Status of Design Criteria for Predicting Departure Characteristics and Spin Susceptibility

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This paper presents the status on efforts made during the past few years to develop and correlate various criteria for predicting full-scale aircraft departure characteristics and spin susceptibility. The criteria discussed are Dynamic Directional Stability, the Lateral Control Departure Parameter (LCDP), and a relatively new criterion known as the Beta Plus Delta Axis Stability Indicator. Data acquired on several operational aircraft and aircraft under development are presented. Correlation is based primarily on free-flight model test results and the interpretation of these criteria relative to predicting full-scale aircraft departure characteristics and spin susceptibility is discussed.

Nomenclature

C_{l_β} = rolling moment derivative per deg sideslip
C_{n_β} = yawing moment derivative per deg sideslip
C_{l_δ} = rolling moment derivative per deg control surface deflection
C_{n_δ} = yawing moment derivative per deg control surface deflection
I_x, I_z = moments of inertia about x and z axes
α = angle of attack, positive when the x body axis is above the projected relative wind vector, deg
β = angle of sideslip, positive when the relative wind vector is to the right of the x-z plane, deg
δ_a = aileron control surface deflection, deg
δ_d = differential horizontal control surface deflection, deg
δ_s = spoiler control surface deflection, deg
δ_r = rudder control surface deflection, deg
δ_T = total lateral control surface deflection (δ_a, δ_d, δ_s)

Introduction

OVER the past few years there have been several studies of design criteria for predicting departure characteristics and spin susceptibility of fighter-type aircraft. Results of previous investigations[1-5] have shown that the $C_{n_{\beta,\mathrm{DYN}}}$ and aileron-alone divergence parameters can be used as preliminary criteria for predicting the angle of attack at which departure from controlled flight occurs, airplane motion at departure, and the degree of spin susceptibility. All of these studies deal with criteria that use static aerodynamic characteristics. Since static force test data are among the first data obtained, the designer has high angle-of-attack static characteristics early in preliminary design from which stability and control analysis can be started and a determination made as to whether or not the airplane might experience stability problems at near-stall angles of attack.

A main objective of these studies has been to evaluate existing stability criteria and possibly develop new criteria which can be used with a reasonable degree of confidence to predict full-scale aircraft departure characteristics and spin susceptibility as early as possible in the design stage. Some very recent studies have been completed[6-11] where data from modified aircraft, past aircraft development programs, and aircraft currently under development has become available and correlated with various departure criteria. This paper presents the status on efforts made during the past few years to develop and correlate various criteria for predicting full-scale aircraft departure characteristics and spin susceptibility. Data recently acquired on the USAF Light Weight Fighter aircraft are presented along with some limited results on the SAAB 37 "Viggen" aircraft. Correlation is based primarily on free-flight model test results with full-scale flight test results presented where available.

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Departure/Spin Susceptibility Criteria

The most familiar criteria for predicting aircraft departure characteristics and spin susceptibility are based on lateral-directional static stability parameters. These criteria are[1-3]

Dynamic Directional Stability Parameter:

$$C_{n_{\beta,\mathrm{DYN}}} = C_{n_\beta} \cos\alpha - (I_z/I_x) C_{l_\beta} \sin\alpha > 0 \qquad (1)$$

Lateral Control (or Aileron Alone) Departure Parameter:

$$\mathrm{LCDP\ (AADP)} = C_{n_\beta} - C_{l_\beta} \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} > 0 \qquad (2)$$

