

RESULTS OF RECENT NASA STUDIES ON
AUTOMATIC SPIN PREVENTION FOR FIGHTER AIRCRAFT

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SUMMARY

The NASA Langley Research Center is currently engaged in a broad-based research program to eliminate or minimize inadvertent spins for advanced military aircraft. Recent piloted simulator studies and airplane flight tests have demonstrated that the automatic control systems in use on current fighters can be tailored to provide a high degree of spin resistance for some configurations without restrictions to maneuverability. Such systems result in greatly increased tactical effectiveness, safety, and pilot confidence.

INTRODUCTION

Recent experience has shown that most contemporary fighter airplanes exhibit poor stall characteristics and a strong tendency to spin. They also have poor spin characteristics, and recovery from a fully developed spin is usually difficult or impossible. As a result of these unsatisfactory stall and spin characteristics, the developed spin is currently an undesirable and potentially dangerous flight condition which should be avoided. There is, therefore, an urgent need to develop guidelines for use in the design of future military aircraft in order to minimize or eliminate spins and insure good handling qualities at high angles of attack. The National Aeronautics and Space Administration (NASA) currently has a broad research program underway to provide these guidelines. As shown in figure 1, the program includes conventional static wind-tunnel force tests, dynamic force tests, flight tests of dynamically scaled models, theoretical studies, and piloted simulator studies.

Two approaches to providing spin resistance are currently under consideration. In the first approach, the basic airframe is configured to be inherently spin resistant by virtue of good stability and control characteristics at high angles of attack. At the present time, however, the configuration-dependent nature of the problem and a lack of understanding of the major factors affecting stability and control characteristics at high angles of attack for current fighters have prevented the development of detailed design procedures for inherent spin resistance. The second more promising approach to providing spin resistance is through the use of avionics and flight control system elements in automatic spin prevention concepts. Such concepts can be highly effective in preventing inadvertent stalls and spins; however, they must be designed so as not to restrict the maneuverability and tactical effectiveness of the airplane.

The present paper discusses the results of recent NASA studies on automatic spin prevention. The studies were conducted at the NASA Langley Research Center (LaRC) using piloted simulator studies.

SYMBOLS

b	wing span, m (ft)
C_{ℓ}	rolling-moment coefficient, $\frac{M_x}{qSb}$
$C_{\ell p}$	damping in roll parameter, $\frac{\partial C_{\ell}}{\partial \frac{pb}{2V}}$
$C_{\ell \beta}$	effective dihedral derivative, $\frac{\partial C_{\ell}}{\partial \beta}$, per deg
$C_{\ell \delta_a}$	aileron rolling-moment derivative, $\frac{\partial C_{\ell}}{\partial \delta_a}$, per deg
C_n	yawing-moment coefficient, $\frac{M_z}{qSb}$
C_{nr}	damping in yaw parameter, $\frac{\partial C_n}{\partial \frac{rb}{2V}}$
$C_{n\beta}$	directional stability derivative, $\frac{\partial C_n}{\partial \beta}$, per deg
$C_{n\beta, dyn}$	dynamic directional stability parameter, $C_{n\beta} - C_{\ell\beta} \frac{I_z}{I_x} \sin \alpha$, per deg
$C_{n\delta_a}$	aileron yawing-moment derivative, $\frac{\partial C_n}{\partial \delta_a}$, per deg
I_x, I_z	moments of inertia about X- and Z-body axes, $\text{kg}\cdot\text{m}^2$ (slug-ft ²)
M_x, M_z	moments about X- and Z-body axes, m-N (ft-lb)
p	rolling velocity, deg/sec
q	free-stream dynamic pressure, Pa (lb/ft ²)
r	yawing velocity, deg/sec
r_s	$\approx r - p\alpha$, deg/sec
S	wing area, m ² (ft ²)
$t_{1/2}$	time to half amplitude, sec

V	airspeed, m/sec (ft/sec)
α	angle of attack, deg
β	angle of sideslip, deg
δ_a	aileron deflection, deg
δ_r	rudder deflection, deg
ϕ	angle of roll, deg

AUTOMATIC SPIN PREVENTION CONCEPTS

Experience has shown that spins can generally be avoided if the proper recovery action is taken immediately after departure from controlled flight while the spin energy is low and the aerodynamic controls are effective. The problem in effecting such early recovery is that the pilot frequently is not able to take immediate corrective action because of disorientation which results from his lack of experience with spins of such aircraft, from the fact that the departure and spin entry occurred unexpectedly when he was intent on another task, and from the violent and confusing nature of the motions during spin entry for many airplanes. This situation would seem to suggest the use of an automatic system which could quickly identify the situation and take the required action. An electronic system capable of this task would have several inherent advantages over the human pilot, including (1) quicker and surer recognition of an incipient spin, (2) faster reaction time for initiation of recovery, (3) application of correct spin-recovery controls, and (4) elimination of tendencies toward spin reversal.

The idea of automatic spin-prevention, or recovery, systems is not new. Stick pushers that prevent, or discourage, stalling the airplane are, in a sense, spin-prevention systems; but they may restrict the pilot from exploiting the full potential-maneuver envelope of the airplane. The installation of more elaborate automatic spin-prevention, or recovery, systems has, until recent years, involved the addition of complete sensing, logic, and control systems at a time when such devices were not very reliable and would probably not have been maintained in proper operating condition because they were protecting against a very rare occurrence. The fact that modern tactical airplanes already incorporate most of the elements of automatic spin-prevention (or recovery) systems, together with a great increase in the reliability of avionics systems, now makes the use of these automatic systems more practical.

Several approaches to automatic spin prevention have been evaluated by NASA. The concepts studied and the area of application of each concept are graphically depicted in figure 2. Yaw rate and angle of attack are used as the primary variables identifying spin entry. For a particular airplane configuration, one can generally identify two important areas in the yaw-rate-angle-of-attack plane: the airplane maneuver envelope involving relatively low values of yaw rate and angle of attack, and the developed spin

region involving relatively high values of yaw rate and angle of attack. Three types of automatic control concepts have been evaluated: (1) automatic spin recovery, (2) automatic spin prevention, and (3) automatic departure prevention.

