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# PRELIMINARY STUDY OF RELATIONSHIPS BETWEEN STABILITY AND CONTROL CHARACTERISTICS AND AFFORDABILITY FOR HIGH-PERFORMANCE AIRCRAFT

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## Abstract

This paper describes a study that is being done as part of the Methods for Affordable Design (MAD) program within the National Aeronautics and Space Administration (NASA), for which the goal is to develop design methods and information that contribute to reductions in the aircraft development cycle time while increasing design confidence throughout the design cycle. The product of the study will be a database of information that relates key stability and control parameters to affordability considerations such as air combat exchange ratio, safety of flight, and probability of loss of the aircraft or pilot. The overall background and methodology are described, and preliminary results are shown for the first phase of the study to evaluate characteristics in the longitudinal axis. For these preliminary results a simplified analytical model of the aircraft response to uncommanded nose-up pitching moments was developed and used to characterize the requirements for recoveries to controlled flight conditions and to evaluate some parameters that affect the survivability of the aircraft and the pilot.

## Introduction

High-performance aircraft traditionally have been developed for maximum performance, with secondary consideration being given to the cost of the aircraft. In the post-Cold War era, however, the emphasis has shifted dramatically to a more balanced design approach, for which cost is a primary influence on aircraft development efforts. NASA's recognition of this shift in aircraft design approach has led to the establishment of an enabling technology goal to cut the development cycle time for aircraft in half. Within the NASA MAD program, selected design method technologies are being developed to contribute to substantial reductions in the development cycle time, and therefore development cost, for high-performance aircraft.

The high-performance class of aircraft is unique in several aspects that significantly affect the overall aircraft design process, including: (1) the use of unconventional configurations that are greatly influenced by new technologies and demanding mission requirements, and (2) the requirement for air combat maneuvering, which can be dominated by flight in the nonlinear high angle-of-attack regime and involve dynamic phenomena which can be difficult to predict, even with the best computational and ground-based experimental tools. Both of these characteristics of this aircraft class can mean that there is a limited level of design knowledge in the early design stages. Limited knowledge of the aerodynamics and flight dynamics of these unconventional high-performance aircraft concepts reduces the quality of configuration trade studies to define the optimum configuration, and increases the likelihood of unexpected technical issues late in the design cycle, when the cost of configuration modifications is substantial.

The objective of the MAD Program is illustrated graphically in Figure 1. The conceptual, preliminary, and detailed design phases are shown on a time line, which indicates that increasing

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periods of time are devoted to each successive phase. As the design cycle progresses in time, the level of knowledge of a particular aircraft configuration increases, but the degree of design freedom decreases due to rising (re-)design costs and schedule requirements. A large payoff in reduced design time can be obtained, however, if the same level of design knowledge can be applied earlier in the design cycle, when design freedom is greater and costs of changes are lower. The strategy for achieving this payoff is to substantially increase the level of knowledge about a particular high-performance aircraft configuration early in the design cycle. This objective will be accomplished by providing more accurate, yet efficient, design tools for reliable use earlier in the design process, especially in the conceptual and preliminary design phases. An additional benefit of this strategy is decreased risk of an unsuccessful aircraft development program. Therefore, the research efforts within MAD are focused on methods to more accurately and rapidly predict the aerodynamics and flight dynamics of high-performance aircraft.

The two types of products that are being developed within this program as design tools for predicting these aircraft characteristics and thus enabling reduced design costs are:
(1) computational fluid dynamics methods that are sufficiently fast, robust and resource-efficient to be used routinely in the early design phase and
(2) flight dynamics design tools. Validated flight dynamics tools that can be confidently applied in the early design phase will allow key design issues to be addressed with minimal cost and schedule delay. The development of flight dynamics design tools focuses on phenomena that threaten flight safety and survivability, especially during air combat maneuvering, and on defining the relative benefits of various levels of tactical agility. Existing methods and data bases are the primary sources of information, augmented by computer simulation studies and additional experimentation, as required.

This paper describes a database that is being developed as a design tool that defines the relationship between aerodynamic stability and control characteristics and affordability considerations. Some of the primary database products and associated preliminary assumptions are illustrated in figure 2. For example, agility for effective air combat maneuvering is one of the most important characteristics for high-performance aircraft. However, the relative benefits (e.g., variations in air combat exchange ratio) derived from varying levels of aircraft agility (provided by stable, commanded control moments) require better definition in order to determine the optimum level of agility as a function of the cost (in terms of both money and the effect on other design characteristics) of providing the agility (see figure 2(a)). Preliminary assumptions are being made that: (1) there is minimal air combat maneuvering capability provided by the controls if the available control moment is only enough to ensure flight safety (i.e., a small margin of controlled positive response to the pilot's command) and (2) the air combat exchange ratio improves with increasing moment capability but levels off if the available moment becomes excessive. On the other hand, providing degraded or unstable control characteristics may save on some types of costs and/or enable the improvement of some other design characteristics, but cause more aircraft and/or pilots to be lost (i.e., decrease survivability). Figure 2(b) illustrates a second database for which the assumption is being made that the probability of losing the aircraft as a consequence of having relaxed stability or unstable characteristics increases with decreasing stability but is negligible if there is at least enough control moment capability for flight safety. Figure 2(c) illustrates a third database for which the assumption is made that the probability of losing the pilot (and therefore the aircraft) increases with decreasing stability but is negligible if the unstable control moment is not so great as to cause the pilot ejection limits to be exceeded or otherwise prevent the pilot from ejecting. Another concern for pilot survivability that can be related to the stability of the aircraft is the acceleration at the pilot's station that can be generated by uncommanded moments.

Information on the likelihood of and/or design requirements that should help prevent these losses (as defined in terms of specific survivability parameters) as a function of the stability and control characteristics should aid in the determination of the costs (e.g. acquisition and other costs due to these losses) of providing other gains that may be associated with less stable designs. This database should also be useful for assessing the effects of the failure of propulsive or other non-aerodynamic controls, which can cause unexpected decreases in stability and control capability and therefore affect survivability. The objective of this research activity is therefore to define the relationships between key stability and control characteristics and relevant affordability considerations such as those shown in figure 2 so that the design of these characteristics can be optimized with respect to the associated costs and benefits. This objective will be accomplished by determining the stability and control characteristics that affect the life-cycle cost for unstable aircraft and then developing a database to aid in making the associated design tradeoffs.

