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Development of a Preliminary High-Angle-of-Attack Nose-Down Pitch Control Requirement for High-Performance Aircraft

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ABSTRACT

This paper discusses the requirements for high-angle-of-attack nose-down pitch control for advanced high-performance aircraft. Background information on fundamental factors that influence and, to a large extent, determine the high-α nose-down control requirement is briefly reviewed. Guidelines currently proposed by other sources which attempt to define these requirements are discussed. A requirement based on NASA analysis of the characteristics of existing relaxed static stability (RSS) aircraft is presented herein. This analysis could provide the basis for a preliminary design guide.

SYMBOLS

$\bar{c}$	mean aerodynamic chord, ft.
C_m	pitching moment coefficient
I_x, I_y, I_z	moments of inertia, slug-ft^2
M	pitching moment, ft-lb.
p,q,r	roll, pitch, and yaw angular rates, rad/sec
$\bar{q}$	dynamic pressure, lb/ft^2
S	wing reference area, ft^2
V_s	stall speed, ft/sec
α	angle of attack, deg
β	angle of sideslip, deg

Subscripts

IC	inertia coupling
KC	kinematic coupling
s	stall
stab	stability axis

INTRODUCTION

The concept of relaxed static stability (RSS) in pitch has been incorporated in a number of current high-performance aircraft for the enhancement of subsonic maneuvering performance. With the growing emphasis on supersonic operations, RSS is expected to be even more important to future combat aircraft since efficient supersonic flight will require balancing the aircraft for near neutral stability at these conditions. This design approach, however, will generally result in a very unstable aircraft at subsonic conditions due to the large shift in aerodynamic center with Mach number. Unfortunately, the use of RSS on fighter configurations can result in extremely demanding stability and control problems at high angles of attack. The fundamental aerodynamic characteristics which cause the problems of RSS configurations are illustrated in figure 1, which shows a simplified plot of aerodynamic pitching moment coefficient C_m versus angle of attack for a typical statically unstable configuration. Data are shown for neutral, full-nose-up and full-nose-down pitch control deflections. The two main potential problem areas are indicated by the shaded regions. The lower angle-of-attack region represents an area of susceptibility to inadvertent loss of longitudinal control and pitch departures due to lack of sufficient aerodynamic nose-down control moment. The primary problem associated with the higher angle-of-attack region is the potential existence of a deep stall trim point from which recovery may be difficult due to degraded control effectiveness. Both of these problems are avoided if sufficient nose-down moment can be generated over the entire angle of attack range. Thus a key design parameter for RSS high performance aircraft is the minimum moment available with application of full nose-down pitch control. Figure 2 illustrates this parameter expressed in the form of the minimum nose-down pitching moment coefficient, which, for convenience, will be referred to as $C_m{}^*$ in this paper. Determining the design goal for $C_m{}^*$ for a given configuration can involve a crucial design trade. Too large a magnitude may result in excessive weight and supersonic performance penalties, whereas too small a magnitude could lead to low-speed high-α controllability problems and degraded maneuvering capability. Unfortunately, no validated, generally accepted design guidelines are currently available for determining the proper level of nose-down pitch control capability for a given configuration. Establishment of such guidelines will require a systematic series of ground-based experimental and analytical studies followed by full-scale flight test and validation. This paper was prepared as a preliminary analysis element in this process. The primary objectives of the paper are to: (1) Summarize the fundamental factors that must be addressed in developing guidelines; (2) highlight some existing proposed guidelines; and (3) present a possible approach for developing preliminary guidelines based on an analysis of the characteristics of current RSS aircraft.

BACKGROUND

The level of high-α nose-down pitch control capability that is required for fighter aircraft is driven by five primary factors: (1) deep stall trim, (2) time required to recover to low angles of attack, (3) inertia coupling, (4) aerodynamic coupling, and (5) kinematic coupling. A brief review of each of these factors follows.

Deep stall - A deep stall trim situation where application of full nose-down control will not generate a nose down moment and provide recovery from high-α conditions is a very undesirable characteristic for combat aircraft.

A current configuration that exhibits deep stall behavior at aft c. g. locations is the F-16. Although the airplane incorporates an angle of attack limiting system, it is possible to defeat this feature and enter the deep stall trim condition. Recovery must then be attempted by the pilot by manually using oscillatory pitch control inputs which oscillate the vehicle until sufficient energy is built up to pitch the airplane down to substall angles of attack. Although control system strategies such as this can be used to address an existing deep stall condition on some airplanes, it is best if the problem can be avoided altogether by designing the vehicle with sufficient nose-down control capability.

High-α recovery - The ability to recover quickly from high angle of attack conditions can be an important capability during air combat. Rapid reestablishment of low-α flight is needed to minimize energy loss and enable effective repositioning for reengagement or for attacking another opponent. Thus, sufficient nose-down pitch acceleration must be provided at high angles of attack to also meet this requirement.

Inertia coupling - Substantial nose-up moments can result from the dynamics of inertia coupling which is given by the expression:

$$M_{IC} = (I_z - I_x)pr \tag{1}$$

A major contributor to this effect is rolling about the velocity vector which is required at high angles of attack to avoid excessive sideslip. The body-axis roll and yaw rates for this type of maneuver are given by $p = p_{stab} \cos\alpha$ and $r = p_{stab} \sin\alpha$. Substituting into equation (1) and simplifying gives:

$$M_{IC} = \frac{1}{2} (I_z - I_x)\, p_{stab}^2 \sin 2\alpha \tag{2}$$

Expressing the moment in terms of pitch angular acceleration gives:

$$\dot{q}_{IC} = \frac{1}{2} \left(\frac{I_z - I_x}{I_y}\right) p_{stab}^2 \sin 2\alpha$$

For typical combat aircraft, $\left(\frac{I_z - I_x}{I_y}\right) \cong 1$, thus:

$$\dot{q}_{IC} \cong .5\, p_{stab}^2 \sin 2\alpha \tag{3}$$

Using equation (3), figure 3 shows the variation of $\dot{q}_{IC}$ with roll rate at three angles of attack. As expected, the results show that the effect is greatest at $\alpha = 45°$ and that large nose-up accelerations can be generated at the higher roll rates. Clearly, there must be sufficient nose-down control to oppose this inertia coupling moment or a pitch departure will likely occur for RSS configurations.

Significant additional nose-up inertia coupling moments can result from uncommanded roll/yaw motions at high angles of attack such as large amplitude lateral oscillations, "wing rock", or departure gyrations. Thus it is important to have sufficient nose-down pitch control to counter nose-up moments due to commanded high-α roll maneuvers as well as additional moments caused by potential out-of-control conditions that could also involve significant inertia coupling.

Aerodynamic coupling - Substantial variations of aerodynamic pitching moment with sideslip have been observed on some combat aircraft designs at high angles of attack. This characteristic is very dependent on configuration geometry, but significant nose-up moments due to sideslip such as those illustrated in figure 4 are not uncommon. Thus, nose-down pitch control capability must be examined not only for zero sideslip but all sideslip conditions that the airplane may be expected to encounter during high-α flight.

Kinematic coupling - Significant increases in angle of attack can result from rolling with proverse sideslip. The approximate equation for the rate change of angle of attack due to this effect is:

$$\dot{\alpha}_{KC} = -(p \cos\alpha + r \sin \alpha)\tan\beta$$

Note that $\dot{\alpha}_{KC}$ is positive if β has the opposite sign as p and r, i.e. rolling with proverse β. Nose-down pitch control is needed to counter the α increase due to this phenomenon to avoid potential pitch departure for RSS designs.