In the automatic-spin-recovery concept, the airplane is allowed to depart from controlled flight, experience the incipient spin, and enter the fully developed spin. Values of yaw rate and angle of attack supplied by the sensors used in the automatic control system are sampled to identify the developed spin condition and actuate the proper recovery controls. The results of a study of the effectiveness and value of such a system (ref. 1) indicated that the primary benefits of this type of concept were: rapid identification of the spin, input of proper recovery controls, and minimization or elimination of spin reversals following recovery. The concept obviously requires the airplane under consideration to have satisfactory spin-recovery characteristics. Inasmuch as most current fighter designs have poor recovery characteristics from developed spins, it would appear that systems of this type would be relatively ineffective. In fact, the concept appears to be working "the wrong end of the problem."

The automatic-spin-prevention concept indicated in figure 2 also allows the airplane to depart from controlled flight; however, recovery controls are actuated during the early stages of the incipient spin when recovery characteristics are generally good. By simultaneously sensing angle of attack and yaw rate, a control actuation boundary can be established which limits the attainable magnitudes of these variables, thereby preventing spins. An automatic-spin-prevention system concept has been studied (ref. 1) using theoretical studies and flight tests of an unpowered drop model of a current military configuration. The results of the theoretical studies showed that such a system was extremely effective in preventing developed spins, and that the exact configuration of the automatic system will depend on the stall/spin characteristics of the airplane design under consideration. The model flight tests verified the theoretical results and showed that current flight-control components could be used to implement the system.

As might be expected, the control actuation boundary for the automatic-spin-prevention concept can be designed to be in proximity to the normal flight envelope, thereby permitting only minimal excursions from controlled flight. It should be pointed out that the concept described does not infringe on the maneuverability of the airplane or restrict the tactical effectiveness of the vehicle. Rather, the system quickly senses an out-of-control condition and impending spin and applies control inputs required of the pilot in a rapid, correct manner.

The automatic-spin-prevention concept appears to be ideally suited for airplanes which are especially susceptible to inadvertent spins. In particular, configurations which exhibit a severe directional divergence and loss of control power at high angles of attack are appropriate for application of the system if no limit is desired on angle of attack attained during normal flight. Fighter configurations, however, may exhibit a divergence at an angle of attack considerably higher than those used in normal maneuvering flight. In this case, artificial angle-of-attack limiting systems may be more appropriate.

Recently, a number of fighter configurations have been developed which are dynamically stable at high angles of attack with no natural tendency to diverge in yaw. However, the designs are subject to control-induced departures from controlled flight as a result of large values of adverse yaw at high angles of attack. These vehicles are well suited for the application of automatic-departure-prevention concepts (ref. 2) which, as indicated in figure 2, operate within the normal maneuver envelope of the airplane in order to prevent natural or control-induced departures from controlled flight. It will be shown that the use of such systems does not inhibit maneuvering of the airplane at high angles of attack and actually increases the usable maneuverability as well as the pilot's confidence during strenuous maneuvers.

EVALUATION PROCEDURES

Several techniques have been developed at LaRC for the evaluation of automatic departure/spin-prevention systems. As previously mentioned, free-flight tests of dynamically scaled models and theoretical studies of flight motions have been extremely valuable in assessing the effectiveness of such systems; however, these techniques do not allow an evaluation of pilot reaction to the effects of automatic systems on maneuverability and tactical effectiveness. The Langley differential maneuvering simulator (DMS) has therefore been used to obtain such information.

The DMS is a fixed base simulator which has the capability of simultaneously simulating two airplanes as they maneuver with respect to one another. Each pilot is provided a visual display of the sky-Earth orientation with respect to his airplane; in addition, a projected image of his opponent's airplane is also provided by way of a computer-controlled television system. A sketch of the general arrangement of the DMS hardware and control console is shown in figure 3. Contained within each of two 40-ft (12.2-m) diameter projection spheres are a cockpit, an airplane image projection system, and a sky-Earth projection system. A photograph of one of the cockpits and the target visual display during a typical engagement is shown in figure 4. A cockpit and instrument display representative of current fighter aircraft equipment are used together with a fixed gunsight for tracking. A programmable, hydraulic, control-feel system provides the capability of representing realistic control-force characteristics. Some of the unique capabilities of the DMS which make it well suited for studies of automatic departure-spin prevention are: the realistic cockpit/visual presentation, the use of realistic evaluation tasks, and the ability to handle comprehensive data packages. Additional details on the DMS facility are given in reference 3.

Previous experience with the simulation of fighter stall/spin characteristics (ref. 4) has shown that visual tracking tasks which require the pilot to divert his attention from the instrument panel are necessary to provide realism in studying the possibility of unintentional loss of control and spin entry. Furthermore, earlier studies have shown that mild, well-defined maneuvers can produce misleading results inasmuch as a configuration that behaves fairly well in such mild maneuvers may be violently uncontrollable in the

complex and pressing nature of high-g, air-combat maneuvering. Finally, for purposes of evaluation in comparing the performance of several configurations, the tasks employed must be repeatable. The test procedures used in the DMS studies account for the foregoing factors and can generally be divided into two phases. The first involves nontracking tasks in which the evaluation airplane is flown through individual high-angle-of-attack maneuvers including 1-g stalls, wind-up turns, high-g roll reversals, hammerhead stalls, and coupling maneuvers. These tests allow a comprehensive examination of the airplane's overall stability and control characteristics at high angles of attack including conditions involving complex aerodynamic and inertia coupling. In addition, they indicate the types of maneuvers which are the most critical in terms of the departure susceptibility of the airplane. The second test phase involves tracking of a target airplane through a series of maneuvers representative of air combat maneuvering (ACM). In order to obtain reasonable maneuvers which, on the other hand, will force the tracking airplane into maneuvering in the critical high-angle-of-attack regime, the target airplane is programmed to have the same thrust and performance characteristics as the evaluation airplane; however, the target airplane is given idealized high-angle-of-attack stability and control characteristics. The target airplane is flown by the evaluation pilot through a series of ACM tasks of varying levels of difficulty while the target's motions are recorded for playback later to drive the target as the task for the evaluation airplane. Results obtained in the first test phase are factored into the generation of these target maneuvers so that the most critical flight conditions will be encountered by the evaluation airplane during tracking. These tracking tasks generally fall into three categories: (a) steady wind-up turns for steady tracking evaluation, (b) bank-to-bank (or horizontal S) tasks with gradually increasing angle of attack up to maximum α to evaluate rapid rolls and target acquisition, and (c) complex, vigorous ACM tasks to evaluate the simulated airplane's susceptibility to high-angle-of-attack handling qualities problems during aggressive maneuvering. These tracking tasks, then, provide the complex, repeatable, pilot-attention-out-of-the-cockpit tasks which are required for realistic investigation of unintentional loss of control and spin entry.

