APPLICATION OF PILOTED SIMULATION TO HIGH-ANGLE-OF-ATTACK FLIGHT-DYNAMICS RESEARCH FOR FIGHTER AIRCRAFT

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SUMMARY

This paper reviews the use of piloted simulation at Langley Research Center as part of the NASA High-Angle-of-Attack Technology Program (HATP), which was created to provide concepts and methods for the design of advanced fighter aircraft. A major research activity within this program is the development of the design processes required to take advantage of the benefits of advanced control concepts for high-angle-of-attack agility. Fundamental methodologies associated with the effective use of piloted simulation for this research are described, particularly those relating to the test techniques, validation of the test results, and design guideline/criteria development.

NOMENCLATURE

b	wing span, ft
C_l	rolling moment coefficient
C_m	static pitching moment coefficient
C_{m_q}	pitch damping coefficient
C_m^*	minimum nose-down pitching moment coefficient at any α
C_n	yawing moment coefficient
h	altitude, ft
M	Mach number
p,q,r	body-axis roll, pitch, and yaw rates, deg/sec
$\hat{p},\hat{r}$	non-dimensional body-axis roll and yaw rates, $\frac{pb}{2V}$ or $\frac{rb}{2V}$
p_w	wind-axis roll rate, deg/sec
q	pitch acceleration, rad/sec^2
S1, S2	slope of C_m versus α curve for α below and above $\Delta\alpha^*$, respectively, per deg
t	time, sec
$t_{\|\Delta\phi\|}$	time to roll through a bank angle change, sec
T/W	thrust-to-weight ratio
V	free-stream velocity, ft/sec
X,Y	airplane body axes
α	angle of attack, deg
α^*	maximum α at which C_m^* occurs, deg
$\Delta\alpha^*$	range of angle of attack over which C_m^* occurs, deg
β	angle of sideslip, deg
γ	velocity vector pitch angle from horizontal, deg
δ_a	differential aileron deflection, positive for left roll, deg
δ_r	rudder deflection, positive for left yaw, deg
ε	tracking error, deg
θ,ϕ	pitch and roll angles, deg
$\Delta\phi_w$	change in wind-axis roll angle, deg
Ω	angular rotation rate, deg/sec

Subscripts:

max	maximum value
o	initial value
rec	value for recovery to low angles of attack

1 INTRODUCTION

Projected scenarios for future air combat indicate the need for highly agile fighter aircraft that can operate effectively over a substantially expanded maneuvering envelope beyond that of current fighters. It is expected that short-range air combat considerations will be dominated by the "all-aspect" capability of short-range missiles and guns. An essential requirement will therefore be to maneuver into a successful firing position as quickly as possible before the opponent can do the same. A number of piloted simulation and analytical studies (refs. 1-5) have shown that rapid, controlled maneuvering at high angles of attack is a key element for meeting this requirement. In response to this requirement, significant activities are currently underway to develop technologies that are needed to provide this enhanced capability. These technology areas include high-angle-of-attack aerodynamics, high-angle-of-attack controls, propulsion systems, pilot/vehicle interface, and weapons. The National Aeronautics and Space Administration (NASA) is actively engaged in these efforts, with a major goal of developing flight-dynamics technology to provide enhanced agility and handling qualities at high angles of attack that will enable aircraft to perform maneuvers that can be very advantageous in air combat.

Figure 1 shows two fundamental maneuvering advantages offered by this enhanced capability. The first involves rapid, large-amplitude rotation of the nose of the aircraft with relatively little change in the flight path. This type of motion can be produced by pure pitch or yaw maneuvers or by rolling about the velocity vector at high angles of attack.

This nose-pointing capability enhances target acquisition for weapons launch and quick recovery to conditions for engagement of another opponent, which is critical in a multi-aircraft combat situation. A second benefit of enhanced high-angle-of-attack maneuvering is the performance of rapid, small radius turns to gain a positional advantage. The use of post-stall angles of attack and very low airspeed conditions enables this repositioning capability. These capabilities can be achieved through the use of advanced control concepts such as vectoring of the engine thrust and unconventional aerodynamic devices that provide significant improvements in effectiveness, especially at high angles of attack.

A key NASA program which was conceived to address these advanced technology opportunities for high-performance aircraft is the High-Angle-of-Attack Technology Program (HATP). The HATP is a fighter technology development and validation program which is focusing on providing flight-validated methods and concepts essential for the design of fighters possessing unprecedented high-angle-of-attack maneuverability and controllability. The program uses the unique expertise and facilities of NASA's aeronautics research centers, including the Langley, Ames, and Lewis Centers. The research approach being taken is a balanced one involving closely-integrated wind-tunnel experiments, computational aerodynamics, piloted simulation, and flight tests of an F-18 research testbed airplane known as the High-Angle-of-Attack Research Vehicle (HARV). This vehicle has been modified to make it capable of testing advanced controls, including multi-axis thrust-vectoring and advanced aerodynamic controls. Reference 6 contains a more complete description of this program.

Piloted simulation has been an integral and key element of high-performance aircraft high-angle-of-attack flight-dynamics research at NASA-Langley for the past 20 years. A variety of studies have been conducted involving 11 aircraft configurations. These studies have included evaluations of advanced aircraft designs, investigations of new concepts such as advanced control effectors, and control law development work. Recent research activities have addressed flying qualities, control system design and effects, design guidelines development, and pilot/vehicle interface. The primary objectives of these simulator studies are to: (1) define and quantify the enhancements in agility provided by advanced control concepts under realistic combat conditions, (2) develop agility/handling qualities design requirements, including tradeoffs, for control laws, control effectiveness, and cockpit information systems, and (3) develop the design tools and methodology to enable these requirements to be met, so that the enhanced high-angle-of-attack capabilities can be effectively exploited.

Piloted simulation studies at Langley have been strongly linked with full-scale flight tests for nine aircraft, and these flight results have validated the simulation study approach. As a result, piloted simulation is playing a major role as a research tool for developing design methodologies in the high-angle-of-attack technology development process in the NASA High-Angle-of-Attack Technology Program. The primary facility used for this piloted simulation research is the Langley Differential Maneuvering Simulator (DMS), a fixed-based simulator which has the capability of simultaneously simulating two airplanes as they maneuver with respect to one another. The capability to simulate one-versus-two air combat is also provided by the use of a smaller dome facility known as the General Purpose Fighter Simulator (GPFS) in conjunction with the two DMS domes, as shown in figure 2. This piloted simulation agility research is illustrated in figure 3.

This paper presents an overview of the use of piloted simulation at NASA Langley for the development of high-angle-of-attack technologies as part of the NASA HATP program. The following sections describe the simulation methodologies used in the conduct of the tests, the validation of the test results, and specific methods used for design guideline/criteria development. Example results from recent research using piloted simulation are presented when appropriate to illustrate the use of these methodologies. Some of these examples are drawn from agility research which was conducted to investigate the use of a preliminary thrust-vectoring concept for the F-18 HARV (ref. 7). Other examples are from a generic program conducted jointly by NASA and the U.S. Navy in which candidate design guidelines for nose-down pitch control margin for relaxed-static stability combat aircraft were developed. This pitch control margin research is described in reference 8.

2 TEST TECHNIQUES

Overall Research Process

The overall approach used to conduct piloted simulation studies is illustrated in figure 4. This approach follows a logical progression from the generation of aerodynamic data using wind-tunnel tests to the final product of flight-validated results. The application of piloted simulation to flight-dynamics studies is, of course, dependent on the development of a valid mathematical model which generates accurate flight motions and handling qualities. Data obtained in static and dynamic wind-tunnel tests are used to develop aerodynamic math models for the studies. Although these tests provide much information on high-angle-of-attack characteristics, they do not allow for a quantitative pilot evaluation of the flying qualities of the full-scale airplane during representative air combat maneuvering. Using the math model data, analysis can be performed prior to the piloted evaluation to characterize the aircraft stability characteristics and maneuvering capabilities as an aid in the interpretation of the results. The simulation validation process involves the use of ground-based testing and correlation with full-scale flight tests. Once the simulation fidelity has been established the piloted evaluation can proceed with added confidence. If appropriate flight test results are available they can be used as an aid in the evaluation process to determine the suitability of the evaluation maneuvers and other aspects of the evaluation methodology. As preparation for flight tests, piloted simulation is extremely useful for developing appropriate maneuvers and providing pilots the opportunity to practice the required maneuver techniques prior to flight. The following sections will include descriptions of the simulation techniques and methodologies associated with the math model formulation, the evaluation of the simulation fidelity, the research evaluation, and validation using full-scale flight tests.