EXISTING GUIDELINES

The importance of high angle-of-attack nose-down pitch control capability for RSS fighter designs has been recognized since the advent of the first generation of relaxed stability aircraft such as the YF-16. Since that time, a number of design guidelines for pitch control have been proposed and this section will summarize four of them. The intent is not to provide a comprehensive review of all existing guidelines, but rather to briefly discuss several of them to provide some perspective on the current status of this area. The four guidelines were chosen because they either have been published in the literature or were developed in studies conducted by other authors.

Reference 1 reported on a design study to evaluate the benefits of certain configuration arrangements for advanced supersonic cruise tactical aircraft. A high-α nose-down pitch control guideline was selected and used in the study. Expressed in terms of $C_m{}^*$, the guideline simply states that $C_m{}^*$ should be large enough to provide a minimum of -5 deg/sec^2 nose-down pitch acceleration. Unfortunately, no discussion of the rationale for the guideline or how it was arrived at was provided.

In reference 2, Mello and Agnew summarized McDonnell Douglas' design philosophy for fighter aircraft departure and spin resistance. The authors stated that discussions with several pilots concerning the nose down control requirements indicated that the ability to quickly generate a discernable nose down pitch rate in very low speed maneuvers was highly desirable. They suggested a minimum capability of 5 deg/sec in 1 second at the 1g stall speed, V_s.

Reference 3 discusses proposed revisions to MIL-F-8785C related to the flight safety of augmented aircraft. The proposed high-α nose-down pitch control requirement is summarized in figure 5. Essentially, it states that the airplane under consideration shall exhibit a $C_m{}^*$ of sufficient magnitude to generate a specified value of nose-down angular acceleration dependent on the vehicle class. For combat aircraft, the requirement would be -.28 rad/sec^2 at V_s. The number was arrived at using published flight test stall recovery data for the S-3A, L-1011, and C-5A airplanes(reference 4). Figure 6 summarizes the results in terms of the maximum nose-down pitch acceleration used during stall recovery. The curve represents the 90% distribution of the data; that is, in 90% of the recoveries for a given airplane, less pitch angular acceleration was used than the value shown on the curve. Based on the fact that the stall recoveries where deemed to be satisfactory, the data were used as the basis for the recommended requirements. For example, for combat aircraft with typical I_y values of about 10^5 slug-ft^2, the curve shows a pitch angular acceleration requirement of -0.28 rad/sec^2.

In 1985, a cooperative McDonnell Aircraft/NASA Langley program was conducted to study high angle of attack flight dynamics and control law design issues on a generic supersonic cruise fighter airplane concept. The manned simulation study was conducted on the Langley Differential Maneuvering Simulator (DMS) facility (reference 5). A brief part of the investigation focused on the high-α nose-down control capability issue. Pilot assessment of high-α recoveries during both open-loop flying as well as simulated air combat were used to define minimum levels of nose-down pitch acceleration capability. The results are summarized in figure 7 which shows pitch acceleration per load factor versus angle of attack for three configurations tested. The baseline configuration had very limited nose-down capability, which was judged to be unsatisfactory by the pilots. Control effectiveness was increased by 50% for the second configuration, which was found to still be deficient at low speeds. Only by doubling the control power was the high-α nose-down pitch response rated minimally satisfactory by the evaluation pilots. Selecting the minimum value on this curve gives a value of .13 rad/sec^2/g. For 1g stall, this results in a requirement of .13 rad/sec^2 at V_s.

Figure 8 presents a summary of the four guidelines discussed above. In comparing the guidelines, it is clear that large discrepancies exist between them, with the range of required nose-down control capability ranging from .087 rad/sec^2 to over three times that number. In view of the very limited technical basis on which these guidelines were developed, it is not surprising that such discrepancies should exist. Clearly, further efforts involving systematic approaches to develop definitive guidelines are needed. The efforts will require extensive ground-based analysis and piloted simulations leading to full-scale flight testing and validation.

ANALYSIS OF EXISTING RSS AIRCRAFT

As a preliminary step in developing a systematic and comprehensive set of guidelines, an analysis was made of the high-α nose-down control capability of existing high performance RSS aircraft. As stated earlier, a substantial data base has been developed over the last 10 to 15 years for aircraft such as F-16A, F-16XL, and F-18. It was felt that the knowledge and experience gained on the high-α flight dynamics of these airplanes could be used to develop a preliminary indication of nose-down control requirements for future RSS aircraft. The basic analysis methodology is illustrated in figure 9 and is based on the relationship:

$$C_m^* = \frac{I_y \dot{q}}{\bar{q} S \bar{c}} = \left(\frac{\dot{q}}{\bar{q}}\right) \cdot \left(\frac{I_y}{S\bar{c}}\right) \tag{4}$$

The first term in equation (4), $\frac{\dot{q}}{\bar{q}}$, can be thought of as a response capability expressed as pitch acceleration at a given dynamic pressure, similar to some of the guidelines discussed in the previous section. The second term, $(I_y/S\bar{c})$, is dependent only on the mass and geometry characteristics of a specific airplane. Thus, according to equation (4) plotting $C_m{}^*$ versus $(I_y/S\bar{c})$ will produce a linear variation with a slope equal to $(\dot{q}/\bar{q})$ as illustrated in figure 9. All airplanes with values that fall on the same line will have equal minimum nose-down pitch control capability, whereas configurations that have values above the line will have less capability, and those with values below the line will have greater capability. A key approach, therefore, is to identify the appropriate slope of the $C_m{}^*$ versus $(I_y/S\bar{c})$ line that defines "satisfactory" high-α nose-down control capability or margin. The procedure used to achieve this consisted of 3 steps: (1) plotting data points for the F-16XL, F-16A, and F-18 on a $C_m{}^*$ versus ($I_y/S\bar{c}$) chart; (2) using piloted simulation and flight results to determine points that correspond to "satisfactory" capability; (3) fairing a line through the "satisfactory" points whose slope would therefore define the "satisfactory" level of high-α nose-down control capability. The results obtained using this procedure are summarized in figure 10.

The data point for the F-16XL is for a nominal combat c. g. of .46$\bar{c}$ and was obtained from reference 6. The F-16XL is an F-16 modified to incorporate a cranked arrow wing designed for high-speed efficiency (figure 11). The airplane is balanced for approximately neutral low-α longitudinal stability at low speeds. The high-angle-of-attack flight dynamics of this configuration were extensively studied using piloted simulation on the Langley Differential Maneuvering Simulator (DMS) facility. The results showed the airplane to have good high-α pitch behavior. In particular, there was no tendency for deep stall trim, and recoveries from post-stall conditions were satisfactory with no "hang-up" or hesitation tendency. These results were subsequently verified during full-scale high-α testing at the Air Force Flight Test Center.

The F-16A (figure 12) is balanced to be slightly unstable (static margin of approximately -.04$\bar{c}$) at the nominal combat c.g. (.35$\bar{c}$). Extensive DMS simulation and full-scale high-α testing were conducted on the airplane (references 7 and 8). Two data points taken from reference 7 are shown on figure 10. At the .35$\bar{c}$ c.g. location, both the simulation and flight results showed that the airplane has unsatisfactory nose-down pitch control capability at high angles of attack. As indicated by the positive value of $C_m{}^*$, this configuration exhibits deep stall trim from which recovery can be difficult; furthermore, at the more moderate angles of attack roll rate limiting is required because there is insufficient nose-down control to counter the associated inertia coupling moments. During the simulation investigation, a brief study was conducted to determine how far forward the c. g. would have to be moved to eliminate these high-α pitch deficiencies. It was found that for a c. g. of $.29\bar{c}$, the airplane had good high-α nose-down pitch control capability and that deep stall trim and inertia coupling were no longer problems.