The results of these studies using the above evaluation procedures are in the form of time-history records of airplane motions and pilot comments regarding the departure/spin susceptibility of particular configurations and the effects of automatic prevention systems on these characteristics. The objectives of such studies are: (1) to determine the controllability and departure resistance of a configuration during 1-g stalls and accelerated stalls, (2) to determine the departure susceptibility of the configuration during demanding air combat maneuvers, and (3) to identify maneuvers or flight conditions which might overpower the departure-resistant characteristics provided by the automatic control system. Some of the more significant results are reviewed in the following section.

RESULTS OF SIMULATION

At the present time, simulator studies of the application of automatic departure/spin-prevention systems have been conducted at LaRC for the F-14,

YF-16, and YF-17 airplanes. The results of the studies show that such systems can be very effective in preventing inadvertent departures from controlled flight during strenuous maneuvering. The resulting improvement in high-angle-of-attack characteristics markedly improves handling, maneuverability, and safety. As a result of these improvements, the pilot's confidence in the capability of the vehicle is greatly increased, and the configuration can be used to its full capability. All of the studies show that these automatic systems can be implemented with current flight hardware. As examples of the applications of such systems, two types of departure/spin-prevention concepts that have been studied will be discussed.

Roll-Yaw Interconnect Systems

Shown in figure 5 are typical lateral-directional control characteristics for fighter configurations with adverse yaw. The data show the variation with angle of attack of yawing moments produced by ailerons and rudder for right roll and right yaw control inputs. The yawing moments produced by ailerons at low angles of attack are favorable (nose right) for right roll control; however, the moments become adverse (nose left) at high angles of attack. Right rudder input produces a normal nose right moment, but at high angles of attack the rudder loses effectiveness because of impingement of the low energy wake from the partially stalled wing. As can be seen, the magnitudes of the adverse moments due to ailerons are much larger than the corrective moments available from the rudder. When the resulting adverse moments are coupled with low directional stability at high angles of attack, a reversal of roll response occurs wherein the airplane rolls in a direction opposite to that desired by the pilot.

Shown in figure 6 are calculated time histories which illustrate the roll reversal phenomenon. The roll response of a typical configuration is shown at an angle of attack of 25° for control inputs of rudder alone and aileron alone for right roll control. The response to the rudder input is seen to be quite normal. The airplane yaws to the right, creating nose-right sideslip. The dihedral effect then rolls the airplane to the right, as desired. In contrast to this result, input of aileron control creates adverse yaw which causes the airplane to yaw to the left, and the sideslip created is in the opposite direction, resulting in the dihedral effect opposing the rolling moment produced by the aileron. After a brief time, the airplane rolls to the left in response to the right roll control.

As would be expected, the reversed roll response to normal lateral control stick inputs presents the pilot with a coordination problem in order to avoid unintentional loss of control and spins. Most fighter pilots adapt to the situation by transitioning from lateral stick inputs for roll control at low α to rudder pedal inputs for roll control at high α . The problem becomes one of how to phase these controls in an optimum manner to obtain maximum performance, particularly during the pressure of combat.

Using the simulator at LaRC, it has been found that configurations which exhibit such characteristics are susceptible to inadvertent departures during vigorous combat maneuvers. Many proposed solutions to this problem have been

evaluated during the simulations, but the most effective has been found to be the general class of roll/yaw control-interconnect (or ARI) systems. With this scheme, the rudder is electronically linked to move with the roll control so as to counter the adverse yaw produced by that control. In addition, for situations such as that described above wherein the adverse moments due to ailerons can be much larger than the corrective moments available from the rudder, the interconnect system must also phase out the aileron deflections. In this case, pilot stick inputs drive the rudder in addition to, or instead of, the normal roll-control surfaces. Because of the wide variation of the control characteristics with angle of attack, roll/yaw control-interconnect systems are necessarily scheduled as a function of α . In addition, in some cases Mach scheduling has also been found to be necessary.

An example of interconnect scheduling is shown in figure 7. Basically, the control system was modified such that deflection of the control stick laterally produced aileron inputs at low angles of attack and rudder inputs at high angles of attack. As shown in the sketch, the ailerons for the example discussed were phased out by $\alpha = 25^\circ$. At that point, lateral stick inputs produced only rudder inputs. In addition, the yawing moments produced by the ailerons above $\alpha = 25^\circ$ were used to advantage in an additional stability augmentation channel which augmented directional stability.

An example of the effectiveness of the roll/yaw control-interconnect system in preventing departures is illustrated in figure 8 which shows two attempted high-g rolling reversals. With the basic control system, the pilot applied left roll control while simultaneously loading the airplane very rapidly. Initially, the airplane responded as desired; however, as α increased, an inadvertent control-induced departure to the right occurred despite the application of full left controls. When the control system was modified with the interconnect, the pilot was able to execute the task with good control throughout the maneuver (the roll was intended to be to the left in both cases). This control scheme essentially eliminated inadvertent spins in the simulator.

The net effect of the automatic interconnect scheme on roll performance is illustrated in figure 9. With the basic control system, the roll rate produced by lateral deflection of the control stick reversed near $\alpha = 20^\circ$, and the pilot could not maneuver at higher angles of attack with only stick inputs. When the control system was modified with the interconnect, the pilot could maneuver the airplane beyond maximum lift using only stick inputs without fear or unintentional departures.

In general, the results of the simulation studies indicate that the use of a roll/yaw interconnect system can eliminate inadvertent departures on airplanes which are inherently dynamically stable at high α yet prone to control-induced departures due to adverse yaw. In addition to enhancing departure resistance, interconnect systems can also greatly improve high- α controllability characteristics such that the airplane becomes much more effective in tracking. However, it should also be mentioned that in a developed spin an interconnect system can be disadvantageous in that it does not allow the application of full recovery controls (δ_a with and δ_r against the spin). Thus, in the event of a spin, these systems should be deactivated.

