Blockage Corrections at High Angles of Attack in a Wind Tunnel

P. A. Gili,* D. M. Pastrone,† and F. B. Quagliotti‡
Politecnico di Torino, Turin, Italy
and
E. Barbantini§
Aeritalia Defense Aircraft Group, Turin, Italy

Recent developments have increased the need to investigate flight conditions at high angles of attack. Because these conditions have to be studied in wind tunnels, it is obvious that the blockage corrections must be assessed as accurately as possible. With this in mind, we thought of comparing the results obtained from the same model in two different wind tunnels: the Aeritalia wind tunnel and the Emmen F + W 32.4 m^2. The size of the Emmen makes the wall and blockage corrections negligible. Therefore, in practice, with any differences in the results coming from tests conducted in the two wind tunnels, it is only necessary to make corrections to those coming from the Aeritalia wind tunnel. Since the Emmen wind tunnel provided us with the exact results, our work consisted of establishing a method of correction whose validity could be verified. Initially we tried to use Maskell's formula introducing constant coefficients according to test conditions but the results were not satisfactory. We then developed Maskell's formula and decided to use the flat-plate pressure coefficient as a base pressure coefficient—which is needed in Maskell's formula—when no such coefficient can be deduced from the model. In all these cases, the induced drag coefficient was expressed as a function of the lift coefficient. Final corrections for lift and moment coefficients were very satisfactory, though the drag coefficient was slightly overcorrected.

Introduction

FLIGHT conditions at high angles of attack have to be assessed with great care for a new generation of fighter aircraft which offer a high degree of reliable maneuverability and for civilian aircraft to guarantee safe flights in the presence of gusts.

Owing to the nonlinear behavior of aerodynamic forces at high angles of attack, aerodynamic coefficients in the stall and poststall region are very difficult to calculate in theory. This makes wind tunnels and flight tests absolutely necessary.

One of the most important problems with wind-tunnel tests is the blockage constraint, which is not always negligible at high angles of attack if one compares the model size to the tunnel one.

Several techniques have been used in an attempt to minimize wall corrections of the test section. For instance we can use models that are small in relation to the test section size or apply linearized corrections to the model data.[1,2] Generally more than one of these techniques are used together. However, at high angle of attack and high blockage constraint, we require accurate measurements from wind-tunnel testing and previously employed techniques are inadequate.

Modern techniques[3] suggest adaption of test-section boundaries or, better still, wall-plus boundary layers so as to free the air streamlined shapes around the model. The principle itself is very simple and there are plenty of benefits (higher Reynold's numbers, reduced tunnel drive power, reduced off line corrections, etc.), though the wall must be constantly adapted and tailored to each test condition. Adequate and very complex hardware are needed, both mechanical and instrumental (problems may arise in the course of operations). It is neither a straightforward nor immediate manner in which to gather data, and it is almost impossible to use adaptive wall techniques when performing dynamic test.

One of the possible methods that can be used to evaluate separation blockage corrections is to measure wall static pressure.[4] This technique is complex, as data processing and gathering is long and cumbersome. We wanted to see whether base pressure coefficients (C_{pb}) could be evaluated by measuring static pressure in a few points on the wings and fuselage in the nonstreamlined flow. The base pressure of sharp-edged flat plates in a two-dimensional flow can be used instead of a model when data are not available.

Aeritalia (AIT) decided to validate results obtained in their 4-m^2, low-speed tunnel located in Turin, Italy in order to test the method used in determining the stationary aerodynamic derivatives and to refine separation blockage corrections on full aircraft configurations. The characteristics of the model, selected among the many available ones, suited the standard calibration model.

Tests were performed in the AIT wind tunnel as well as in the 32.4-m^2 F + W Emmen, Switzerland wind tunnel. The size of the latter—compared to the model—makes the wall and blockage corrections of Emmen negligible with a good approximation. Corrections will therefore exclusively be applied to the AIT set of tests. Emmen test results will be considered exact and taken as reference.

The angle of attack reached 52 deg in investigating the stall and poststall regions because of the aforementioned requirements.

