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INVESTIGATION OF HIGH-α LATERAL-DIRECTIONAL CONTROL POWER REQUIREMENTS FOR HIGH-PERFORMANCE AIRCRAFT

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ABSTRACT

Designers of the next-generation fighter and attack airplanes are faced with the requirements of good high-angle-of-attack maneuverability as well as efficient high speed cruise capability with low radar cross section (RCS) characteristics. As a result, they are challenged with the task of making critical design trades to achieve the desired levels of maneuverability and performance. This task has highlighted the need for comprehensive, flight-validated lateral-directional control power design guidelines for high angles of attack. A joint NASA/U.S. Navy study has been initiated to address this need and to investigate the complex flight dynamics characteristics and controls requirements for high-angle-of-attack lateral-directional maneuvering. A multi-year research program is underway which includes ground-based piloted simulation and flight validation. This paper will give a status update of this program that will include a program overview, description of test methodology and preliminary results.

INTRODUCTION

Designers of the next-generation fighter and attack airplanes are faced with the requirements of good high-angle-of-attack maneuverability and efficient high speed cruise capability with low radar cross section (RCS) characteristics. The desire for enhanced maneuverability has resulted in significant increases in control power requirements compared to current conventional configurations while the performance considerations have driven new designs toward relaxed static stability and smaller controls. In response to these needs, advanced control effectors have been developed, such as thrust vectoring and novel aerodynamic surfaces, which have the potential to provide the needed increases in high-angle-of-attack control power and contribute to reducing drag and RCS. However, as illustrated in figure 1, the maneuverability and performance needs often result in opposing design requirements. For example, the weight and complexity involved with providing controls for maneuverability may degrade performance to unacceptable levels. In many cases, control power requirements can be a key driver in determining the configuration geometry. Due to the performance penalties and potential monetary costs associated with incorporating increasing control power, it has become crucial that the designer understands the impact of maneuverability on mission effectiveness. Therefore designers are challenged with the task of making critical design tradeoffs and achieving the desired balance in maneuverability and performance over an expanded flight envelope.

To effectively perform these design tradeoffs, comprehensive design guidelines are necessary which allow the designer to clearly assess the impact of a change in performance or maneuverability on mission effectiveness. Well-accepted guidelines exist for performance, which include range and endurance specifications, and low-angle-of-attack control power specifications have been successfully applied to many configurations. Recent studies have focused on high-angle-of-attack nose-down control power requirements which are providing critical flight-validated design guidelines [1-3]. However, as illustrated in figure 2, additional control power design guidelines for the lateral-directional axes are also needed. This includes angles of attack for conventional maneuvering up to maximum lift as well as low speed maneuvering at post-stall conditions.

In recent years, several studies have been undertaken to evaluate high-angle-of-attack roll performance requirements [4-8]. The study described in reference 4 investigated the impact of advanced controls on maneuvering during air combat and illustrated advantages provided by this technology. Reference 5 describes maneuvers that were developed which could be used to evaluate high-angle-of-attack flying qualities and agility from early design phases through flight testing.

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References 6-8 describe the development of linear flying qualities guidelines for high-angle-of-attack target acquisition and tracking tasks using piloted simulation. These studies have provided critical handling qualities design guidance and exposed the need for further analysis of the complex, non-linear flight dynamics issues and the need for flight-validated controls design guidelines.

The problem of addressing lateral-directional control power requirements is complex due to the highly non-linear effects introduced by rolling at high angles of attack. Typically, rolling about the velocity vector is desired to minimize departure inducing kinematic coupling, but this requires high levels of yaw control power that increase with angle of attack and that are generally unattainable using conventional aerodynamic controls. Thus, recent configurations, such as the Navy F/A-18, are capable of aggressive pitch maneuvering at post-stall angles of attack but are unable to perform aggressive rolling maneuvers at these conditions due to the lack of directional control power from rudders. Aerodynamic non-linearities (e.g. aerodynamic coupling, non-linear control effectiveness) associated with high angles of attack introduce additional complexities in achieving the desired roll performance and handling qualities. In response to the need for increased control power, a trend has developed in the design of new configurations which involve a significant increase in the number of control effectors. As shown in figure 3, the requirement to integrate twenty controls or more is expected on future configurations. This trend has not only introduced the need to develop methodologies that effectively blend multiple controls to achieve the desired control characteristics, but also to investigate the associated handling qualities issues. In addition, evaluation of high-angle-of-attack lateral-directional maneuvering requirements is difficult due to lack of operational flight experience at those conditions. Recently, high-angle-of-attack flight research vehicles, such as the NASA F-18 HARV and ARPA/Navy/ GMD X-31, have been developed to address many of the high-angle-of-attack handling qualities and flight dynamics issues and validate the results from ground-based studies.

The NASA and U.S. Navy have initiated a joint program to develop flight-validated lateral-directional control power design guidelines for high-performance airplanes at moderate to high angles of attack. Specifically this multi-year program is focusing on the requirements for the fighter and ground attack roles for class IV high performance aircraft and is addressing the tradeoffs between control power and mission effectiveness. It is intended that results from this effort will provide design guidance as new advanced configurations are developed. This paper will present an overview and status of this program including the program plan and schedule, approach and methodology, and preliminary results.

