Total Incidence Plane Aerodynamics: The Key to Understanding High Incidence Flight Dynamics?

Peter J. Lamont* and Andrew Kennaugh†
University of Manchester, Manchester M13 9PL, England, United Kingdom

This paper advocates the use of total incidence plane aerodynamics to simplify the problems of aircraft aerodynamics/flight dynamics at high angles of attack. The advantages of this approach are illustrated by considering the problem of aircraft sideslip behavior at high angles of attack. Force components on circular cross-section aircraft forebodies at combined angles of attack and sideslip are successfully synthesized from zero sideslip data, which covers a wide range of incidence and roll attitude. In addition, the wide variety of published Cn vs β curves for circular cross-section forebodies are shown to be particular examples of the multiple solutions that are possible due to side force switching effects. The value of applying this approach to complete aircraft is demonstrated by the remarkable agreement obtained between experimental data for the Cn vs β curve of an F-111 and a prediction based on the contribution of its forebody alone. The significance of these multiple solutions to the resultant aircraft motion is discussed and a new wind-tunnel testing procedure is advocated to ensure a full discovery of all possible high-incidence behavior.

Nomenclature

Cm	= pitching moment coefficient (body axes)
Cm_{aero}	= pitching moment coefficient (total incidence plane)
CN	= normal force coefficient (body axes)
CN_{aero}	= normal force coefficient (total incidence plane)
Cn	= yawing moment coefficient (body axes)
Cn_{aero}	= yawing moment coefficient (total incidence plane)
CY	= side force coefficient (body axes)
CY_{aero}	= side force coefficient (total incidence plane)
D	= forebody base diameter
U	= freestream velocity
x,y,z	= body axes
α	= angle of attack in pitch plane
β	= sideslip angle
σ	= total incidence angle
ϕ	= roll attitude (total incidence plane)
ψ	= yaw angle

Introduction

MODERN fighter aircraft can be flown at high angles of attack because their swept wing platforms still generate useful steady lift at these incidences. However, serious lateral directional stability problems have been encountered at high angles of attack. These problems are attributed to the large side forces and yawing moments that can be generated by the asymmetric flow that occurs at high angles of attack over the slender forebodies of these aircraft. The yawing moment produced by the forebody can be much greater than that produced by full rudder deflection, even at low incidence, and the rudder effectiveness reduces to zero as incidence increases.

The side forces and yawing moments on slender bodies at high angles of attack have been studied extensively in the last 10 years in order to provide aircraft and missile designers with information about the nature and magnitude of these lateral forces and moments. The most comprehensive data set is that obtained by Lamont[1-3] on ogive-cylinder forebodies in the 12-ft pressure wind tunnel at NASA Ames Research Center. The effects of angle of attack, fineness ratio, and Reynolds number are fairly well established, and this body-alone data can be applied directly to give the forebody's contribution to the aircraft's side force and yawing moment.

However, a full understanding of the aircraft's flight dynamics at high angles of attack requires a knowledge of other aerodynamic behavior, particularly that due to sideslip. Variations of side force and yawing moment with sideslip for pointed bodies of revolution[4,5] and complete aircraft[6] have been measured at high angles of attack. However, when these measurements were used to predict the aircraft's spin motion, very poor correlations were obtained with the actual motions of a model in a radio-controlled drop test.[6] The poor correlation was ascribed to the randomness of the yawing moment on the long pointed nose, and it was postulated that a wide variety of different types of airplane motion might develop from any given set of initial conditions and control inputs.

This paper will show how side force and yawing moment data at combined angles of attack and sideslip can be synthesized from zero sideslip data that covers a range of incidence and roll attitude. This can be done because a model at combined incidence and sideslip is equivalent to the same model at a different effective incidence and roll attitude in the total incidence plane. This approach is applied in this paper to simplify the especially troublesome case of circular cross-section forebodies. However, the method can be applied equally well to any shape of body or complete aircraft.

In the case of circular cross-section forebodies, the change in effective roll attitude for different sideslip angles can lead to a switch in the direction of the aerodynamic side force that drastically effects the shape of the CY and Cn vs β curves. Even more significant, it leads to the inevitability of multiple solutions for the same nominal geometry because the roll signature of every circular cross-section forebody will be different.