A three view drawing of the F-18 configuration is shown in figure 13. The airplane is balanced to be slightly stable at low angles of attack, but exhibits a mild pitch-up at higher angles of attack due to vortex lift from the wing-body strake. At aft c.g. locations ($.25\bar{c}$ and aft), both simulation and flight data show unsatisfactorily slow recoveries from post-stall conditions, particularly if there are significant roll/yaw motions to cause nose-up inertia coupling moments. At a mid-c.g. of $.224\bar{c}$, the results show good high-α nose-down control capability such that post-stall recoveries are satisfactory with no hesitation or "hang-up" tendencies.

In summary, figure 10 shows three data points (represented by open symbols) for configurations that have been shown to exhibit good high-α nose-down pitch control capability and two data points (represented by filled symbols) for configurations with unsatisfactory characteristics. Following the rationale discussed earlier, fitting a line through the three open symbols then defines a "satisfactory" level of high-α nose-down control capability at the most critical condition. Stated another way, the line represents a "satisfactory" control margin at the point where the nose-down capability is the lowest. Thus, based on this result, a possible guideline would be a plot of $C_m{}^*$ versus $Iy/S\bar{c}$ in which all points falling below the line $C_m{}^* = -.006\ (Iy/S\bar{c})$ would be considered "satisfactory" and all points above this line would be "unsatisfactory", as previously illustrated in Figure 9. Using this guideline, a new configuration with a value of $Iy/S\bar{c}$ of 20 slug/ft., for example, would be required to have a minimum nose-down pitching moment coefficient, $C_m{}^*$, of -.12.

In order to compare this guideline with those discussed earlier, it is necessary to express it as a pitch angular acceleration requirement at Vs. As shown earlier, the slope of the $C_m{}^*$ versus $(Iy/S\bar{c})$ is simply equal to $\dot{q}/\bar{q}$, thus:

$$\left.\frac{\dot{q}}{\bar{q}}\right)_{required} = -.006$$

$$\dot{q}_{required} = -.006\bar{q}$$

Using a value $\bar{q}_s$ of 40 lb/ft^2 which is typical of current fighter aircraft:

$$\dot{q}_{required} = (-.006)(40) = -.24 \text{ rad/sec}^2$$

Thus, the required nose-down angular acceleration capability at stall speed would be:

$$\left|\dot{q}\right| \geq .24 \text{ rad/sec}^2 \text{ at } V_s$$

As discussed earlier and summarized in figure 8, the four existing guidelines ranged from .087 rad/sec^2 to .28 rad/sec^2. The current analysis indicates that the required nose-down control capability should be closer to the upper end of the range of values proposed by the existing guidelines.

It should be noted that the foregoing results were obtained from a limited analysis of existing RSS aircraft. As pointed out in the "Background" section, a number of factors influence the required level of high-α nose-down pitch control capability. These factors are only indirectly reflected in the above analysis. As a result, they should only be used as rough preliminary guidelines for determining high-α nose-down pitch control requirements.

CONCLUDING REMARKS

High-angle of attack nose-down pitch control capability is a key design parameter for advanced fighter aircraft incorporating relaxed longitudinal static stability. Unfortunately, no definitive design guidelines are currently available for determining the proper level of nose-down pitch control capability for a given configuration. This paper has briefly discussed the key factors that must be addressed in developing such criteria. In addition, some existing guidelines were reviewed and results of an analysis of current RSS aircraft were presented. It is hoped that these preliminary results will provide a starting point for developing definitive design guides based on systematic ground-based experiments and analysis followed by full-scale flight test and validation.

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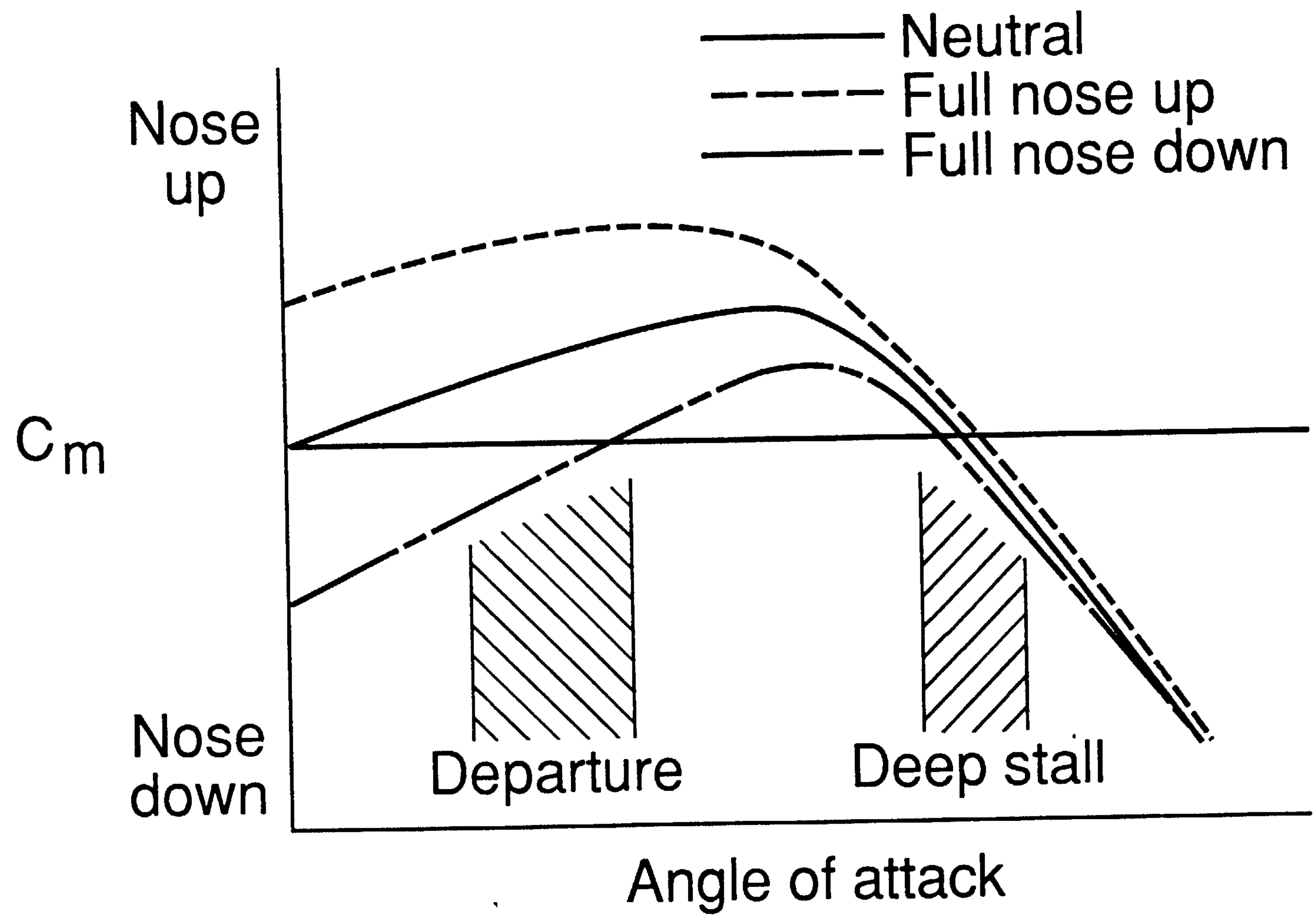

Figure 1 - Generic pitching moment variation with α for RSS configurations.