Aileron Plus Rudder Proportional to Sideslip Angle

$$C_{n_\beta} - C_{l_\beta} \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} + K_1\left(\frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} C_{l_{\delta_r}} - C_{n_{\delta_r}}\right) > 0 \qquad (3)$$

where $K_1 = -\delta_r/\beta$

Aileron Plus Rudder Proportional to Aileron:

$$\mathrm{LCDP} = C_{n_\beta} - C_{l_\beta}\left(\frac{C_{n_{\delta_a}} + K_2 C_{n_{\delta_r}}}{C_{l_{\delta_a}} + K_2 C_{l_{\delta_r}}}\right) > 0 \qquad (4)$$

where $K_2 = \delta_r/\delta_a$. Equation (4) has been used in modified form as:

$$\mathrm{LCDP} = C_{n_\beta} - C_{l_\beta}\left(\frac{C_{n_{\delta_a}}\delta_a + K_2 C_{n_{\delta_r}}\delta_r}{C_{l_{\delta_a}}\delta_a + K_2 C_{l_{\delta_r}}\delta_r}\right) \qquad (4a)$$

$$\mathrm{LCDP} = C_{n_\beta} - C_{l_\beta}\left(\frac{C_{n\delta_T}\delta_T + C_{n_{\delta_r}}\delta_r}{C_{l\delta_T}\delta_T + C_{l_{\delta_r}}\delta_r}\right) \qquad (4b)$$

Obviously, one can modify Eqs. (3) or (4) depending upon the airplane design (i.e., spoilers or no spoilers, differential horizontal tail for roll control as well as ailerons, etc.) and the form of the aerodynamic data being used (derivatives, incremental yawing moment due to aileron deflection, etc.). Equation (2) is the simplest form of Eq. (4) since the calculation does not include a rudder control input, for example, from an aileron-rudder interconnect.

β Plus δ Axis Stability Indicator

A relatively new and recently introduced criterion for predicting departure angle of attack is known as the "β Plus δ Axis Stability Indicator." A detailed derivation and explanation of this criterion can be found in Ref. 9. Briefly summarizing, the "β axis" is in the direction of the initial acceleration following a sideslip change in the direction which reduces the sideslip. The "δ axis" is in the direction of the initial acceleration following a lateral or lateral-plus-directional control input. The vector sum of these two acceleration vectors acting along the β and δ axes represents the initial response of the aircraft due to both sideslip and control inputs and whose direction defines the "β plus δ" axis.

The "stability indicator" involves the magnitude and direction of the components of the β plus δ vector, that is, the orientation of the β and δ axes which is given by

$$\alpha_{-\beta} = \alpha - \arctan\left(\frac{C_{n_\beta}}{C_{l_\beta}} \frac{I_x}{I_z} \right) \tag{5}$$

for the β axis and

$$\alpha_{\delta} = \alpha - \arctan\left(\frac{C_{n_\delta}}{C_{l_r}} \frac{I_x}{I_z} \right) \tag{6}$$

for the δ axis. Reference 9 should be consulted for a graphical definition of Eqs. (5) and (6).

The stability indicator is (for stability)

$$\alpha_{-\beta} > \alpha_\delta \text{ and } \alpha_{-\beta} > 0 \tag{7}$$

In order to predict aircraft departure angles of attack, $\alpha_{-\beta}$ and α_δ are plotted vs aircraft angle of attack over the desired range of angles of attack. If the α_δ line is above the $\alpha_{-\beta}$ line at a given angle of attack, or if $\alpha_{-\beta} < 0$, then a tendency toward instability can be expected at the lower of these angles of attack. Because of the direct relationship between $C_{n_{\beta,\mathrm{DYN}}}$ and the β axis,[9] when $\alpha_{-\beta} = 0$ then $C_{n_{\beta,\mathrm{DYN}}} = 0$. Also, when $\alpha_{-\beta} = \alpha_\delta$ then LCDP $= 0$.

The parenthetical expression in Eq. (5) warrants some additional discussion. The reciprocal of this expression, that is,

$$\frac{I_z}{I_x} \frac{C_{l_\beta}}{C_{n_\beta}} \tag{8}$$

was at one time suggested as a possible criterion for determining spin susceptibility.[12] At the maximum positive trimmed angle of attack, an airplane having a large positive value of Eq. (8) was considered less likely to transition from the stall to an erect spin.