Simulator Capabilities

The use of piloted simulation at Langley for high-angle-of-attack studies evolved from the initial use of a simple, single cockpit with a limited visual display (the GPFS) to the present twin-dome DMS. Early simulation efforts with the simple hardware identified several important simulator characteristics. Results of these studies indicated that in order to obtain a realistic evaluation of high-angle-of-attack flight characteristics, the simulation must present the pilot with a realistic air-combat-maneuvering environment. By providing a wide-angle visual display, air combat engagements could be simulated which required the pilot to be almost constantly looking outside of the cockpit to acquire and maneuver against an adversary; therefore, his opinion of the flying qualities and maneuvering capability would be based on similar visual information as in flight. In addition, it was found that there must be provided a good simulation of the cockpit environment in terms of pilot visibility, the display of flight instruments, and the use of a realistic force-feel system for the pilot stick and rudder pedals. Reference 9 describes some of these early piloted simulation studies.

As the simulation work at Langley progressed, the DMS was employed to meet these required characteristics. Unlike many other domed facilities, it is used exclusively for research, and has been used extensively for flight-dynamics research and air combat studies. The DMS is a twin-dome fixed-base simulator with many state-of-the-art features which enhance its utility as a research tool. It has a number of capabilities which provide a realistic maneuvering environment for the pilot and allow for flexibility and repeatability of maneuvering conditions, and it has other capabilities which are necessary for high-angle-of-attack research. A computer-generated imaging (CGI) system provides a high-definition wide-angle visual scene with rotational and translational cues for the pilot. Fully-programmable CRT displays and a head-up display (HUD) provide information within the cockpit, as shown in figure 5. One-versus-one air combat engagements can be simulated by using both DMS domes, and one-versus-two capability is also available by using the third, smaller GPFS dome. As many as two target images can be provided for each of the three domes using laser-generated or airplane model images with the proper apparent size, location, and orientation. The cockpits are equipped with a conventional center stick, rudder pedals, and a throttle. Provisions can be made for other pilot controls if required. A hydraulic force-feel system provides desired stick and pedal force and dynamic characteristics. Reference 10 contains a detailed description of the DMS.

Software Requirements

Aerodynamic Math Model. - In the development of a valid mathematical model for high-angle-of-attack simulation studies of specific configurations, sufficiently accurate models of the engine and flight control system are relatively easy to define. The ability to accurately predict high-angle-of-attack motions such as those shown in figure 1, however, is also highly dependent on the accuracy of the math model used to represent the aerodynamics during complex maneuvering. The aerodynamic modeling is the most difficult aspect of the high-angle-of-attack math model development, due to the extremely complex nature and configuration dependence of the flow phenomena at conditions beyond the conventional flight envelope. Comprehensive, non-linear data bases are required to accurately represent these high-angle-of-attack aerodynamic characteristics. A major concern is that the mathematical modeling for the prediction of these motions is highly dependent on the results of wind-tunnel tests for the required static and dynamic aerodynamic data. The aerodynamic modeling accuracy will therefore only be as good as the accuracy of the wind-tunnel results and the accuracy of the application of these results to the math model.

In the past, conventional math models incorporating extensive data bases which combine static and small-amplitude damping wind-tunnel results have been applied with some success due to the fact that the simulated aircraft were quite limited in their ability to maneuver at stall/post-stall angles of attack because of poor control effectiveness (refs. 11 and 12). It is projected that technologies currently being explored will enable future fighters to have a greatly expanded high-angle-of-attack maneuvering envelope. Furthermore, these aircraft will have the capability of generating rapid angular motions throughout this enlarged envelope. Figure 6 conceptually illustrates the anticipated increases in maximum pitch- and roll-rate capability in an expanded angle-of-attack envelope. The ability to accurately predict these motions using mathematical models presents a most difficult challenge for the flight dynamicist. For these highly agile combat aircraft, recent results have shown that conventional aerodynamic math models may be deficient in correctly representing these aerodynamics. In particular, certain phenomena such as wing rock are not yet understood well enough to be modeled with high accuracy. The impact of incorporating additional terms in the modeling of high-angle-of-attack aerodynamics is being investigated. Examples of these terms include those which account for dynamic stall phenomena during pitch maneuvers and those which represent the effects due to steady rotational motions about the velocity vector (rotary derivatives) and lateral accelerations ($\dot{\beta}$ derivatives) during rolling conditions.

Large-amplitude aircraft maneuvers, however complex, can essentially be broken down into combinations of simple characteristic maneuvers. As is illustrated in figure 7, three basic characteristic maneuvers are: (1) pure pitch motion about the aircraft Y axis, (2) a constant angle-of-attack roll about the velocity vector, and (3) a pure sideslip motion. The first two types of maneuvers are the focus of current modeling studies at Langley. Reference 13 describes these investigations. The ability to roll effectively at high angles of attack is of particular importance to combat aircraft. There is concern that conventional math models which represent the dynamic effects by linear derivatives may not adequately represent the aerodynamics associated with rapid, large-amplitude coning rolls at high angles of attack that future highly agile aircraft will be able to perform. As a first step in investigating potential refinements to the aerodynamic math models, incorporation of rotary balance wind-tunnel data was studied. Assessment of the potential effects of this model refinement was made by comparing calculated motions from a six-degree-of-freedom simulation using both types of aerodynamic models. The simulation was of a representative current fighter airplane for which static, forced-oscillation, and rotary balance wind-tunnel data had been obtained. Figure 8 compares the time history responses to a maximum pilot roll command at $\alpha_0 = 35°$ using the conventional model and the rotational model. The results show substantial differences in the time histories of aircraft maneuver states such as sideslip and angular rates as well as control deflections. These results suggest that refinements to the currently used conventional aerodynamic models may be necessary to more accurately predict the maneuver performance, stability, and controllability of future highly agile aircraft. The identification and implementation of appropriate refinements presents a major challenge for flight dynamicists. Methods to accurately apply wind-tunnel results based on comparisons between simulation and flight motions are being investigated using techniques such as parameter identification, time history matching routines, and computational fluid dynamics.

Flexibility. - Another key software requirement for piloted simulation studies is flexibility in the model for the purpose of examining the effects of parametric variations of various aircraft characteristics. The math model and cockpit displays in the DMS are fully programmable, which make this facility uniquely suited for flight-dynamics research. Past simulation studies at Langley have involved the variation of performance, flight control law and control system characteristics, stability characteristics, and control effectiveness. Often, these variations can be easily implemented by assigning to a variable name a numerical value which can be changed at will. However, in some cases, multipliers or extrapolations which are functions of some variable or a completely different representation may be required. The purposes of these investigations have been to: (1) assess the effect of airframe and engine modifications and advanced control concepts on the stability characteristics and/or maneuvering performance, (2) develop flight control laws to effectively utilize high-angle-of-attack maneuvering capability, and (3) develop design criteria for control laws and control effectors. An example of a significant agility result obtained from a simple parametric variation is shown in figure 9. The sea-level static thrust-to-weight ratio of a configuration with thrust-vectoring (TV) controls was varied to evaluate the effect of thrust changes on the enhancements in maneuvering capability due to their use in rapid nose-up pitch maneuvers. A maximum pitch command was applied from 1g trim conditions at various angles of attack. The use of thrust-vectoring controls increased the maximum trim angle of attack from 55° (for the baseline configuration without thrust vectoring) to as high as 80°. The results were expressed in terms of the maximum pitch rate achieved during these maneuvers, and showed that even configurations with conventional thrust-to-weight ratios of about .7 could realize substantial increases in pitch-rate capability over an expanded angle-of-attack range compared with the baseline configuration without thrust-vectoring controls.

Simulation Fidelity

Historically, high-angle-of-attack simulations on the DMS have correlated well with flight tests, especially with respect to the identification of flight-dynamics problems as well as airframe and flight control concepts to alleviate these problems. However, as was mentioned previously, the need for flight validation of the simulation fidelity has become apparent in recent airplane development efforts. In some aircraft programs significant discrepancies have been encountered between ground test facilities and between some ground test facilities and flight, as described in references 14 and 15. These experiences strongly suggest the need for flight validation to ensure confidence in ground-based results.