Wind Tunnel and Model Description

F + W Emmen is a closed-circuit, low-speed wind tunnel with a closed rectangular 5 × 7-m test section and blunted corners (32.4 m^2). It was used as a term of comparison because of its well-known reliability (see Fig. 1a).

The AIT wind tunnel in Turin is an open-circuit facility with a closed-square, 2.1 × 2.1-m test section with blunted corners (4 m^2) (see Fig. 1b). The two tunnels are compared in Fig. 1c.

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*Assistant Professor, Aeronautical and Space Department.
†Ph.D. Student, Department of Energy Engineering.
‡Associate Professor, Aeronautical and Space Department.
§Director of the Wind Tunnel, Wind Tunnel Department.

The model is chosen mostly on the basis of the following requirements for the validation tests: simple geometry and material steadiness to guarantee repeatability.

AIT decided to use a pre-existing model (M2). Even though the M2 does not have a very simple geometry, it was chosen because of its stability, processing quality, and large amount of available data (see Fig. 2).

Data Processing

AIT data were corrected using standard corrections without considering separation blockage. In fact, the two support rigs (AIT and Emmen) were nearly identical and differed exclusively in the part further away from the model. They were used to obtain comparable results.

As Figs. 3–5 show, both AIT and Emmen data coincide until the angle of attack becomes so high that we enter the stall region. This shapens for values of about 15 deg. Such discordance may be due to a separation blockage that is no longer negligible and to a possible substantial difference in flow quality.

Corrections suggested in Refs. 5 and 6 do not satisfy these data. If the dominant effect is taken to be equivalent to a simple increase in the freestream speed, the following relation should hold

$$C_i/C_{ic} = 1 + \Delta q/q \tag{1}$$

where C_i is the measured value of the i-aerodynamic coefficient, C_{ic} is its corrected value, and Δq is the effective increase in dynamic pressure. In a fixed flight condition, the ratio is constant for every coefficient.

To check the validity of Eq. (1), lift, drag, and pitching moment ratios—related to AIT/Emmen tests—were calculated (see Fig. 6). Curves were comparable only for angles of attack exceeding 30 deg.

The suggested correction[6] for stalled wings of finite span is

$$\Delta q/q = \mu C_{Ds}(S/C) \tag{2}$$

$$C_{Ds} = C_D - C_{Di} - C_{D0} \tag{3}$$

$$\mu = 5/2 \tag{4}$$

where μ is an appropriate coefficient, D_s the drag associated with the stalled regions, S the reference surface, C the tests section area, D_i the induced drag, and D_0 the conventional profile drag.

As you can see in Fig. 6, the assumption that the main separation blockage effect can be considered equivalent to a velocity increase does not hold if the angle of attack is smaller than 30 deg. In fact

$$1 + (\Delta q/q) < 1$$

may be due to the different situations of stall onset in the two wind tunnels.

We are interested in the over 30-deg range, though above 30-deg correction is excessive (see Fig. 7). Consequently, a more appropriate value of μ has to be found.

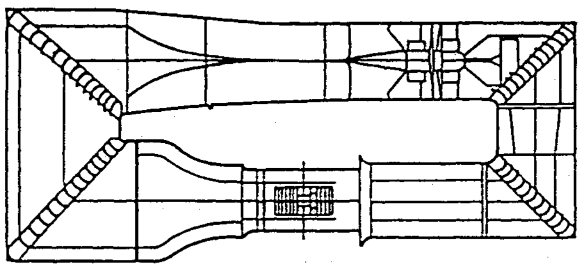

Fig. 1a Emmen F+W wind tunnel.

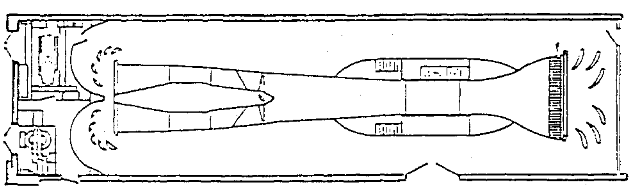

Fig. 1b AIT wind tunnel.