There are a family of possible CY and Cn vs β curves for circular cross-section forebodies at high angles of attack. The various radically different forms of CY and Cn vs β curves in the literature,[4-6] see Fig. 1, are shown to be different examples of the multiple solutions that are possible.

The approach outlined in this paper synthesizes results at combined angle of attack and sideslip angles from zero

Presented as Paper 89-0645 at the AIAA 27th Aerospace Sciences Meeting, Reno, NV, Jan. 9-12, 1989; received July 10, 1989; revision received Aug. 4, 1990; accepted for publication Sept. 2, 1990.

*Lecturer, Department of Engineering, Simon Building, Oxford Road. Member AIAA.

†Temporary Lecturer, Department of Engineering, Simon Building, Oxford Road. Member AIAA.

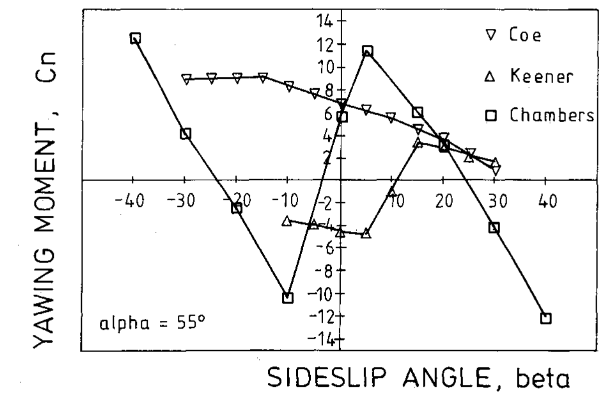

Fig. 1 Variety of published *Cn* vs β curves for ogive forebodies.

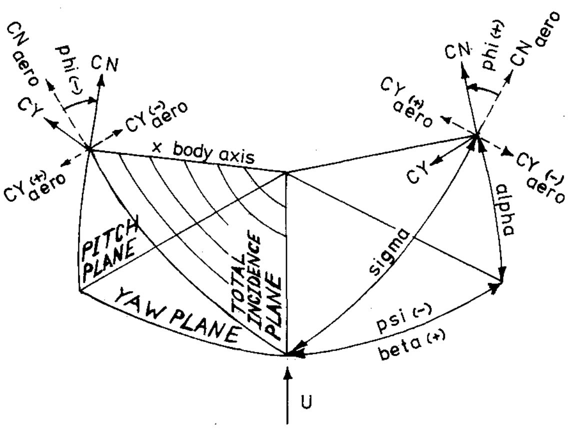

Fig. 2 Geometry of problem.

sideslip data. The agreement with forebody-alone data is very good but most remarkable of all is a comparison between experimental data for an F-111 model and a prediction based on the effect of its forebody alone. This clearly demonstrates that the forebody is responsible for the form of the *Cn* vs β curve for the complete aircraft at high incidences.

Geometry of the Problem

Aircraft flight dynamicists have tended to work in terms of the angle of attack in the pitch plane because this relates directly to the effective incidence of the wings, which are still the most important component of the complete aircraft in their eyes. However, at high angles of attack, the fuselage (particularly the forebody) plays a much more important role in the overall aerodynamics of a complete aircraft. Historically, missile aerodynamicists have paid much more attention to body aerodynamics because, on small winged missiles, the body effects are more significant, even at low incidences. Therefore, this paper will adopt the missile aerodynamicists' approach of considering the aerodynamic force and moment components relative to what they call the total incidence plane. This total incidence plane is a plane containing the freestream velocity vector and the aircraft's x-body axis. The included angle in this plane is the total incidence angle usually called σ.

When an aircraft is at a combined angle of attack α and yaw ψ, the total incidence plane rotates in space about the velocity vector, see Fig. 2. As the yaw angle increases, the total incidence angle σ increases above the angle of attack α and the effective roll attitude ϕ decreases from its zero datum at zero yaw. The relationship between the two coordinate systems can be found by simple geometry; this gives the following two equations:

$$\cos(\sigma) = \cos(\alpha) \cdot \cos(\psi) \tag{1}$$

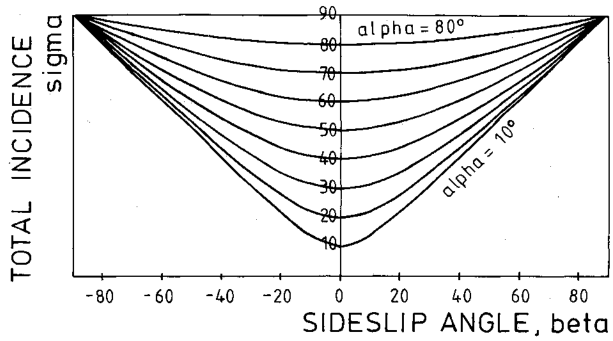

Fig. 3 Variation of total incidence angle with sideslip.