As was described previously, NASA is currently conducting full-scale flight tests of a research testbed F-18 known as the HARV, as part of the HATP program in which the use of advanced controls for agility research and control margin/control law design criteria development methods is being investigated. The HARV is uniquely suited for high-angle-of-attack flight validation activities, as it is equipped for the monitoring of more than 700 flight test parameters and the use of flow visualization techniques. This flight test program will be used as an example to illustrate the process of assuring simulation fidelity. The approach to flight testing the HARV equipped with thrust-vectoring controls will be similar to other high-angle-of-attack flight tests which have been conducted. This approach includes updating the aerodynamic data base so that it consists of the best currently known information about the aerodynamics of the vehicle in order to validate the ability of ground-based simulations to predict reliably the dynamic response of the airplane to any pilot inputs. As flight data are becoming available at high angles of attack, parameter estimation efforts are under way to refine the aerodynamic data base for the HARV. An important research objective of the HATP program is the improved modeling of aircraft dynamics at large angles of attack and sideslip, as was previously described.

One method of correlating large-amplitude simulation and flight motions is to compare numerical values of various parameters associated with such maneuvers. An example of this correlation between simulation and flight results for the HARV (without thrust-vectoring controls) is shown in figure 10. Shown is the time to roll through a bank angle change of 90° and the maximum roll rate achieved, starting from wings-level 1g trimmed flight and from M = 0.6 (accelerated conditions) with an initial bank angle of about 90°, versus angle of attack. Results for several maximum-command roll maneuvers performed in flight tests are compared with the results obtained in the DMS simulation. These particular results indicate good correlation between simulation and flight, so that no modifications to the simulation math model are indicated. However, if such results show a significant difference between simulation and flight, then corrections should be applied to the math model. Additional correlation efforts are continuing at NASA which involve the use of parameter estimation techniques and non-real-time (batch) computer routines which use the recorded pilot control inputs or control surface deflections from flight to generate the resulting motions predicted by the simulation math model.

Evaluation Maneuvers

A fundamental test technique for high-angle-of-attack piloted simulation studies is the systematic progression, in distinct phases, from the performance of "open-loop" (i.e. pilot in the loop performing simple inputs) maneuvers to one-versus-one air combat, to one-versus-two engagements. Normally the first phase of an evaluation of a particular configuration with advanced controls involves pilot familiarization with the simulated airplane, evaluation of the high-angle-of-attack maneuvering characteristics of the airplane, and development of closed-loop and air combat maneuvering tasks for use in the next phase of the study. For studies to develop control margin design criteria, the primary evaluation maneuvers may be very few and "open loop", in order to focus on specific response characteristics for various levels of control effectiveness and to remove as many control system effects as possible. Pilot familiarization of each configuration in such a study can be relatively brief.

The second phase of these piloted evaluations involves having the pilots fly the simulated airplane in closed-loop maneuvers. These maneuvers may involve the capture of a specific flight condition, flying against repeatable recorded air combat tasks, or engagements against a pilot in the second DMS dome. For agility research, this phase of the evaluation serves the purpose of quantifying the maneuvering benefits of advanced controls in realistic one-versus-one air combat situations and to uncover any handling qualities considerations or airframe/control system deficiencies which should be corrected. Agility and handling qualities research are closely related, as effective use of enhanced agility must be accompanied by acceptable handling qualities. Examples of studies which have specifically addressed handling qualities requirements at high angles of attack are described in reference 16. For control margin design criteria development, the performance of closed-loop and complex air combat maneuvering serves to validate or define any adjustments/refinements to the design criteria developed in the "open-loop" primary evaluation. The definition of control margin, agility, and handling qualities requirements determines the fundamental control law characteristics for enabling these requirements to be met. Unfortunately, a systematic, proven set of design guidelines and methodologies for the high-angle-of-attack control system development process to maximize agility and fully exploit high-angle-of-attack maneuvering capability does not yet exist. The HATP program is addressing this need.

Agility characteristics and design criteria must be evaluated under the most real-world conditions so that the complex maneuvers can be performed in rapid succession and the pilot's attention must be divided between flying the maneuvers, keeping track of a target, and managing a weapon system. Piloted simulation studies of one-versus-one air combat with one configuration having enhanced high-angle-of-attack agility and the other being a conventional fighter have been conducted for this purpose (refs. 1 and 2). Results from these investigations have shown large benefits from the use of high-angle-of-attack agility. They have also quantified to some extent the level of benefit obtained from given amounts of control margin augmentation. The significant advantages seen in one-versus-one scenarios often come from the use of very high-angle-of-attack and low airspeed maneuvers. In an m-versus-n environment the level of augmentation required to obtain a significant advantage may be higher, and energy management will increase in importance. The next step in investigating high-angle-of-attack agility and design requirements is the simulation of one-versus-two engagements in which one highly agile vehicle engages two conventional configurations. The Highly Agile Vehicle Versus Two (HAVV TWO) program is currently under way at Langley to identify and evaluate additional considerations which the multi-bogie environment places on control effectiveness requirements and pilot situational-awareness needs. Some early results from this study are described in reference 3. This study began with very simple engagements and is progressing towards more complex engagements in order to enable quantification of the exchange ratio improvements due to enhanced agility and identification of the configuration characteristics that played a significant role in producing the improvements.

An important requirement for evaluation maneuvers used in piloted simulation studies is that they should relate as directly as possible to the airplane characteristics being evaluated, so that the pilot comments and ratings are meaningful and so that the quantitative results can be used as directly as possible. The maneuvers should be performed in a manner which insures that the critical flight conditions, pilot techniques, and resulting aircraft motions are examined. As was discussed previously, two significant high-angle-of-attack large-amplitude maneuvers are pure pitch maneuvers and rolls about the velocity vector. For high-angle-of-attack agility/advanced controls research, then, maneuvers which involve full pilot inputs in pitch and roll should be performed over the angle-of-attack and speed envelope of interest. The maneuvers should fully define the limits of the enhanced maneuvering envelope and agility/handling qualities design requirements and tradeoffs. These maneuvering characteristics can be defined by analyzing maneuvers in which the pilot inputs are held until the maximum maneuvering rates are attained and those which involve closed-loop captures of specific conditions. These types of maneuvers should be performed in non-combat situations (for ease of analysis) as well as in tasks involving repeatable targets and in simulated air combat engagements. This approach also helps to identify any weaknesses or deficiencies in the control law design being used.

As was mentioned previously, for some simulation research only one "open-loop" primary evaluation maneuver may be required. For control margin design criteria development, this approach allows many parametric variations of control effectiveness to be made and evaluated by several pilots. The initial conditions for evaluation maneuvers must also be carefully considered. For example, maneuvers used in the evaluation of control margin requirements, of which pilot ratings and comments on aircraft response may be an integral part, should be designed so that the motions that the pilot observes visually are generated as much as possible only by the control moment capability of the airplane. Unrelated or secondary motions such as those due to control system effects, thrust or other performance characteristics, or kinematic and other coupling motions should be minimized. By initiating such maneuvers at 1g stabilized trim conditions, at which there are no net forces or moments acting on the airplane such that $q = \dot{\alpha} = \dot{\gamma} = \ddot{h} = 0$, the thrust/performance effects are minimized. Figure 11 depicts this flight condition. The flight path angle (γ) will be less than zero (descending flight) at angles of attack where there is insufficient thrust to maintain level flight. These maneuver conditions are ideal for directly assessing the control moment available at that angle of attack. The primary maneuver used in the evaluation of nose-down pitch control requirements was a pushover from these conditions at a high angle of attack to low angles of attack (ref. 8). A nose-down command applied at initial conditions at which the pitch attitude or the flight path angle is changing ($\dot{\theta}$ or $\dot{\gamma} \neq 0$) will result in changes in angle of attack that are not due solely to the nose-down moment generated by the application of nose-down controls. More complex maneuvering at a variety of flight conditions will be performed as part of the validation process in this study.

For purposes of quantifying and documenting the fundamental aircraft response characteristics and agility/maneuvering capabilities in a way which will be reproducible in flight tests for correlation with simulation results, the non-combat maneuvers performed in these evaluations should be repeatable and easily executable by the pilots. Maneuvers for which the initial conditions are dynamic (i.e. there are forces or moments acting on the airplane) will make the maneuver less repeatable, and will add complexity to the pilot technique if the timing of the pilot input is to be made at a specified point during the changing conditions. Pilot technique complexity is also increased if a sequence of inputs is required. Maximizing the repeatability and ease of execution of the maneuvers also minimizes difficulties in analyzing the results and comparing the results with full-scale flight motions. For closed-loop maneuvers in which flight conditions are captured within specified tolerances, these tolerances need to be tight enough to give meaning to the results and yet not so tight that they cannot be met in simulation and flight tests. In the progression from "open-loop" to closed-loop to air combat maneuvering, the repeatability and ease of pilot technique naturally decreases; however, by first obtaining a fundamental understanding of the results from simpler maneuvering, the analysis of more complex maneuvering will be simplified.