If Eq. (8) is large and positive, then the last term in Eq. (5) is small and positive which tends to make $\alpha_{-\beta}$ a large positive value. In effect then, some degree of directional static instability can be tolerated so long as positive effective dihedral exists at a particular angle of attack. Similarly, the angle $\alpha_{-\beta}$ tends to be large and positive if Eq. (8) is negative (i.e., $C_{n_\beta} > 0$) regardless of the magnitude. At the time that expression Eq. (8) was suggested as a spin susceptibility criterion, very limited experimental results were available for correlation.

Nonsymmetric Flight Departure Boundaries

A recently completed study deals with application of the linearized, uncoupled, small perturbation lateral-directional equations of motion to an unsymmetric high angle-of-attack flight condition. The simplified equations of motion are used to define an airplane's angle of attack, sideslip angle envelope and from this predict stability characteristics at near-stall angles of attack by establishing a departure boundary. It should be noted that the method of analysis described in this study was applied to a particular airplane but the method appears to satisfactorily predict the general conditions under which high angle of attack lateral-directional stability might be a problem.

Generally, the stability derivatives used in calculating these various criteria are applicable over only a small sideslip angle range; for example, $\pm 5°$. The higher the angle of attack, the more nonlinear C_n and C_l vs β becomes and it is possible to calculate positive values for, say $C_{n_{\beta,\mathrm{DYN}}}$ over a small β range and negative values over a larger β range (e.g., $\pm 10°$). Consequently, the aerodynamic data used in calculations should also take into account nonlinearities over the large as well as over the small β range.

Correlation of Criteria

β Plus δ Axis Stability Indicator

Data correlating this criterion with the results of analytical studies and flight tests conducted on the F-4E aircraft are presented in Ref. 9. It was found that this criterion in general predicts with good accuracy the angle of attack for divergence due to lateral or directional static instability.

The β Plus δ Axis Stability Indicator criterion is shown in Figs. 1-4 for the A-7, Saab 37, and two USAF Light Weight Fighter (LWF) configurations. Full-scale A-7 flight tests results[13] show that departure is characterized by a yaw in either direction followed by rolling motion in the direction of yaw, that is, a rolling departure. The departure angle of attack range is shown in Fig. 1. A tendency toward instability is first indicated at about 18.5° angle of attack and at 22° the β axis indicator is slightly negative, remaining near zero up to 26°. Correlation with flight test results is quite good for this airplane.

Free-flight model test results are not available for the Saab 37 airplane. Figure 2 indicates that the airplane should have reasonably good lateral-directional characteristics up to at least 35° angle of attack. Data from full-scale flight tests conducted to date have indicated this to be so.[14]

The stability indicator criterion for LWF configuration A is shown in Fig. 3. At about 31° angle of attack tendency toward instability is indicated and at about 36°, where $\alpha_{-\beta}$ is zero, the model experienced a directional divergence. Correlation with free-flight model test results appears to be good (formal publication of experimental test results is expected in the near future).

As shown in Fig. 4, LWF configuration B tends toward instability at approximately 29° angle of attack and then improves at about 38°. With the beneficial effect of an aileron-rudder interconnect (ARI), possible stability problems are not indicated until an angle of attack of about 34° is reached. Free-flight model test results (not formally published at this time) indicated a "nose wandering" above 30° and at an angle of attack of about 35° a very mild divergence in the form of a sideward sliding motion was experienced. Note that the β axis indicator is always positive. Again, there is reasonably good correlation with model test results.

