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Determination of an Angle-of-Attack Sensor Correction for a Light Airplane

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A comprehensive investigation into the flow correction for an angle-of-attack sensor mounted ahead of the wing tip of a general aviation research airplane has been conducted at the Langley Research Center. This correction has been determined in wind tunnels using a full-scale model up to angles of attack of 45 deg and a 1/5-scale model up to angles of attack of 80 deg. The flow correction has also been obtained in flight by using a standard technique at low angles of attack and in spinning flight at larger angles of attack, by using both a simple approximate technique and a parameter estimation technique. The results show the correction is significant, reaching 10 deg at a measured angle of attack of about 90 deg. The flow correction was sensitive to the angle of sideslip at measured angles of attack greater than 60 deg and was not influenced by wing leading-edge modifications or aileron deflections.

Nomenclature

a	= body axis linear acceleration vector, m/s^2
a_x, a_y, a_z	= linear accelerations along the X, Y, Z airplane body axes, m/s^2
b	= wing span, m
C_D	= drag coefficient
C_L	= lift coefficient
g	= body axis gravitational acceleration vector, m/s^2
J	= cost function
K_w	= angle-of-attack scale factor
L	= angular rate transition matrix
N	= number of data points
p,q,r	= measured angular rates about the X, Y, Z airplane body axes, rad/s
R	= position vector of angle-of-attack sensor relative to the accelerometer location, m
T	= transformation matrix from body to Earth axes
u, v, w	= velocity components along X, Y, Z airplane body axes, m/s
V	= velocity of the airplane, m/s
V_I	= initial velocity vector relative to the air, m/s
$V_{l,c}$	= local flow velocity with the boom and angle-of-attack sensor in the calibration apparatus, m/s
$V_{l,m}$	= local flow velocity with the boom and angle-of-attack sensor mounted on the model, m/s
V_v	= velocity vector relative to the air, m/s
X, Y, Z	= airplane body axes, origin at the center of gravity
α	= angle of attack, deg
β	= angle of sideslip, deg
ΔV	= Earth axis velocity difference, m/s
ϵ	= flow correction, deg
θ_s	= model mounting-strut angle, deg
Ω	= total angular velocity in the spin, rad/s
ω	= angular velocity vector, rad/s

Subscripts

b	= bias
m	= measured
t	= true

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Introduction

In flight test investigations it is necessary to know the true angle of attack of the airplane so that flight data can be compared directly to wind tunnel results or theoretical predictions. Typically the angle of attack during flight tests is measured with a self-aligning vane or flow direction sensor.[1] The sensor is mounted on a boom ahead of the wing near each wing tip and measures the local flow direction. To determine the true angle of attack of the airplane, corrections must be applied to this measured local flow direction (called the measured angle of attack, herein) to account for the change in the flow direction at the sensor location due to the presence of the airplane.

For airplanes in the normal, unstalled flight regime, this flow correction may be easily determined both experimentally from flight tests and theoretically.[2-6] However, at angles of attack above the stall these standard methods are no longer usable. In fact the nature of the flow correction at these large angles of attack is largely unknown.

The NASA Langley Research Center is conducting a comprehensive stall/spin investigation of general aviation airplanes to help improve their safety. The program includes the use of full-scale and radio-controlled model flight tests, static wind tunnel tests of full-scale airplanes and models, spin tunnel tests, rotary balance tests, and computer simulation studies. At the large angles of attack encountered during the stall/spin flight tests, the flow correction is substantial[7] and, therefore, it must be applied to the flight data to enable correlation with data from other phases of the stall/spin programs.[8] Also, any theoretical approach to the stall/spin problem would require the true angle of attack to be known.

This paper presents a summary of some of the work done at the Langley Research Center to determine the flow correction to be applied to the measurement of a vane angle-of-attack sensor over a large angle-of-attack range. This correction was determined in wind tunnels using a full-scale model up to angles of attack of 45 deg and a 1/5-scale model up to angles of attack of 80 deg. The effect of the angle of sideslip, wing leading-edge modifications, and aileron deflections on the flow correction was studied in both series of tests. The flow correction was obtained in flight by using two different techniques in spinning flight at large angles of attack and a standard technique at low angles of attack.