Role of Simulator Pilots in Evaluations

There are several factors which influence the effective use of research pilots for high-angle-of-attack simulation studies: (1) the number of participants and their backgrounds, (2) their involvement in the research process, (3) the establishment of their learning curves, (4) their acclimation to high-angle-of-attack motions, and (5) the approach taken to pilot ratings and comments.

It is highly desirable to use several research test pilots in these studies in order to assure that the results will be generally applicable, particularly in studies involving the use of pilot ratings. They should ideally have extensive flight testing background and come from a variety of sources, including the military and industry. They should be familiar with air combat maneuvers, tactics, and weapons systems employed with current fighter airplanes, and should be involved throughout the program. Any pilots who are involved in full-scale flight tests of a specific test configuration associated with the study will need to fly the simulator to obtain information prior to the test flights or to validate the simulation results if test flights have already been made.

Pilot involvement in the research process should begin with a thorough briefing regarding the background and purpose of the program and the simulator characteristics, if they are not familiar with them. They should be involved as much as possible in the development of the test techniques and the methodology to be used in the study, including the maneuvering techniques, rating approaches, and the determination of figures of merit.

An important aspect of the assessment method is the establishment of the learning curve before pilot comments are expressed or ratings are given. For simple, highly repeatable tasks, a particular configuration or parametric variation may be evaluated with very few runs; however, for more complex tasks in which the motions may vary due to the use of different pilot techniques, a number of runs may be required to establish the learning curve.

The performance of maneuvers at high angles of attack can produce unconventional motions which affect the pilot's perception of aircraft responses to his inputs. A primary example of this motion is the change in the aircraft's lateral-directional response to roll inputs at increasing angles of attack. Lateral inputs at high angles of attack to command a coordinated roll about the velocity vector produce an increasing proportion of body axis yaw rate compared with roll rate as the angle of attack is increased. When first encountered, this yawing motion can be disorienting or can appear to be a departure from controlled flight. Additional simulation time may be required for pilots to become acclimated to it. This phenomenon will be discussed further in a later section.

For some research in which specific pilot ratings are required in order to quantitatively document the pilot's opinion of an aircraft characteristic, existing accepted rating scales such as the Cooper-Harper handling qualities rating scale (see figure 12 and reference 17) may not be appropriate. A new rating scale and/or rating approach may need to be developed. For instance, the Cooper-Harper scale is not applicable to piloted assessments of "open-loop" responses to simple inputs for which pilot compensation is not usually a factor, such as assessments of departure/spin recovery or rate capability. An example of a scale that was developed for the quantitative assessment of "open-loop" response to nose-down pitch commands for recovery from high angles of attack is shown in figure 13 and is described in reference 8. The evaluation pilots as well as the engineers and flying qualities specialists were actively involved in the development and refinement of this scale, which has some structural similarity to the Cooper-Harper scale. In addition to the rating scale, a questionnaire which provided suggestions for qualitative pilot comments concerning additional pitch response characteristics and one which addressed the characteristics of the evaluation maneuvers were used and are shown in figures 14 and 15. These questionnaires were useful for generating additional pilot comments during the simulator sessions and debriefings. As a general practice for all piloted simulation studies, it has been found to be useful to obtain written summaries from pilots after each simulation session as further documentation and clarification of their evaluations. The information obtained from the pilots' ratings and comments enabled the definition of two primary levels of response, as shown in the figure. These levels were important for establishing design requirements based on safety of flight and tactical considerations.

Analysis of Results

The overall results of piloted simulation studies are generally derived from the analysis of aircraft motions and controls, pilot qualitative comments concerning workload and aircraft response, and quantitative pilot ratings. When qualitative or quantitative pilot opinion is used to make comparisons of maneuvering capability at different flight conditions or between aircraft configurations, it is desirable for them to be involved in the analysis process as much as possible in order to aid in the definition of the figures of merit which most influenced their opinions. The results should be expressed in terms of maneuvering performance and the effect of the variations which were made. For agility research, many figures of merit have been used and/or proposed to quantify the results of maneuvering capability. These figures of merit include the time to reach a flight condition or to capture it within a specified tolerance, and maximum angular changes, rates, or accelerations achieved during the maneuver. As yet, there is no generally accepted specific set of figures of merit (also referred to as metrics) for quantifying high-angle-of-attack agility. A sample presentation of the results for simulated "open-loop" roll maneuvers was shown in figure 10. The DMS results for the F-18 HARV with and without thrust-vectoring controls are shown in figure 16. The results show significant maneuvering improvements (shorter time to bank and increased roll rate) for the configuration with thrust vectoring. The two figures of merit used, though very simple, are clearly useful for quantifying enhanced roll agility, and are therefore useful for identifying the maneuvers which are most appropriate for agility evaluations. Such results can also be used to define control law design goals.

A number of ways to meaningfully quantify maneuvering enhancements in simulated air combat engagements also exist. In particular, such overall figures of merit as the angle (ε) between the aircraft X body axis and the range vector to the opponent and the rate of change of this angle indicate instantaneous maneuvering advantage. The time on advantage, defined as the cumulative time during which the aircraft $\varepsilon < 90°$ and the opponent's $\varepsilon > 90°$ is an indicator of sustained maneuvering advantage. The results as indicated by these and other measures of maneuvering advantages during air combat should be expected based on an understanding gained from earlier analysis of non-combat maneuvers. Of course, the victor in any air combat engagement will be the first one who satisfies the weapons firing/launching parameters, which normally involve ε, the range between aircraft, and other requirements. By performing sufficient numbers of engagements, a meaningful probability of a specific configuration being the victor against some other configuration can be determined. References 1 through 3 contain analyses of combat maneuvers and engagements for configurations with and without thrust-vectoring controls.

A particular data analysis process is appropriate for the determination of control margin design guidelines involving pilot ratings. The determination of appropriate candidate figures of merit for the analysis will be discussed in a later section; however, for each candidate figure of merit selected, the level of statistical correlation should be determined between the quantitative values achieved by the aircraft for that response characteristic and the pilot comments and ratings assigned. In this manner the most significant figure(s) of merit that best characterize those aspects of the response that the pilots evaluated can be determined. This process is depicted in figure 17. The statistical correlation method that was found to work well for the determination of the figures of merit for nose-down control response was to compute the mean values of the figure of merit versus pilot rating and the 95-percent confidence intervals about the mean at each rating value. For this study, one figure of merit that was determined by this analysis technique to be significant was the maximum nose-down pitch acceleration achieved within the first second of a full nose-down command at high angles of attack. These results are shown in figure 18. The clear dependence of pilot rating on the amount of pitch acceleration achieved and the generally small confidence intervals were evidence of a meaningful correlation. This information was then used in the determination of design criteria.

3 FLIGHT VALIDATION OF RESULTS

As was shown in figure 4, final determination of the results of high-angle-of-attack piloted simulation studies involves the use of ground-based testing and full-scale flight testing to validate the simulation results. These tests are used to determine any refinements needed to the simulation mathematical model or the evaluation methodology used, such as the maneuvers and rating approaches. The simulation also serves as a tool for flight test planning and practice for the test pilots. In flight tests, real-world considerations with respect to pilot/vehicle-interface needs can be evaluated and their effect on the validity of the simulation results assessed. These considerations include cockpit displays and controls as well as motion/physiological effects such as spatial disorientation and accelerations experienced by the pilot. The following sections will discuss the use of flight testing for the validation of simulation results.

Validation of Maneuvers and Rating Approaches

Considerations. - An evaluation of the maneuvers performed and the validity of the rating approaches used in the simulation studies must also be made in flight tests. It is important that the simulation results be based on realistic maneuvers that can be performed in flight within acceptable tolerances for the maneuver performance without violating any aircraft restrictions or requiring excessive pilot workload. As an example, during full-input large-amplitude rolls at high angles of attack, holding the angle of attack nearly constant during the maneuver can be a high workload task, both in simulation and flight tests. If an additional requirement such as capturing a roll angle is added, the workload may be unacceptably high, especially if the tolerances are tight and the handling qualities are poor. The simulation results should also accurately predict the pilot's qualitative opinion and numerical ratings in full-scale flight. If the pilot's opinion of the aircraft response is significantly affected in flight due to factors such as the effects of motion, the fixed-based simulation results will need to be modified. It may also be determined in flight tests that the pilot rating approach itself needs to be altered. Future flight tests of the HARV will yield such information concerning the validity of the nose-down control margin study conducted on the DMS and the application of the Cooper-Harper handling qualities rating scale to enhanced high-angle-of-attack flight.

