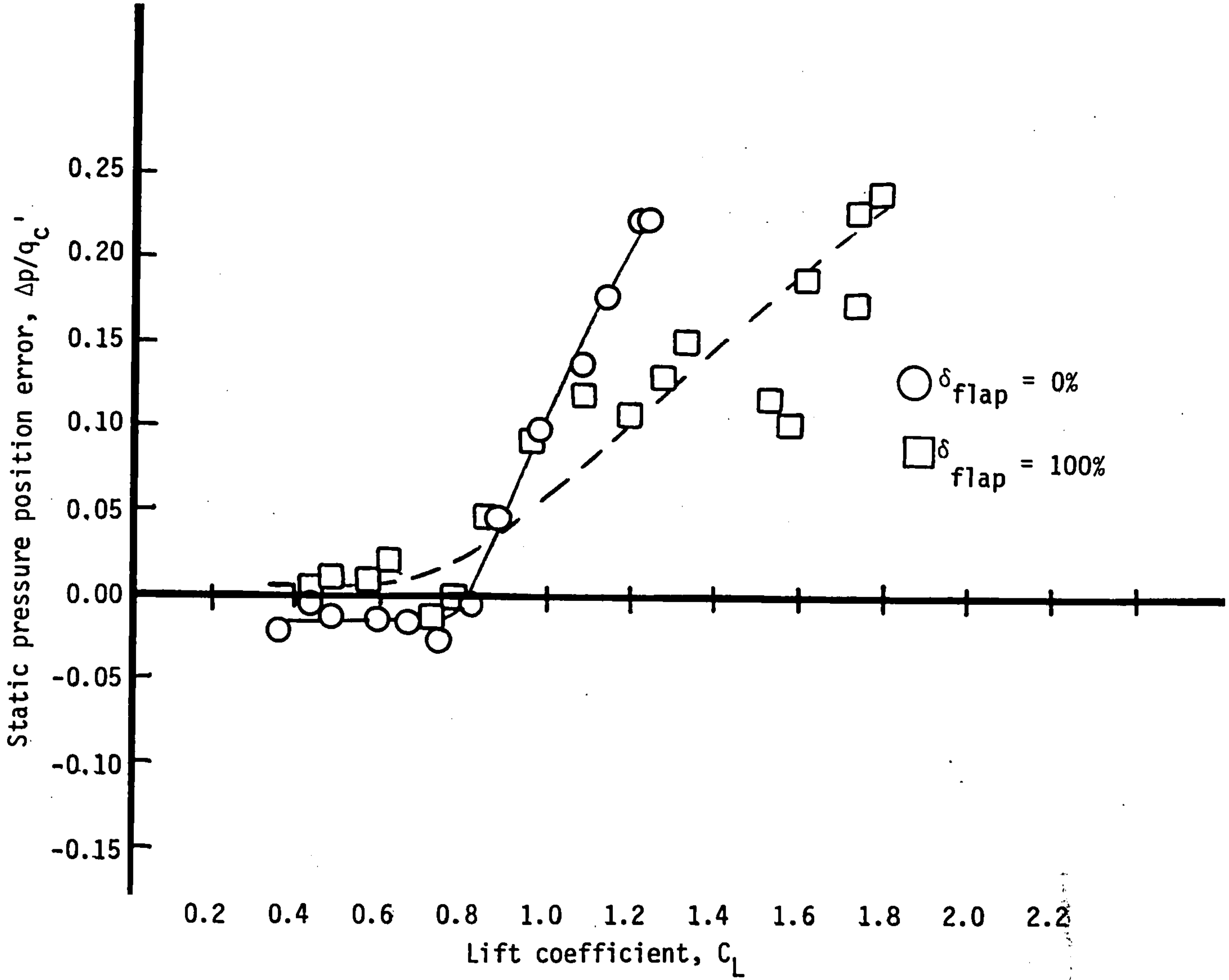