NOMENCLATURE

Symbols:

g	acceleration due to gravity, ft/sec^2
h	altitude, ft
M	Mach number
$\dot{p}$	roll acceleration, deg/sec^2
p_{ss}	steady-state roll rate, deg/sec
p_{stab}	stability axis roll rate, deg/sec
r	body axis yaw rate, deg/sec
α	angle of attack, deg
Δt_{ϕ}	time to a given bank angle, sec
$\Delta\psi$	heading change, deg
τ_R	roll mode time constant, sec

Subscripts:

max	maximum value obtained

Abbreviations:

AOA	angle of attack
DMS	Differential Maneuvering Simulator
HARV	High-Alpha Research Vehicle
HQR	handling qualities rating
LaRC	Langley Research Center
NASA	National Aeronautics and Space Administration
RCS	radar cross section
RPC	roll performance classification

PROGRAM PLAN

The study team is composed of engineers and test pilots from NASA and the U.S. Navy as illustrated in figure 4. NASA is providing unique ground-based test facilities and research personnel, including evaluation pilots. Test engineers and pilots from the Naval Air Warfare Center (NAWC) and Naval Air Systems Command (NAVAIR) are providing current operational perspectives. In addition, supporting graduate level research is being provided by Virginia Polytechnic Institute and State University (VPI) through a research grant [9-11]. To ensure all issues are addressed and to provide timely information to industry, the program is also maintaining close interaction with all major airframe companies and the U.S. Air Force through periodic program reviews.

The program consists of four major elements as illustrated in figure 5. The first element is ground-based research using piloted simulation. In this element experimental data will be gathered that includes the pilot's opinions on roll performance and mission effectiveness with related comments on handling qualities. In the second element, a preliminary lateral-directional control power design guideline will be developed based on these data. This preliminary guideline will undergo extensive validation in simulation and will be available for near-term applications. In the third element flight test maneuvers will be developed that demonstrate compliance with the guidelines. Finally, this will be followed by flight test to validate the test methodology, preliminary guideline and demonstration maneuvers.

The general program schedule is shown in figure 6. Currently, the program is in the first element as described above which includes piloted simulation testing and development of methods to analyze results and develop the design guidelines. Although the flight test validation is not planned for several years, it is expected that limited flight test data will be available from current programs for correlation with preliminary results. This paper will summarize activity completed to date.

APPROACH

General

The approach adopted for investigating the control power requirements was to divide the total requirement into three general categories: 1) roll performance, 2) stability and coupling, and 3) margin for uncertainties, as illustrated in figure 7. The control power for roll performance is defined as that required to effect the roll accelerations or rate as required by the pilot for maneuvering. This requirement is highly dependent on the mission requirements and desired handling qualities. The second category of control power is that required to provide stability to maintain the desired closed-loop dynamic characteristics or to prevent out-of-control flight. This may include compensation for lack of static or dynamic stability or compensation for inertia coupling moments generated during dynamic maneuvering. Lastly, an increment of control power must be provided to account for uncertainties. This may include measurement uncertainties and a margin for turbulence. The total control power requirement is a unique combination of these three elements that may vary significantly with flight condition. As previously mentioned, the designer must blend the available controls to provide the desired control power about the appropriate axis.

Currently, this study is focusing on the roll performance element as previously described. The other elements mentioned, stability and coupling and uncertainties, and controls blending methods will be addressed in the future as part of this program. Because roll performance requirements are dependent on the pilot's ability to perform mission tasks, piloted simulation is being used as the key research tool in this study. A methodology has been developed to quantify the pilot's opinion of roll performance that includes lateral-directional maneuverability, handling qualities and the impact on mission effectiveness. For this study, a systematic simulation evaluation process has been developed that is illustrated in figure 8. This process begins with the definition of critical maneuvers that clearly expose the lateral-directional control power requirements. These maneuvers are then evaluated in piloted simulation. From these results, key figures of merit are extracted from which the preliminary design guidelines are developed. The following sections will discuss each of these elements in the evaluation process.

Simulation Description

The primary simulation facility used for this study is the Langley Differential Maneuvering Simulator (DMS) which is illustrated in figure 9. The DMS is a twin-domed, fixed-base simulator that is representative of current fighter aircraft. The cockpit contains fully programmable instruments and displays, including a head-up display (HUD). A center stick and rudder pedals are provided and control feel is achieved by a programmable force-feel system. A computer-generated imaging system (CGI) provides a high-definition wide-angle visual scene for the pilot inside the 40 ft diameter spheres. The target imaging system provides a unique capability by projecting simple computer driven targets, slaved targets, pre-recorded targets, target driven by computer maneuvering logic, and one-versus-one combat against a pilot in the second dome.

The simulation dynamic model provides generic response characteristics in the lateral-directional axes that can be parametrically varied to provide a variety of response characteristics. The baseline model is a linear, first-order roll response, illustrated in figure 10, that provides a perfectly coordinated stability axis roll. Stability axis steady-state roll rate and the roll mode time constant can be parametrically varied to provide a full range of response. Lateral stick input commands steady-state roll rate and a shaping function provides the desired stick sensitivities. An approach to modeling response non-linearities has been developed that provides a wide variety of characteristics such as dynamic oscillations due to sideslip excursions, kinematic coupling and inertial coupling. These non-linearities can be individually or simultaneously combined with the linear response model so that individual effects may be studied.