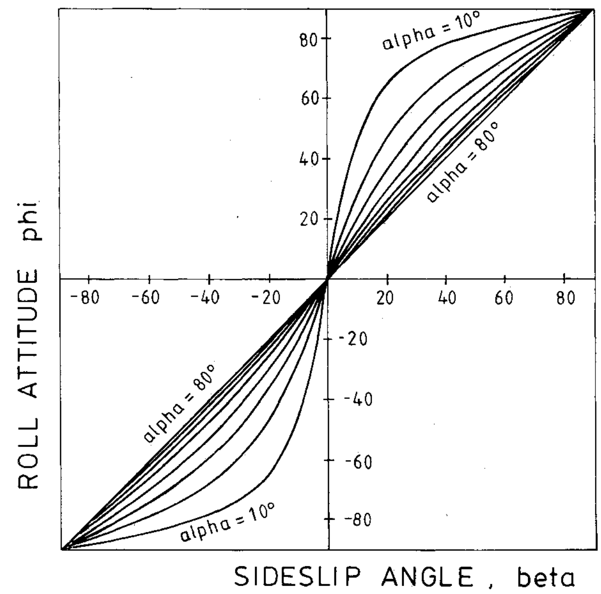

Fig. 4 Variation of roll attitude with sideslip.

$$\tan(\phi) = -\tan(\psi)/\sin(\alpha) \tag{2}$$

It appears to be common practice to work in terms of sideslip angle β rather than yaw angle ψ, and so with $\beta = -\psi$, the effect of sideslip on angle of attack and roll attitude is illustrated in Figs. 3 and 4, respectively. Figure 3 shows that increasing sideslip in either direction increases the total incidence angle. This increase is more pronounced at lower angles of attack. Figure 4 shows that positive sideslip produces positive changes to the roll attitude (positive roll attitude is right wing down viewed by the pilot). The changes to effective roll attitude are greater at lower angles of attack. Negative sideslip produces equivalent negative changes to roll angle.

The aerodynamic force components relative to the total incidence plane are independent of the orientation of this plane. Hence, they have a universality not shared by the pitch plane aerodynamics. They might be considered to be true aerodynamic coefficients and, hence, they will be denoted by CN_{aero} and CY_{aero}. They are the force coefficients measured in zero sideslip tests at the same angle of attack as the total incidence angle σ and at the same roll attitude ϕ.

The conventional body axes force components at any aircraft attitude can be found from these total incidence plane coefficients (subscript aero) by resolving them into body axes directions through the roll attitude change ϕ. Referring to Fig. 2, it can be seen that the force and moment components are related by the following equations:

$$CN = CN_{\text{areo}} \cdot \cos(\phi) + CY_{\text{aero}} \cdot \sin(\phi) \tag{3}$$

$$Cm = Cm_{\text{aero}} \cdot \cos(\phi) + Cn_{\text{aero}} \cdot \sin(\phi) \tag{4}$$

$$CY = CY_{\text{aero}} \cdot \cos(\phi) - CN_{\text{aero}} \cdot \sin(\phi) \tag{5}$$

$$Cn = Cn_{\text{aero}} \cdot \cos(\phi) - Cm_{\text{aero}} \cdot \sin(\phi) \tag{6}$$

Note that these coefficients must be based on the same reference area and reference length. This is the normal practice for body aerodynamics but not for aircraft aerodynamics where the conventional reference length in the longitudinal plane is the mean chord, whereas that in the lateral plane is the wing span.

This geometric transformation seemed to be an obvious simplification to the authors, but as far as we can see, this approach has only had one previous advocate[7] among aircraft aerodynamicists.