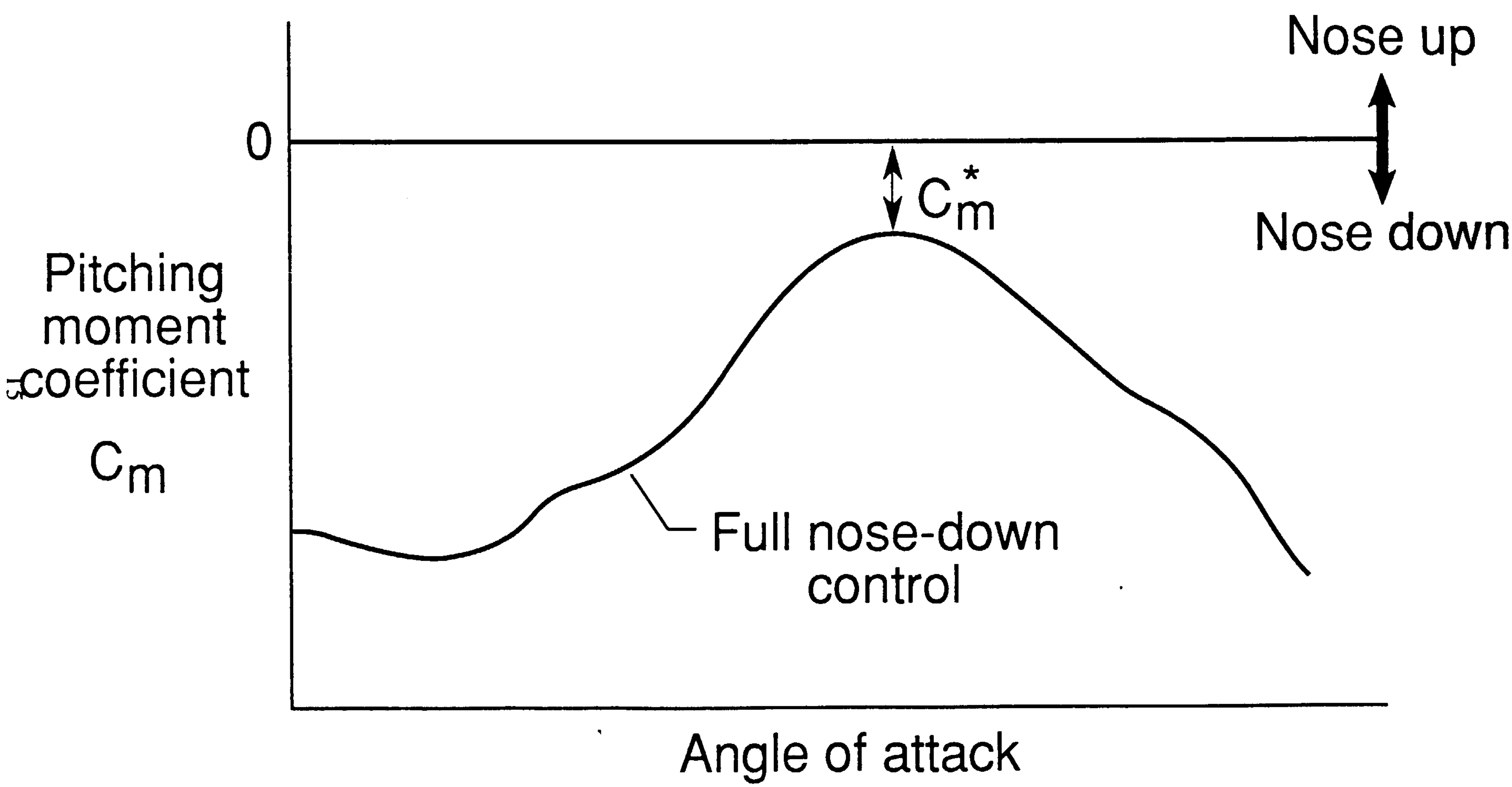

Figure 2 - Definition of $C_m{}^*$

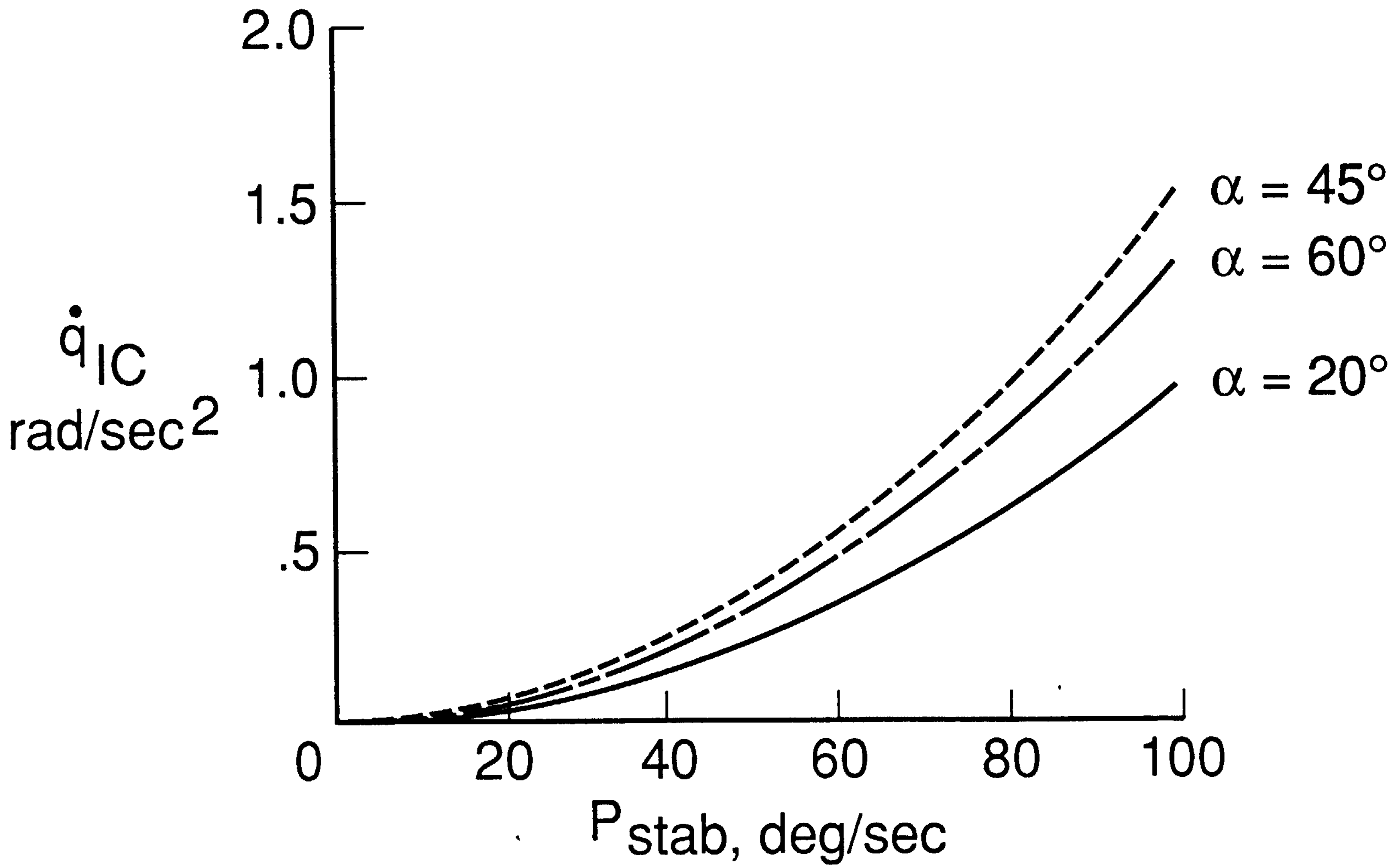

Figure 3 - Typical inertia coupling pitch angular acceleration due to stability-axis roll.