## Nomenclature

| | |
|---|---|
| $a_n$, $a_x$ | normal and axial accelerations, g units |
| $C_m$ | static pitching moment coefficient |
| q | pitch rate, deg/sec |
| $\dot{q}$ | pitch acceleration, rad/sec$^2$ |
| $qdd_1$, $qdd_2$ | rates of change of pitch acceleration with time (defined as negative), rad/sec$^3$ (see fig. 7) |
| t | time, sec |
| x | ratio of rates of change of pitch acceleration, $qdd_2/qdd_1$ |
| $\bar{x}$ | distance along longitudinal body axis from center of aircraft rotation, ft |
| y | ratio of pitch acceleration to maximum nose-up value, $\dot{q}/\dot{q}_{max}$ |
| $\alpha$ | angle of attack, deg |
| $\Delta\alpha$ | range of angle of attack in which uncommanded nose-up moments occur, deg |
| $\Delta\alpha_r$ | decrease in angle of attack required for recovery, deg |

Subscripts:

| | |
|---|---|
| max | maximum value |
| min | minimum value |
| o | initial value |
| p | value at pilot's station |
| r | value for recovery |

## Study Approach and Methodology

The subject study is composed of two major phases. An evaluation of the relationship between longitudinal stability and control parameters and affordability considerations is being conducted as the first phase of the study, and is illustrated in figure 3, which shows representative pitching moment curves for full-nose-down aerodynamic controls. Studies that were conducted jointly by NASA and the U.S. Navy to define required minimum values of nose-down aerodynamic pitching moment coefficient ($C_m$) for relaxed static stability aircraft, for safe recoveries from high angles of attack and for tactical utility, have been performed.[1-9] (See curves labeled "1" in the figure.) A "safe" recovery was defined as one which, when commanded with full forward stick deflection at trimmed, stabilized, wings-level unaccelerated flight conditions, would occur with pitch acceleration values of less than or equal to zero in such a way that the pilot did not doubt that the recovery would be completed.

However, the design guidelines derived from these studies have been considered to be too restrictive and costly for some future high-performance aircraft configurations. For these aircraft the design trend has been towards less aerodynamic pitch stability and more reliance on propulsive controls, in order to gain other design advantages such as fewer control surfaces and/or low radar cross-sections. Therefore, to provide enough information for a more complete optimization of the minimum nose-down aerodynamic control power, these earlier studies have been expanded to include evaluations of the levels of pitch instability at which the survivability of the aircraft and pilot are adversely affected if a propulsive control failure or other situation results in an uncommanded nose-up pitching moment. (See curves labeled "2" and "3" in figure 3.) A similar study of the lateral-directional characteristics will follow.

An experimental approach for the study has been defined and is shown in figure 4. Stability and control characteristics are being evaluated, using analysis involving the aircraft equations of motion and computer simulation, as required. Parametric variations of these characteristics and the resulting aircraft response to pitch commands are being modeled and computed. These computed motions are then being evaluated with respect to life-cycle cost considerations such as flight safety, the survival of the aircraft and the pilot, and tactical utility. The results will then be used to determine design tradeoffs between stability and control characteristics and life-cycle cost considerations for high-performance aircraft.

<u>Analysis of Recoveries Evaluated in Earlier Studies</u>

Previous studies have been used to develop guidelines for aircraft with nose-down aerodynamic control power available throughout the angle-of-attack envelope. Guidelines were developed, based on the results of piloted simulation studies and flight tests, for recoveries from high-angle-of-attack flight for two levels of response: (1) the minimum for safety, based primarily on whether or not the pilot had doubt that the recovery would occur, and (2) response that was considered to be useful for air combat maneuvering. (See pitching moment curves labeled "1" in figure 3.) The response model that describes the motion during these recoveries is illustrated in figure 5. This model assumes the following: (1) the flight path (i.e. direction of the velocity vector) is constant so that the pitch rate is the same as the time rate of change of angle of attack, (2) the airspeed and dynamic pressure are constant, and (3) the command to recover the aircraft is initiated at stabilized, trimmed, unaccelerated, wings-level flight conditions, such that there are no net forces or moments acting on the aircraft.

The pilots who participated in the studies considered the short-term response following the initiation of the forward stick command to be the most important figure of merit in their assessment of the overall response. The guidelines for minimum nose-down control moment versus angle of attack were therefore based on a response model with a constant pitch acceleration for most of the first two seconds. (About one-half second was allowed for control surface actuator response time.) After two seconds and until the recovery is completed no further increase in nose-down pitch rate is required and no positive pitch acceleration is allowed.

As was mentioned previously, the recommended aerodynamic nose-down pitching moment requirement for safety of flight has been considered to be excessive for some applications because of the high cost associated with it. A more complete and therefore effective design tradeoff can be made between this and competing requirements if the effect of variations in this requirement on the recovery characteristics can be made. One way to assess the effect of this variation is to compare the aircraft responses using relevant figures of merit. An example of this assessment is shown in figure 6, for which the time to pitch the aircraft through a variety of angle of attack changes, $\Delta\alpha_r$, was computed for a range of nose-down pitch acceleration values, according to the response model of figure 5. It is apparent that for very small levels of nose-down pitch control the time to pitch through even relatively modest changes in angle of attack can be greater than 10 seconds, whereas for nose-down pitch accelerations of about .1 rad/sec$^2$ or more, recoveries of as much as 80 degrees of angle of attack can be completed in less than 10 seconds. However, for more tactically useful levels of nose-down control power, and in particular for levels greater than about .2 rad/sec$^2$, the recoveries, even those of up to 80 degrees of angle of attack, all take only about two to five seconds to accomplish. Therefore, within this upper range of response there is not much additional time savings for making large angular changes in tactical situations as the control power is increased. The information in this figure is part of the information that will be used for the development of the proposed database product illustrated in figure 2(a).

<u>Analysis of Recoveries from Uncommanded Nose-up Moments</u>

As aircraft static pitch stability decreases, there is more likely to be a range of angle of attack in which there is no available aerodynamic nose-down control moment, as shown in the curves labeled "2" and "3" in figure 3. If there is a stable break in the moment characteristics at the higher angles of attack in this range and the $C_m$ values cross from positive to negative, then there is a deep stall trim angle of attack (not shown in the figure) at which nose-up but not nose-down moments can be generated and above which nose-down moment can be generated. Pitch-up departures and hung stalls can therefore occur at these conditions, from which recoveries to low angles of attack may or may not be possible, depending on a number of factors, including the flight motions present when this angle of attack range is entered or exceeded. A goal of the subject study is to develop aerodynamic pitch control guidelines for aircraft with these characteristics which can be used to define the conditions under which an uncommanded nose-up moment will result in the loss of the aircraft because it will not recover to low angles of attack. The survivability of the pilot is in question if the pilot wants to but cannot eject, whether or not the aircraft recovers. The guidelines that this part of the longitudinal study addresses are therefore based more heavily on the flight dynamics that the aircraft and pilot experience rather than pilot opinion of the response, which was the basis for the guidelines developed in the earlier studies.