Lateral-Directional Stability Augmentation

In addition to adverse yaw and lack of control effectiveness at high angles of attack, another factor that causes inadvertent departures from controlled flight is the degradation in lateral-directional stability at high angles of attack. This characteristic can be due to a loss in either static stability, $C_{n\beta}$ and $C_{l\beta}$, or damping, C_{nr} and C_{lp} , or to a combination of the two. A solution to this problem that has been studied during the simulation investigations is the use of stability augmentation tailored for high-angle-of-attack conditions. An effective control law has been found to be $r - p\alpha$ to rudder feedback, or stability axis yaw damping. Shown in figure 10 are Dutch roll mode damping characteristics versus α in 1-g flight for an airplane with and without a stability axis yaw damper. The data show that the damper was quite effective in increasing Dutch roll stability up to 30° angle of attack; at higher α , its effectiveness decreased due to a combination of reduced rudder power and loss of static stability. In addition to augmenting damping, the use of r_s feedback also restricts the airplane to roll about its flight path which is necessary to prevent the generation of large amounts of sideslip during rolling maneuvers at high angles of attack. If the airplane is rolled about its body axis in this region, a kinematic interchange between angle of attack and sideslip occurs. The large magnitudes of sideslip thus generated, coupled with low directional stability, could result in a departure. However, if the airplane is rolled in a conical motion about its flight path, then α/β coupling does not occur, and the susceptibility to departure is decreased. The simulation results have verified that this concept does indeed enhance departure resistance in addition to providing increased damping at high angles of attack.

Degradation of lateral-directional dynamic stability at high angles of attack is most often due to loss of static directional stability and dihedral effect. Damper systems based on rate feedback, such as the stability axis yaw damper discussed above, are generally less effective in augmenting stability in this situation. Obviously, the best solution is to directly augment $C_{n\beta}$ and $C_{l\beta}$ by driving the appropriate controls with a sideslip signal. Figure 11 shows data for a configuration which typifies the loss of dynamic stability at high angles of attack due to degraded $C_{l\beta}$ and $C_{n\beta}$ characteristics. The loss in static stability above 25° angle of attack is reflected in a sharp drop in the parameter $C_{n\beta, \text{dyn}}$ which indicates a possible directional divergence at $\alpha = 30^\circ$. Also shown in figure 11 are results obtained by augmenting $C_{n\beta}$ and $C_{l\beta}$ above $\alpha = 25^\circ$. The resulting $C_{n\beta, \text{dyn}}$ values remain large at high angles of attack indicating no instability in this region. This characteristic is confirmed in figure 12 which shows that the response of the augmented airplane to an applied rudder doublet at $\alpha = 30^\circ$ is a well-damped, higher-frequency oscillation than that of the basic airplane. In this case, the augmentation of $C_{n\beta}$ and $C_{l\beta}$ was accomplished by feeding a β signal, estimated using conventionally available measurements, to drive the ailerons above $\alpha = 25^\circ$. Aileron deflection on the particular configuration produced very large adverse yawing moments at high angles of attack such that they

could not be used for rolling above $\alpha = 25^\circ$. These large yawing moments, however, were used very advantageously to augment stability as shown below:

$$\text{Augmentation law: } \delta_a = K_\beta \cdot \beta, K_\beta > 0$$

$$C_{l\beta\text{aug}} = C_{l\beta} + K_\beta \cdot C_{l\delta_a}$$

$$C_{n\beta\text{aug}} = C_{n\beta} + K_\beta \cdot C_{n\delta_a}$$

Since $C_{l\delta_a}$ is negative, the β feedback to the ailerons augments dihedral effect; in addition, because $C_{n\delta_a}$ is positive, the feedback also augments directional stability by the increment $K_\beta \cdot C_{n\delta_a}$ which is considerable since

$C_{n\delta_a}$ is large. Note that the simultaneous augmentation of dihedral effect and directional stability using the single control would not be possible if $C_{n\delta_a}$ were not adverse. This case illustrates the important concept of using all available control moments for augmentation and control at high angles of attack, including those that are conventionally considered adverse, since these controls can often be quite powerful in the stall region.

CORRELATION WITH FLIGHT RESULTS

As indicated earlier, all the LaRC stall/spin simulations performed to date have involved actual, current, combat aircraft configurations. This situation permits correlation of the simulation results with those obtained in actual flight. In addition, qualitative validation of the simulations is obtained early in the programs by the participation of appropriate individuals to fly the simulator. These individuals include company as well as military test pilots directly involved with flight testing of the particular study configuration. Results to date have shown good qualitative correlation between simulator and flight results. The simulations have been found to be effective in predicting the general high-angle-of-attack stability and control characteristics of particular configurations; in addition, potential problems as well as benefits of various control schemes identified during the simulations have agreed well with flight results. Thus, an additional benefit of the simulation technique is that it can be used to study the effect of general control schemes, such as normal acceleration and roll-rate command, on high- α flight characteristics.

Many of the departure prevention concepts studied in the simulation programs have been implemented and are employed in current fighter aircraft. For example, LaRC studies on roll/yaw-interconnect concepts were instrumental in the development of the ARI system currently used on the F-14 airplane.

CONCLUDING REMARKS

This paper has discussed recent NASA studies on automatic spin prevention for fighter airplanes. This approach to providing spin resistance is a promising method to achieve this goal. This concept has become widely accepted by industry in the United States, and such systems have been implemented on the F-14, F-15, F-16, and F-18 designs. In order to be effective, however, the approach must be considered early in the design stages of military aircraft.

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Figure 1.- Scope of stall/spin research program.