Nonsymmetric Flight Departure Boundaries

The A-7 airplane was analyzed in an unsymmetric high angle-of-attack flight condition using the method of analysis described in Ref. 7. Figure 5 is an example of the results obtained from this study. The line labeled "$C_{n_{\beta,\mathrm{DYN}}}$" represents the locus of the smallest sideslip angle at which this parameter first indicates instability (a negative value). Likewise, the lines labeled "LCDP" and "roots" represent the points where the lateral control departure parameter first becomes negative and where the real part of the Dutch Roll pair of complex roots first become positive. The dashed line is a departure boundary based on A-7 flight test data and considering that actual departures represent dynamic flight conditions, the

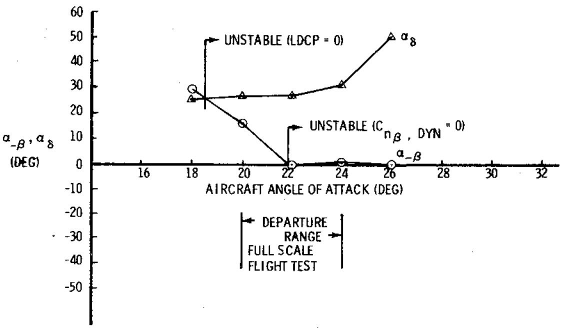

Fig. 1 β **plus** δ **Axis Stability Indicator, A-7 airplane.**

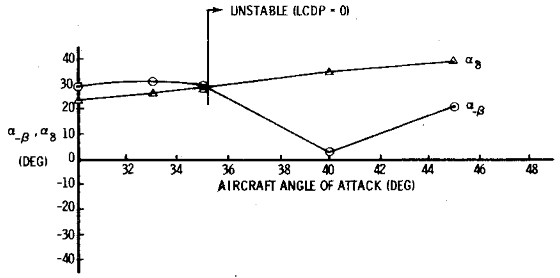

Fig. 2 β **Plus** δ **Axis Stability Indicator, SAAB 37 airplane.**

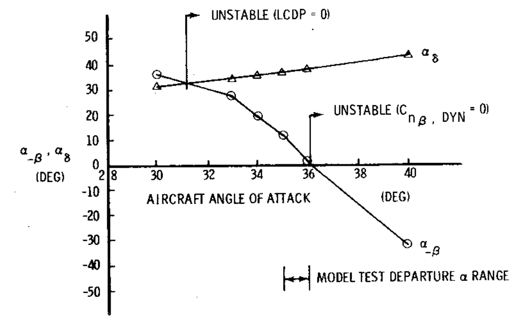

Fig. 3 β **Plus** δ **Axis Stability Indicator, LWF configuration A.**

correlation is quite good. LCDP and $C_{n_{\beta,\mathrm{DYN}}}$ correlate very well with instabilities indicated by the roots of the characteristic equation. Since these results are based on a single application to a particular aircraft, this method of analysis needs to be applied to several other aircraft and the results correlated before definitive conclusions can be made regarding its utility.

$C_{n_{\beta,\mathrm{DYN}}}$ and LCDP

There has been a considerable amount of effort regarding the correlation of these two parameters with experimental data as well as with results of analytical studies. The studies described in Refs. 5, 8, and 9 are some examples. The use and interpretation of these parameters for predicting aircraft departure characteristics and spin susceptibility is presented[8] along with a limited correlation of experimental data relative to the F-4, F-111, A-7, and F-5 aircraft. Additional data on several other aircraft have since been obtained and these data are presented here along the lines of Ref. 8. Figure 6 illustrates the use of the $C_{n_{\beta,\mathrm{DYN}}}$ and LCDP parameters for predicting departure characteristics and spin susceptibility.

Figure 7 presents data for the F-8, F-102, F-106, and Saab 37 aircraft. Model flight test data[6] show a departure angle of attack of 26° for the F-8 while full-scale flight test results[15] indicate the departure characteristics are basically mild to moderate rolling departures, that is, the motion immediately following departure is primarily a rolling motion. The use of lateral control at near-stall angles of attack induces adverse