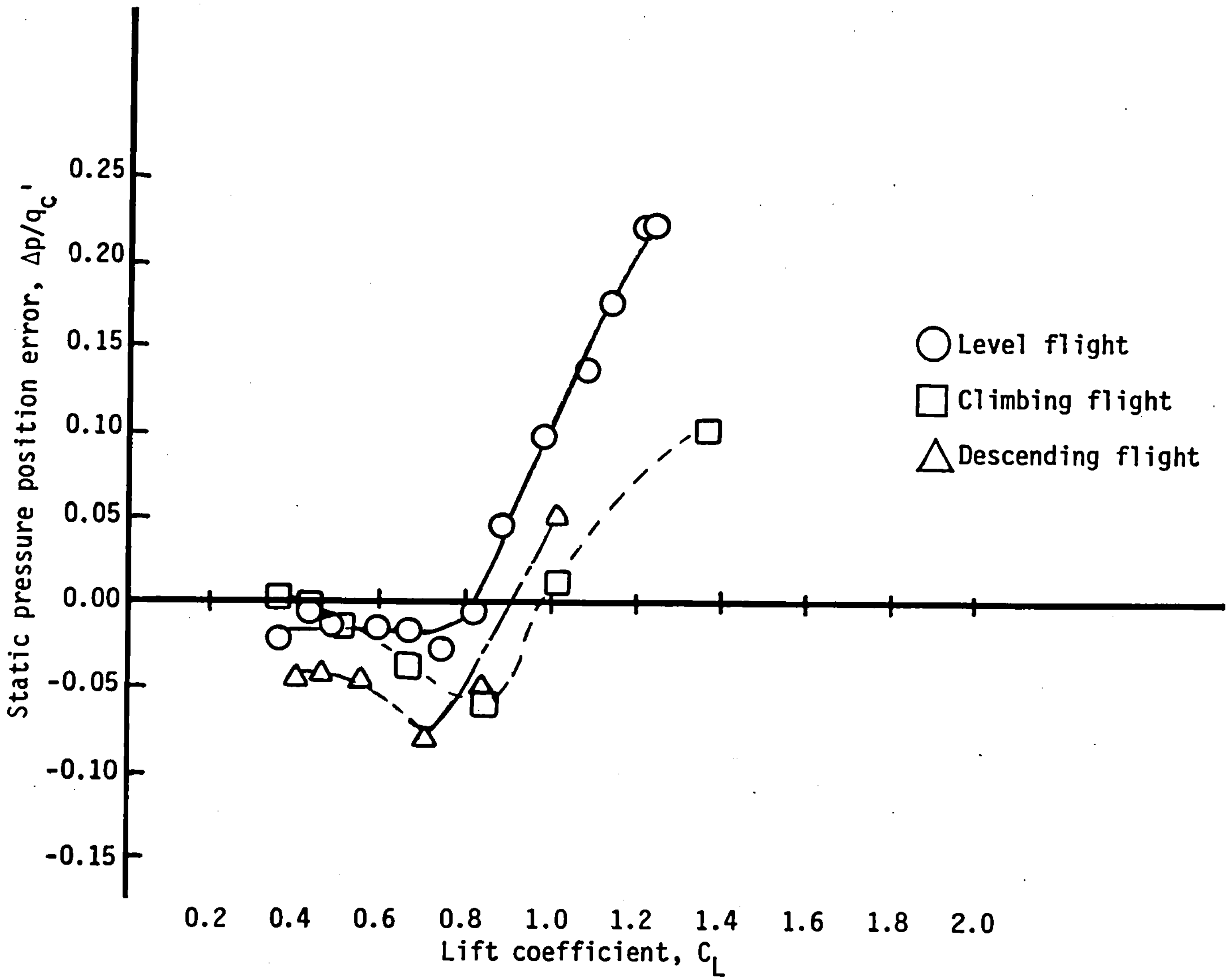