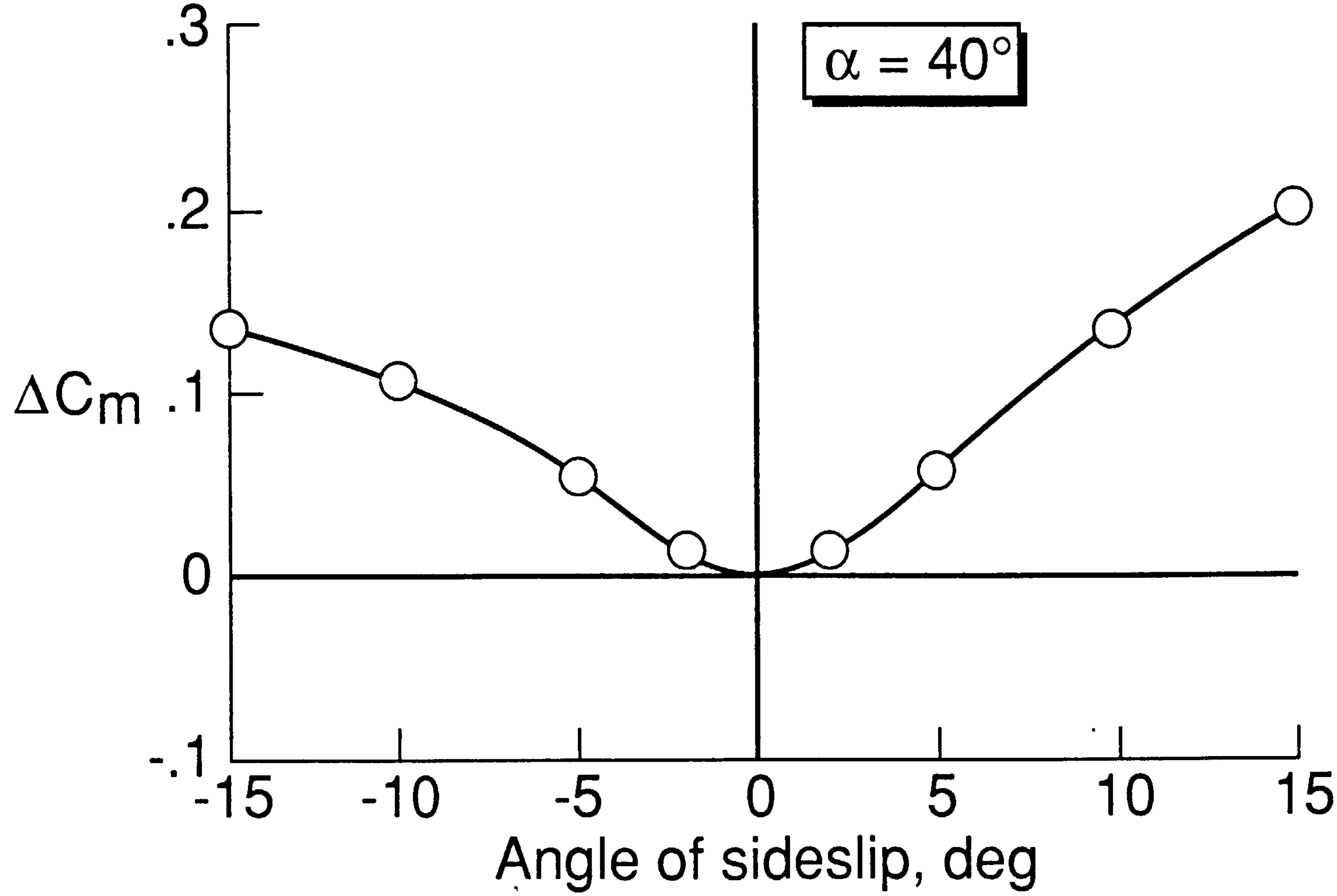

Figure 4 - Example of incremental pitching moment coefficient due to nonzero sideslip.

3.2.8.6.4 **Stall and high angle of attack.** In any Airplane Normal State or Failure State of 1.6.1 or 1.6.2 within the Permissable Flight Envelope, for all angles of attack from zero lift to 90° or the structural limits, with full nose-down control the airplane shall exhibit a net nose-down pitch moment of sufficient magnitude to generate ______________ rad/sec^2 nose-down angular acceleration.

CLASS	$\dot{q}$, rad/sec^2 at V_S
I	-0.28
II	-0.20
III	-0.08
IV	-0.28

Figure 5 - Proposed high-α nose-down pitch control requirement from reference 3.

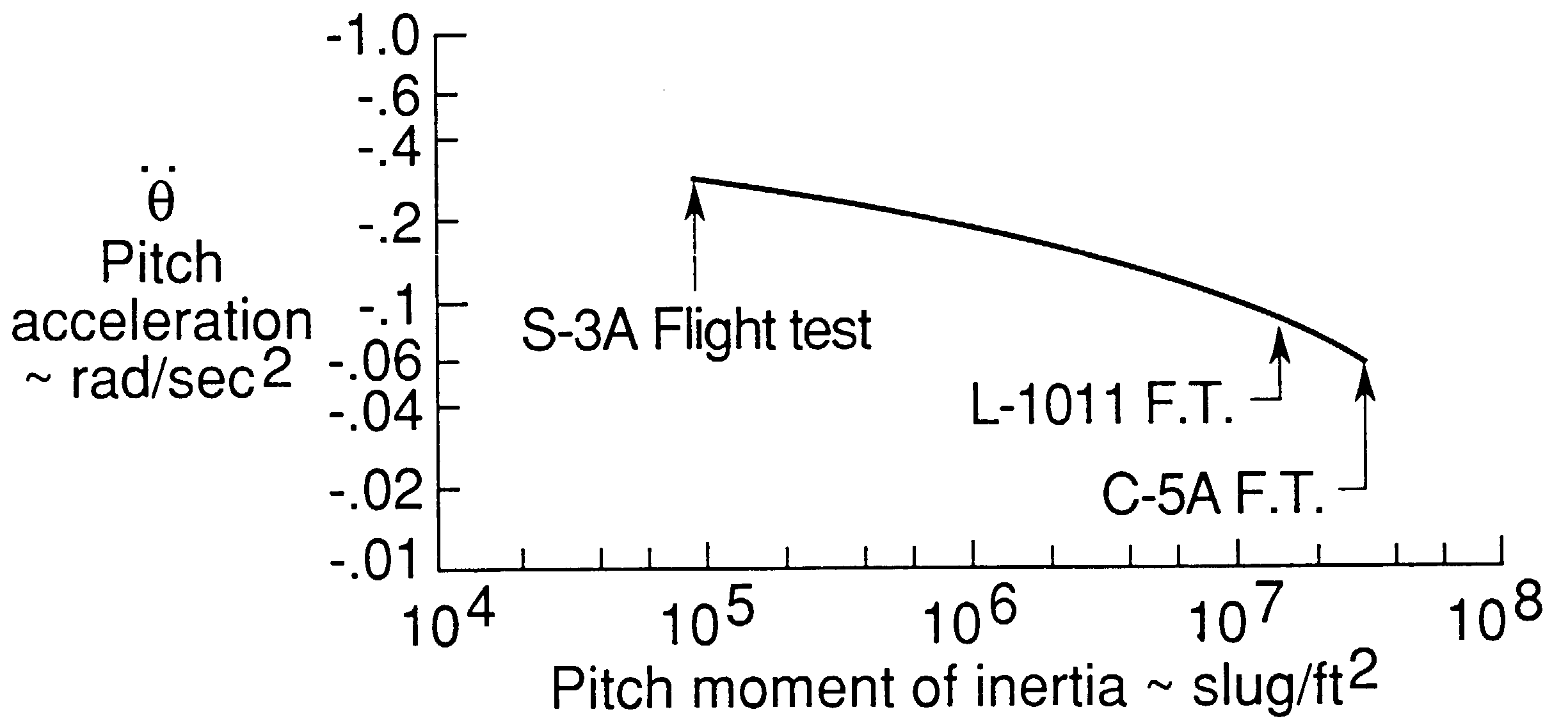

Figure 6 - Nose-down angular acceleration used for stall recoveries (Reference 4).