Status of Maneuver Definition. - During flight test programs, as the airplane is cleared for different regions of the flight envelope from benign flight conditions to more demanding ones, maneuvers and tests performed during piloted simulation are repeated for evaluation/validation purposes. Accepted task performance guidelines for nonlinear piloted simulation of high-angle-of-attack maneuvering and corresponding evaluation procedures/guidelines for flight test do not currently exist. Historically, different ad hoc approaches have been used by various organizations during specific programs. However, little attempt has been made to pull together these various approaches and take advantage of the lessons learned over the years. Therefore, development of open- and closed-loop task performance guidelines and evaluation procedures that are generally accepted for agility research and control law evaluations is a current and future research challenge.

High-angle-of-attack research programs are attempting to address the issue of task definition. NASA has proposed that a set of standard, representative tasks be defined and used in all ongoing high-angle-of-attack research flight programs, with the same tasks being evaluated in simulation and flight. Still unresolved is what the specific tasks should be. Research activities are underway to develop and ultimately flight-validate candidate tasks. Starting with the fundamental characteristic maneuvers shown in figure 7 as a basis, a preliminary set of candidate maneuvers which could be used for high-angle-of-attack agility and control law design research is being evaluated using the DMS. A wide variety of maneuvers were initially considered on the basis of their potential for quantifying the enhancements in agility due to the use of advanced control effectors. Figure 19 describes the resulting candidate set of maneuvers, which is designed to evaluate the aircraft's ability to rapidly point the nose relative to the flight path, as depicted in figure 1, by pitching or rolling about the velocity vector. In addition to these nose-pointing maneuvers, others are being developed on the DMS which will demonstrate the second aspect of agility shown in figure 1 -- the ability to reposition the aircraft by quickly turning the velocity vector. The DMS is also being used to develop flight test maneuvers based on the handling qualities evaluations described in reference 16. Flight tests of these various types of maneuvers using the F-18 HARV will validate their utility for high-angle-of-attack agility, handling qualities, and control law evaluations.

Pilot/Vehicle Interface Considerations

An important goal of the research within the HATP program is to define the considerations and needs of the pilot with respect to cockpit displays and controls, the possibility and consequences of spatial disorientation during maneuvers, and the severity and effect of g loads experienced by the pilot. Any or all of the potential difficulties associated with these factors can affect the validation of piloted simulation results because they can cause problems with the accuracy and repeatability of the test points.

The presentation of cockpit displays and the mechanization of the controls can affect both the pilot's ability to perform a maneuver and his opinion of the aircraft response. For example, if a display of critical information for performance of the maneuver is difficult to read because of its design or placement, the maneuver performance and/or pilot opinion may be affected. Because of the nature of high-angle-of-attack flight and potential problems with spatial disorientation, the performance of large-amplitude maneuvers at these conditions may require the use of unconventional displays. The DMS is being used to investigate the use of helmet-mounted displays with a view towards flight tests of such a system on the F-18 HARV.

Spatial disorientation, which can cause the maneuver performance to suffer due to a reduction in situational awareness, can result due to the occurrence of unusual flight attitudes or motions. Such disorientation can occur within the conventional flight envelope at angles of attack below the stall; however, the possibility exists, based on simulation experience, that more severe disorientation may result during the performance of maneuvers such as high-angle-of-attack rolls about the velocity vector. Pilots who are used to rolling about the longitudinal body axis at low angles of attack may become very disconcerted at first by the substantial initial yawing motion observed in response to a roll input. Pilots have adapted to this phenomenon in simulations; however, there is currently a lack of flight experience with these motions. Simulation results related to agility and design criteria development may have to be altered after comparing these results with flight test data. Applicable data should be available soon from the F-18 HARV flight tests and other high-angle-of-attack flight programs. This issue is also being addressed as part of the research being conducted with helmet-mounted displays mentioned previously.

A second physiological consideration for pilot/vehicle interfacing is the potential for excessive accelerations (g loads) encountered at the pilot station during rapid maneuvering at high angles of attack. The primary concerns are the onset rate of normal acceleration on the pilot during rapid pitch maneuvers, the buildup of axial acceleration ("eyeballs-out" g's) due to high yaw rates during high-angle-of-attack rolls, and the lateral accelerations experienced due to rapid yaw accelerations in these rolls. These values can be easily calculated from simulation data; however, only flight tests will determine exactly how the pilots will respond to these motions and how much they will affect the results of simulation studies.

4 CONSIDERATIONS FOR DESIGN CRITERIA DEVELOPMENT

The overall piloted simulation research process as shown in figure 4 is valid for design criteria development. However, for some types of research, it is appropriate to adapt or extend the general techniques. For example, in addition to the test techniques/methodology and validation considerations previously described, there are three particular aspects of piloted simulation studies which should be included in the development process for high-angle-of-attack design criteria: (1) the evaluation of candidate criteria, (2) the relationship of these criteria to the design process, and (3) the specification of requirements for demonstrating in flight that the design criteria have been met. The process being used in the development of nose-down pitch control margin design criteria is shown in figure 20. The DMS was used to obtain quantitative results based on the pilot rating scale shown in figure 13. These results were used to develop preliminary design guidelines which are beginning to be applied to specific aircraft. Additional simulation work is being performed to validate the early results, including closed-loop maneuvers. A preliminary set of requirements for demonstrating in flight that the design criteria have been met has been defined. Flight tests of two F-18 aircraft will be performed to validate this process.

Evaluation of Candidate Criteria

Any study to define design criteria should include the evaluation of candidate criteria, beginning with a review of any available literature for existing or proposed criteria or guidelines, in order to determine how much work has been done, how systematic and comprehensive the work was, and how well the results agree with each other. If a reasonable data base of simulation and flight test results exists, sufficient information may be obtained to define a preliminary guideline which can be compared with the simulation results at the completion of the study. The results of such a review of existing guidelines and data bases for nose-down pitch control criteria are contained in reference 18.

An important step in the evaluation of candidate design criteria which relates to the use of pilot rating approaches as well as to the analysis of the simulation results is the establishment of figures of merit to be used in evaluating the aircraft response. As many potential figures of merit as possible should be considered. They can best be compared by characterizing them according to the strength of their relationship to the parameter under design and an appropriate time scale. Figure 21 shows this overall relationship for a number of potential figures of merit which were considered for nose-down pitch control design based on their relationship to pitch control power and the time scale relative to initiation of the pilot command. Those figures of merit on the left side of the scale would be expected to be the more critical ones for design considerations, although the others could also be useful as supplemental or check parameters. For this application it is clear that in the absence of significant angular rates, pitch acceleration ($\dot{q}$) bears a strong relationship to pitch control power because it is directly proportional to static pitching moment coefficient (C_m). The longer time-scale parameters shown on the right end of the plot have a much weaker association with control power and are more closely associated with airplane performance effects such as thrust and drag. As was shown in figure 18 pitch acceleration was in fact found to be a significant figure of merit, based on the piloted simulation results. The results also showed that the long-term parameters did not correlate as well with pilot opinion of the recoveries from high angles of attack, so this approach to evaluating candidate figures of merit was beneficial.

A final area of consideration for the evaluation of candidate design criteria is the generation of a systematic, comprehensive data base of simulation results, from which the final criteria can be derived. The performance of sufficient runs to ensure the establishment of the pilots' learning curves and a statistically meaningful set of results was discussed previously. For control margin design these results should also incorporate the variation of critical parameters affecting control capability and response. For example, those parameters which were chosen to characterize the static nose-down pitching moment characteristics are illustrated in figure 22 and include: (1) the minimum value of C_m, C_m*, (2) the angle-of-attack range over which C_m* occurs, $\Delta\alpha$*, and (3) the slopes of the pitching moment curve for angles of attack below and above $\Delta\alpha$*, S1 and S2. Such parameters should be varied individually and systematically for the piloted evaluations. For the nose-down control margin study, 25 separate parametric variations of the nose-down pitching moment capability were evaluated. The range of variations for each characteristic evaluated were based on the characteristics of current aircraft and projected future designs. As a preliminary check on the validity of the initial quantitative analysis of the simulation results, additional maneuvers were performed to verify that the pilot ratings could be predicted for a wide variety of control margin characteristics.

<u>Relationship of Simulation-Derived Criteria to the Design Process</u>

During the early design stages of a new aircraft, the aircraft designer requires guidelines which enable him to design for the desired aircraft performance. Ideally it is best to apply design guidelines as early as possible in the design process such that significant design problems can be identified and design tradeoff studies can be conducted. The format of design guidelines must be easy to apply and yet comprehensive in including the most significant factors which influence the performance. An example of the early application of design guidelines is during preliminary wind-tunnel screening of candidate configurations in which quick assessments of stability levels and control effectiveness are made.