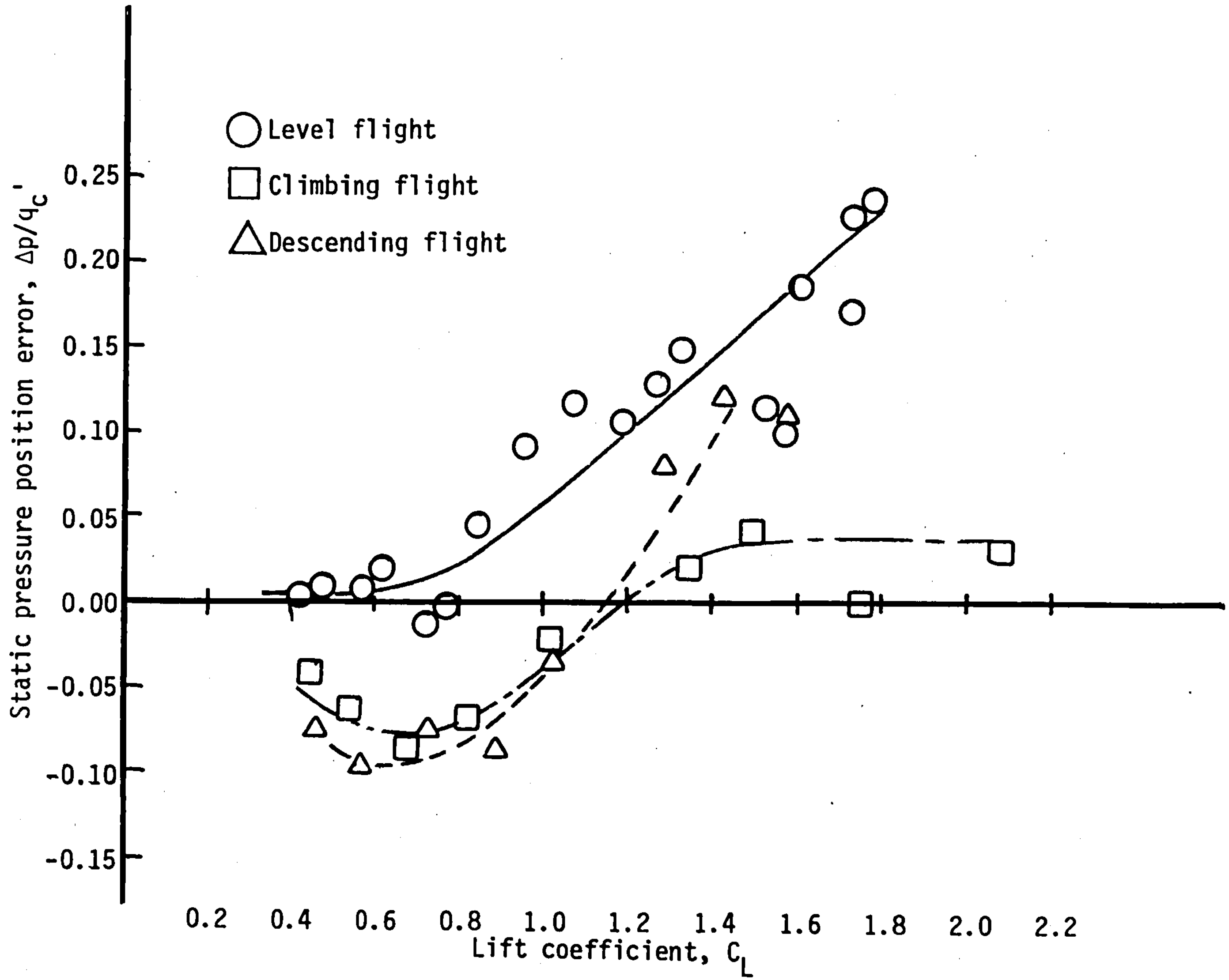