Airplane Configuration

A single-engine, low-wing general aviation research airplane was used for the wind tunnel and flight tests reported herein. The dimensions of the airplane are shown in Fig. 1. The airplane had a wing area of 9.11 m^2 and an aspect ratio of 6.1. The wing employed a modified NACA 64_2-415 airfoil

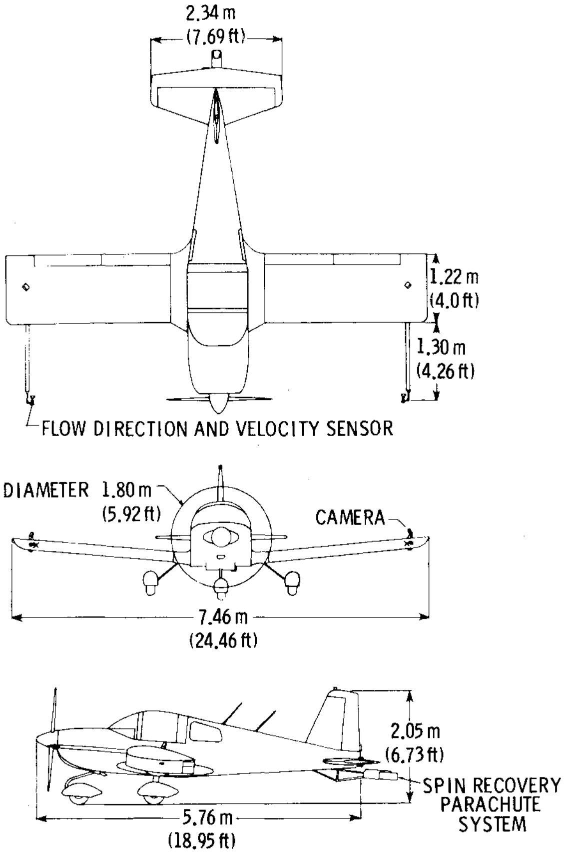

Fig. 1 Dimensions of the research airplane in meters (ft).

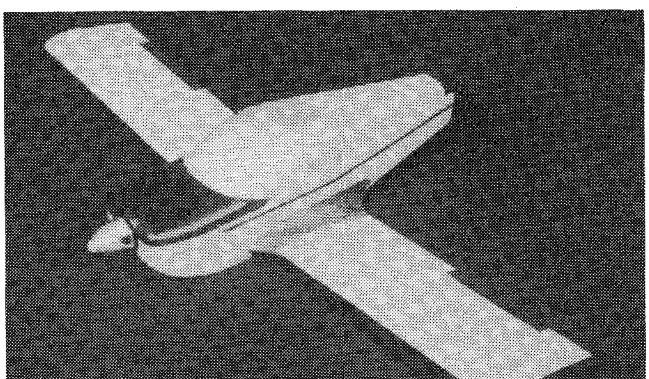

Fig. 2 Photograph of the 1/5-scale model.

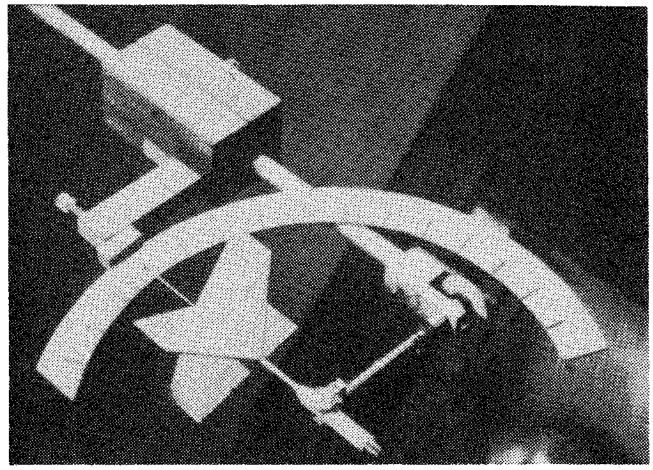

Fig. 3 Photograph of the scaled flow direction sensor and the calibration protractor.