The pitch axis is controlled by a generic angle-of-attack-command control system that provides desired flying qualities to minimize adverse influences on the lateral-directional evaluations. Velocity characteristics are provided by a thrust/drag model representative of current fighters.

Maneuver Development

For this study, it was recognized that the combat scenario and type of maneuver can significantly influence the pilot's opinion of roll performance. Because of the need to investigate requirements for fighter and attack airplanes throughout a large flight envelope, it was necessary to consider maneuvers used for offensive as well as defensive air combat throughout a wide range of speed and angle of attack. Therefore candidate evaluation maneuvers were carefully developed by a team of research engineers and pilots prior to initiation of the evaluations. The criterion used for development of these maneuvers were that they should; 1) represent realistic combat scenarios over a wide range of flight conditions, 2) clearly show the impact of lateral-directional control power on mission effectiveness, and 3) produce data appropriate for deriving design guidelines. In addition, maneuvers were desired that were easy to set up and perform and were not significantly influenced by pitch maneuvering characteristics.

Preliminary piloted simulation was conducted to refine the evaluation maneuvers which exposed several factors that can influence the maneuver ratings and key results are summarized as follows. During small to moderate amplitude maneuvers (less than 90 deg bank angle change) or those where the roll rate was high, the pilots did not desire to use full lateral stick because of the rapid and large stick motions that would result. Therefore full lateral stick input during maneuvers was not required. Secondly, the pilots strongly preferred to perform tasks involving a target instead of a cockpit display such as a bank angle indicator. This was because the maneuver was more realistic using a target as a reference to judge roll performance. Thirdly, for all of the maneuvers, it was important to carefully choreograph the motion of the target to allow the lateral-directional response to be properly evaluated at the desired flight condition. As the test angle of attack increased, this became increasingly important due to the high sink rate that resulted. Lastly, it was found that maneuvers which involve significant longitudinal maneuvering can influence pilot opinion of the lateral-directional response because of the additional workload. Therefore, most maneuvers in this study were conducted at constant angle of attack. However, it was recognized that many combat situations involve simultaneous longitudinal and lateral-directional maneuvering and this effect will be investigated.

The resulting maneuvers are summarized in table I and show the flight conditions and the type of rating for each maneuver. The rating approach will be described in more detail in the next section. The maneuvers were found to fall in two broad categories - nose pointing and repositioning. Nose pointing maneuvers are generally performed at low speeds and 1 g load factor and involve rolling about the velocity vector without changing its orientation. These maneuvers are used to point the nose of the aircraft without significantly changing the flight path. Repositioning maneuvers are generally performed at higher speeds and elevated load factor. During these maneuvers, the rolling maneuver is used to rotate the lift vector. The combination of an elevated load factor and rotated lift vector changes the aircraft's flight path which allows the pilot to reposition the aircraft to a different maneuvering plane. This distinction was found to have a significant influence on desired roll performance which will be discussed in the results section.

For the nose pointing maneuvers the test aircraft was trimmed in unaccelerated flight at test angles of attack of 15°, 30°, 45° or 60°. The maximum effort roll, bank-to-bank roll, and lateral gross acquisition maneuvers are very similar in that each is used to investigate the 1 g roll performance and capture of a final condition or target. The maximum effort roll and bank-to-bank roll are bank capture maneuvers, but the bank-to-bank roll uses a target fixed at the bank angle to be captured. An illustration of the lateral gross acquisition is shown in figure 11(a). The tail chase acquisition is a series of captures and reversals as illustrated in figure 11(b). This maneuver highlights the 1 g load factor roll performance and also allows the pilot to examine roll reversals. The flat scissors is a standard basic fighter maneuver that is used to evaluate a series of rolls and roll reversals without any captures. The first reversal of the flat scissors is also examined to investigate just the roll reversal portion of the maneuver.

The repositioning maneuvers are initiated at high speeds (M = 0.5 to 0.8) and the pilot maneuvers to the test angle of attack. The defensive roll, illustrated in figure 11(c), highlights the loaded roll performance and is used to investigate the roll requirements during defensive, large amplitude maneuvers. The offensive loaded reversal also highlights loaded roll performance but incorporates both a reversal and a capture (fig. 11(d)). The high speed tracking maneuver is a series of rolls, reversals, and captures and highlights the loaded roll, reversal, and capture performance while giving the pilot a long look at the test parameters.

Pilot Evaluation

The evaluation pilots include numerous NASA and U.S. Navy test pilots with experience in fighter and attack aircraft and high-angle-of-attack flying qualities. The pilots have been involved in the development of the test methodology, including maneuver development and refinement as well as definition and refinement of the rating approach.