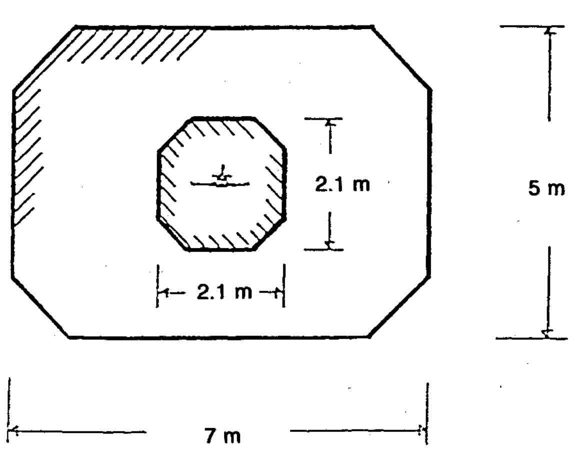

Fig. 1c Test-section comparison.

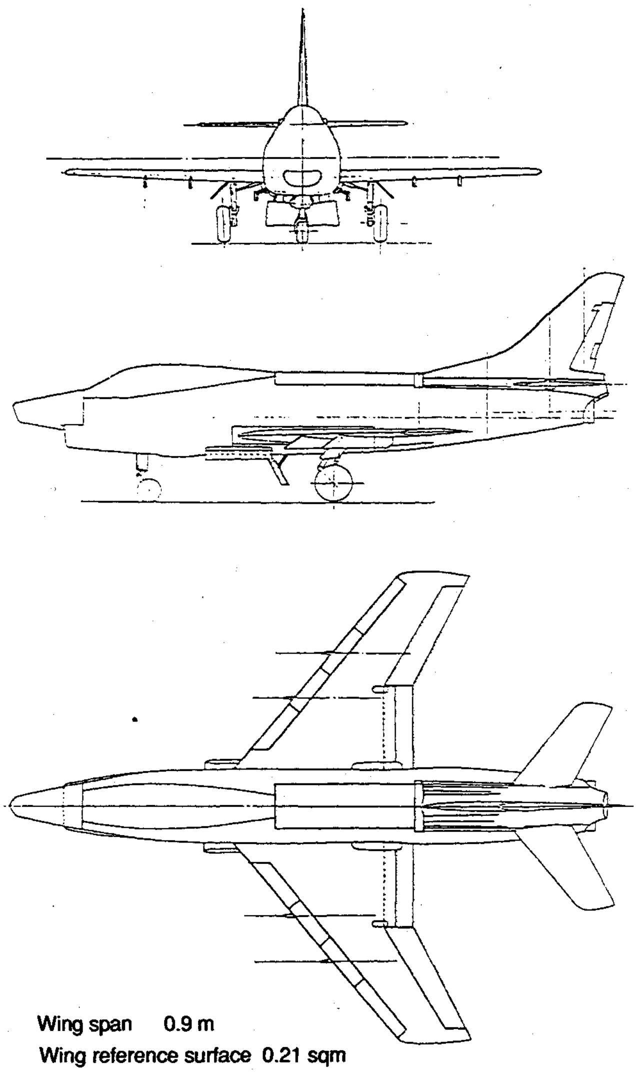

Fig. 2 Calibration model (M2).

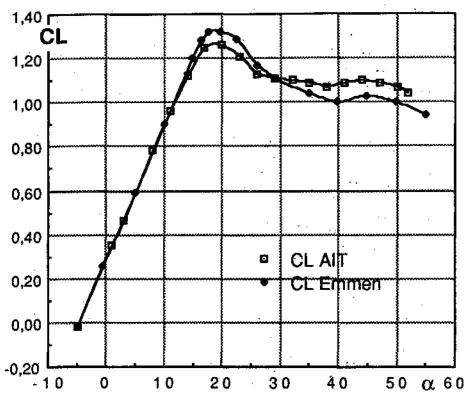

Fig. 3 Lift coefficients.