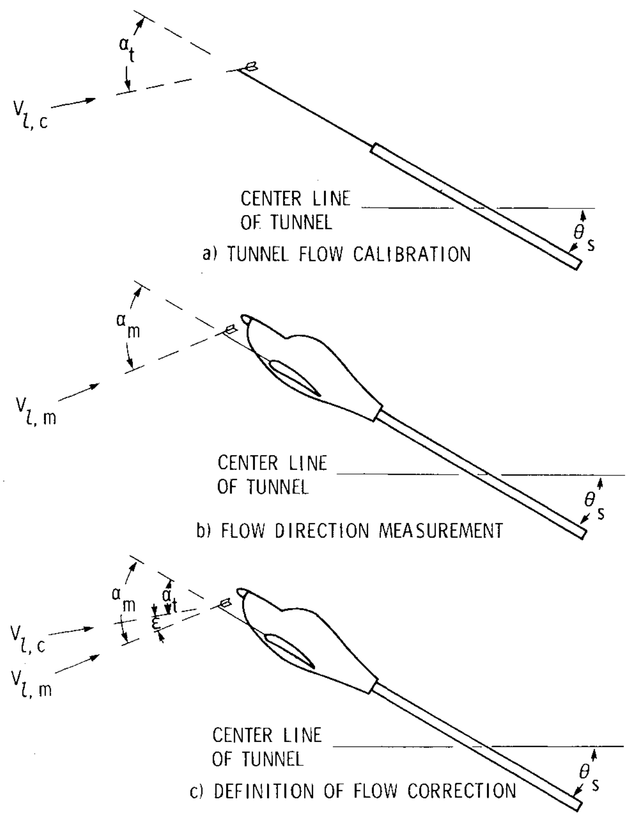

Fig. 4 Definitions of the angles measured to determine the flow correction.

section and was untapered and untwisted. The wing had a 5 deg dihedral and a constant 3.5 deg incidence along the span.

Both the airplane and the full-scale model of the airplane were equipped with a flow direction and velocity sensor[1] mounted on a boom ahead of each wing tip. The sensors measured the true airspeed and the angles of attack and sideslip of the airplane; however, the angle of attack was the only measurement considered in this report. The measurement of the angle of attack was repeatable within 1 deg.[9]

A 1/5-scale model of the research airplane was also tested (Fig. 2). The rear fuselage section including the horizontal and vertical tails was removed to facilitate mounting the model. The model did not have landing gear and had the propeller removed for the tests.

The 1/5-scale model was equipped with a scaled flow-direction sensor (Fig. 3), similar to those used on the full-scale airplane. The sensor was mounted in front of the left wing tip and was instrumented to measure the angles of attack and sideslip. This was the same sensor used in the previous flow correction tests,[7] but for the present tests the signals were hard wired to readout displays in the control room as opposed to the radio link used before. This change resulted in increased accuracy with the angle-of-attack measurements being repeatable within 1 deg.

Test Techniques and Conditions

Wind Tunnel Tests

1/5-Scale Model Tests

The 1/5-scale model of the research airplane was tested at the Langley Research Center in a low-speed wind tunnel with a 3.66 m octagonal test section. The model was tested at angles of attack from 0 to 80 deg and at angles of sideslip of 0, 20, and −20 deg. A glove providing a leading-edge droop[10] was applied to the leading edge of the airfoil for some of the tests. The droop extended from 57 to 95% $b/2$ on each wing. The effect of this wing leading-edge modification, aileron deflections, and the angle of sideslip on the flow correction was investigated. The tests were run at a tunnel speed of 17.7 m/s, providing a Reynolds number of 0.3×10^6 based on the wing chord. No attempt was made to simulate flow conditions at the flight Reynolds number by tripping the boundary layer on the model.

To account for flow irregularities in the tunnel, a calibration was conducted. To accomplish this, the boom and sensor were removed from the model and placed in a calibration apparatus. This apparatus positioned the boom and sensor at the same point in the tunnel as they were when mounted on the model. With the model out of the tunnel and the boom and sensor in this calibration setup, the sensor measured the true or freestream angle of attack as a function of the model mounting-strut angle θ_s (Fig. 4a). Calibration runs were made at angles of sideslip of 0, 20, and -20 deg.

After the calibration runs were made, the boom and the sensor were mounted on the model and the model tests were started. In this configuration the sensor gave the measured angle of attack as a function of the mounting-strut angle (Fig. 4b).

Full-Scale Model Tests

The full-scale model of the research airplane was tested in the 9.1-× 18.3-m open test section of the Langley full-scale tunnel.[11] The model was tested over an angle-of-attack range from -10 to 45 deg and an angle-of-sideslip range from -20 to 20 deg. The outboard droop leading-edge modification (tested on the 1/5-scale model) and a full-span version of the droop modification were tested on the full-scale model. The effect of these wing leading-edge modifications, aileron deflections, and the angle of sideslip on the flow correction was studied. The tests were conducted with a tunnel speed of 29.3 m/s, giving a test Reynolds number based on the wing chord of 2.4×10^6.