The roll performance characteristics that the pilot evaluates can be divided into two major elements, maneuvering and handling qualities, as illustrated in figure 12. Maneuvering refers only to the ability to generate roll accelerations and rates. This element includes primarily open-loop, large amplitude maneuvering and the pilot's opinion may be influenced by other factors such as time to perform the maneuver. Handling qualities refers to the ability to perform a precision, small amplitude task, such as a target acquisition. It is understood that roll acceleration and rate can effect handling qualities, however other influences not related to control power, such as control feel and dynamic characteristics, can influence the pilot's opinion as well. Because only the influence of control power is of interest in this study, it is critical that the effects of control power and handling qualities be separated.

For this study, a unique rating methodology has been developed to isolate the effects of control power on maneuvering characteristics. Maneuverability is rated according to mission effectiveness utilizing the roll performance classification (RPC) chart, shown in figure 13, which was developed as part of this study. For maneuvers with a well-defined task, as indicated in table I, handling qualities characteristics are simultaneously rated using the Cooper-Harper handling qualities rating (HQR) scale [12]. The Cooper-Harper scale is used only to evaluate the ease and precision of completing the defined maneuvering task. Mission effectiveness is not directly addressed using the Cooper-Harper scale however maneuverability required to perform the task is implicitly evaluated. This evaluation approach not only allows the pilots to separately evaluate maneuverability and handling qualities but provides a method to investigate the interaction between them. This is needed to assess control power requirements for maximum performance maneuvers versus the requirement to achieve desired closed-loop handling qualities.

Data Analysis

From the piloted simulation data, the key figures of merit are extracted which best quantify the pilot's opinion of roll performance. The judgment of which figure of merit is best is based on correlation with the rating scale and pilot comments. Candidate figures of merit are shown in figure 14 which illustrates that some of these are more of a direct indication of required lateral-directional control power than others. For example, roll acceleration is directly proportional to control power whereas parameters describing the ability to change orientation are also dependent on the lift, drag and thrust characteristics of the airplane. For this study, the task is to develop meaningful design guidelines based on the most significant figures of merit. The relationship of mission effectiveness, as defined in the roll performance classification, to control power provides information for design tradeoffs as previously discussed.

PRELIMINARY RESULTS

Preliminary simulation testing has been completed with six NASA and U.S. Navy test pilots using the evaluation maneuvers listed in table I. Data were obtained using the baseline linear model where maximum stability axis steady-state roll rate was varied and τ_R = 1 second. Roll performance was evaluated using the rating process described in the previous section. The preliminary results have been used to assess the test methodology as well as establish some preliminary trends. For the purposes of illustrating key results in this paper, only roll rate is shown as a figure of merit and specific values are not included. However, as previously mentioned other parameters, such as roll acceleration, are being evaluated as figures of merit.

The effect of angle of attack on roll rate requirements for nose pointing maneuvers (maximum effort roll, bank-to-bank roll, lateral gross acquisition) is shown in figure 15(a). As expected, for all angles of attack, mission effectiveness decreased as the maximum stability axis roll rate decreased. These data also show that less roll rate is desired for a given level of mission effectiveness as angle of attack increases which is consistent with previous studies [6-8]. However, figure 15(b) shows desired maximum body axis yaw rate is nearly invariant for all angles of attack. Pilot comments indicated this result was due to the coning motion effects as angle of attack increases and that the pilot desires precise and predictable directional control for nose pointing tasks which does not vary with angle of attack. Figure 15(a) also shows that the data for all three angles of attack converges at a rating of "inadequate" indicating there existed a non-zero, minimum acceptable stability axis roll rate that was nearly invariant with angle of attack.

The effect of maneuver type is shown in figure 16 for $\alpha = 30°$. The repositioning maneuvers consistently required higher stability axis roll rates than the nose pointing maneuvers for all levels of mission effectiveness better than "inadequate". Pilot comments indicate this higher roll rate requirement is due to the need to rapidly rotate the lift vector to allow a maneuver out of plane rather than pointing the nose of the airplane. These data also show that the two lines converge at the rating of "inadequate" as was seen in figure 15(a). This indicated that the minimum acceptable value of stability axis roll rate was also independent of maneuver type as well as angle of attack as previously discussed.

Figure 17 shows the simultaneous effect of maximum attainable roll rate on the HQR and RPC for a given task. Low to moderate values of roll rate produced Level 1 (adequate) handling qualities ratings, however, as roll rate increased to high values, the handling qualities rapidly degraded to nearly Level 3 (inadequate). This degradation was due to the decrease in roll predictability and increased pilot workload required to complete the task within the specified tolerances. It would be expected that very low values of roll rate would hinder completion of the task and produce degraded handling qualities as well.

The trends in HQR and RPC shown in figure 17 indicate the relationship between handling qualities and roll maneuverability. As illustrated, a range of roll rate can be identified where desired handling qualities and mission effectiveness are simultaneously achieved. The maximum value of roll rate can be determined where the desired level of handling qualities can be maintained. In similar fashion, the minimum value of roll rate can be determined which maintains the desired level of mission effectiveness. Using this format as a design guideline, the tradeoff between maneuverability and handling qualities can be assessed.