Figure 4.- NASA-510 T-34C airspeed calibration; level flight; effect of flaps; sideslip = 0^{o}



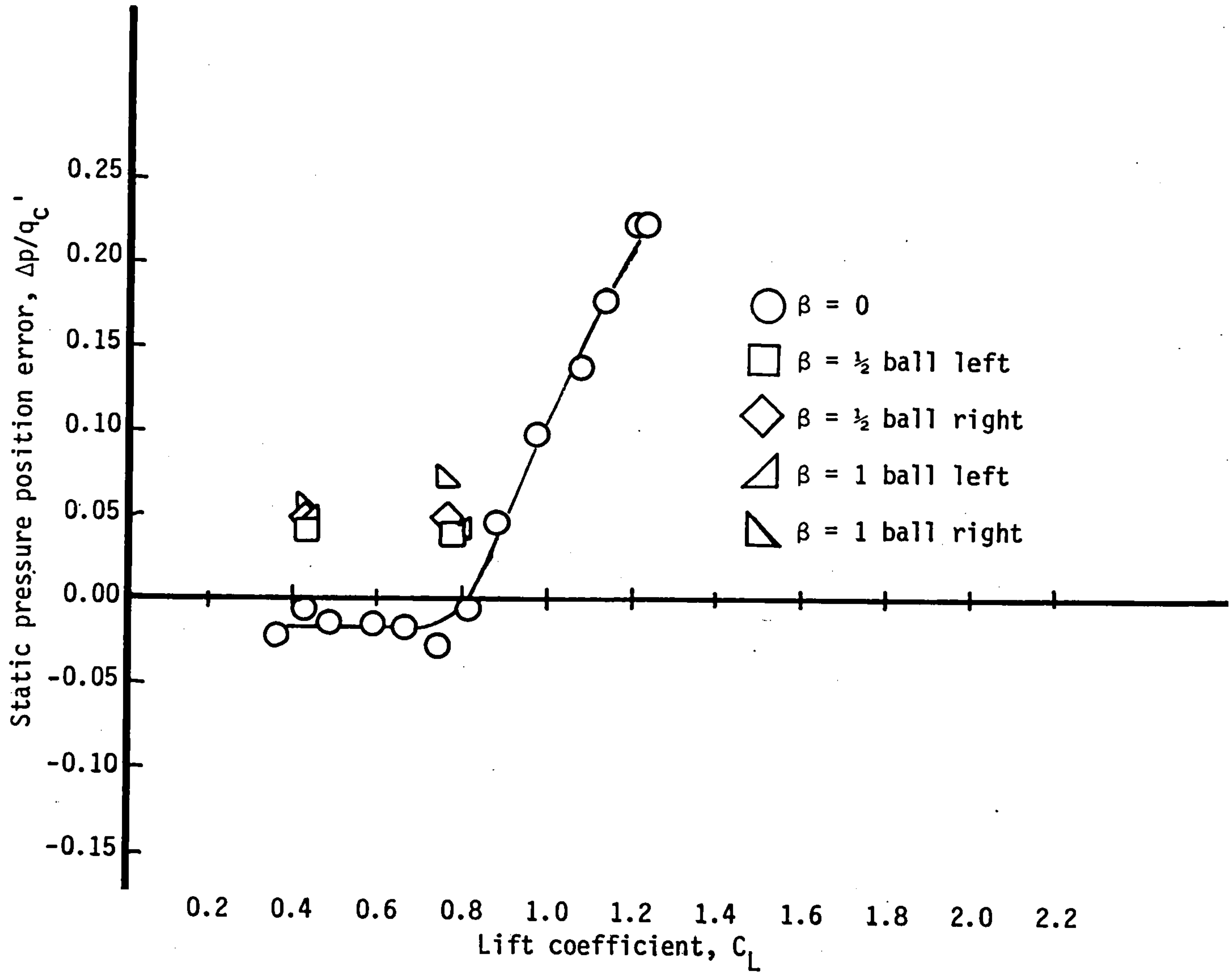
(a).- δ_{flap} = 0%

Figure 5.- NASA-510 T-34C airspeed calibration; effects of power and pneumatic lag; sideslip = 0^o.