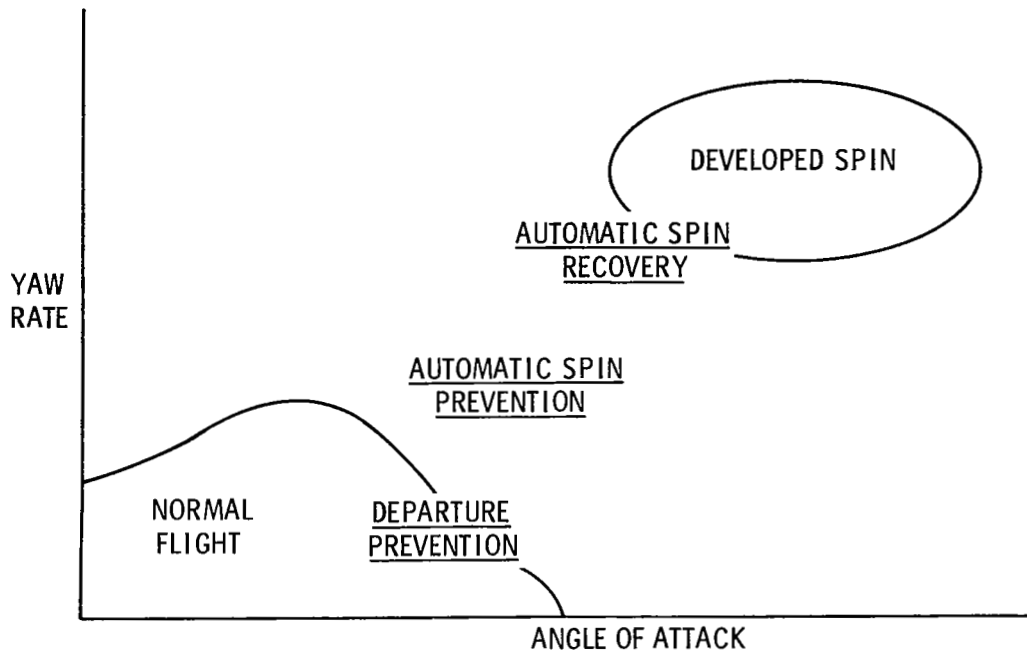


Figure 2.- Automatic control concepts for departure/spin prevention.

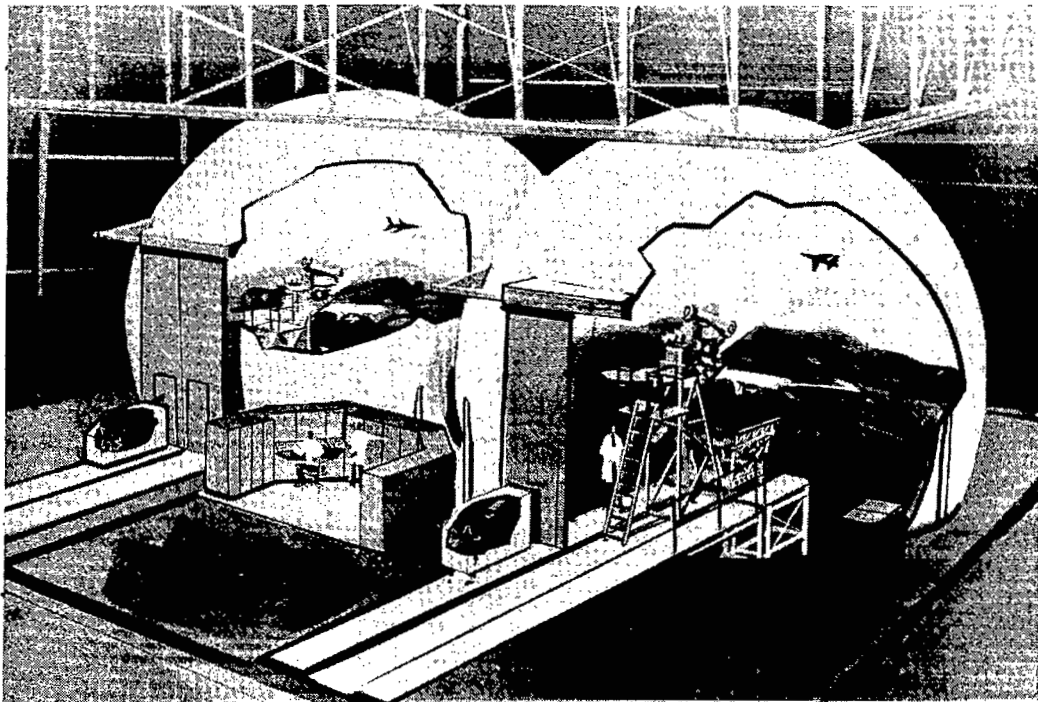


Figure 3.- General arrangement of the Langley differential maneuvering simulator facility.