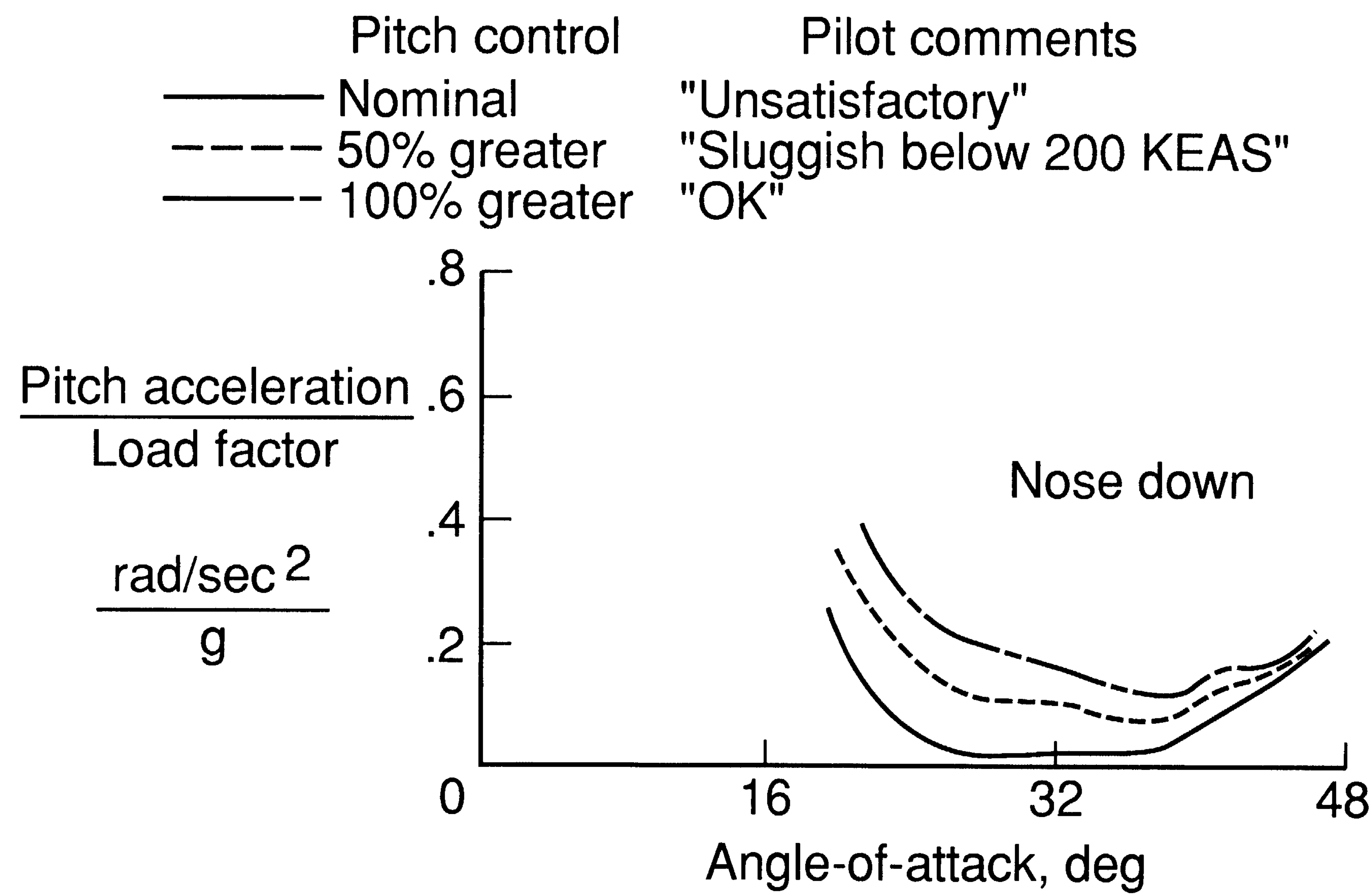

Figure 7 - High-α nose-down control results of DMS simulation study.

- Boeing (Kehrer, 1979): $|\dot{q}| \geqslant 5$ deg/sec^2 (.087 rad/sec^2)
- MCAIR (Mello, 1979): $|q| \geqslant 5$ deg/sec in 1 sec. at V_S ($\approx |\dot{q}| \geqslant 5$ deg/sec^2)
- MIL-F-8785 C: (Proposed revisions, 1982) $|\dot{q}| \geqslant 0.28$ rad/sec^2 at V_S
- MCAIR/NASA DMS study: (1985) $|\dot{q}| \geqslant 0.13$ rad/sec^2 at V_S

Figure 8 - Summary of four existing guidelines.

$$\dot{q} = \frac{\bar{q} S \bar{c} C_m}{I_y}$$

$$C_m = \frac{I_y \dot{q}}{\bar{q} S \bar{c}} = \underbrace{\left(\frac{\dot{q}}{\bar{q}}\right)}_{\text{response capability}} \cdot \underbrace{\left(\frac{I_y}{S \bar{c}}\right)}_{\text{airplane specific}}$$

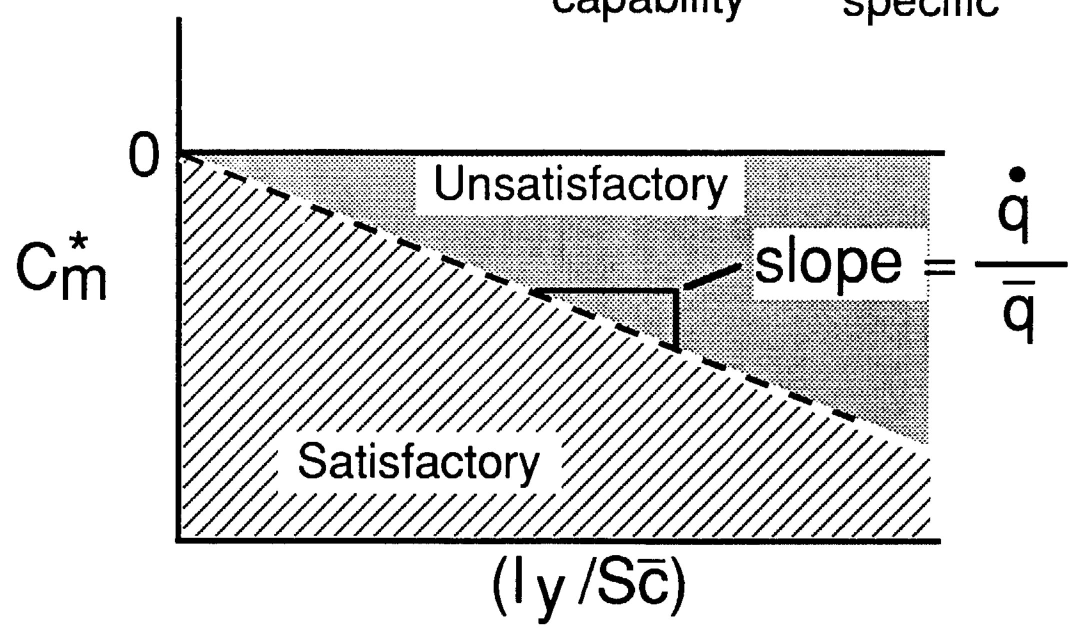

Figure 9 - High-α nose-down pitch control analysis methodology.