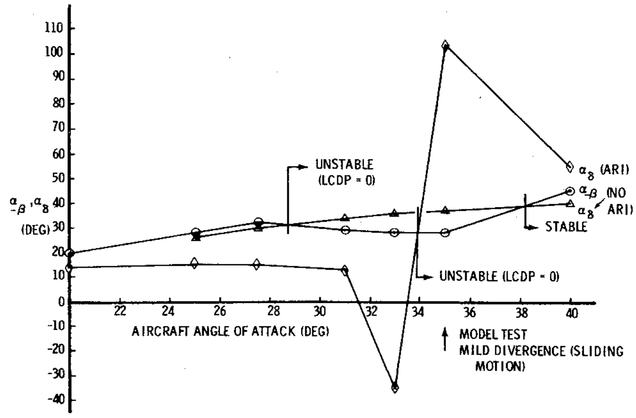

Fig. 4 β **Plus** δ **Axis Stability Indicator, LWF configuration B.**

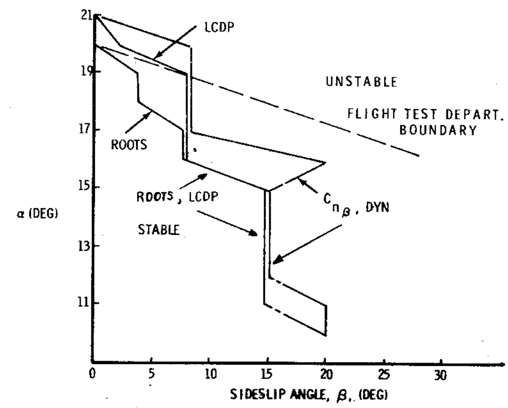

Fig. 5 Correlation of predicted departure boundary with flight test results.

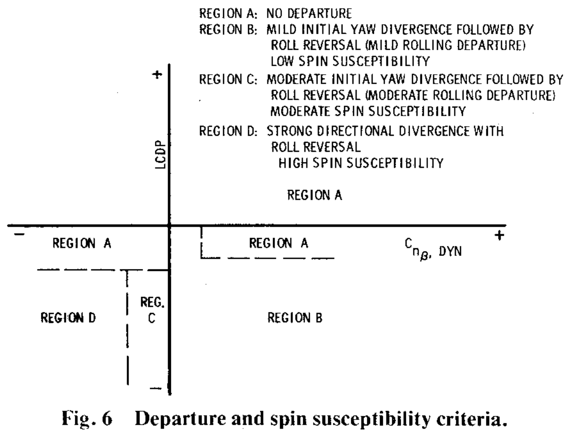

Fig. 6 Departure and spin susceptibility criteria.

yaw and consequently increase the possibility of a spin. Note that at near-stall angles of attack the criteria plot in region B (Fig. 7) for the F-8 and therefore correlation with experimental results is considered satisfactory.

Based on model test results,[16] an F-102 departure is characterized by a directional divergence at about 28° angle of attack. Above 25°, it was difficult to maintain small sideslip angles (less than 5°) and the tendency to diverge increased. Above 28° the model would experience a rapid directional divergence. At an angle of attack of 30° the criteria plot between regions C and D and in region A for 25°. The model could be flown at 25° at small sideslip angles although control over sideslip angle was difficult. Correlation with model test results is considered good.

Flight tests results on the F-106 airplane[17] indicate that the cruise configuration stall is characterized by an abrupt in-

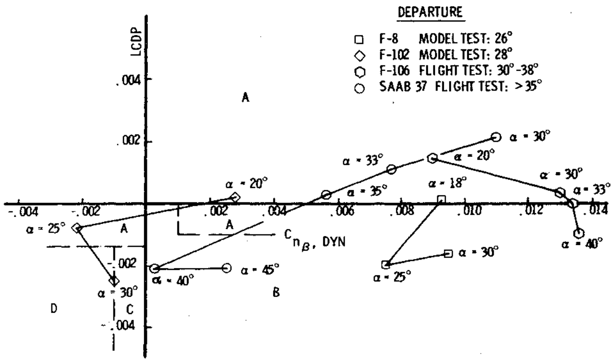

Fig. 7 Correlation of criteria: F-8, F-102, F-106, SAAB 37.