Variation of Forces with Sideslip

This section presents variations of force and moment coefficients with sideslip for a 3.5D ogive nose. Both side force and normal force components and their corresponding moments can be synthesized from zero sideslip data in the manner suggested earlier using Eqs. (1–6). The zero sideslip data used are taken from the extensive data set obtained by Lamont in his NASA Ames tests.

It is now common practice to test circular cross-section bodies through a range of roll angles at high angles of attack because of the well-known effect of side force variation and switching. If complete aircraft models were tested over a complete range of angle of attack and roll angle, then all of the required body force components could be synthesized from these results without the need for sideslip tests.

At low angles of attack, there is no aerodynamic side force and the body side force generated by sideslip results from a component of the aerodynamic normal force. As angle of attack is increased, a point will be reached at which sideslip will increase the total incidence σ beyond the critical onset of aerodynamic side force. Such a situation is portrayed in Fig. 5 where at an angle of attack of 20 deg and a sideslip angle of about 20 deg the effective angle of attack is such as to produce aerodynamic side force. This side force could be either positive or negative (right or left). Therefore, the curve must branch, as shown in Fig. 5, to reflect the two possible side force states. This behavior can be explained by referring again to Fig. 2. For negative aerodynamic side force (to the left) at positive sideslip angles (as depicted on Fig. 2), the aerodynamic side and normal force components combine to produce a larger negative body side force coefficient CY. This is the lower branch in the positive sideslip half of Fig. 5. In contrast, if the aerodynamic side force is positive (to the right), it opposes the contribution from the aerodynamic normal force producing the upper branch in the positive sideslip half of Fig. 5. The behavior in the negative sideslip half of this figure shows larger positive body side force associated with positive aerodynamic side force and the lower branch is produced by negative aerodynamic side force. At higher angles of attack where aerodynamic side force is always present, the CY vs β curves are of the form shown in Fig. 6. Here, the upper curve represents positive aerodynamic side force and the lower one negative side force.

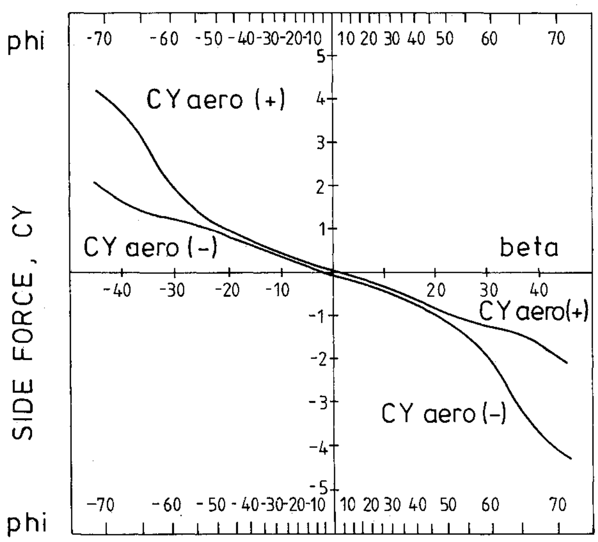

Fig. 5 Effect of sideslip on body side force at α = 20 deg.

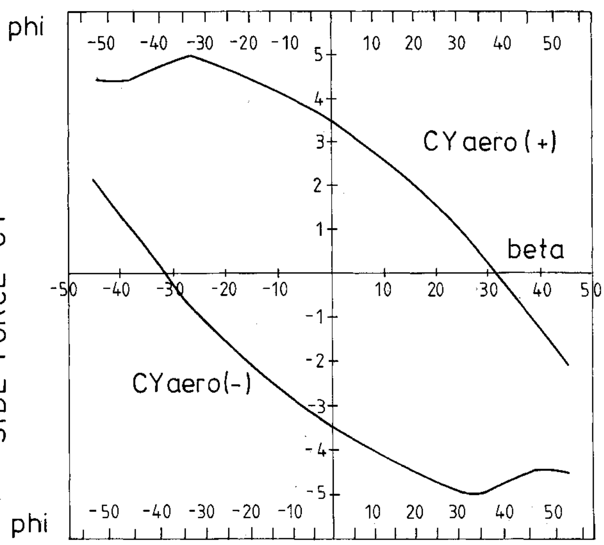

Fig. 6 Effect of sideslip on body side force at α = 50 deg.