Flight Tests

Level Flight Tests

The research airplane was flown in steady, straight, and level flight at different airspeeds to obtain an airspeed and angle-of-attack calibration. From these runs a low angle-of-attack flow correction was determined.

Spin Flight Tests

The airplane was involved in the Langley Research Center's general aviation stall/spin research program[12] and underwent extensive spin flight testing at the NASA Wallops Flight Center. The spins were entered from an idle power, 1 *g* stall by applying prospin controls at the stall break. The prospin controls consisted of full aft stick and full rudder deflection with one of the following aileron positions: neutral ailerons or full aileron deflections either against or with the desired direction of the spin. Data from several different steady spins have been used to determine the true angle of attack in the spin.

Analysis Techniques

Wind Tunnel Tests

1/5-Scale Model Tests

At each strut angle tested, the true angle of attack from the appropriate calibration run is plotted against the measured angle of attack from a model test as described in Ref. 7. The flow correction is the difference between the true angle of attack vs the measured angle-of-attack data line and the 45-deg, $\alpha_t = \alpha_m$ line. Or, more simply, the flow correction, ϵ, is the difference between the measured and the true angles of attack at a particular strut angle (Fig. 4c), that is

$$\epsilon = \alpha_m - \alpha_t \tag{1}$$

Full-Scale Model Tests

In the full-scale tunnel tests, tunnel flow corrections were applied to the flow direction measurements from each sensor. These corrected measurements were averaged resulting in a measured angle of attack. The true angle of attack was subtracted from the measured angle of attack to obtain the flow correction.

Flight Tests

Level Flight Tests

During the steady, straight, and level flight runs the true angle of attack was given by the inverse sine of the longitudinal acceleration. Since the true and measured angles of attack were known, the flow correction was determined using Eq. (1).

Steady Spin Approximation

If the airplane is in a steady spin and if it can be assumed that the angular velocity vector is oriented along the relative wind axis, then the following relationships hold:

$$p = \Omega \cos\alpha_t \cos\beta \tag{2}$$

$$q = \Omega \sin\beta \tag{3}$$

$$r = \Omega \sin\alpha_t \cos\beta \tag{4}$$

Equations (2) and (4) can be combined to give the true angle of attack at the center of gravity of the airplane in a steady spin

$$\alpha_t = \tan^{-1}(r/p) \tag{5}$$

Parameter Estimation Technique

It is possible to compute changes in the angle of attack of an airplane given time histories of its linear acceleration and angular velocity. Extreme sensitivity to instrumentation inaccuracies usually cause such calculations to have unacceptable errors. It has been possible to avoid such difficulty, however, by using parameter estimation to determine selected instrument biases, initial conditions, and multiplicative scaling factors from flight data. In particular, an angle-of-attack scale factor, K_w, which can be used to correct flight measurements of the angle of attack, can be estimated. Alternatively, the process can be used to estimate the angles of attack and sideslip in lieu of direct flight measurements. The other parameters determined simultaneously are instrument biases in all three components of angular velocity and linear acceleration and the initial pitch and roll Euler angles.

The difference ΔV between the change in velocity as determined by integrating the linear accelerations and that obtained by measuring airspeed and angles of attack and sideslip, can be expressed as

$$\Delta V = \int_0^t (Ta + g)\,d\tau - T(V_v - \omega X R - V_I) \tag{6}$$

where

$$V_v = \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} V_m \cos\alpha_m \cos\beta_m \\ V_m \sin\beta_m \\ K_w V_m \sin\alpha_m \cos\beta_m \end{bmatrix} \tag{7}$$

$$\omega = \begin{bmatrix} p \\ q \\ r \end{bmatrix} = \begin{bmatrix} p_m - p_b \\ q_m - q_b \\ r_m - r_b \end{bmatrix} \tag{8}$$

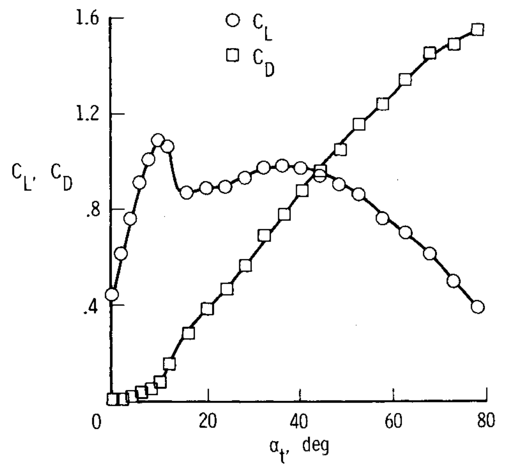

Fig. 5 Longitudinal force data for the 1/5-scale model.