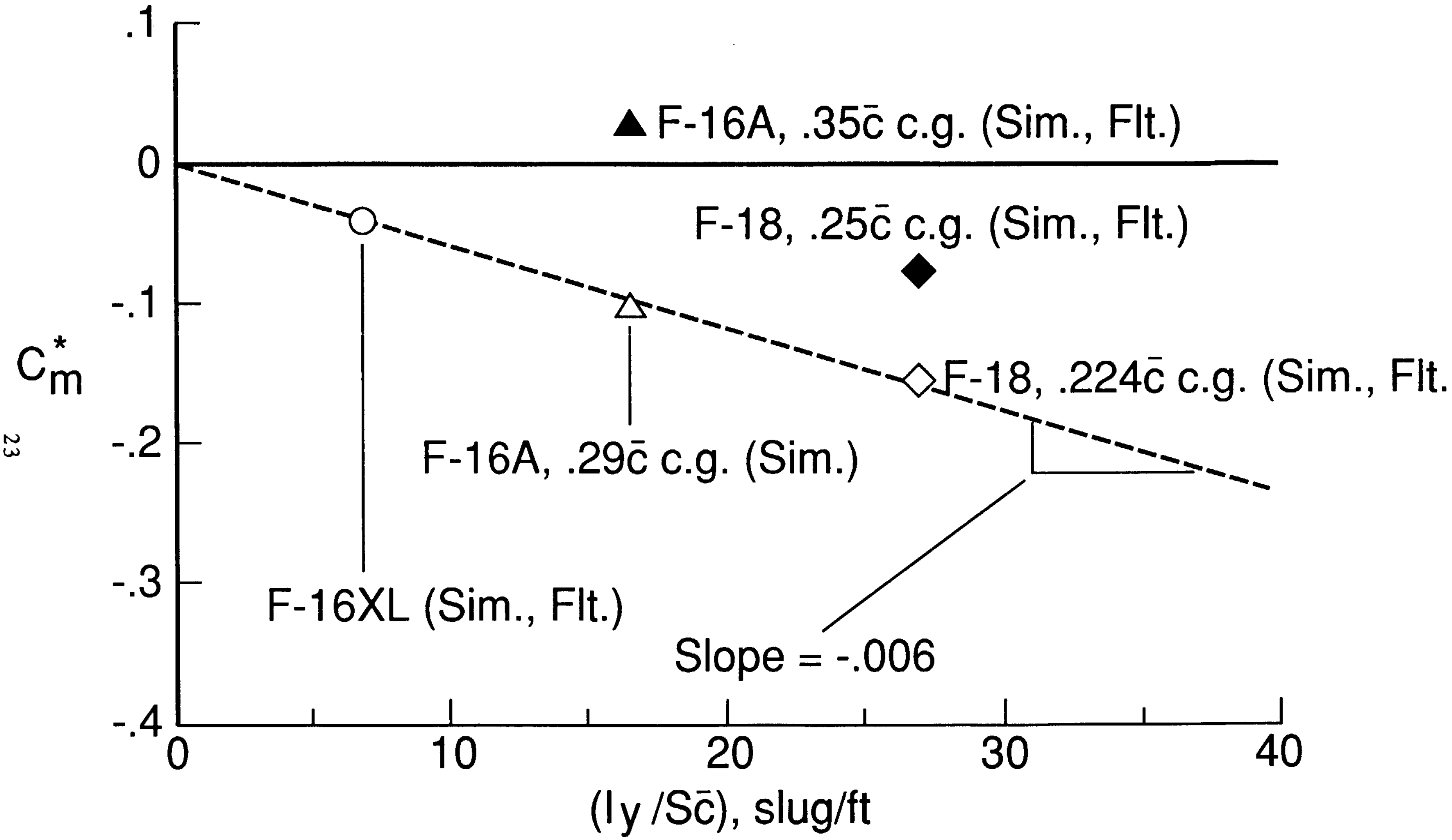

Figure 10 - Summary of data points from existing RSS aircraft.

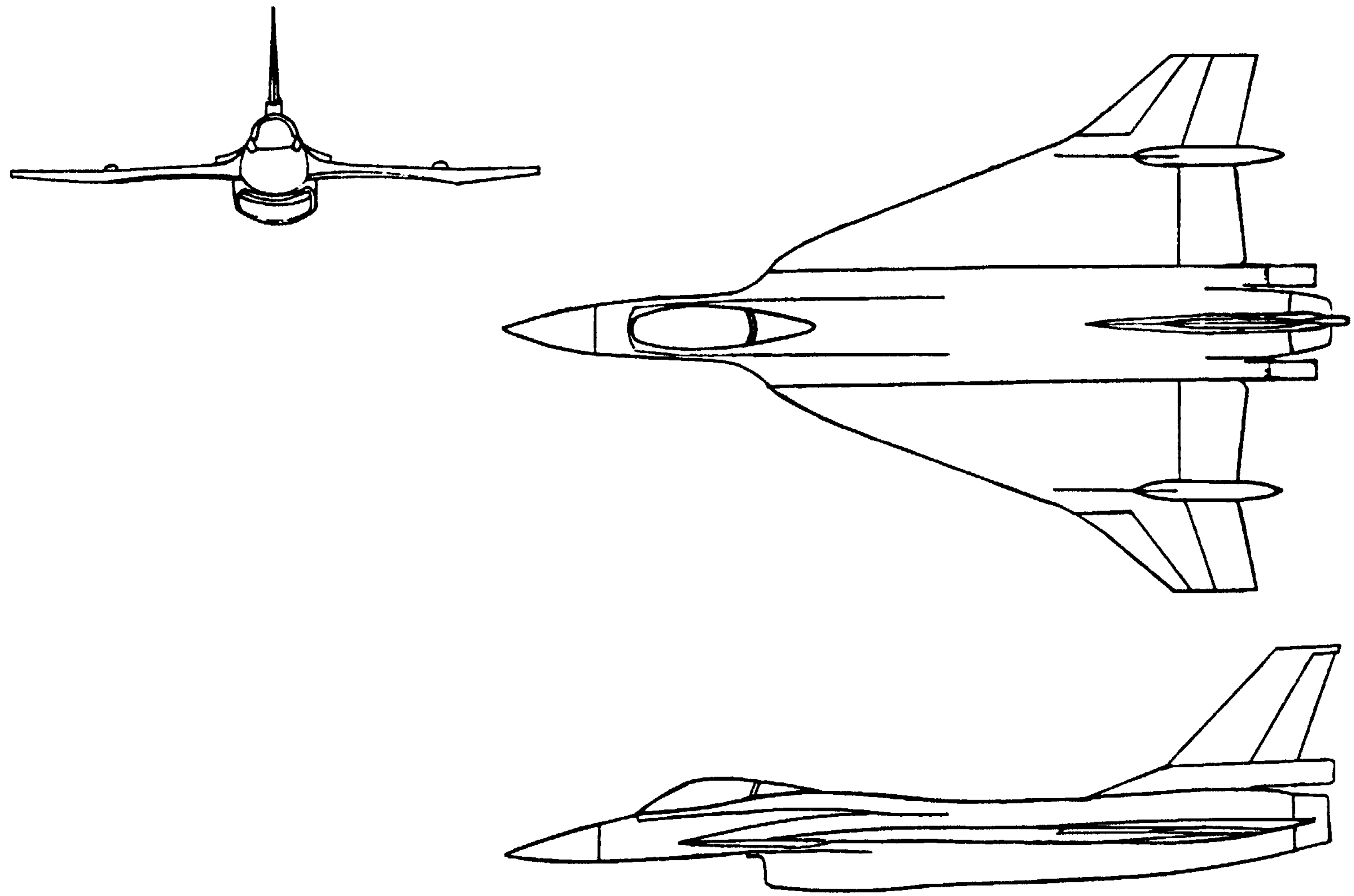

Figure 11 - Three-view sketch of F-16XL configuration.