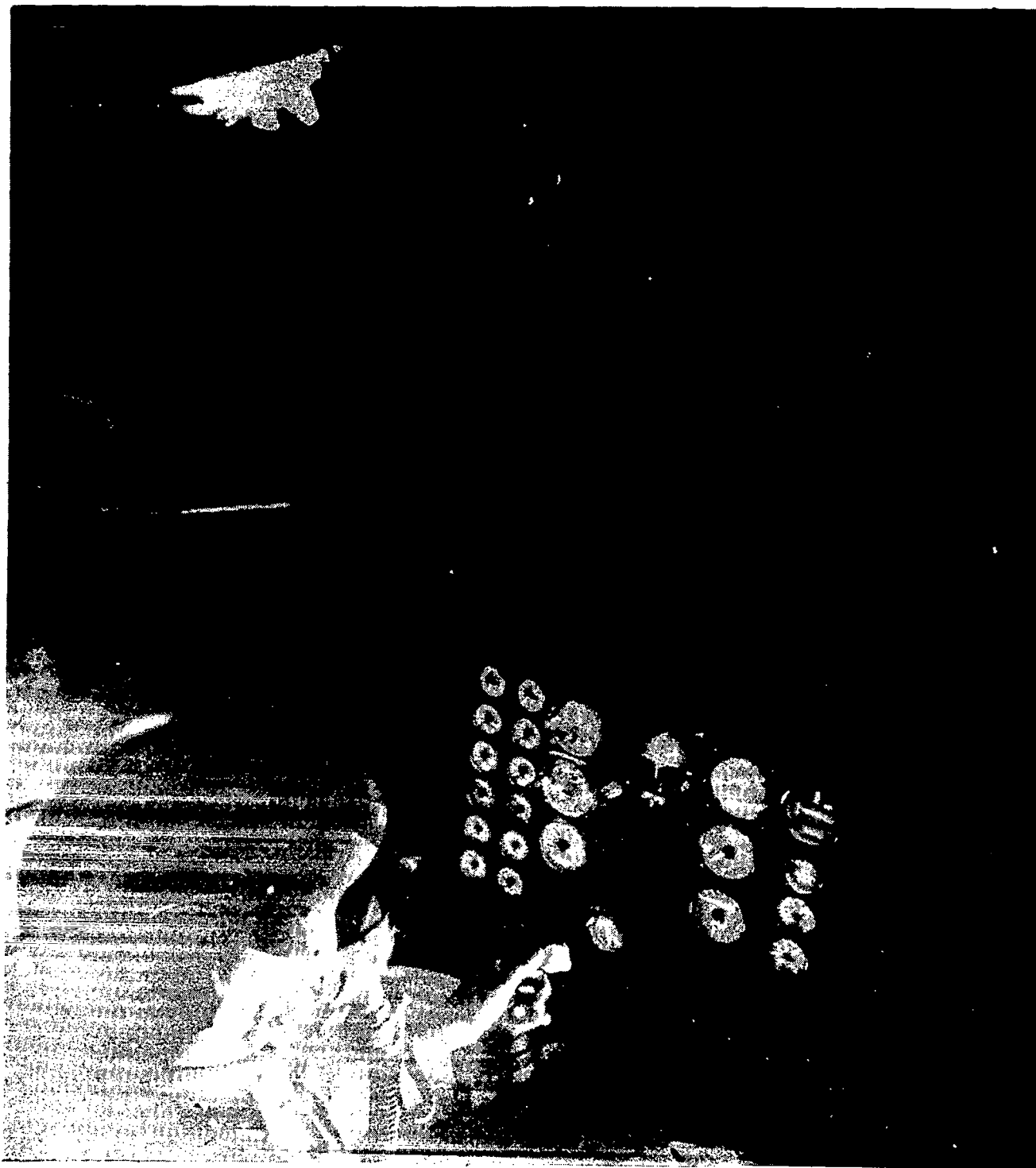


Figure 4.- View of cockpit and visual display within one sphere of DMS.

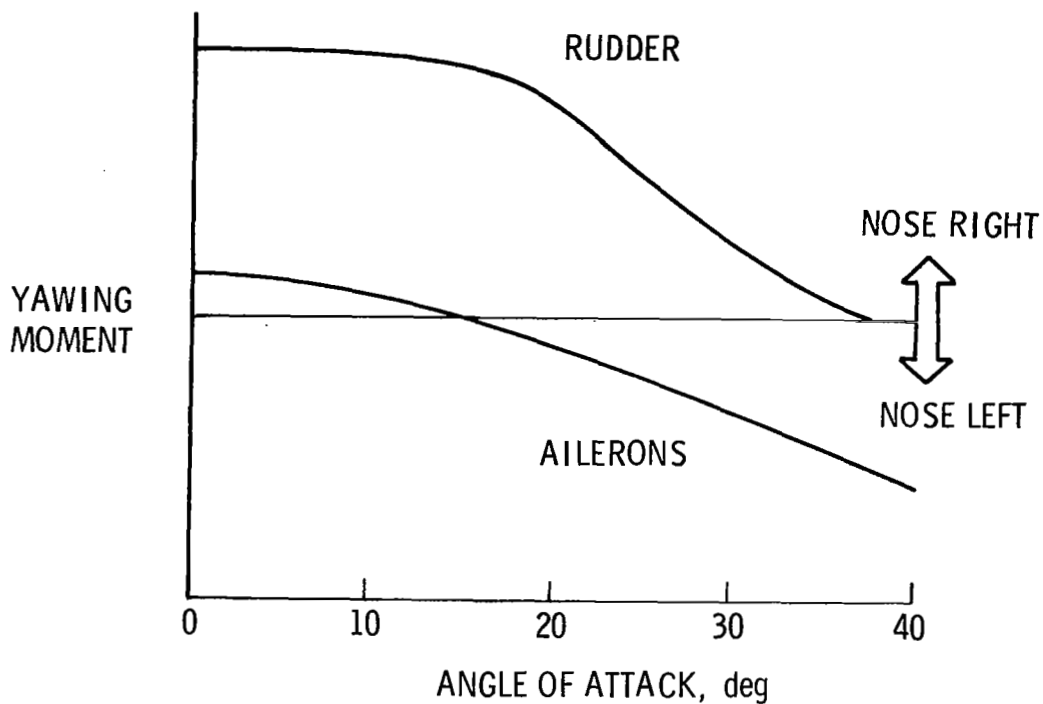


Figure 5.- Yawing moments produced by lateral-directional controls.

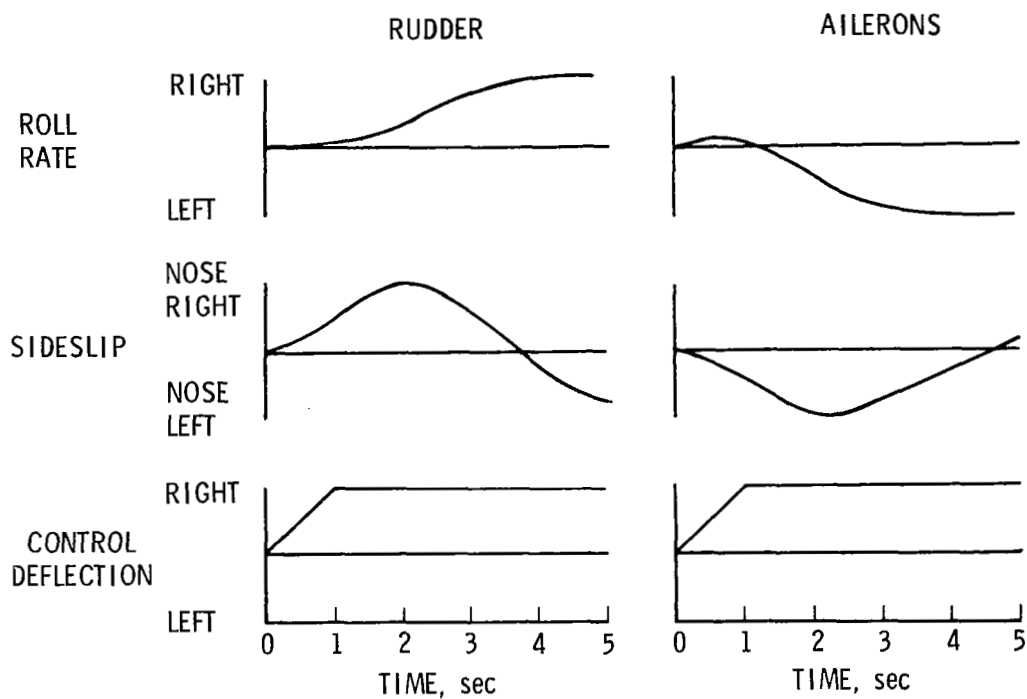


Figure 6.- Illustration of roll reversal.