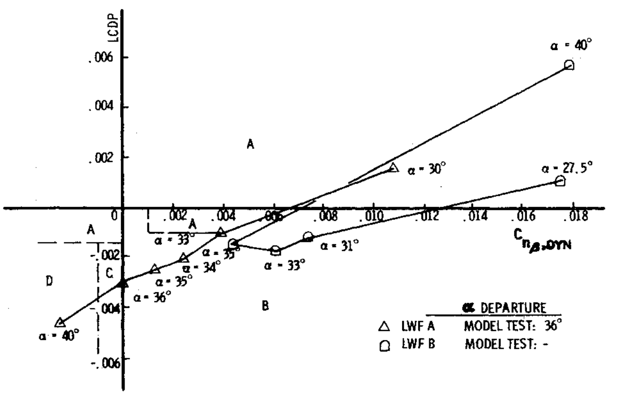

Fig. 8 Correlation of criteria: LWF configurations.

crease in angle of attack accompanied by a sudden roll off. At a sideslip angle greater than about 10° post-stall gyrations often occurred, the motion being primarily a rolling motion (mild rolling departure). Departure angles of attack where post-stall gyrations occurred were between 34 and 38°. Regarding spin susceptibility, the airplane's tendency to spin depends upon the use of lateral control at near-stall angles of attack. Criteria correlation with F-106 flight test results appears to be reasonable since points between 33° and 40° angle-of-attack plot in region B.

Data for the Saab 37 airplane is also shown in Fig. 7. Full-scale flight test results have shown reasonably good flying qualities up to at least 35° angle of attack (i.e., no fortuitous departures). At the higher angles of attack up to about 50° and with lateral control input, departure characteristics and spin susceptibility appear to be as predicted for region B.

Figure 8 shows correlation of the criteria with model test results for the LWF configurations A and B. Note that for configuration A between 36° and 40° angle of attack, the motion immediately following departure is predicted to be primarily a yawing motion and as was noted previously the model did experience a directional divergence at about 36°. A moderate or strong directional divergence is not predicted for configuration B and one was not experienced from model tests. It perhaps should be noted that the magnitude of the adverse yaw due to differential horizontal control surface deflection used to compute LCDP for configuration B is considered greater than it should be. The adverse yaw used was for a stabilator deflection of zero degrees but unpublished wind-tunnel data indicates that at trim stabilator deflections of $-10°$ to $-12°$ there is less adverse yaw due to a differential deflection. Consequently, the negative values of LCDP shown in Fig. 8 between 31° and 35° angle of attack would be less and as was noted above, free-flight model test results indicated no directional divergence at stabilator deflections greater than zero.

Although not shown here the effect of an ARI produced positive values of LCDP between 31° and 33° angle of attack for the LWF configuration B (see Fig. 4). Similarly, the effect of an ARI produced a positive LCDP at 33° for LWF configuration A.

Conclusions

Criteria now in use for predicting aircraft departure characteristics and spin susceptibility correlate well with experimental test results and can be used with a reasonable degree of confidence during preliminary design. The interpretation of these various criteria which are based on lateral-directional static stability characteristics has been open to question and all of the study efforts have dealt with interpretation relative to predicting full-scale aircraft departure angle of attack, departure characteristics, and the tendency to spin or spin susceptibility.

The β plus δ Axis Stability Indicator predicts the angle of attack for divergence or departure due to low levels of lateral-directional stability at near-stall angles of attack. These criteria, the β axis and δ axis, are in essence analogous to the $C_{n\beta,\text{DYN}}$ and LCDP parameters. Regarding the prediction of departure characteristics (the kind of motion experienced at and immediately following a departure from controlled flight) and spin susceptibility, the $C_{n\beta,\text{DYN}}$ and LCDP parameters are better suited for this purpose and, of course, departure angles of attack are also indicated.

The method of analysis to determine a nonsymmetric flight departure boundary, in terms of angle of attack and sideslip angle, shows considerable promise. However, it is cumbersome to work with in preliminary design as compared to the other criteria discussed here. Dynamic stability derivatives are also needed and these are often hard to obtain particularly in early design.

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