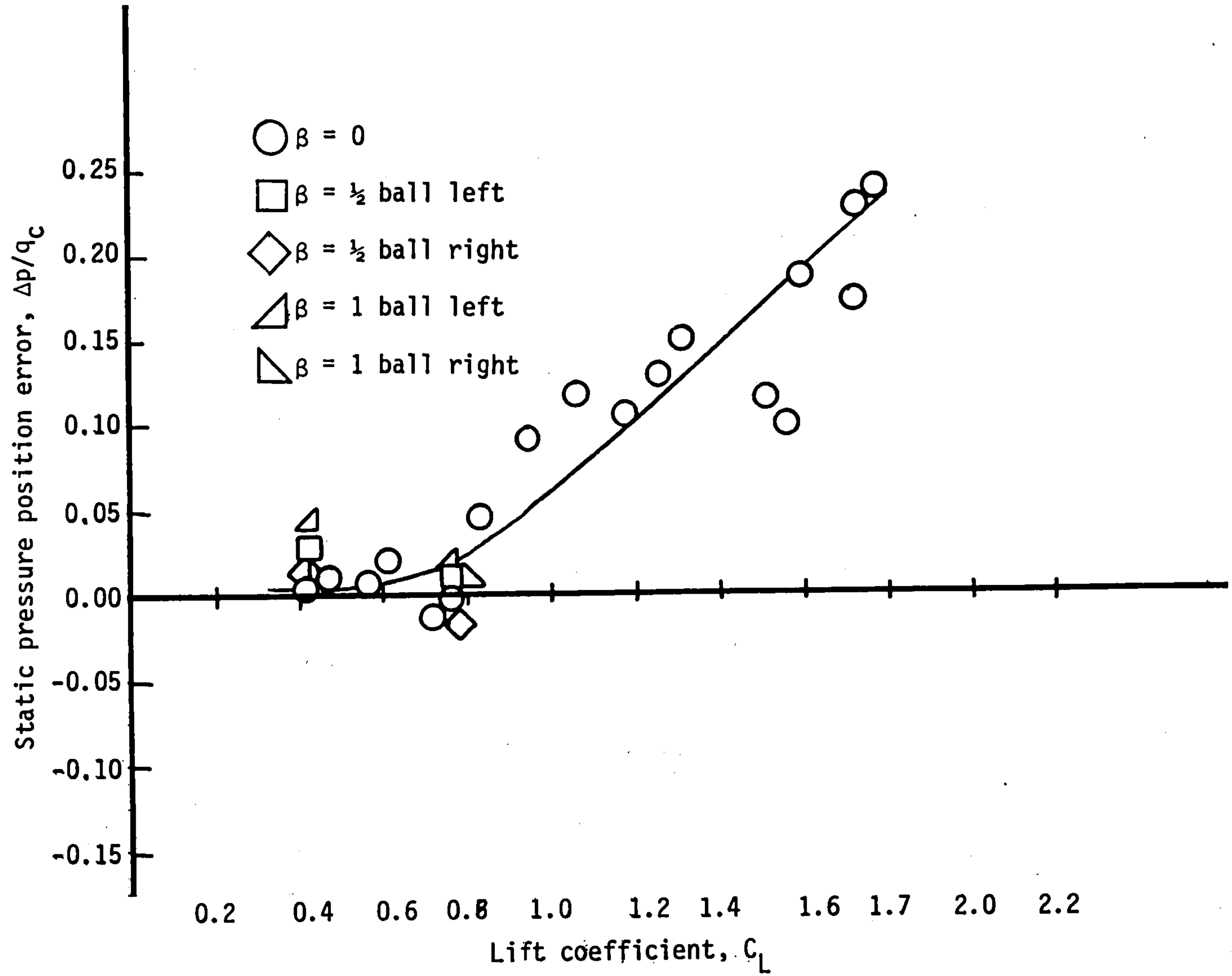
(b).- δ_{flap} = 100%

Figure 5.- Concluded.