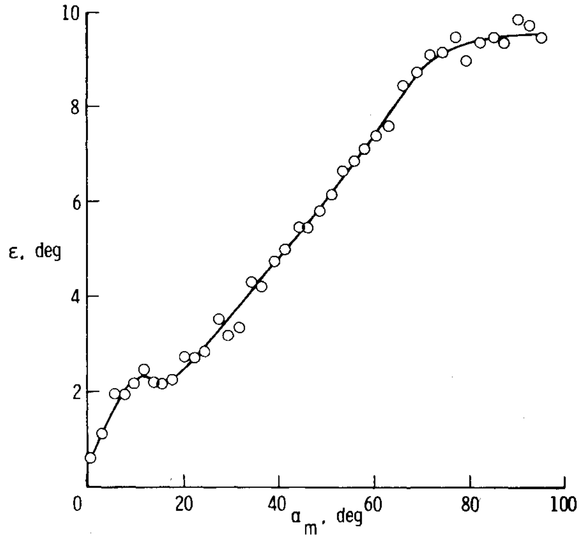

Fig. 6 The flow correction determined from the 1/5-scale model tests.

$$a = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} a_{x,m} - a_{x,b} \\ a_{y,m} - a_{y,b} \\ a_{z,m} - a_{z,b} \end{bmatrix} \tag{9}$$

T is a transformation matrix, made up of direction cosines, which is used to transfer measurements from the airplane body axis system to an Earth axis system. The transformation matrix can be generated using

$$\dot{T} = TL(\omega) = T \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \tag{10}$$

The initial value of T is determined by the initial values of the Euler angles. The values of the pitch and roll Euler angles were estimated as part of the parameter estimation process. The value of the yaw Euler angle was set to zero.

Given time histories of the measured angular velocity and linear acceleration, the preceding equations can be solved using a particular set of instrument bias values, initial conditions, and an angle-of-attack scale factor. By computing the sensitivities of the pertinent variables to changes in the unknown parameters, a modified Newton-Raphson technique[13] can be used to estimate the unknown parameters. The cost function chosen for the iterative procedure was the

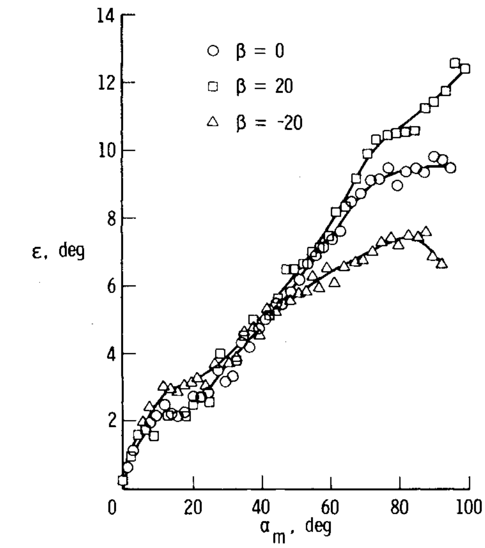

Fig. 7 The effect of the angle of sideslip on the flow correction, 1/5-scale model tests.

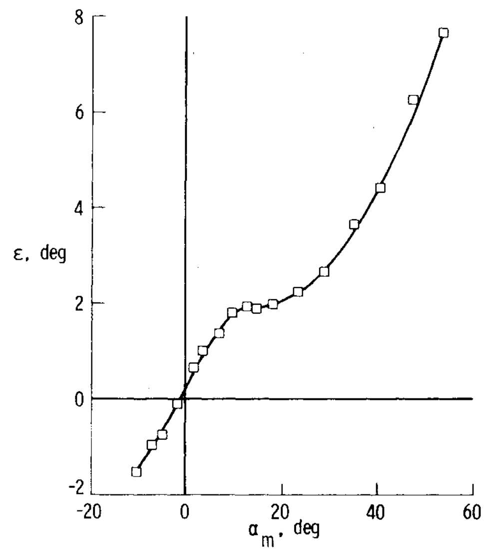

Fig. 8 The flow correction determined from the full-scale model tests.