Criteria developed from piloted simulation results can be very useful in developing design guidelines. Usually the intent will be that the aircraft achieve the desired performance demonstrated as satisfactory in the simulator. Very importantly, the designer must have a high level of confidence that use of simulation-derived guidelines will ultimately produce aircraft which meet the original criteria. To achieve this high level of confidence the design guideline must capture the intent of the criteria, including pilot opinion, and ideally should be flight-validated on a variety of aircraft.

A design guideline was developed from nose-down pitch control margin simulation results reported in reference 8. This guideline provided a methodology to determine the minimum value of C_m required at the pinch point (C_m*) and the shape of the available nose-down pitch response. The basis for this guideline included considerations for pitch acceleration and pitch rate requirements during 1g pushover maneuvers, which were determined to be the most significant figures of merit to use for the design criteria. This guideline is illustrated in figure 23. A methodology was developed to determine design requirements based on the consideration of various maneuvers and motions which involve the significant figures of merit. For nose-down control power the process to select the pitching moment required at each angle of attack, including inertia coupling considerations for rolling maneuvers and motions, is illustrated in figure 24. Three values of C_m are computed based on the maneuvering requirements shown and the largest C_m value is selected.

<u>Flight Test Demonstration Requirements</u>

In the final stages of the design process for a new configuration, flight test is used to demonstrate that the configuration meets design requirements and/or is in compliance with the specifications. Typically a comprehensive set of flight demonstration requirements is outlined prior to the flight test phase and is methodically completed as the flight envelope is expanded.

Piloted simulation is very useful for developing flight demonstration requirements, especially those which are related to simulation-derived design criteria. The specific test techniques and flight conditions can be developed in the simulator in order to determine optimum piloting techniques and the most efficient methods for acquiring the demonstration data. Specific test conditions which are difficult to achieve or assess can be identified prior to flight test. Also, operational constraints on flight demonstrations can be evaluated and alternative demonstration requirements can be developed when required.

Flight demonstration maneuvers which are used to demonstrate design criteria ideally should be closely related to maneuvers used in simulation to develop the criteria. This approach allows the fundamental understanding of the flight dynamics gained from simulation to be applied to flight test and assures that the design methodology is reflected in the maneuver requirements. The flight demonstration should be repeatable and easily accomplished using normal flight testing techniques and not require unusual flight instrumentation for data documentation.

The DMS was used to develop flight demonstration requirements for the nose-down pitch control criteria as previously discussed. The recommended flight maneuvers were closely related to the basic criteria development maneuvers used in simulation. These maneuvers included stabilized 1g pushovers, pushovers during rolling maneuvers, pull-push and zoom climb maneuvers. Successful demonstration of meeting the design criteria included achieving threshold values of pitch acceleration and pitch rate within specified time periods. The DMS was particularly useful for developing the specific test techniques for the flight demonstration. Techniques for achieving 1g stabilized conditions at high angles of attack were evaluated including initial conditions, stabilization criteria, and the impact of engine operating limitations. Also, maneuvers were developed to demonstrate nose-down pitch control during rolling maneuvers which were very complex and difficult to evaluate. An understanding of the flight mechanics associated with recoveries from zoom climbs was also achieved. In summary, piloted simulation using the DMS proved to be invaluable in developing maneuvers which would safely and efficiently demonstrate compliance with these design requirements. As a final step, these simulation-derived maneuvers will be evaluated in a flight validation program using the F-18 HARV.

5 CONCLUDING REMARKS

Piloted simulation has been an important tool for high-performance aircraft flight-dynamics research at NASA-Langley. It has a major role in the high-angle-of-attack technology development process in the NASA High-Angle-of-Attack Technology Program (HATP), particularly for agility research and design criteria development. The Differential Maneuvering Simulator is the primary facility used for this research, and has been used as an effective research tool to develop the design methodologies required to implement advanced technologies on future aircraft.

Test techniques and methodologies have been developed for the effective use of the simulation capabilities. Certain simulator characteristics are desirable, in order to provide a realistic maneuvering environment. Software requirements, particularly the high-angle-of-attack math modeling of the aerodynamic characteristics, are critical to the successful application of the simulation results. Evaluation maneuvers which are repeatable, easy to execute, and relevant to the research objectives are developed and are usually performed in a progression from the most simple to complex maneuvering and air combat engagements. The most effective use of simulator pilots requires their participation in the research process, particularly for the development of maneuvers and rating approaches and for the identification of appropriate figures of merit for analysis of the results. The data base generated should reflect the establishment of the pilots' learning curves and for design criteria development have statistical significance.

Correlation with full-scale flight results is the primary means of validating the simulation results and approach. The fidelity of the simulation math model can be verified by comparing flight and simulation motions. The utility of evaluation maneuvers and pilot rating approaches used in simulation can be examined in flight. Pilot/vehicle interface considerations and their impact on the simulation results can also be assessed. Flight tests are now underway to validate the approaches used for agility research and design criteria development.

In order to develop design criteria, additional steps are required in the simulation study approach. Candidate design criteria must be carefully evaluated and a systematic, comprehensive data base of simulation results generated. The final criteria developed must be easily applicable to the design process and successfully predict the aircraft performance. Piloted simulation can be used to define flight test demonstration requirements, which can be evaluated in full-scale flight tests.

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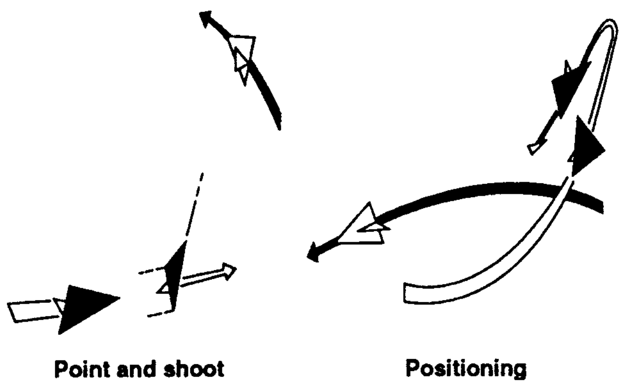