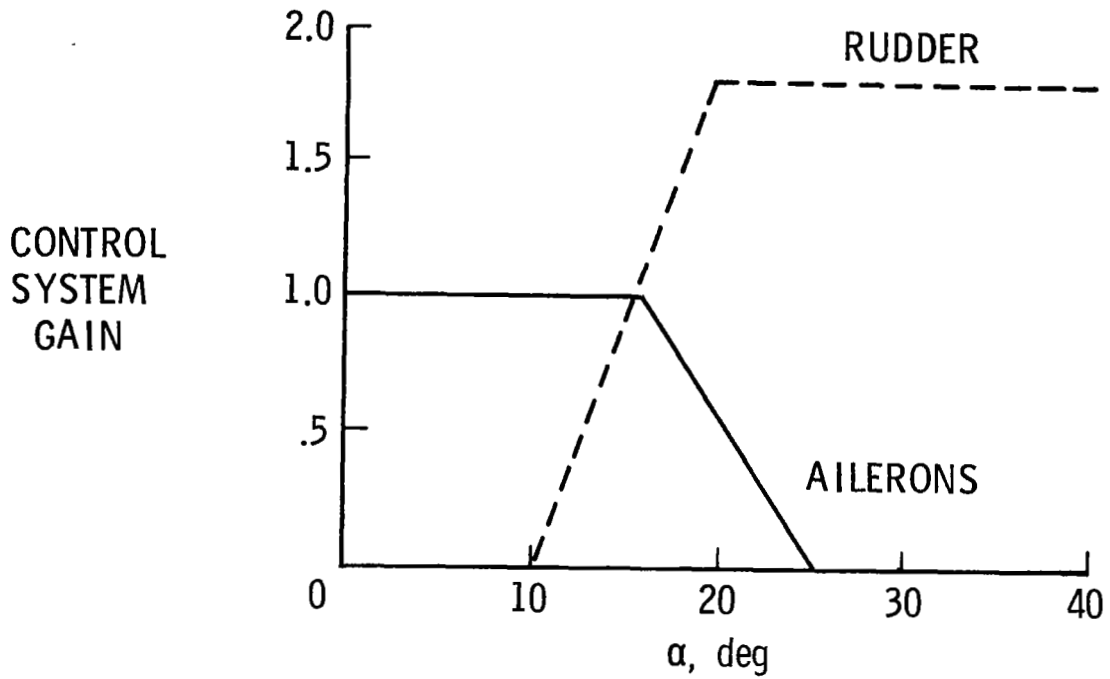


Figure 7.- Stick-to-rudder interconnect concept.

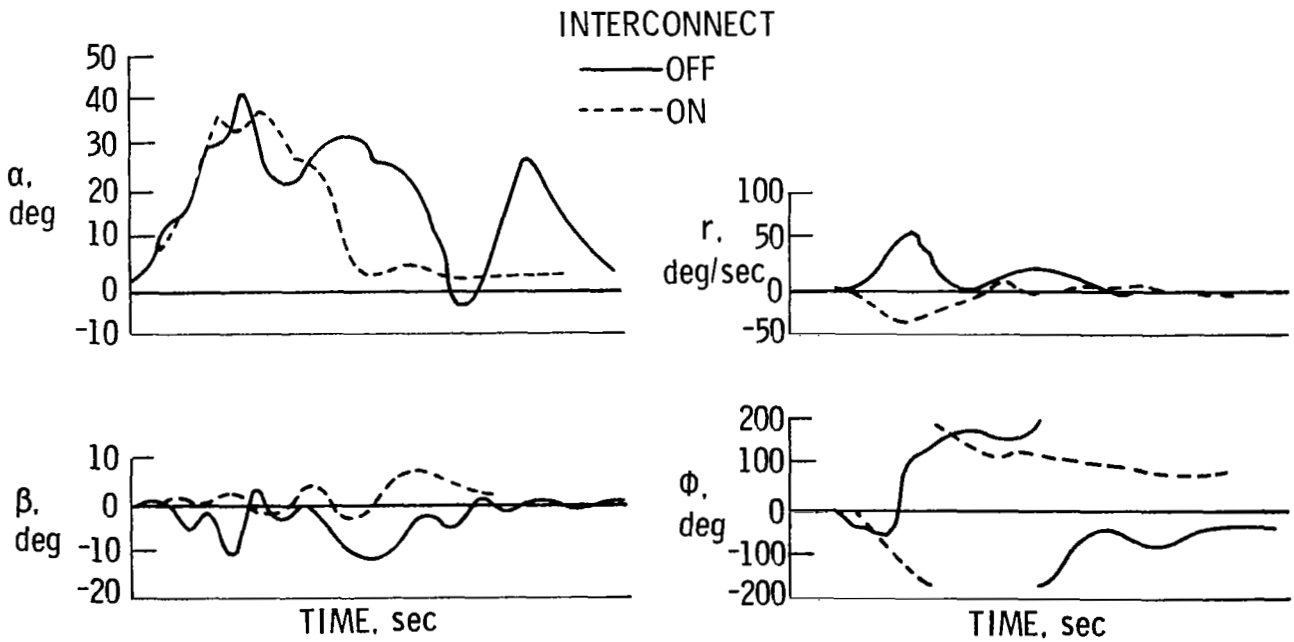


Figure 8.- Effect of roll/yaw interconnect in rolling reversal maneuver.