A summary of the preliminary simulation results for 1 g maneuvering compared to current configurations is shown in figure 18. Based on the methodology developed in this study, these results indicate F-18 roll performance is significantly degraded at angles of attack above 20° but remains adequate to about 30°. This result is consistent with pilot comments on tactical utility of the F-18 which indicate that most maneuvering at high angles of attack is in the pitch axis due to the rapid and predictable pitch response whereas lateral-directional maneuvering is limited due to the lack of roll response.[13] In contrast, roll performance with advanced control effectors, based on the NASA F-18 HARV design guideline [14], produces highly desirable performance for all angles of attack. Preliminary flight test results of the F-18 HARV using multi-axis thrust vectoring have indicated large tactical benefits when taking advantage of the enhanced roll maneuvering capability.[15]

In summary, the initial simulation testing has provided an assessment of the test methodology and allowed a preliminary evaluation of high angle of attack lateral-directional control power requirements. The repeatable data trends, consistent pilot comments, and comparisons with previous studies have provided confidence in the overall test methodology which includes the evaluation maneuvers, rating process and data analysis techniques. Most importantly, the methodology developed in this study will allow an investigation of the tradeoffs between mission effectiveness and control power requirements and expose critical handling qualities and flight dynamics issues.

FUTURE PLANS

Piloted simulation is continuing to refine the evaluation methodology that will include identification of critical maneuvers and refinements to the rating process. The development of a comprehensive database is in progress and a wide variety of parametrics are planned for pilot evaluation that will include more complex dynamic response characteristics. From this database, efforts are continuing to identify key figures of merit from which the preliminary guideline will be derived. Limited flight data correlation's are planned using flight data from the F-18 HARV and X-31 and planning will continue toward full flight validation.

SUMMARY

A joint NASA/Navy program has been initiated to develop high-angle-of-attack lateral-directional control power design guidelines for next generation high-performance aircraft. A comprehensive multi-year program is planned which includes piloted simulation evaluations and flight validation. A unique test methodology has been developed which uses pilot comments to quantify levels of roll performance in terms of mission effectiveness. Using this methodology, piloted simulation evaluations are in progress to compile a database from which preliminary guidelines will be developed. Initial simulation results indicate that the desired roll performance is highly dependent on the type of maneuver and initial flight condition. Planning is in progress to validate the preliminary guidelines in flight test.

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Table I. Simulation evaluation maneuvers

Nose Pointing Maneuvers

Maneuver	Load Factor		Test Aircraft Initial Condition			Rating Type*	
	1 g	> 1 g	Offensive	Neutral	Defensive	HQR	RPC
Maximum effort roll	✓					✓	✓
Bank-to-bank roll	✓		✓			✓	✓
Lateral gross acquisition	✓		✓			✓	✓
Tail chase acquisition	✓		✓				✓
Flat scissors	✓			✓			✓

Repositioning Maneuvers

Maneuver	Load Factor		Test Aircraft Initial Condition			Rating Type*	
	1 g	> 1 g	Offensive	Neutral	Defensive	HQR	RPC
Defensive roll		✓			✓		✓
Offensive loaded reversal		✓	✓			✓	✓
High speed tracking		✓	✓				✓

* HQR = Handling qualities rating (Cooper-Harper scale)
RPC = Roll Performance Classification