Figure 1. - Illustrations of high-angle-of-attack agility

Figure 2. - Simulator facilities used for one-versus-two air combat studies

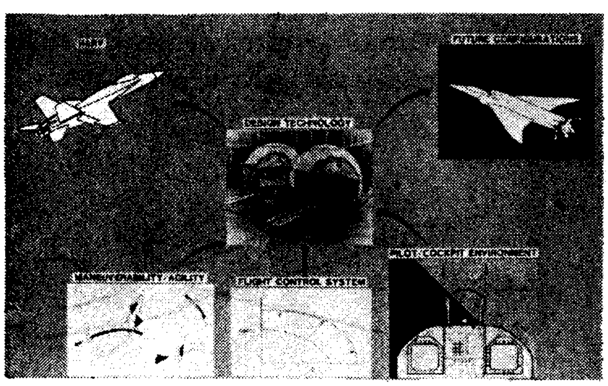

Figure 3. - Piloted simulation agility research

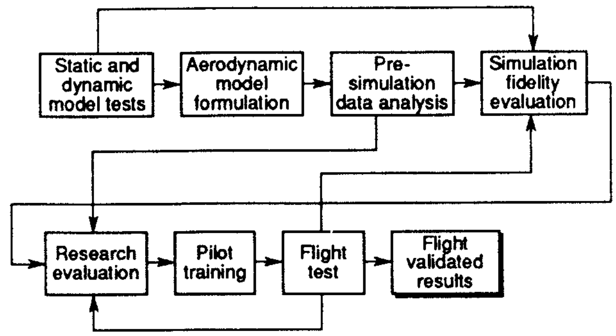

Figure 4. - Approach used for piloted simulation studies

Figure 5. - View of DMS cockpit and visual display

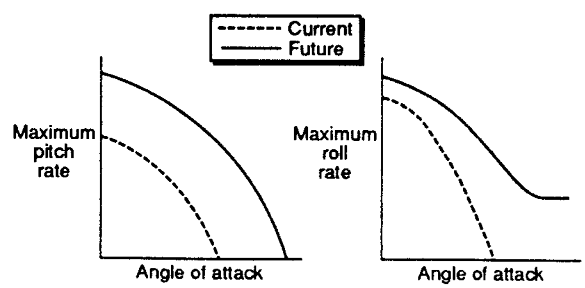

Figure 6. Comparison of current with future pitch and roll rate capability

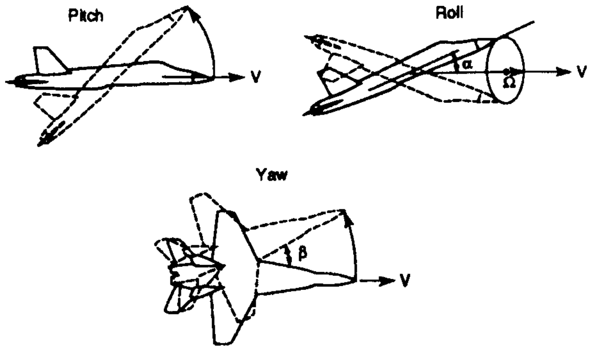

Figure 7. - Characteristic maneuvers

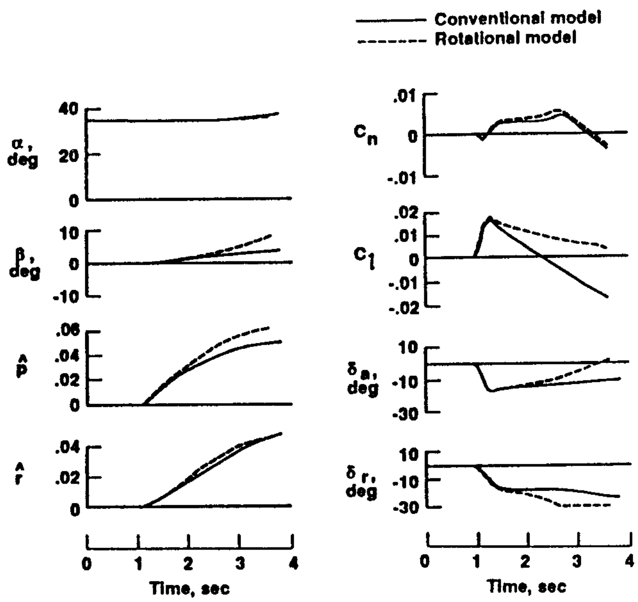

Figure 8. - Time history of large amplitude roll maneuver at α_o = 35° with and without rotary aerodynamics modeled

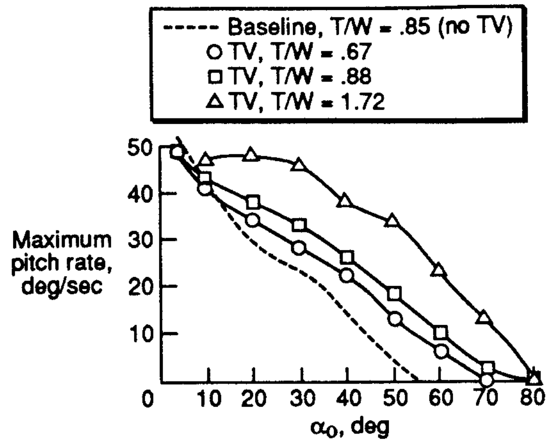

Figure 9. - Maximum pitch rates achieved from 1g trim conditions for various levels of T/W for a configuration with thrust vectoring. h_o = 20,000 ft.

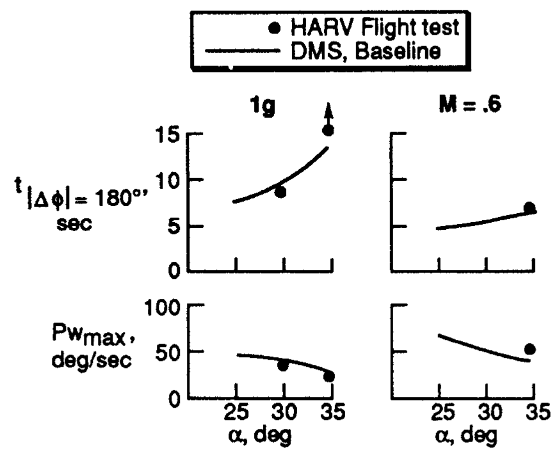

Figure 10. - Comparison of roll maneuvering results for simulation and flight. h_o = 25,000 ft.

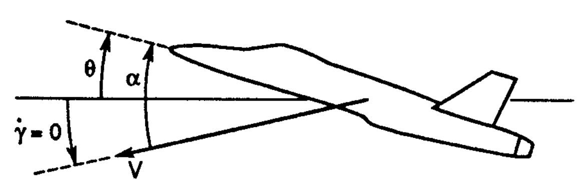

Figure 11. - Stabilized 1g trimmed conditions

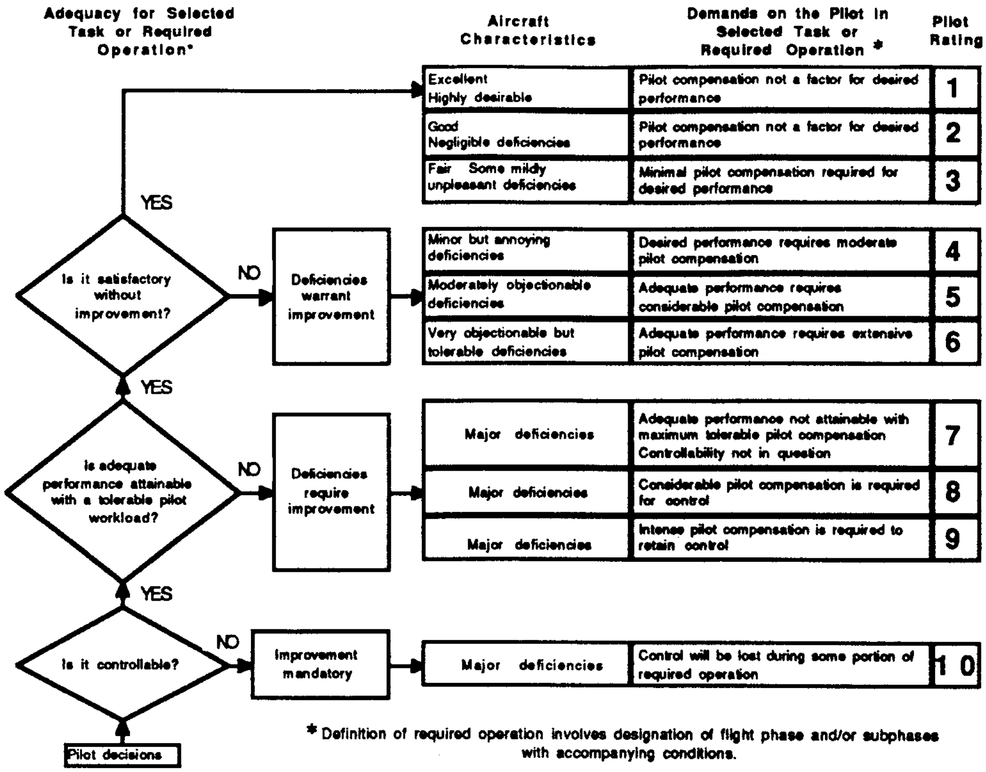

Figure 12.- Cooper-Harper handling qualities rating scale

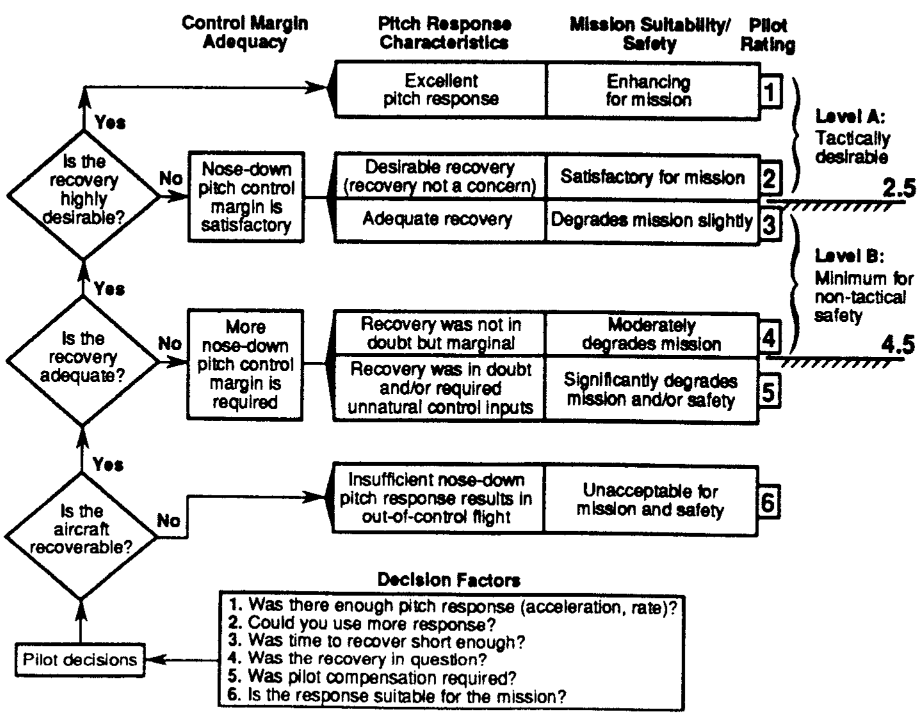

Figure 13. - Pitch recovery rating scale

Use the following questions as a guideline for describing and evaluating each test point.