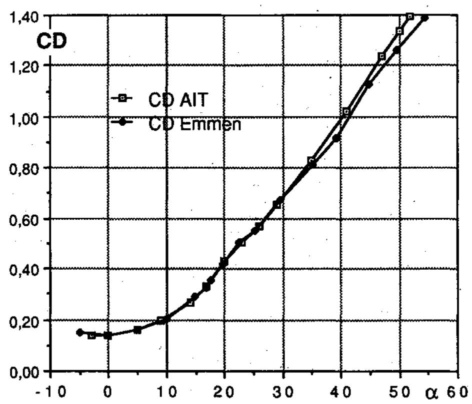

Fig. 4 Drag coefficients.

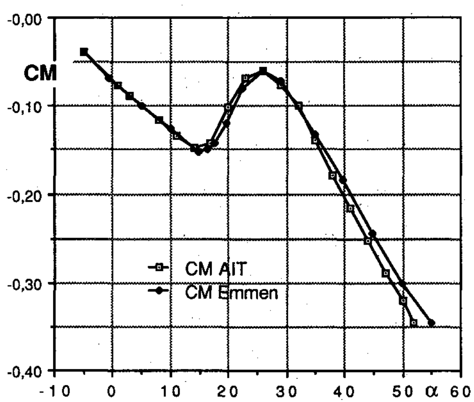

Fig. 5 Pitching-moment coefficients.

Maskell's Formula with Base Pressure Coefficients

The fact that the Emmen wind tunnel is larger than the small size model tunnel, suggests that the flow around the model is not influenced by boundaries. Emmen data are thus taken to be "exact."

We have, therefore, found an application of Maskell's formula whereby AIT and Emmen rough data are very close.

We can also target Maskell's formula. According to Maskell's theory, the corrective coefficient is

$$w = C_i/C_{ic} = 1 + \Delta q/q$$

$$= 1 + (1/k_c^2 - 1)C_{Ds} \cdot (S/C) \tag{5}$$

i.e.,

$$\mu = 1/(k_c^2 - 1) \tag{6}$$

which can also be written as

$$w = k^2/k_c^2 \tag{7}$$

where k^2 is a function of base pressure coefficient C_{pb}:

$$k^2 = 1 - C_{pb} \tag{8}$$

From Eqs. (5) and (7)

$$k_c^4 - k_c^2[k^2 + 1 - C_{Ds}(S/C)] + k^2 = 0 \tag{9}$$

The quartic equation is then solved in relation to k_c^2 using the appropriate sign and gives

$$k_c^2 = 1/2B + \sqrt{B^2/4 - k^2} \tag{10}$$

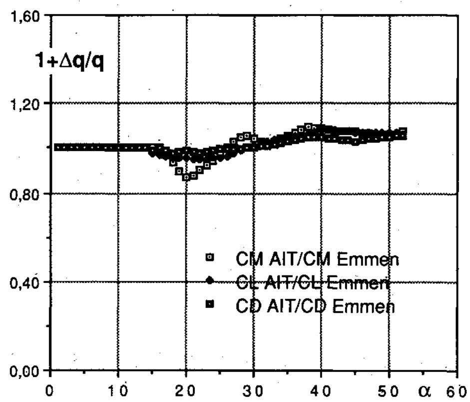

Fig. 6 AIT to Emmen coefficients ratio.

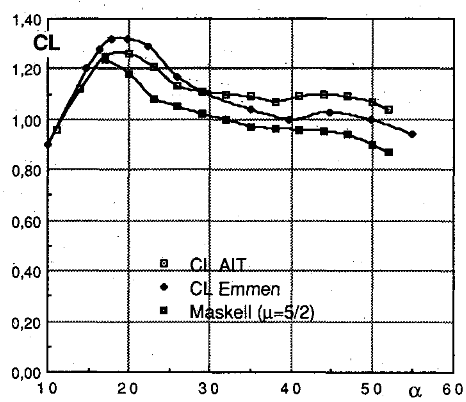

Fig. 7 Maskell correction with μ constant.