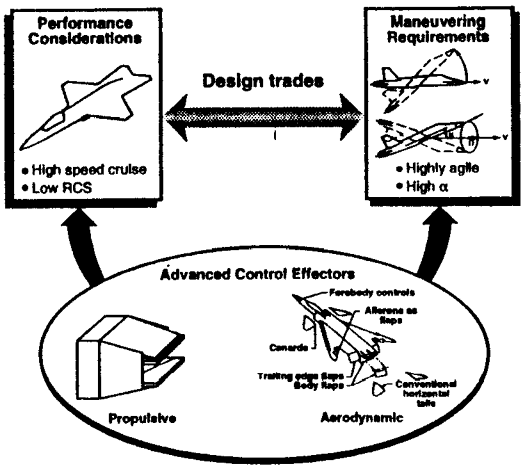


Figure 1. - Impact of control requirements on preliminary design

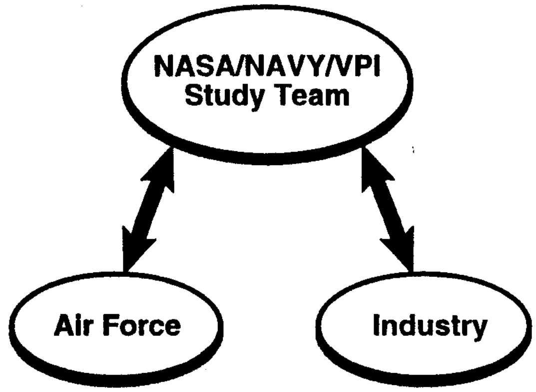


Figure 4. - Study structure

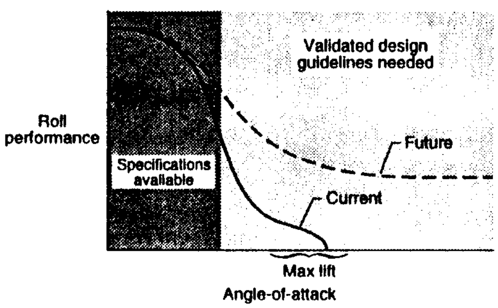


Figure 2. - Status of lateral-directional control power design guidelines

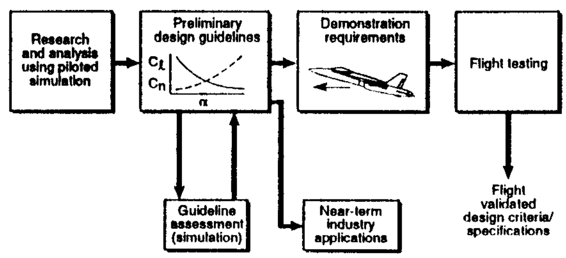


Figure 5. - Program plan

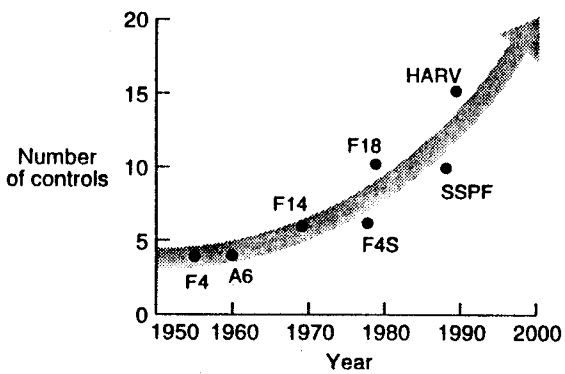


Figure 3. - Trend in number of control effectors

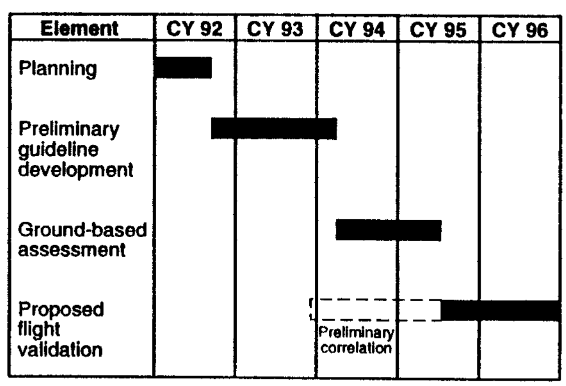


Figure 6. - Program schedule

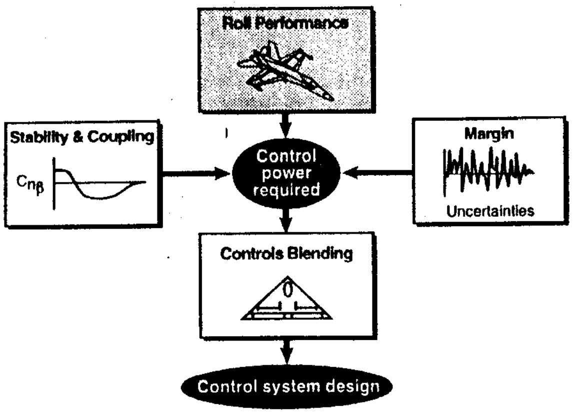