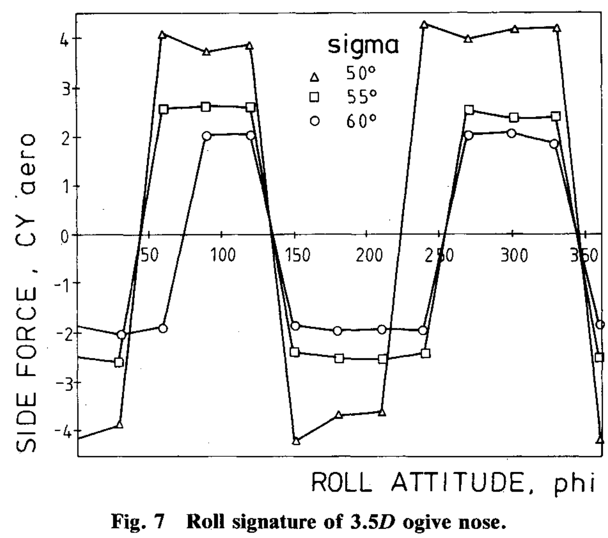

Fig. 7 Roll signature of 3.5D ogive nose.

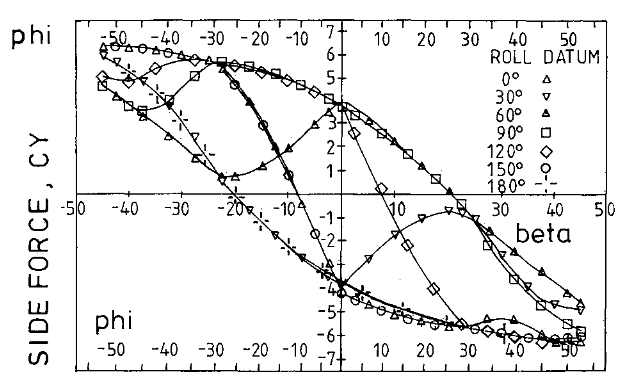

Fig. 8 Multiple solutions for CY vs β for 3.5D ogive at α = 50 deg.

Side Force Switches with Roll Angle

The figures in the previous section show alternate forms of behavior with sideslip depending on the direction of the aerodynamic side force. The changes in the effective roll attitude of the body ϕ with sideslip are indicated on the bottom of these figures. Note that these roll attitude changes are quite large; 30-deg sideslip changes roll attitude by about 40 deg at an angle of attack of 50 deg. It is now well known that changing the roll attitude of an inclined body of revolution will cause the side force to switch direction. The variation with roll angle is repeatable and is ascribed to asymmetric imperfections of the model geometry. However, the precise connection between the asymmetry of the model and that of the flow has not yet been established.[8]

The roll signature of the 3.5D ogive being considered here is shown in Fig. 7. The roll signatures of other noses made to the same specification will be different relative to the arbitrarily chosen zero roll attitude datum. The effect of different specimens from a batch of noses can be simulated by simply shifting the zero datum point on the roll signature shown in Fig. 7. If this is done, a family of possible CY vs β curves is obtained, as shown in Fig. 8.

This behavior can be explained by considering Figs. 7 and 8 together. First, consider the curve for the case where the zero datum is shifted to 90 deg. Figure 7 shows that this puts the datum at the center of a positive aerodynamic side force regular state and varying roll attitude by up to 30 deg on either side of this datum does not produce a side force switch. The variation of CY with sideslip for this case, see Fig. 8 (90-deg case), follows the upper envelope of all positive aerodynamic side force shown on Fig. 6. This form of variation was the one found in Coe's test[5] as shown in Fig. 1. A radically different variation of body side force with sideslip is obtained if the zero datum is shifted to 30 deg. At this datum, the initial aerodynamic side force is negative, but positive sideslip will produce an increase in effective roll attitude and the aerodynamic side force will switch to positive values, see Fig. 7. This will produce a jump from the lower to the upper envelope as beta increases from zero, see Figs. 6 and 8. This produces a similar variation to the one obtained by Keener et al.,[4] see Fig. 1. A switch about zero beta, as in the results of Chambers et al.[6] (also shown in Fig. 1), can be obtained from the roll signature of Fig. 7 by shifting the datum to 50 deg. This does not, however, exhaust the variety of possible curves. If the datum is shifted to 120 deg, then, for negative sideslip angles, the aerodynamic side force is positive, whereas positive sideslip produces a rapid jump to the lower envelope equivalent to negative aerodynamic side force.