1. **Describe respone to stick input.**
   a. Pitch response
   b. Accompanying roll/yaw motions
   c. Disorienting motion

2. **Compare this response to other aircraft you have flown.**
   a. Aircraft
   b. Conditions
   c. Similar, better or worse

3. **Give your opinion on the application of this maneuver to combat.**
   a. Characteristics that enhance or degrade combat effectiveness
   b. Describe what you would most like to improve on this response

4. **Determine impact of other influences on your opinion.**
   a. Did recovery time affect your opinion?
   b. Did altitude loss affect your opinion of the recovery?
   c. Were you most concerned about mission safety or mission accomplishment during this maneuver?
   d. Did pilot technique affect results?
   e. What pilot compensation was required to complete maneuver?

Figure 14. - Pilot questionnaire for additional comments

Use the following questions as a guideline for describing the potential tactical applications of each type of maneuver.

1. Based on your experience, would this maneuver be tactically useful for current or future aircraft?

2. What would you like to improve on this maneuver to increase the tactical effectiveness?

3. If this aircraft displayed "excellent" response capability, would this maneuver be tactically useful?

4. Would you desire to have more AOA capability than that demonstrated during this maneuver and why?

5. Describe a tactical situation where you would most likely see this setup and desire to perform this maneuver.

6. What maneuver/s would likely precede and follow this in a tactical situation?

Figure 15. - Pilot questionnaire for evaluation of maneuvers

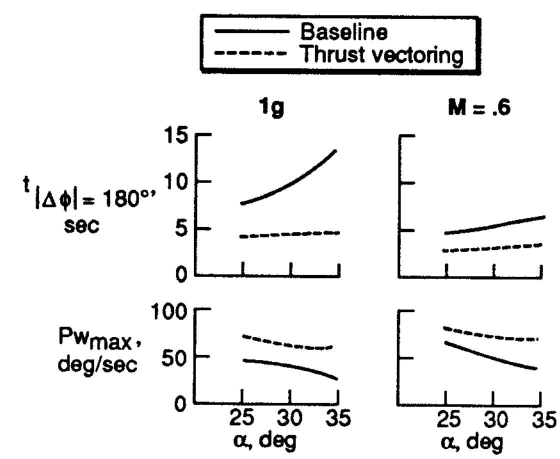

Figure 16. - Roll maneuvering results from simulation evaluation. h_o = 25,000 ft.

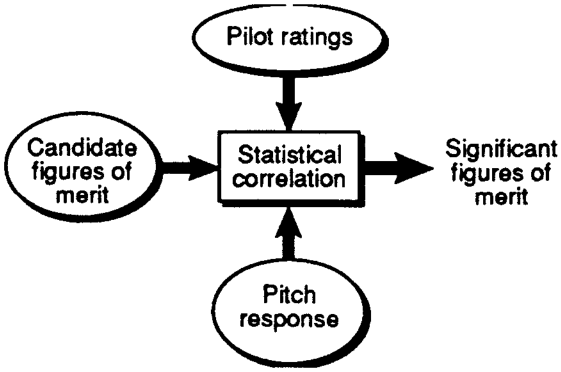

Figure 17. - Approach to data analysis for control margin studies

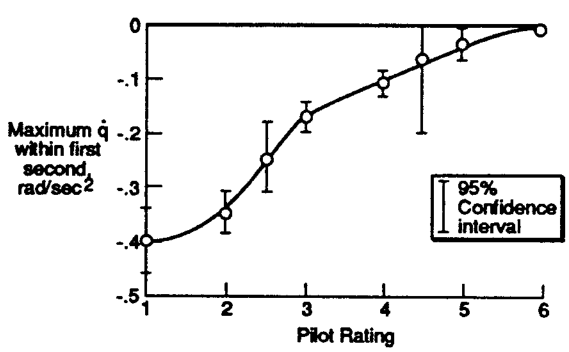

Figure 18. - Variation of maximum q̇ achieved within one second of recovery initiation with pilot rating

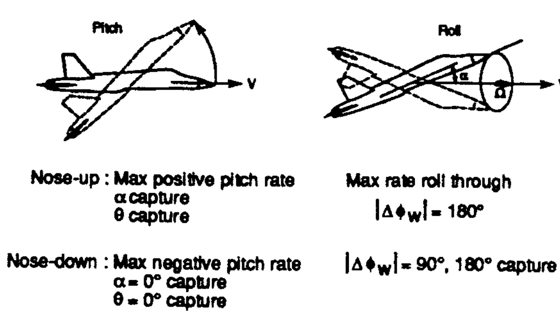

Figure 19. - Candidate maneuvers for agility and control law evaulations

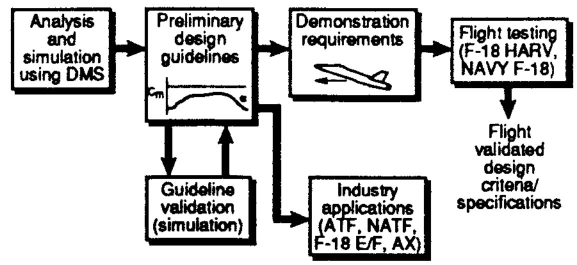

Figure 20. - High-alpha nose-down pitch control margin requirements program

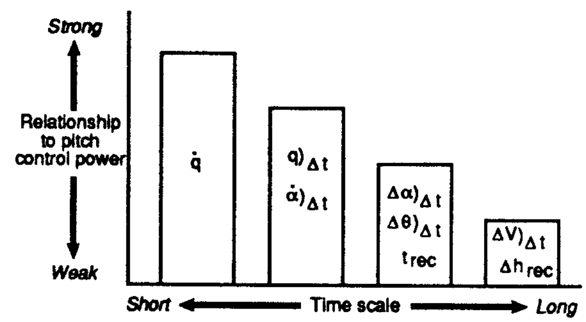

Figure 21. - Candidate figures of merit

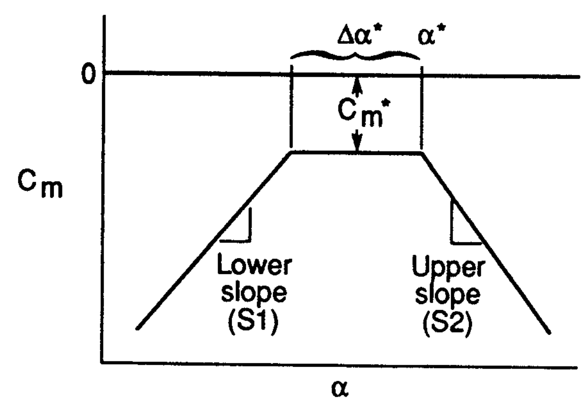

Figure 22. - Parametric variations of nose-down pitching moment used in simulation study

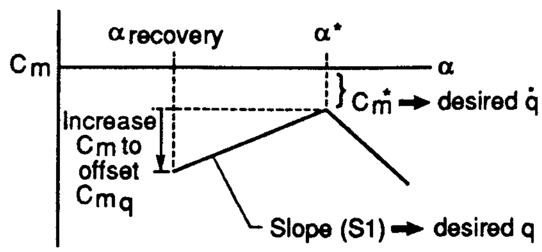

Figure 23. - Illustration of C_m design guidelines for nose-down pitch response

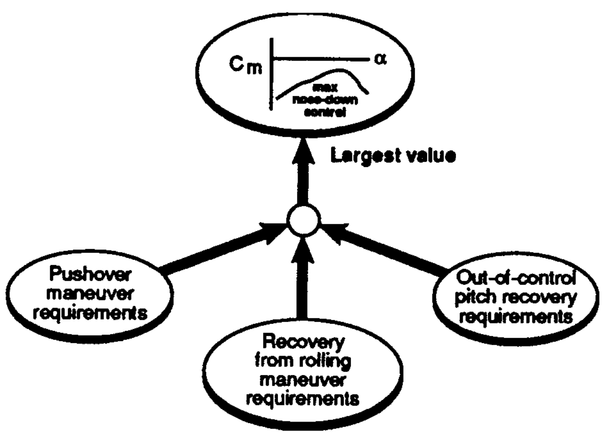

Figure 24. - Illustration of determination of required C_m at each angle of attack