Figure 7. - Elements of control power requirements

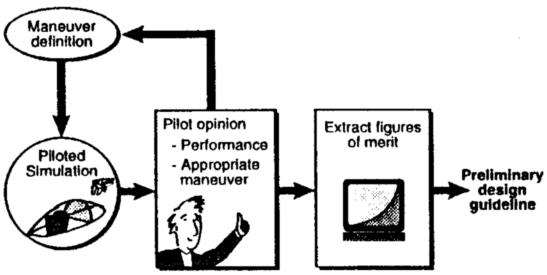


Figure 8. - Roll performance evaluation process

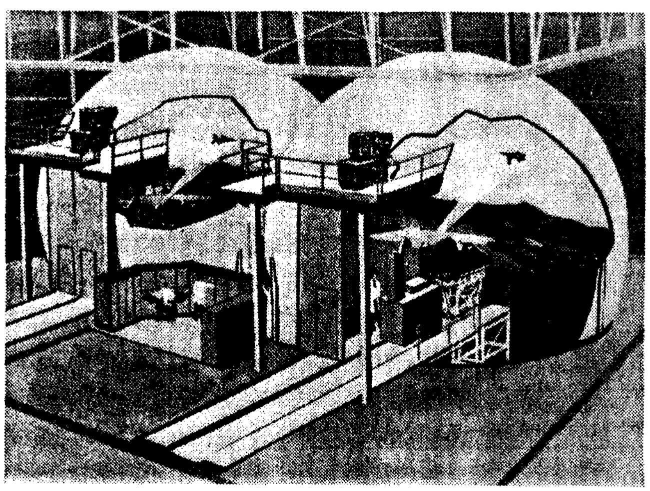


Figure 9. - Illustration of the Langley Differential Maneuvering Simulator

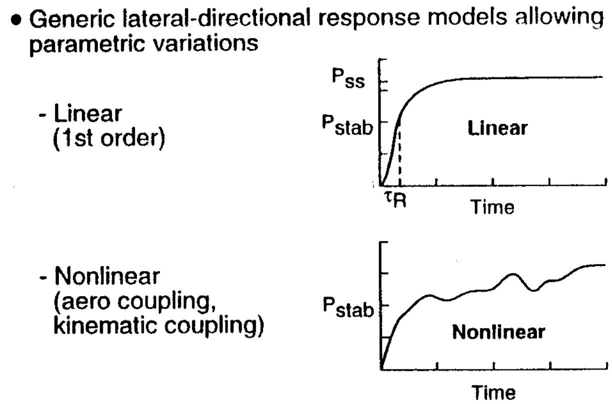
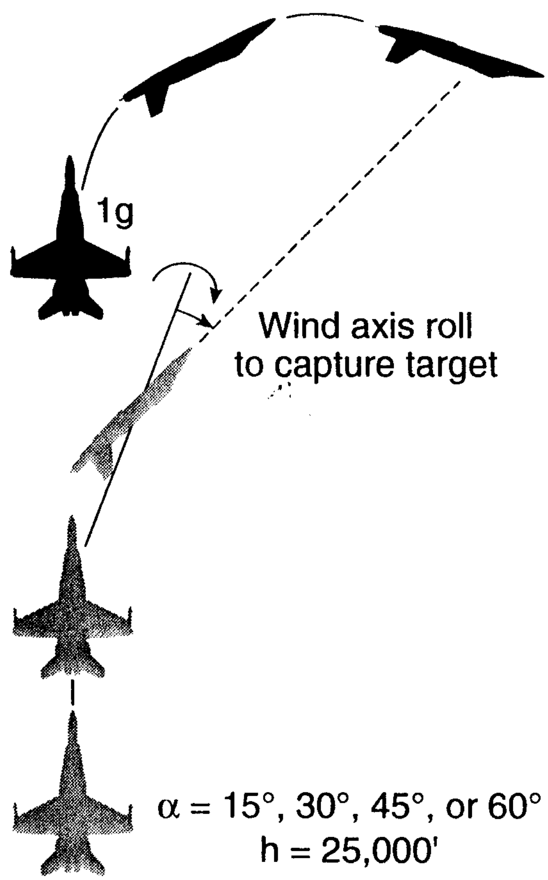
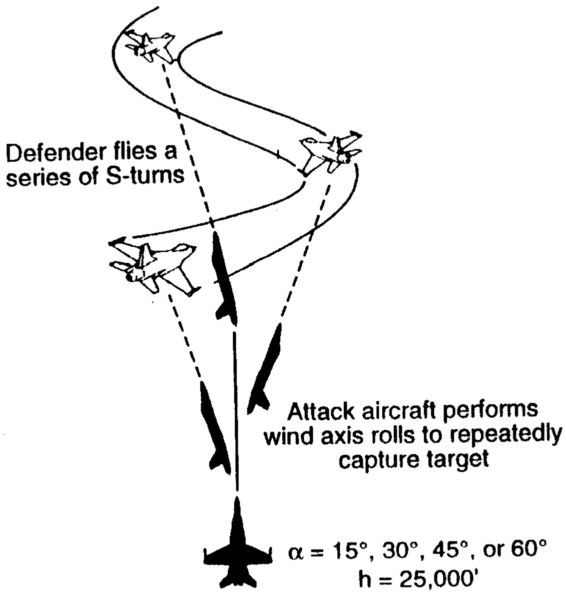


Figure 10. - Simulation lateral-directional dynamic models

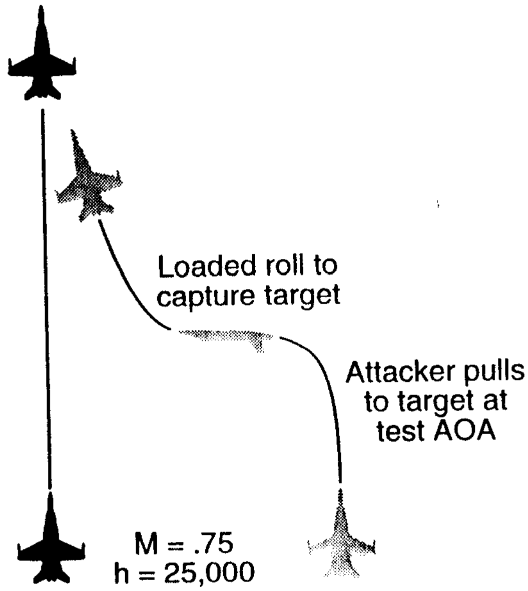


(a) Lateral gross acquisition

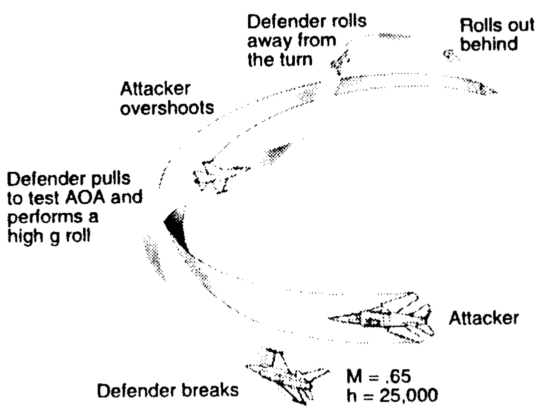
Figure 11. - Illustrations of selected evaluation maneuvers