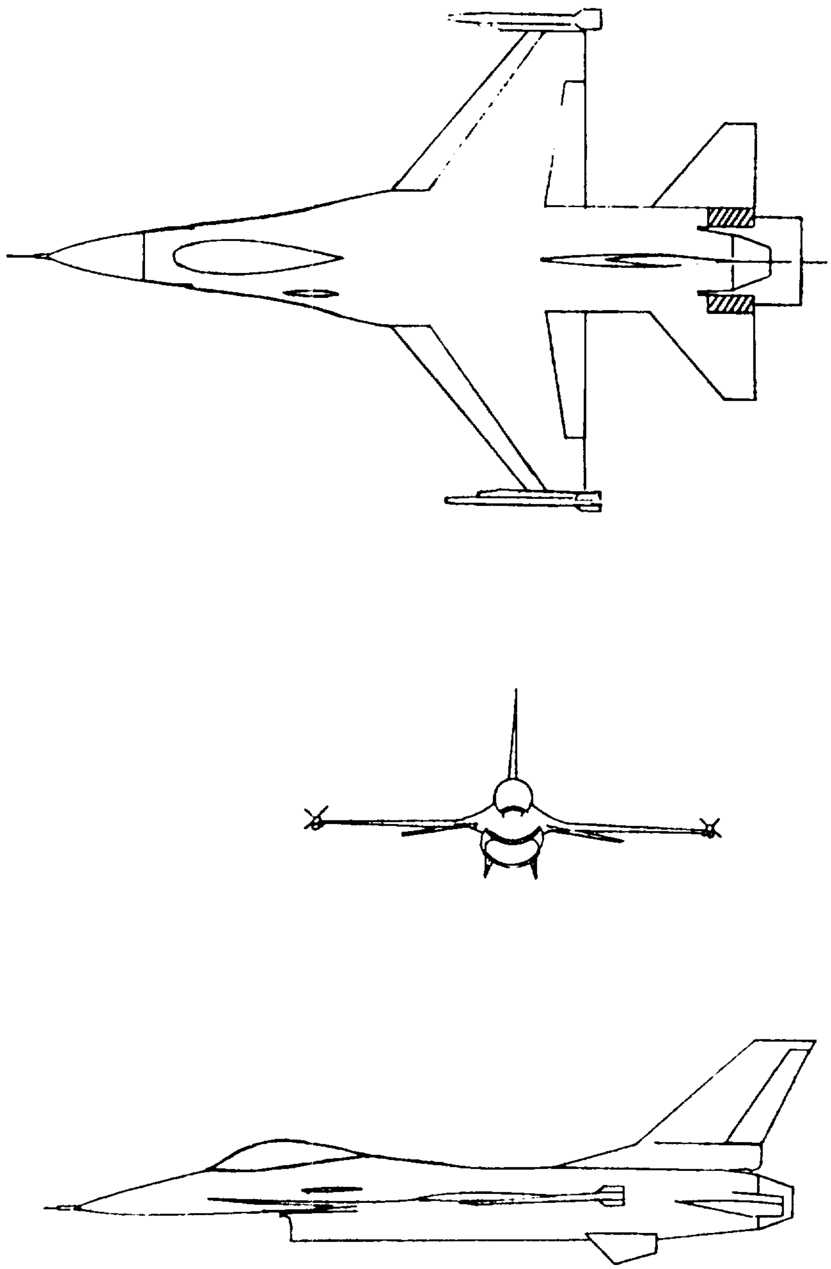

Figure 12 - Three-view sketch of F-16A configuration.

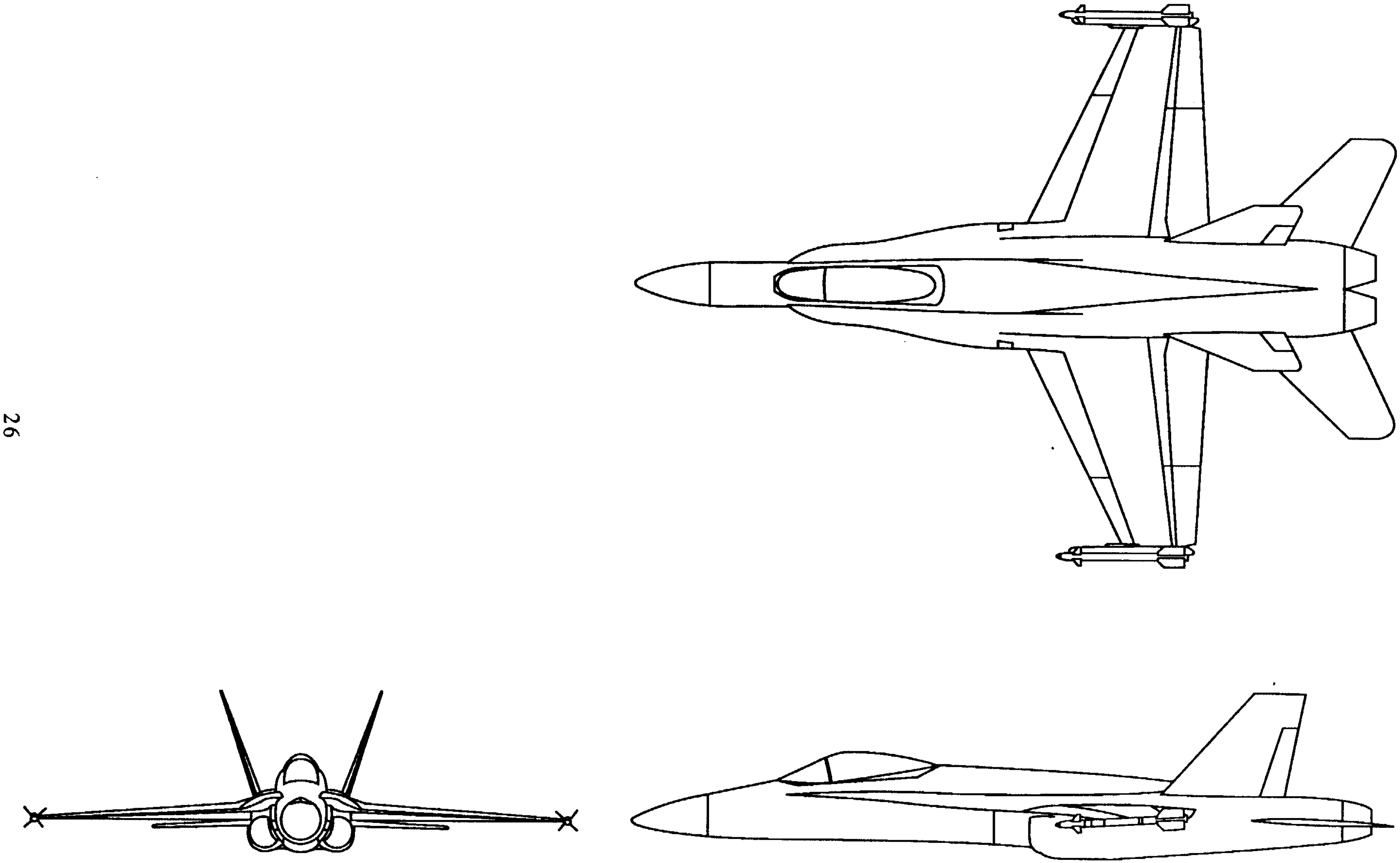

Figure 13 - Three-view sketch of F-18A configuration.

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16. Abstract

This paper discusses the requirements for high-angle-of-attack nose-down pitch control for advanced high-performance aircraft. Background information on fundamental factors that influence and, to a large extent, determine the high-angle-of-attack nose-down control requirement is briefly reviewed. Guidelines currently proposed by other sources which attempt to define these requirements are discussed. A requirement based on NASA analysis of the characteristics of existing relaxed static stability (RSS) aircraft is presented herein. This analysis could provide the basis for a preliminary design guide.

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