Preliminary Model

In order to begin to develop nose-down pitch control design guidelines for aircraft that are susceptible to pitch-up departures it is first necessary to understand the flight motions that occur during the departure and the requirements for recovery. The general character of the motions during a pitch-up departure and recovery is an uncommanded nose-up motion followed by commanded nose-down motion. Pitch acceleration ( $\dot{q}$ ) can be related directly to the static aerodynamic moment ($C_m$), if the contribution of pitch damping to $\dot{q}$ is not included. Consider the shape of the pitching moment curve versus angle of attack for full-nose-down controls, as shown in figure 3, the curve labeled "2". Assuming that at the higher angles of attack for the uncommanded nose-up moment there is a stable break in the curve such that there is a deep stall trim angle of attack, above which there is an increasing amount of available nose-down control moment, a pitch-up departure and recovery can occur under certain conditions. Using aerodynamic pitching moment capability only, for aircraft with these nose-down control characteristics one of three outcomes will occur as a consequence of encountering this uncommanded nose-up moment:

(1) If there is already sufficient nose-down pitch rate present, there will be no pitch-up departure and the negative pitch rate will become less negative in the angle-of-attack range of the uncommanded moment but not become positive as the angle of attack decreases, so the aircraft will recover.
(2) If sufficient nose-up pitch rate is present or can be generated, the aircraft will pitch up to a high enough angle of attack so that sufficient negative pitch acceleration can be generated for a recovery to occur.
(3) If there is insufficient positive or negative pitch rate for a recovery to occur, the aircraft angle of attack will converge to the deep stall trim point, from which a recovery may not be possible.

One simple method of modeling the pitch-up departure and recovery motions for the pitching moment characteristics just described is illustrated in figure 7, and served as the basis for the preliminary analysis for this study. Desirable characteristics for any such model are that it be the following: (1) generic, yet representative of unstable aircraft, (2) relatively straightforward for calculating or simulating the aircraft response, and (3) useful for developing design guidelines and tradeoffs. The most representative and useful model is one that models the static and dynamic pitching moment characteristics as functions of angle of attack, for which a computer simulation must be created in order to calculate the response time histories. A simplified model which uses information on the total pitch acceleration characteristics versus time so that the response time histories can be calculated easily, using simple equations, was developed and used as a first step prior to the development of the simulation, in order to perform a preliminary evaluation of the aircraft responses and candidate survivability parameters, including trends in the results.

As was the case for the earlier studies for recoveries without uncommanded nose-up moments, this model assumes that the magnitude and direction of the velocity vector are constant and that there are no net forces acting on the aircraft, so that pitch rate is the same as the rate of change of angle of attack. Unlike the earlier model, however, changes occur in pitch acceleration throughout each time segment of the motion which are linear with time, and the motion is initiated with an uncommanded nose-up pitch acceleration. It is also assumed that the response is completely symmetric with angle of attack such that that there are no hysteresis or unsteady aerodynamic effects as the aircraft pitches up and down through large changes in angle of attack. The complete time history as shown in figure 7 represents the motions generated during the second of the three outcomes of an uncommanded nose-up moment, as described earlier in this section, for the case in which there is just enough positive pitch rate during the initial pitch-up departure for a recovery to occur. The static pitching moment characteristics that could generate such a time history are therefore similar to those shown in curve "2" of figure 3. The negative acceleration that occurs on the stable part of the curve at the higher angles of attack continues until the nose-up pitch rate is completely arrested and the maximum angle of attack is reached. As the angle of attack then decreases, the character of the pitch acceleration reverses so that it becomes less negative and then positive as the angle of attack returns to the region of the uncommanded nose-up moment. The aircraft will recover to an angle of attack below this region if the nose-down moment generated at the maximum angle of attack is high enough that a negative pitch rate is maintained as the angle of attack decreases.

The pitch motions during each segment of continuously changing pitch acceleration during the pitch-up and recovery, using this model, are described by simple one-degree-of-freedom equations, assuming that there is a constant rate of change of pitch acceleration with time (qdd = constant) and that the velocity vector does not change direction such that the pitch rate equals rate of change of angle of attack:

$$\dot{q} = (qdd)\,t + \dot{q}_o$$

$$q = \frac{(qdd)\,t^2}{2} + \dot{q}_o\,t + q_o$$

$$\alpha = \frac{(qdd)\,t^3}{6} + \dot{q}_o\,\frac{t^2}{2} + q_o\,t + \alpha_o$$

The character and time histories of the motions are then completely determined by specifying the values of $\alpha_o$, $q_o$, $\dot{q}_o$, and qdd, which is determined by the values of $\dot{q}_{max}$, $qdd_1$, and $qdd_2$, as shown in figure 7. The first and third dashed lines on the figure indicate that when $\dot{q} = 0$, the magnitude of the pitch rate is at a maximum and the rate of change of angle of attack is maximized. The middle dashed line indicates that $\dot{q}_{min}$, q = 0, and the maximum angle of attack occur simultaneously. Using these simplifying equations, a preliminary assessment was made of the pitch-up response and recovery requirements and some associated parameters that affect the survivability of the aircraft and pilot. The preliminary analysis that has been done is described in the following sections.

## Recovery Requirements and Characteristics

Pitch rate. - Examination of the pitch recovery model just described reveals that the aircraft will not recover from an uncommanded pitch-up moment to a recovery angle of attack of $\alpha_r$ or less unless the magnitude of the pitch rate during the pitch-up moment is greater than a value that is determined by the values of $\dot{q}$, $\dot{q}_{max}$, $qdd_1$, and $qdd_2$. (Recall that earlier studies defined nose-down guidelines for an initial pitch rate of zero.) When the uncommanded moment is encountered at angles of attack above that for $\dot{q}_{max}$, this value of pitch rate required for recovery is computed as follows:

$$|q| > \dot{q}_{max}^{2}\,\frac{(x + 1 - y^2)}{-2\,(qdd_2)},$$

where $x = qdd_2/qdd_1$ and $y = \dot{q}/\dot{q}_{max}$. When the uncommanded moment occurs at an angle of attack at or below that for $\dot{q}_{max}$, this value is computed as:

$$|q| > \dot{q}^{2}/(-2\,qdd_1).$$

The absolute value of the pitch rate required for recovery at any point in time is equivalent to the area under the $\dot{q}$ versus time curve between t = 0 (where $\dot{q}$ = q = 0) and that time, as depicted in figure 7. Therefore, for a given set of values for $\dot{q}_{max}$, $qdd_1$, and $qdd_2$, the highest absolute value of pitch rate is required for recovery if the uncommanded moment occurs at an angle of attack near the deep stall trim point ($\alpha > \alpha$ for $\dot{q}_{max}$, $\dot{q}$ = y = 0), and is indicated in the time history of figure 7 by $q_{max}$ and - $q_{max}$. In contrast, nearly zero pitch rate is required for recovery if the uncommanded pitch-up moment occurs near the lowest angle of attack of the pitch-up region ($\alpha < \alpha$ for $\dot{q}_{max}$, $\dot{q} = 0$, which is also the recovery angle of attack, $\alpha_r$). Therefore, $|q_{max}|$ for recovery is computed as:

$$|q_{max}| = \dot{q}_{max}^{2} \frac{(x+1)}{-2\,(qdd_2)}.$$

One way to help ensure a recovery, then, according to this response model, would be for the aircraft to have or be able to generate a pitch rate such that $|q| > |q_{max}|$ during the time that the angle of attack is within the range of the uncommanded nose-up moment. Recoveries from deep stall trim conditions may also be possible if there is enough nose-up control power available to generate the pitch rate required for the angle of attack to reach that for $\dot{q}_{min}$. Values for $|q| = |q_{max}|$ are plotted in figure 8 versus rate of change of pitch acceleration, for the case that $qdd_2 = qdd_1$, for several values of $\dot{q}_{max}$. As the maximum pitch-up moment $\dot{q}_{max}$ increases and/or the rate of change of pitch acceleration decreases, the absolute value of the pitch rate required for a recovery to occur increases. This result suggests that a design tradeoff could be made between the aerodynamic pitching moment characteristics and the pitch rate required for a successful recovery.

The effect of a difference between $qdd_1$ and $qdd_2$ on the pitch rate required for recovery is illustrated in figure 9, for two values of $\dot{q}_{max}$ and three values of the ratio (x) of $qdd_2$ to $qdd_1$. The figure shows that as $\dot{q}_{max}$ increases, significant differences can occur in $|q_{max}|$ as the value of x is varied between .5 and 2 for a given value of $qdd_2$. The difference in the pitch rate required due to variations in this ratio is also higher for the lower absolute values of $qdd_2$.

<u>Time to recover</u>. - Given that the pitch rate requirements are satisfied so that a recovery occurs, another potential survivability parameter would be the time that it takes for the aircraft to recover from the initial angle of attack that the uncommanded pitch-up moment occurs to the angle of attack below the region of this uncommanded moment. One concern would be that if the recovery takes too long to occur, the aircraft may lose so much altitude that it crashes or the pilot must eject before the recovery is completed. Using the recovery model described previously, the time to recover the aircraft is maximized for the case in which the uncommanded pitch-up moment takes place in the presence of a small positive pitch rate at $\alpha = \alpha_r$, when $\dot{q} = 0$ (i.e., at the beginning of the time history of figure 7), and no additional nose-up motion is commanded. The entire time history must then take place before the recovery is completed, and the time to recover (i.e., the time that it takes for the angle of attack to return to $\alpha_r$) is computed as follows:

$$t_r = \dot{q}_{max} \frac{-2\,(x+1+(1+x)^{.5})}{qdd_2}.$$

Figure 10 shows the results for the time to recover versus $qdd_1 = qdd_2$ (i.e., x = 1), for a range of values of $\dot{q}_{max}$ of .05 to .3 rad/sec$^2$. The results show that the time to recover increases significantly as the slopes $qdd_1$ and $qdd_2$ become more shallow (less negative) and as the maximum uncommanded pitch-up moment increases. The time to recover to $\alpha = \alpha_r$ approaches or exceeds one minute in some cases, so for aircraft designs with these characteristics there could be concerns about the potential loss of the aircraft and/or the need for the pilot to eject.

The effect of differences between values of $qdd_1$ and $qdd_2$ on the time to recover is illustrated in figure 11 for two values of $\dot{q}_{max}$ and three values of x. The results show that as $\dot{q}_{max}$ increases, significant differences can occur in the time to recover for a given value of $qdd_2$ as the ratio of the slopes is varied between .5 and 2. The difference in $t_r$ due to variations in this ratio is also higher for the more shallow values of $qdd_2$.

<u>Angle-of-attack range of uncommanded nose-up moment</u>. - Another characteristic of the pitch response that is of interest and can be related directly to any design requirements for aerodynamic pitching moment versus angle of attack is the range of angle of attack within which there is no aerodynamic nose-down moment available. This range is shown as $\Delta\alpha$ in the pitch response model of figure 7 and can be calculated from specified values of $\dot{q}_{max}$, $qdd_1$, and $qdd_2$ as follows:

$$\Delta\alpha = (\dot{q}_{max}^{3}) \frac{(x^2+3x+2)}{-6\,(qdd_2^{2})}.$$

Figure 12 shows how $\Delta\alpha$ varies with $\dot{q}_{max}$ and $qdd_2 = qdd_1$ (i.e., x = 1). As would be expected, as the rate of change of pitch acceleration becomes less negative and/or the maximum pitch-up moment $\dot{q}_{max}$ increases, the value of $\Delta\alpha$ increases and could become quite large for some unstable aircraft configurations. This characteristic is related to the uncommanded pitch-up and recovery characteristics and could be included as part of the analysis for design tradeoffs if, for example, it is so large that the aircraft is susceptible to uncommanded nose-up moments in an unacceptably significant portion of its flight envelope.

The effect of differences between values of $qdd_1$ and $qdd_2$ on $\Delta\alpha$ is illustrated in figure 13 for two values of $\dot{q}_{max}$ and three values of x. As was seen for the pitch rate required for recovery (figure 9) and the time to recover (figure 11), as $\dot{q}_{max}$ increases, significant differences can occur in $\Delta\alpha$ for a given value of $qdd_2$, as the ratio of the slopes is varied between .5 and 2. The difference in $\Delta\alpha$ due to variations in this ratio is also higher for the lower absolute values of $qdd_2$.

## Analysis of Incremental Accelerations at the Pilot's Station

### Computation

One potential concern for the design of unstable aircraft that is related to the probability of loss of the aircraft because the pilot must eject and/or loss of the pilot because of inability to eject is the axial, normal, and lateral accelerations (g's) that the pilot can experience during rapid aircraft motions. If these accelerations and/or the rates of g onset are excessive, then the pilot may feel uncomfortable, want to eject, and/or be unable to eject. The survivability of the pilot from the standpoint of g tolerance could be an issue whether or not the aircraft experiences a departure from controlled flight and whether or not it recovers from the departure. The (incremental) acceleration that the pilot feels relative to the center of aircraft rotation is proportional to the distance between the center of rotation and the pilot's location. In particular, for pitch motions only, if it is assumed that the pilot location is forward from the center of rotation and the vertical and lateral offsets are small, then incremental axial and normal accelerations (due only to the rotation) will be experienced by the pilot according to the following equations:

$$\Delta a_{x,p} = -(q^2 \bar{x}_p) / g \text{ , where } q = \dot{q}t, \text{ for constant } \dot{q}$$

$$\Delta a_{n,p} = (\dot{q} \bar{x}_p) / g$$

Figures 14 through 16 show computed values of these incremental accelerations at the pilot's station versus pitch acceleration. A value of 20 feet is used for the distance of the pilot from the center of rotation to illustrate the phenomenon because this value is representative of current fighter aircraft.