(b) Tail chase acquisition



(d) Offensive loaded reversal



(c) Defensive roll

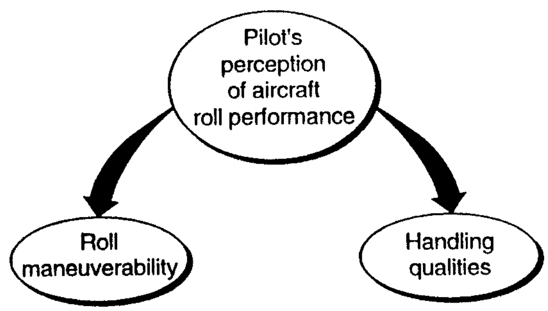


Figure 12. - Elements of pilot evaluation of the lateral-directional axes

Roll Performance for Mission Effectiveness	Improvements in Roll Performance	Numerical
Enhancing - Tactically superior	None warranted	1
Satisfactory - Mission requirements met	May be warranted, but not required	2
		2.5
Unsatisfactory - Mission requirements not met	Required	3
Inadequate - Could not perform maneuver	Mandatory	4

Figure 13. - Roll performance classification

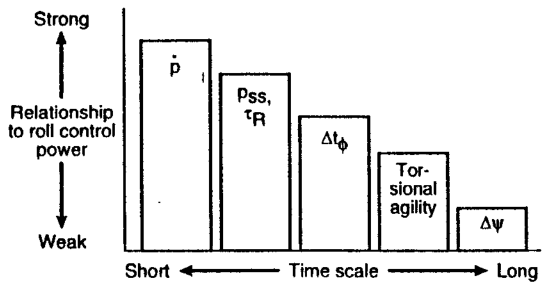


Figure 14. - Potential figures of merit

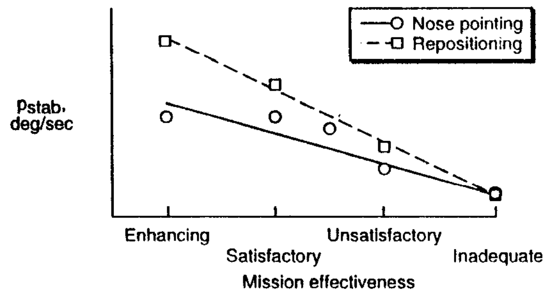
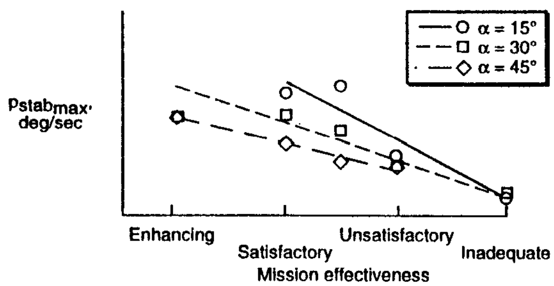
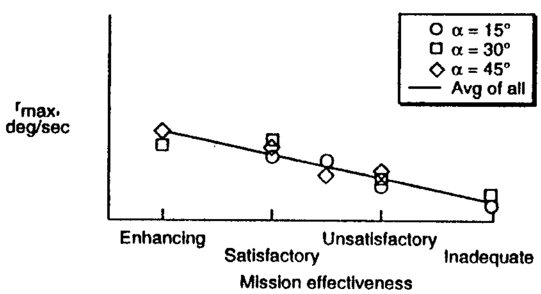


Figure 16. -Effect of maneuver type on maneuvering requirements; $\alpha = 30°$



(a) Effect on roll rate



(b) Effect on yaw rate

Figure 15. - Effect of angle of attack on maneuvering requirements; Nosepointing maneuvers

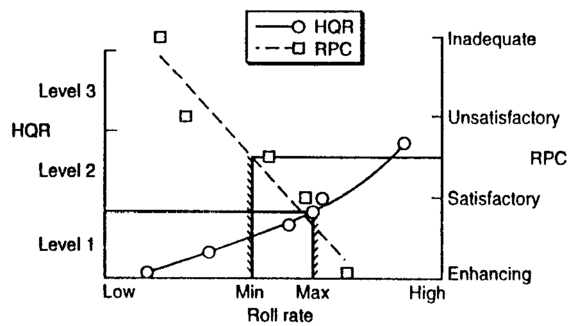


Figure 17. - Illustration of the use of HQR and RPC ratings to determine desired roll performance

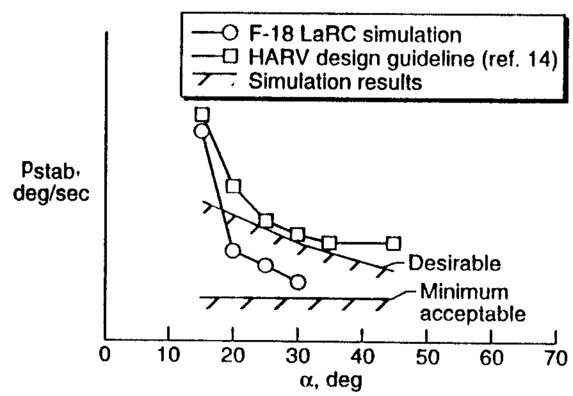


Figure 18. - Summary of preliminary simulation results; Nosepointing maneuvers