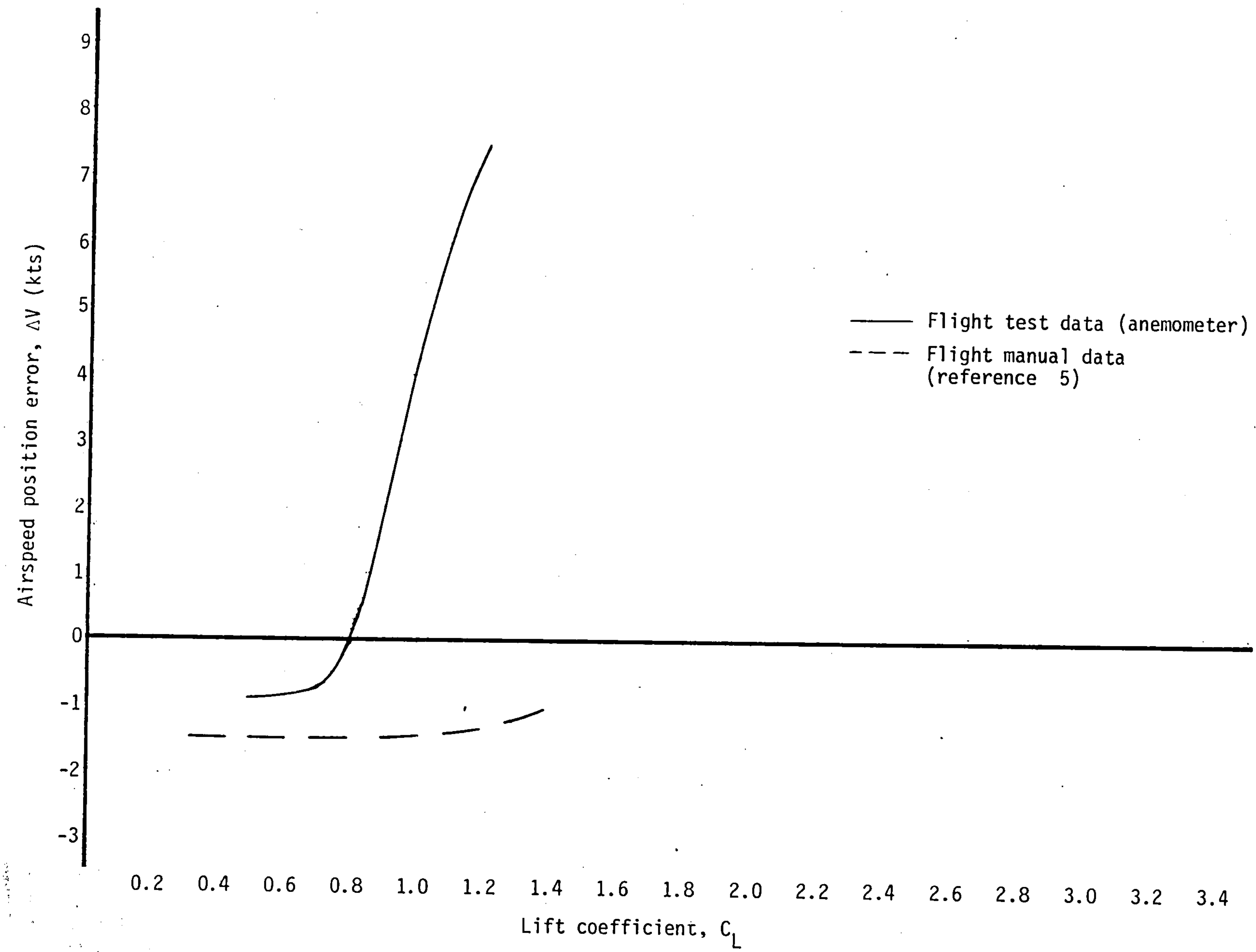
(a).- $\delta_{flap} = 0^{0}$

Figure 6.- NASA-510 T-34C airspeed calibration; level flight; effect of sideslip.