### Axial Acceleration

Values of $\Delta a_{x,p}$ versus $|\dot{q}|$, time, and $|q|$ are shown in figure 14, assuming that pitch rate is generated by a constant value of $\dot{q}$ acting over time. Negative values of $a_{x,p}$ are commonly referred to as "eyeballs-out g", and several g units can be very uncomfortable for the pilot. The results show that for nominal values of $|\dot{q}|$ that act over a few seconds, the pitch rates generated are not so large as to create more than small values of $\Delta a_{x,p}$. However, there would be concern for the pilot's welfare if, for example, a pitch-up departure and recovery occurred during which excessive time was spent recovering the aircraft while it experiences large pitch rates. Unstable pitching moment characteristics that include large values of $\dot{q}_{max}$ and/or small rates of change of pitch acceleration with time ($|qdd_1|$ and $|qdd_2|$) not only result in high pitch rates that are required/generated for recovery from pitch-up departures (see figures 8 and 9) but also result in lengthy times to recover (see figures 10 and 11).

The average onset rate of the incremental axial acceleration can be determined by dividing the value of $\Delta a_{x,p}$ by the time to generate it. For example, the average incremental onset rate for $\dot{q}$ = .25 rad/sec$^2$ sustained for 15 seconds is about -.6 g/sec (see figure 14). The onset rate will be highest at the end of the motion, so for this example, at t = 14 sec (after the pitch rate has reached 200 deg/sec), $\Delta a_{x,p}$ = -7.6 g units, but during the next second more than 1.1 additional negative g units are generated, or almost twice the average onset rate.

### Normal Acceleration

Figures 15 and 16 show the incremental normal acceleration at the pilot's station versus nose-up (figure 15) and nose-down (figure 16) pitch acceleration. For the range of values of $\dot{q}$ previously evaluated (0 to .3 rad/sec$^2$), figure 15 shows that less than .2 g of incremental normal acceleration is produced. If, however, starting with

$\dot{q} = 0$, a constant rate of change of pitch acceleration (i.e., $|qdd_1|$ or $|qdd_2|$) of as much as .3 rad/sec$^3$ is sustained for as long as 30 seconds, then $\dot{q}$ values of as much as 9 rad/sec$^2$ (i.e., $\Delta a_{n,p}$ = 5.6 g units, with a constant g onset rate of slightly less than .2 g/sec) will be generated just from the pitching motion. This motion would be of concern with respect to the pilot's positive normal g tolerance, therefore, during those portions of pitch-up departures and recoveries with sustained positive rates of change of pitch acceleration that generate high values of $\dot{q}$.

The pitch-up departure and recovery model of figure 7 shows that the minimum (most negative) value of $\dot{q}$, $\dot{q}_{min}$, is encountered at the maximum angle of attack achieved during the recovery, and has a greater absolute magnitude than $\dot{q}_{max}$. The value of $\dot{q}_{min}$ is related to that of $\dot{q}_{max}$ as follows:

$$\dot{q}_{min} = -\dot{q}_{max} (x + 1)^{.5}.$$

Negative incremental normal acceleration values at the pilot's station are generated by negative values of $\dot{q}$, so at the time that $\dot{q}_{min}$ occurs the negative incremental acceleration is maximized. Figure 16 shows the relationship between $\Delta a_{n,p}$ (the most negative value encountered, for which $\dot{q} = \dot{q}_{min}$) and the specified pitch acceleration characteristics of $\dot{q}_{max}$ (based on its relationship to $\dot{q}_{min}$) and x (= $qdd_2/qdd_1$). Normal accelerations of zero and negative g can be uncomfortable to the pilot, so excessively negative values of $\dot{q}_{min}$ (because of high values of $\dot{q}_{max}$ and/or x), especially if they are sustained, would cause concern and therefore could be a consideration for design tradeoffs.

## Concluding Remarks

The overall methodology and experimental approach have been defined and a preliminary analysis has been performed to examine the effect of unstable static aerodynamic pitching moment characteristics on selected life-cycle cost considerations such as the survivability of the aircraft and/or pilot, for high-performance aircraft. This work is being done as part of NASA's MAD program. This study extends the results from earlier studies of more stable aircraft for which at least some nose-down aerodynamic control power was always available at high angles of attack such that levels which are suitable for the definition of the minimum for safe, controlled recoveries and tactical utility could be defined. A simple analytical model was developed and used to represent the general character of the pitch motions during uncommanded nose-up moments and recoveries that can occur for aircraft that are longitudinally unstable. This one-degree-of-freedom model assumes that these motions consist only of periods of nose-up and nose-down pitch acceleration with constant rates of change of pitch acceleration with time, pitch rate equal to the rate of change of angle of attack, and no hysteresis or unsteady aerodynamic effects. The parameters that are used to define the numerical response characteristics of the model are the maximum positive uncommanded pitch acceleration and the time rates of change of the pitch acceleration.

Using this preliminary model, the pitching moment characteristics were varied and several parameters were examined which are related to life-cycle cost considerations, such as the survivability of the aircraft and/or the pilot. As would be expected, as the maximum value and time of the uncommanded nose-up acceleration increased, the values of the survivability parameters worsened. A successful recovery from an uncommanded nose-up pitching moment (and therefore the survival of the aircraft) occurs only when there is a minimum pitch rate, the absolute value of which is determined by the specified pitch acceleration characteristics and the current pitch acceleration. One design tradeoff which could be defined would be between the longitudinal stability characteristics of the aircraft and the pitch rate generation capability. The time to recover the aircraft to angles of attack below the region for uncommanded nose-up pitching moments was also evaluated because excessive recovery times can mean that the aircraft may lose too much altitude before it recovers, so that it crashes or the pilot must eject. Another characteristic of interest is the range of angle of attack within which no nose-down aerodynamic pitching moment is available. If this range is excessively large or includes angles of attack at which a pitch-up departure would be especially troublesome then it may be included with other design tradeoffs. The survivability of the pilot was also addressed by examining the incremental axial and normal accelerations at the pilot's station generated by pitching motions. If the aircraft pitch characteristics are sufficiently unstable such that the pitch rates and/or accelerations generated during a pitch departure and/or recovery are high and/or sustained, then the pilot's g tolerance could form the basis for another necessary design tradeoff.