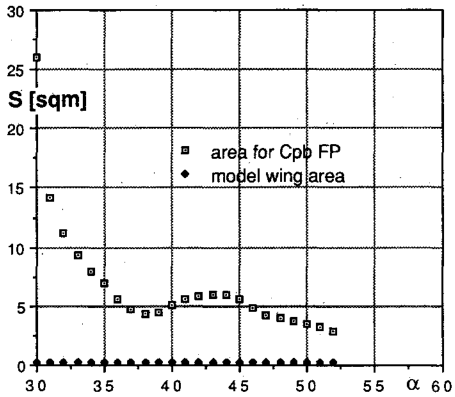

Fig. 8 Reference surface to C_{pb} flat plate compared with the model wing area.

where

$$B = k^2 + 1 - C_{Ds}(S/C)$$

thanks to k_c^2 and k^2 from Eq. (8), the correction coefficient w is obtained using Eq. (7).

In this case, w is obtained using Eq. (5), where the measured coefficients C_i are the AIT data and the corrected coefficients C_{ic} are the Emmen data.

Equations (7–9) were used to compute the reference areas using a known value of the base-pressure coefficient or to calculate the base pressure coefficients using one of the model characteristic surfaces as a reference area. In this first case, we took the base pressure coefficients for sharp-edged flat plates in two-dimensional flow since the C_{pb} values were not

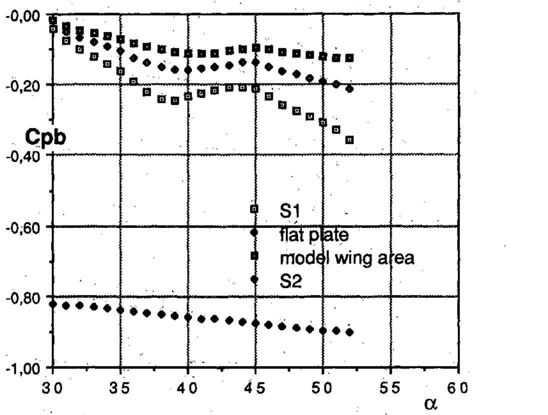

Fig. 9 C_{pb} for different reference surfaces: model wing area = 0.21 m^2, $S1 = 1.0$ m^2, and $S2 = 0.5$ m^2.

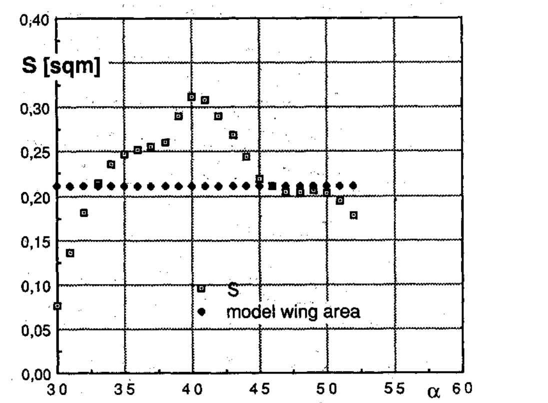

Fig. 10 Reference surface for C_{pb} flat plate compared with the model wing area.

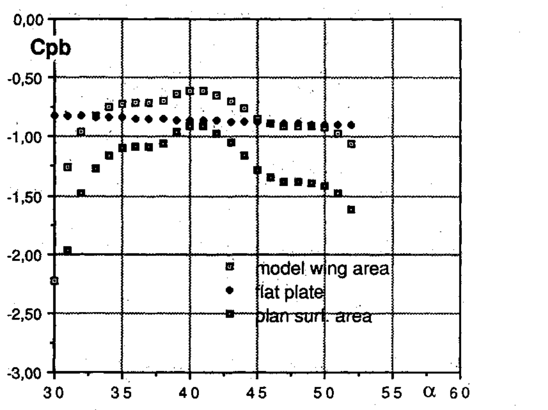

Fig. 11 C_{pb} for different reference surfaces: model wing area = 0.21 m^2 and plan surface area = 0.33 m^2.

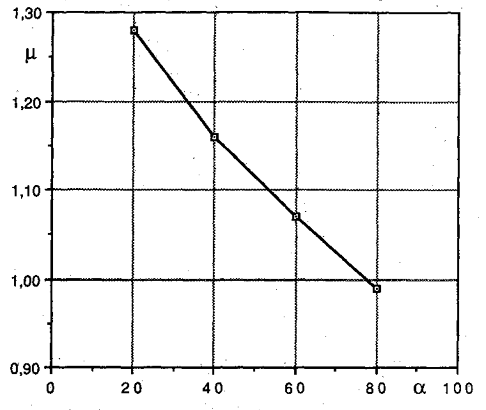

Fig. 12 μ factor as a function of angle of attack.