mean square of the velocity difference ΔV and is given by

$$J = \frac{1}{N} \sum_{n=1}^{N} \Delta V^T \Delta V \tag{11}$$

Results and Discussion

Wind Tunnel Tests

1/5-Scale Model Tests

A plot of the lift and drag coefficients as a function of angle of attack for the 1/5-scale model is shown in Fig. 5. These data follow the trends of lift and drag curves of typical general aviation airplanes.[10]

The flow correction for the 1/5-scale model is shown as a function of the measured angle of attack in Fig. 6. This figure shows a flattening of the flow correction curve at a measured angle of attack of 15 deg due to the loss of lift on the wing at stall. The curve appears to peak at a 90-deg measured angle of attack with a flow correction of almost 10 deg at that point. It should be noted that the data from Ref. 7 shows a 12.5-deg correction for the basic model. However, it is felt that the present data is more reliable because the angle-of-attack signal was hard wired to the readout device and because the angle-of-attack sensor was calibrated more carefully.

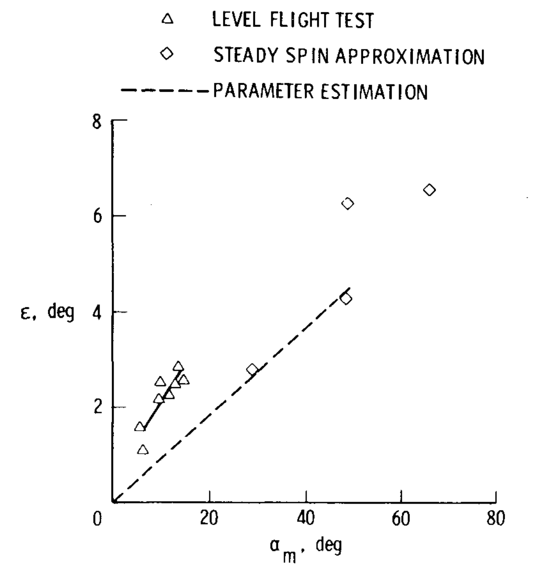

Fig. 9 The flow correction determined from full-scale flight tests using three different techniques.

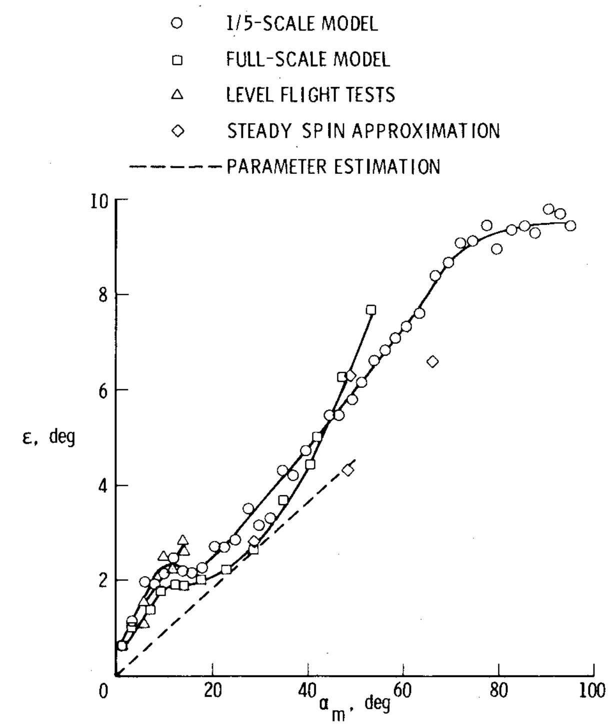

Fig. 10 Comparison of all of the flow correction data.

The effect of the angle of sideslip on the flow correction is shown in Fig. 7. This figure shows slight differences in the flow correction around a 15-deg angle of attack but other wind tunnel data, both 1/5 scale and full scale, not presented in this report show no such difference. However, there is a difference in the flow correction due to the angle of sideslip at measured angles of attack above 60 deg. At an angle of sideslip of 20 deg, the flow correction is more than 12 deg at a 100-deg measured angle of attack with no indication of having reached a maximum. On the other hand, at an angle of sideslip of −20 deg, the flow correction peaks at a measured angle of attack of 80 deg with a flow correction of only 7.5 deg.

The effect of wing leading-edge modifications and aileron deflections on the flow correction was also investigated. However, neither the outboard droop leading-edge modification or the ailerons deflected full up or full down affected the measured flow correction.