This study will continue in order to define databases of design information, including tradeoffs, for safety/survivability and tactical utility of high-performance aircraft. After phase one of the work is completed for the pitch axis, databases will be developed for the lateral-directional axes. To complete the longitudinal study, a more realistic and useful model of pitching moment characteristics versus angle of attack will be developed and used for computer simulations of pitch response to uncommanded nose-up moments. The definition of the key survivability parameters and the associated motion requirements in pitch will be completed and guidelines for the specific design of the pitching moment curve, based on these requirements, will be developed. Consideration will be given to the applicability of forces acting on the airplane, various types of coupling, and kinematic effects to the study. The parameters that affect ejection envelope limitations will be examined. The study will also be extended to include extremely unstable configurations that are susceptible to autorotation in pitch (i.e., tumbling). As the research progresses, consideration will be given to the inclusion of information in the database products that is more closely related to manufacturing costs.

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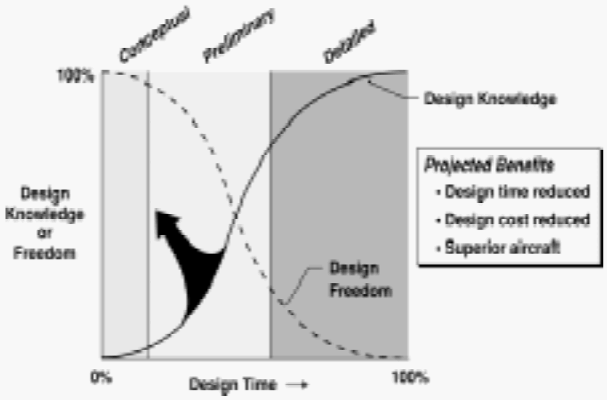



Figure 1. - Objective of MAD program

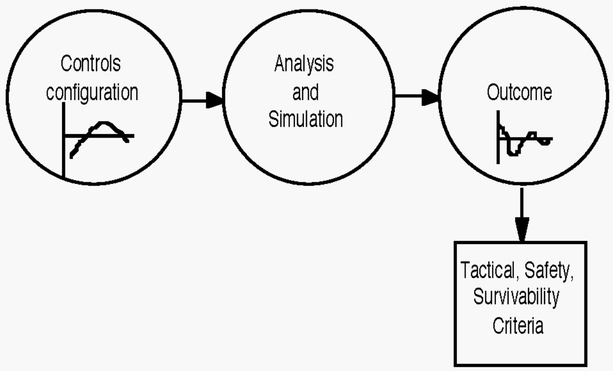
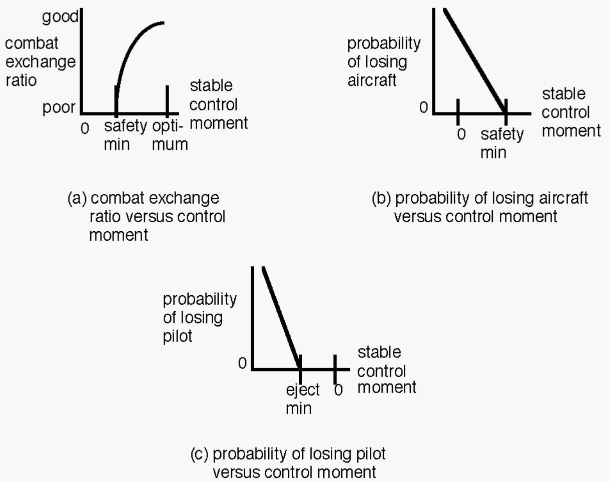



Figure 4. - Experimental approach




(a) combat exchange ratio versus control moment

(b) probability of losing aircraft versus control moment

(c) probability of losing pilot versus control moment

Figure 2. - Examples of database products

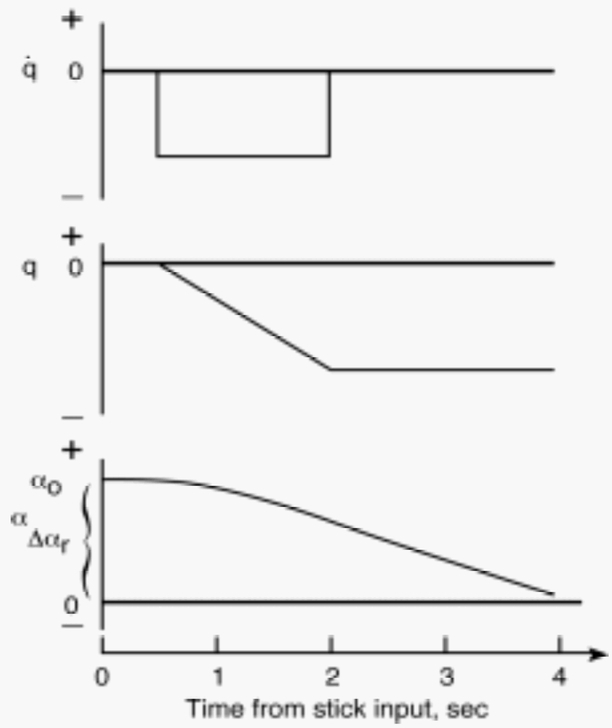



Figure 5. - Recovery model used for guidelines developed in earlier studies

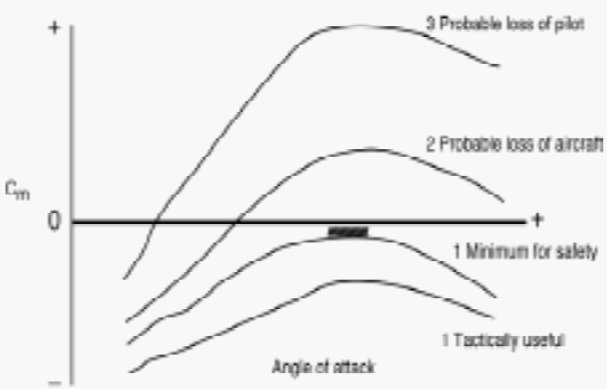



Figure 3. - Effect of full-nose-down aerodynamic pitching moment characteristics on survivability