The multiple solutions shown in Fig. 8 are based on zero sideslip data taken every 30 deg of roll. Therefore, the switching between positive and negative aerodynamic side force curves takes place over a sideslip angle that is equivalent to 30 deg of roll. However, a limited number of the NASA Ames Research Center tests were done in 10-deg roll increments. These results indicate that complete switches from maximum positive to maximum negative aerodynamic side force can occur over just a 10-deg roll angle. This more rapid switching would produce steeper crossover lines on plots like Fig. 8. The CY vs β curves that correspond to this more rapid switching can be constructed on the positive and negative aerodynamic side force curves of, say, Fig. 6 by joining points on the upper and lower curves a distance of 10 deg apart on the ϕ scale superimposed on this figure.

Comparison with Other Data

The value of the total incidence approach advocated in this paper is illustrated in this section by some comparisons with experimental yawing moment against sideslip data. The first two comparisons involve ogive forebodies and the final comparison concerns an F-111 model.

The first comparison is made with the experimental results of Coe et al.[5] for a 3.5D ogive forebody at a test Reynolds number of 0.35×10^6. As mentioned before, Coe's data is an example where no side force switches occur. Hence, the sideslip data can be synthesized by the positive aerodynamic side force curve alone, see Fig. 9. The agreement between the results synthesized from zero sideslip data collected in the same test program (solid lines on figure) and the experimental sideslip results (individual experimental points) is excellent at all angles of attack. This simply confirms the correctness of the geometric transformations given in Eqs. (1-6).

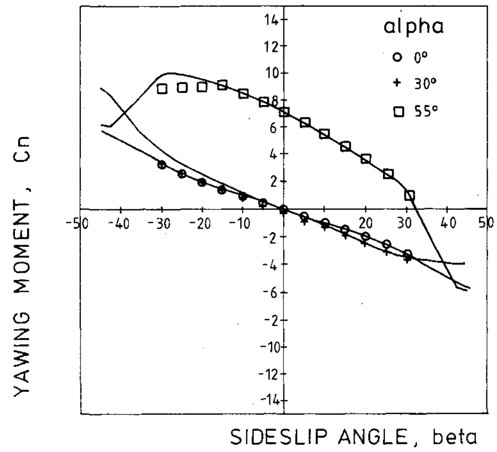

Fig. 9 Comparison with Coe's data (3.5D ogive, 0.35×10^6 Reynolds number).

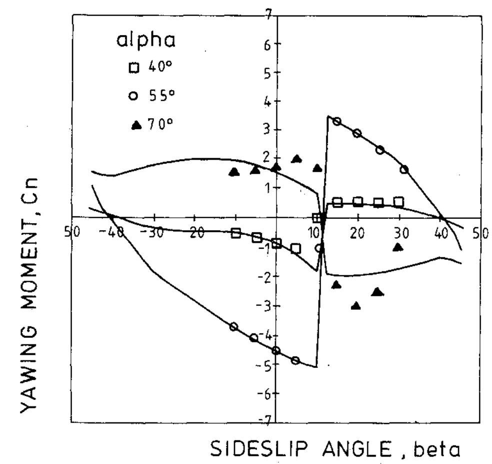

Fig. 10 Comparison with Keener's data (3.5D ogive, 0.8×10^6 Reynolds number).

A second comparison is made with the results of Keener et al.[4] for a 3.5D ogive forebody at a Reynolds number of 0.8×10^6, see Fig. 10. Here, side force switching occurs at a positive sideslip angle of about 11 deg. Once again, the agreement between the synthesized results (lines) and the experimental sideslip data (points) is excellent.