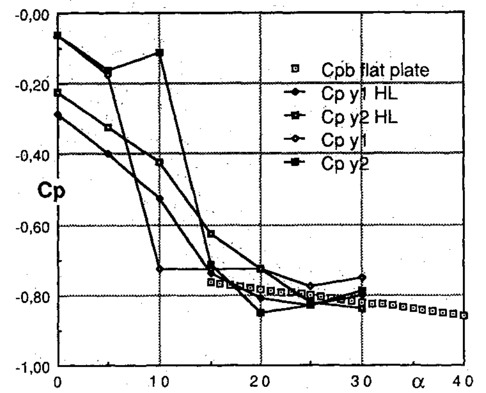

Fig. 13 Pressure coefficients of the calibration model.

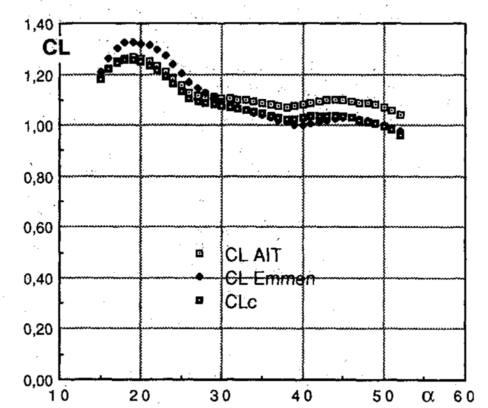

Fig. 14 AIT, Emmen, and corrected lift coefficients.

available for the calibration model. We shall explain how the C_{pb} values were obtained further on. C_{Ds} was taken as the difference between AIT and Emmen data, which is the meaning that Maskell's theory seems to suggest.

Figure 8 shows the S trend as a function of the angle of attack. Values are not always the same and diverge from the model wing area (0.21 m^2).

C_{pb} was computed for different reference areas ($S = 0.21$ m^2 is the wing area, whereas the others are trial surfaces) and compared to the base-pressure coefficients of the two-dimensional flat plate (see Fig. 9). The gap is too great, even if the slope for the wing area is roughly comparable.

Results suggested another method should be followed to evaluate C_{Ds}. Calculations were therefore carried out following Eq. (3), where C_{Di} is defined as

$$C_{Di} = (C^2L/e\pi A) \tag{11}$$

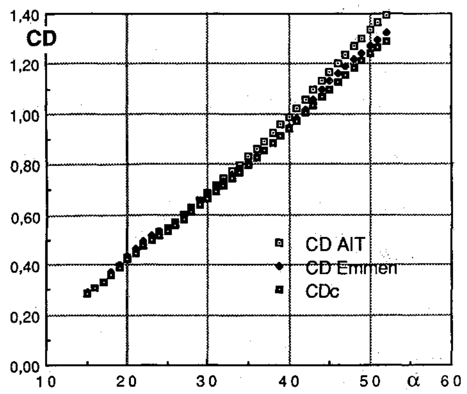

Fig. 15 AIT, Emmen, and corrected drag coefficients.

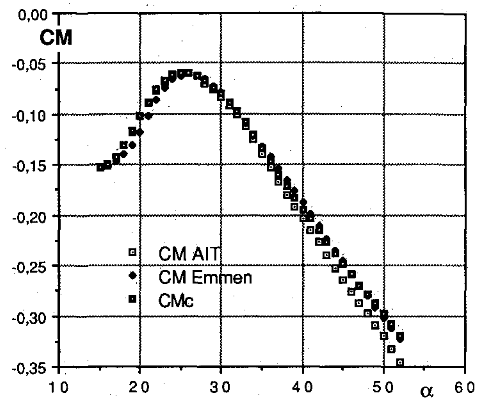

Fig. 16 AIT, Emmen, and corrected pitching-moment coefficients.

where A is the aspect ratio and e the Ostwald's factor.