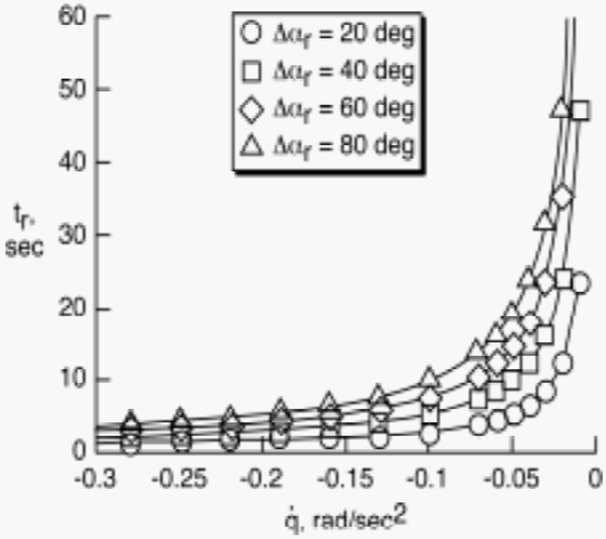



Figure 6. - Time to recover using recovery model developed in earlier studies

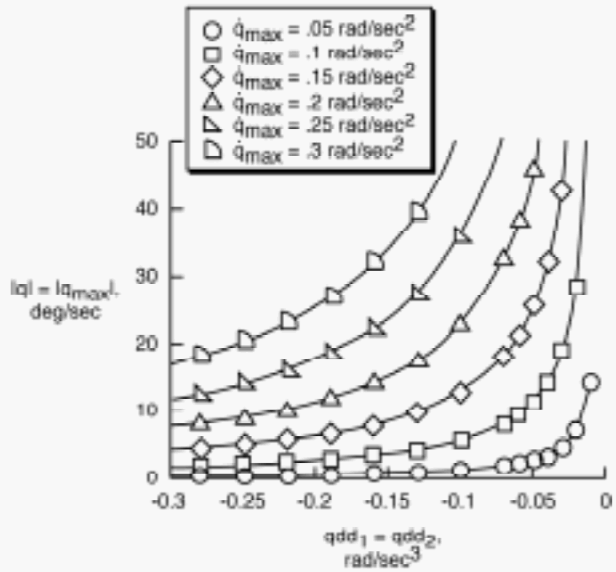



Figure 8. - Pitch rate required to assure recovery; $qdd_1 = qdd_2$

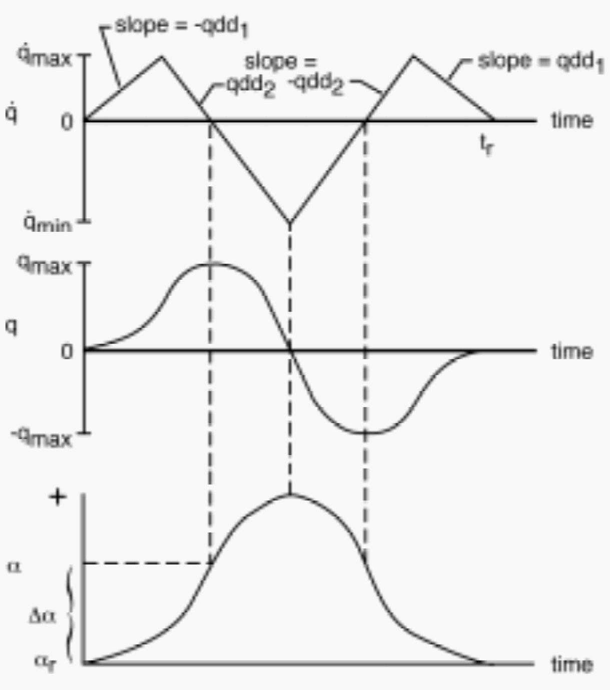



Figure 7. - Preliminary pitch-up departure and recovery model

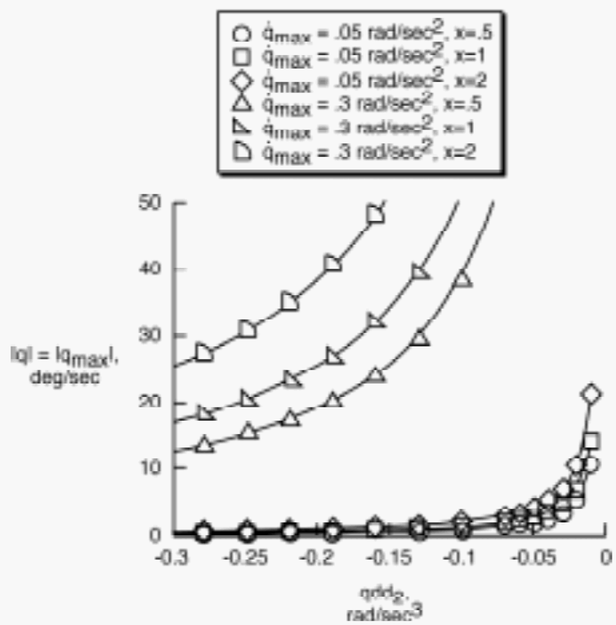



Figure 9. - Pitch rate required to assure recovery; $qdd_1$ π $qdd_2$

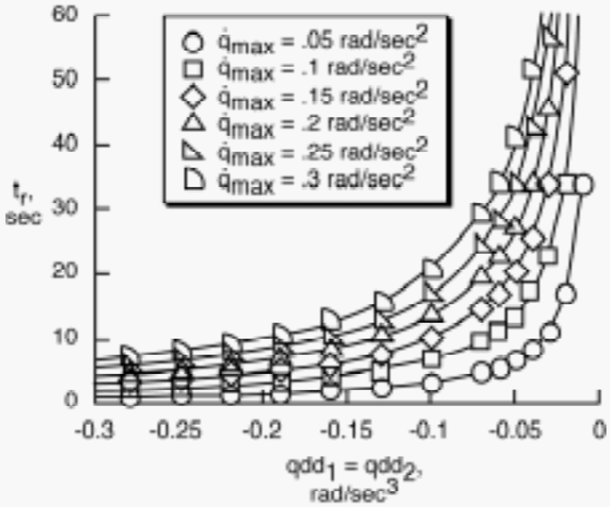



Figure 10. - Time to recover from pitch-up departure; $qdd_1 = qdd_2$

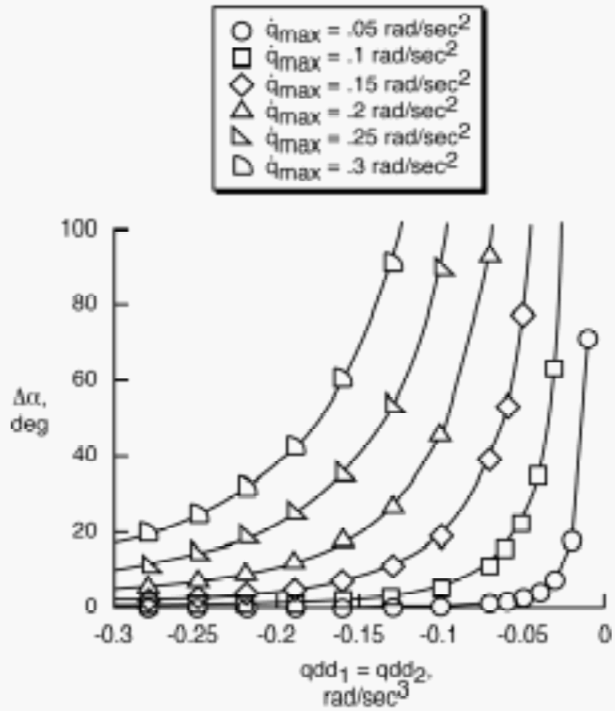



Figure 12. - Range of angle of attack for uncommanded nose-up moment; $qdd_1 = qdd_2$