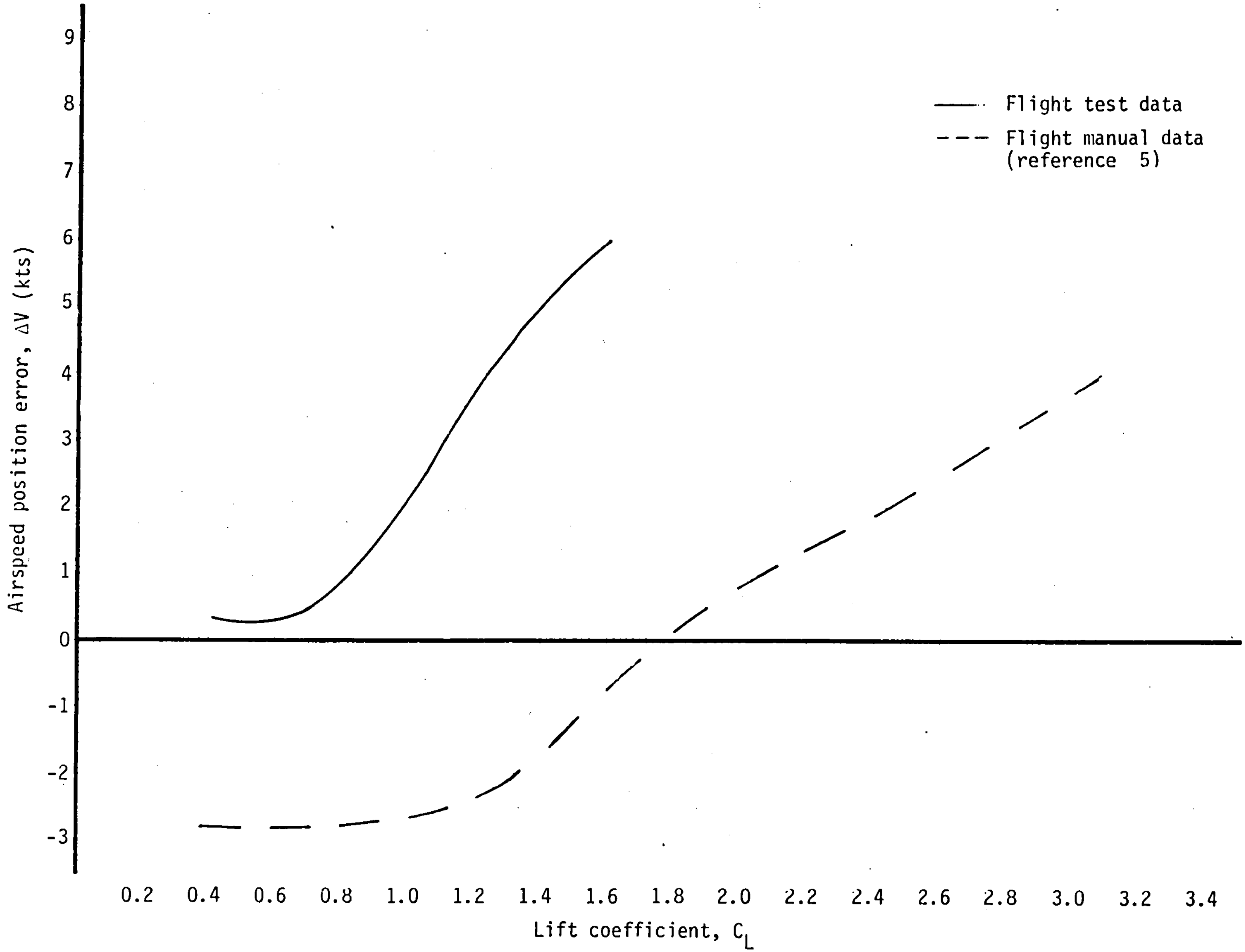
(b)- δ_{flap} = 100%

Figure 6.- Concluded.



(a).- δ_{flap} = 0%

Figure 7.- Comparison of anemometer measured and manufacturer's measured airspeed calibration data for NASA-510 T-34C



(b).- δ_{flap} = 100%

Figure 7.- Concluded.

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15. Supplementary Notes

16. Abstract

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