The aircraft aerodynamicist might ask at this point, "how important are the forebody effects previously demonstrated to the sideslip behavior of a complete aircraft at high angles of attack?" This question was answered by approximating the forebody shape of an F-111 by an ogive cylinder and then using Lamont's NASA Ames Research Center data to predict the contribution of this forebody to the Cn vs β curve for an F-111 at 55-deg angle of attack and 0.3×10^6 Reynolds number. The comparison with Chambers' experimental results[6] for an F-111 model are shown in Fig. 11. The agreement of the synthesized forebody contribution (solid lines) with the results of the complete aircraft (dashed line) is remarkable.

This clearly shows that it is the forebody that is responsible for this yawing moment behavior. The particular model tested must have a roll signature that produced an aerodynamic side

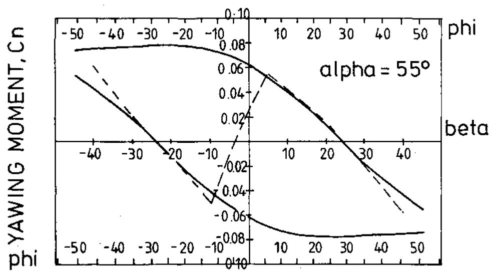

Fig. 11 Forebodies contribution to the *Cn* vs β curve for an F-111.

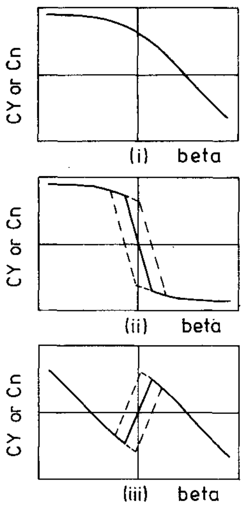

Fig. 12 Characteristic forms of side force/yawing moment variations with sideslip.

force switch near the zero datum. However, it has been demonstrated earlier that this is only one of a family of possible variations. Therefore, it is not surprising that applying this one particular Cn_β curve to a different drop test model did not produce good predictions of its flight dynamics.[6]

Effect on Aircraft Flight Dynamics

This section will briefly discuss the significance of multiple sideslip solutions to the flight dynamics of an aircraft at high angles of attack. The multiple solutions for *CY* and *Cn* that are possible can be grouped into three characteristic forms. These forms are sketched in Fig. 12. Type (i) is that found by Coe, whereas type (iii) was found by Keener and Chambers. Type (ii) is also possible, but we have found no published examples.

Type (i) behavior is statically unstable as increased negative sideslip leads to increased positive yawing moment. Type (ii) behavior, involving a switch from negative to positive aerodynamic side force as sideslip becomes more negative, is even more unstable. In contrast, type (iii) curves involving a switch from positive to negative side force as sideslip decreases are statically stable and the aircraft may oscillate within the limits of the switch.

This side force/yawing moment behavior cannot be looked at in isolation. A different normal force/pitching moment behavior will accompany each of the three side force/yawing moment types. Therefore, the resultant aircraft motion will be radically different depending on which of these three types of behavior is occurring. It cannot be stressed too strongly that, for circular cross-section forebodies, different wind-tunnel models or complete aircraft made to the same specification will exhibit different spin characteristics. This explains the problems encountered by Chambers in reconciling results from different models.

The following testing procedure is suggested in order to discover all of the possible variations for a given aircraft configuration at high angle of attack. The model should be tested over a full range of angle of attack, and at each incidence a full roll sweep should be done. The geometric transformations given in this paper then enable sideslip variations to be synthesized from this data. In addition, if the forebody (or even just the nose tip) is circular in cross section, it should be rotated relative to the wings and the tests repeated until all possible variations have been found.

The dramatic effect that different forebody behavior can have on the static stability is demonstrated in this paper. It might be worthwhile for those involved in the more complex dynamic testing of fighter aircraft at high angles of attack to consider the implication of these findings to their test results.

Conclusions

1) Variations of force and moment components (in body axes) with sideslip can be calculated from total incidence plane data using simple geometric transformations.

2) The side force switching that occurs at high incidence for all circular cross-section forebodies produces a family of possible variations with sideslip.

3) This variety of solutions will produce a variety of aircraft flight dynamics at high angles of attack.

4) A new wind-tunnel testing procedure is advocated for all aircraft at high angles of attack. It must be employed in all static and dynamic tests on aircraft that have circular cross-section noses in order to find all of the possible force/moment variations that can exist.

5) Total incidence plane aerodynamics might be the key to successful flight simulations at high angles of attack.

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