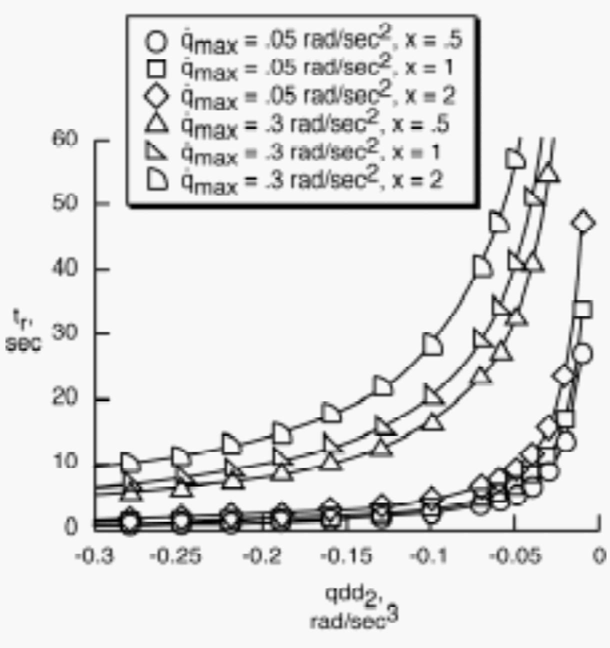



Figure 11. - Time to recover from pitch-up departure; $qdd_1$ π $qdd_2$

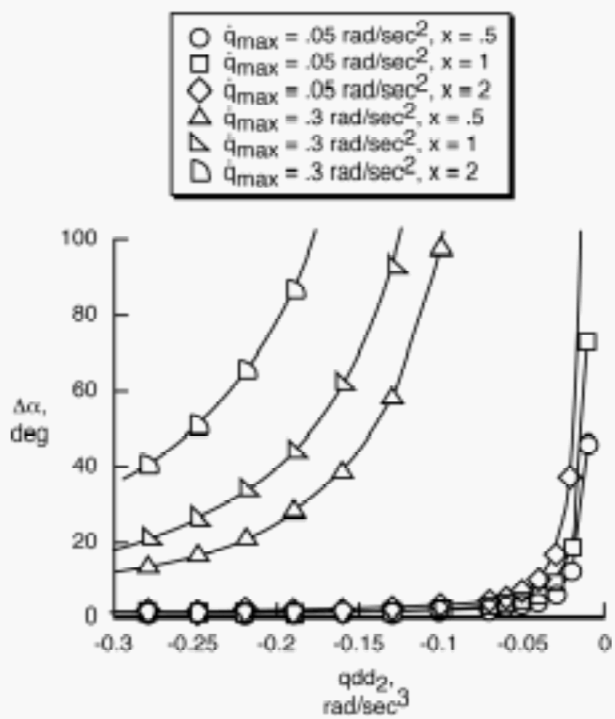



Figure 13. - Range of angle of attack for uncommanded nose-up moment; $qdd_1$ π $qdd_2$

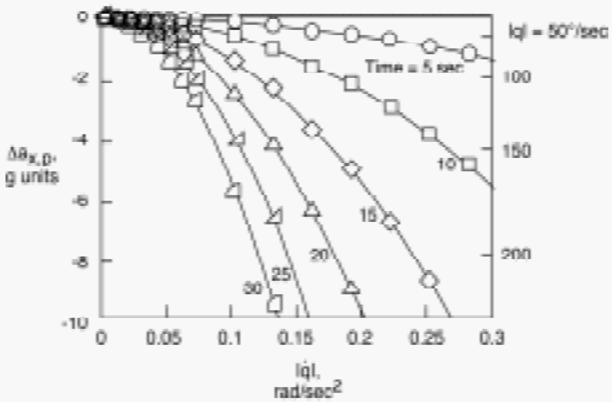



Figure 14. - Incremental axial acceleration at the pilot's station due to pitch motion;

$\bar{x}_p = 20$ ft

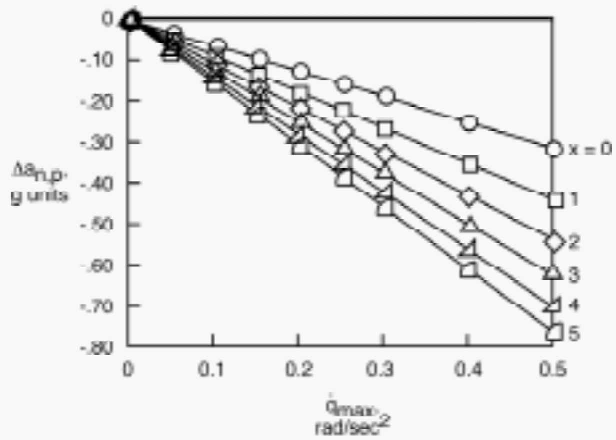



Figure 16. - Incremental normal acceleration at the pilot's station due to pitch motion;

$\bar{x}_p = 20$ ft

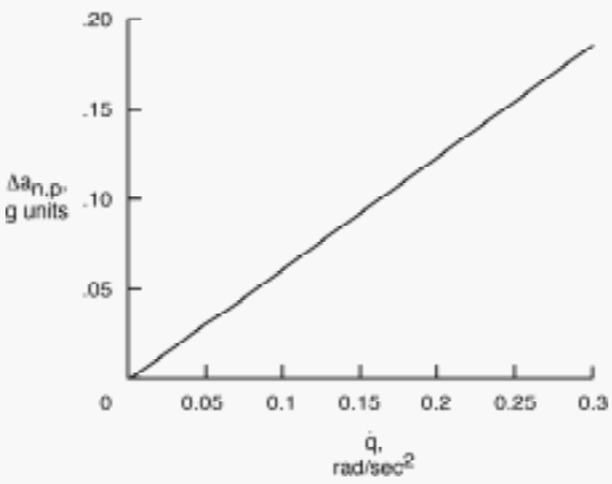



Figure 15. - Incremental normal acceleration at the pilot's station due to pitch motion;

$\bar{x}_p = 20$ ft