Full-Scale Model Tests

The flow correction obtained with the full-scale model in the full-scale tunnel is shown in Fig. 8. This figure also shows a flattening of the flow correction curve in the vicinity of the stall angle of attack. In these tests the flow correction was not influenced by the angle of sideslip, the outboard droop leading-edge modification, the full-span droop leading-edge modification, or aileron deflections.

Flight Tests

The simple trigonometric approximation was applied to data taken during several steady spins. The parameter estimation technique was applied to the data from one of these spins but this technique does not require a steady spin to be used. In fact, the parameter estimation technique was applied to the spin flight data from before the airplane stalled until after it had recovered from the spin. Within this segment of data, the measured angle of attack ranged from 2 to 50 deg and the measured angle of sideslip ranged from −10 to 17 deg. However, it should be noted that the magnitude of the angle of sideslip in the steady portion of the spin was generally less than 5 deg. The flow correction data obtained from these two high angle-of-attack techniques and from the low angle-of-attack level flight method are shown in Fig. 9.

Comparison of all Flow Correction Data

The flow correction data obtained from the 1/5-scale and full-scale wind tunnel tests, as well as from low and high angle-of-attack flight tests are shown in Fig. 10. There is reasonable agreement between the two sets of wind tunnel data up to almost 50-deg measured angle of attack. Beyond that point the trend of the full-scale tunnel data indicates even larger flow corrections than those found from the 1/5-scale model tests.

The slope of the flow correction determined from the low angle-of-attack level flight tests agrees well with the slopes of both sets of wind tunnel data. However, there are slight discrepancies between the magnitude of the three sets of data.

The flow correction points obtained from the steady spin agree within 1.5 deg of the 1/5-scale model data. This is encouraging because the technique is so simple and because it can be applied to any airplane as long as it is in a steady spin. However, there are more sophisticated techniques of estimating the true angle of attack in a steady spin that should be investigated further.

The flow correction determined from spinning flight using the parameter estimation technique is less than the flow correction found using the other techniques. Even though this technique predicts a smaller flow correction the results look promising and it appears desirable to refine the technique. The big advantage of this technique is that it can be used for any airplane and can be used through the stall and incipient portions of the spin and even in unsteady, oscillatory spins.

One possible explanation of the difference in the flow corrections between the techniques applied in spinning flight and the wind tunnel tests is the effect of rotational rates. That is, if the flow correction is a function of the wing lift distribution and, since the lift distribution is altered by rotational motion, then the results obtained in the steady spin should be different than the static wind tunnel tests. However, the present data is insufficient to determine the effect of rotation on the flow correction.

Finally, as an illustration of the application of these flow correction data, the correction from each technique discussed herein has been applied to the average of the right and left measured angles of attack taken during several steady spins. This results in a value of the true angle of attack in the spin for each technique. These values of the true angle of attack, as well as the average measured angle of attack, have been tabulated for each spin and are presented in Table 1. The difference between the true angles of attack determined using the different techniques are generally less than 2 deg, with better agreement in some cases.

Table 1 Comparison of the true angles of attack in spinning flight determined using different techniques

Average measured angle of attack during the spin, deg	True angle of attack, deg			
	1/5-scale model tests	Full-scale model tests	Steady spin approximation	Parameter estimation
48.9	43.0	42.5	42.6	44.5
66.2	58.0	—[a]	59.6	—[a]
28.9	25.4	26.2	26.1	26.3
48.5	42.6	42.1	44.2	44.1

[a] Beyond the angle-of-attack range of the data.

Concluding Remarks

Wind tunnel and flight tests have been conducted to determine the flow correction to be applied to angle-of-attack sensor measurements taken on a general aviation research airplane. It was shown that the flow correction is significant, reaching almost 10 deg at a measured angle of attack of 90 deg. The flow correction is influenced by the angle of sideslip at angles of attack above 60 deg, being increased for positive sideslip angles and decreased for negative sideslip angles. On the other hand, neither wing leading-edge modifications nor aileron deflections affect the flow correction. Data from the 1/5-scale and full-scale model tests agree with the flow correction determined in straight and level flight. The two techniques used to determine the flow correction from flight data taken during spins show promise and should be refined. Finally, in order to compare the flow corrections obtained from spinning flight with those from wind tunnels with more confidence, the effect of rotation on the flow correction should be studied further.

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