The reference area for the C_{pb} of the two-dimensional flat plate is fairly constant as it is a function of the angle of attack (see Fig. 10), and the values are close to that of the wing area, obviously bearing in mind the scale used in the figures is very large.

Figure 11 represents the C_{pb} trend as a function of α. When the wing area is the reference area, results agree with the flat-plate ones. If the plan surface area is used as a reference, agreement is not so good.

Final Corrections

Previous considerations highlight how the last C_{Ds} is to be used instead of extrapolating C_{Di} from the measured properties of the unstalled model as suggested in Ref. 4.

However, the C_{pb} trend has to be identified when some of the required pressure taps are not available on the model. To check if it is possible to use the two-dimensional flat plate C_{pb}, data available from another calibration model tested in the AIT wind tunnel were used. The data referred to a classical fighter aircraft model equipped with pressure taps along the wing chord a several wing spans. Pressure orifices were at 15, 30, 45, 60, 75, and 90% from the leading edge of the wing chord in two different points taking the vehicle symmetry plane as a reference: at 53% ($y1$) and 72% ($y2$) of the half-wing span. Tests were performed for clean and high-lift configuration up to a 30-deg angle of attack but the curve trends are undoubtedly close to the flat plate one.

Data from current literature[4] were used to calculate the flat-plate, base-pressure coefficient. Calculations were not too complex as the factor μ trend is obtained using a diagram similiar to the one in Fig. 12 as a function of the angle of attack. The factor is defined by Eq. (6). Using Eqs. (8) and (10), the base-pressure coefficient is easily obtained in relation to the angle of attack.

Figure 13 clearly shows that $y1$ and $y2$ are the two different positions along the span and HL indicates the high lift configuration. This diagram shows the pressure coefficients corresponding to the taps in the nonstreamlined flow, selected among the available pressure coefficients.

The trend shown in Fig. 13 highlights how the flat-plate, base-pressure coefficients can be assumed for the M2 calibration model. Furthermore, values of the base-pressure coefficients cannot vary too much in relation to the model and are mainly characterized by the fact that they are pressure coefficients of a nonstreamlined flow.

The different support rig of the model does not affect base-pressure coefficients unless it is a sting.

Figures 14–16 show C_L, C_D, and C_M as a function of α. For every coefficient there are 1) rough AIT data, 2) Emmen data, and 3) coefficients corrected as described previously.

The final corrections for C_L, C_D, and C_M are very satisfactory. A better approximation may be reached by using the actual C_{pb} data.

A moderately satisfactory result was obtained in correcting the lift coefficient around a 20-deg angle of attack. At these angles, the difference in coefficients had already been observed when comparing rough results from the two tunnels (AIT and Emmen) (see Fig. 3). If these inconsistencies persist, one might suggest that flow qualities differ in the two tunnels and that the turbulence factor is causing diverse surface-flow conditions in the wind tunnel in which the model is being tested. Several swept-wing transitions may take place under the heading boundary-layer phenomena. The transitions can be traced back to different stall conditions depending on the tunnel.

Particular care was taken in evaluating corrections above 30 deg as the nonstreamlined wake blockage is likely not to be negligible, though it holds only in that range.

Conclusions

The interesting result of this research is the possibility of evaluating the separate-flow, wake-blockage effects in a relatively small wind tunnel, compared to the model size. In fact, corrected values can be computed for the longitudinal coefficients even at high angles of attack if the function C_{pb} (α) for the two-dimensional flat plate is known.

This method can be improved easily if a few pressure taps are provided on the model wings and afterbody. This requirement does not involve significant complications on the model design. In fact, pressure values must be measured only at high angle of attack, when flow is separated and it is therefore possible to use an external probe without affecting aerodynamic behavior.

When the C_{pb} (α) trend is available, corrections related to the separated flow blockage can be computed with a good approximation without adding on pressure taps on the wind tunnels.

The method is applied to a single configuration, but some investigations lead us to believe that it can be used for most fighter aircraft configurations.

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