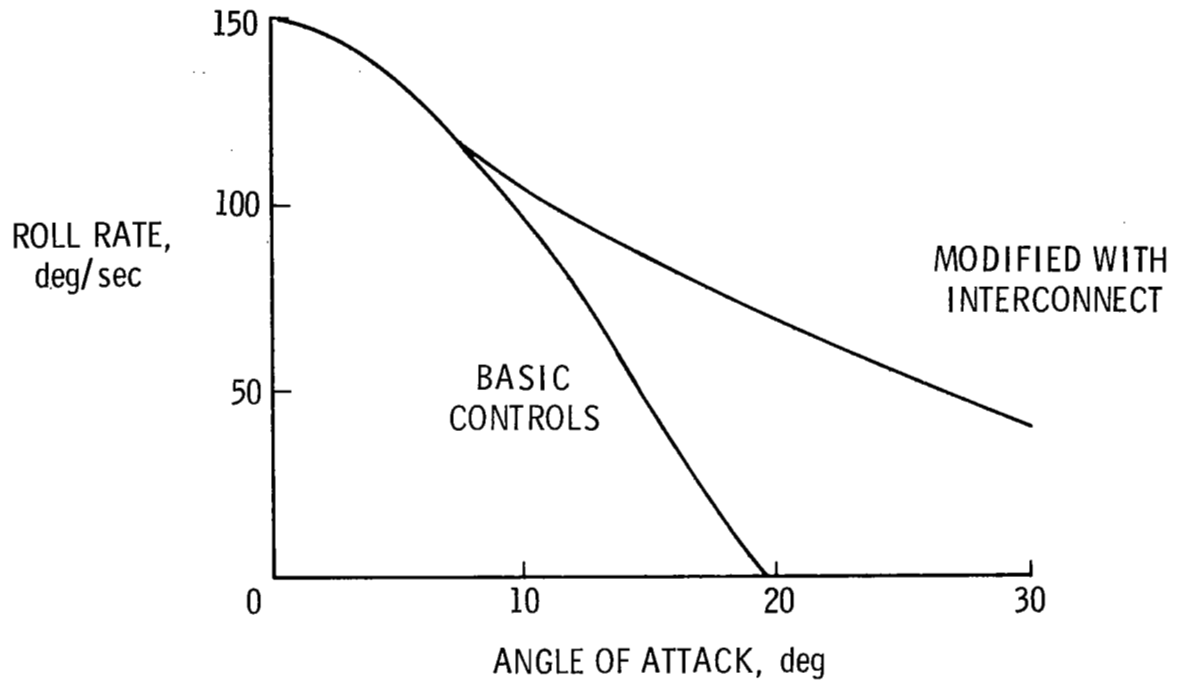


Figure 9.- Effect of interconnect on roll response to lateral stick input.

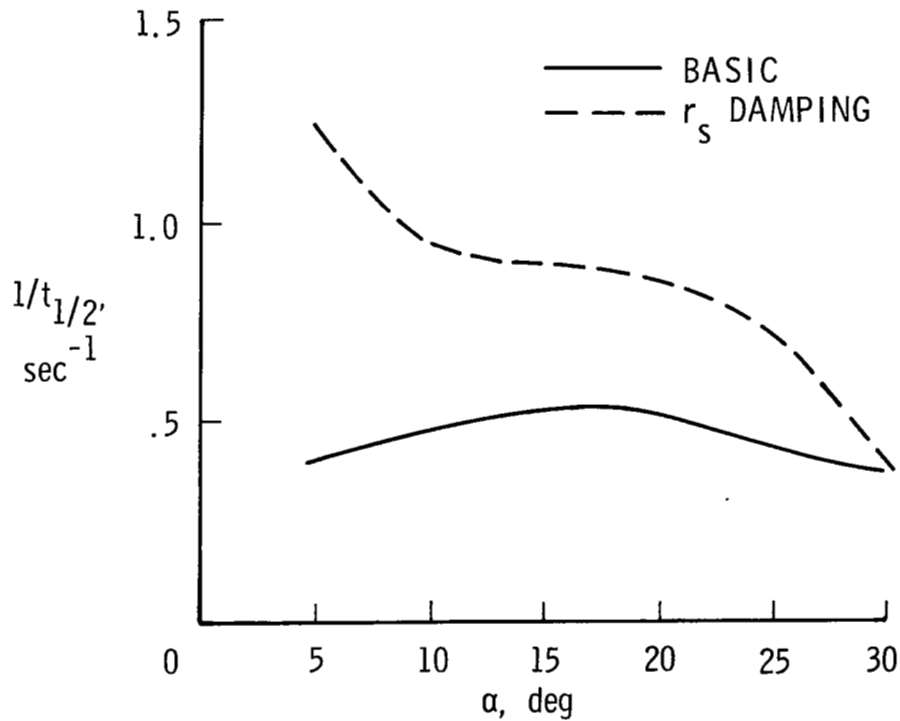


Figure 10.- Effect of stability axis yaw damping on Dutch roll mode damping.

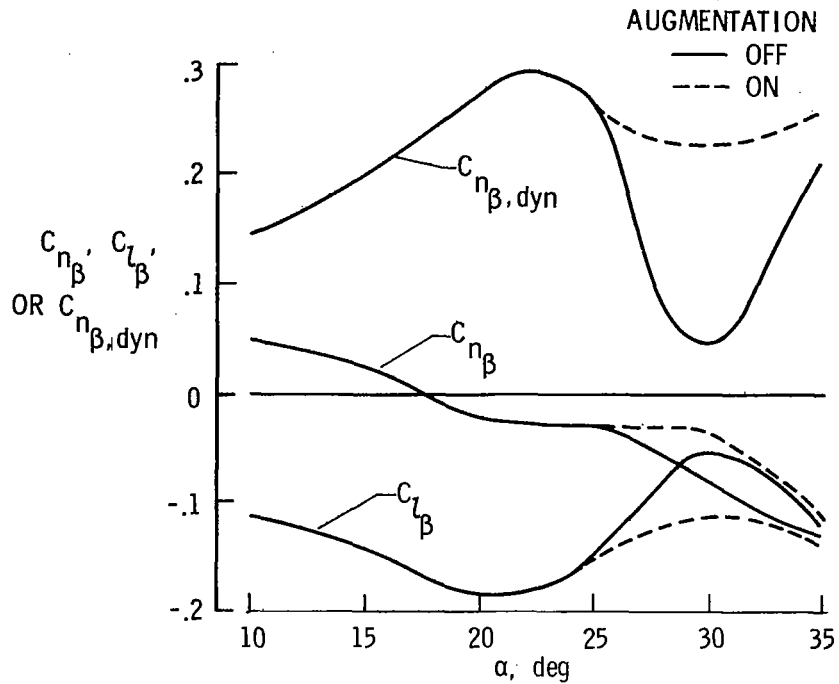


Figure 11.- Variation of lateral-directional stability characteristics with and without augmentation.

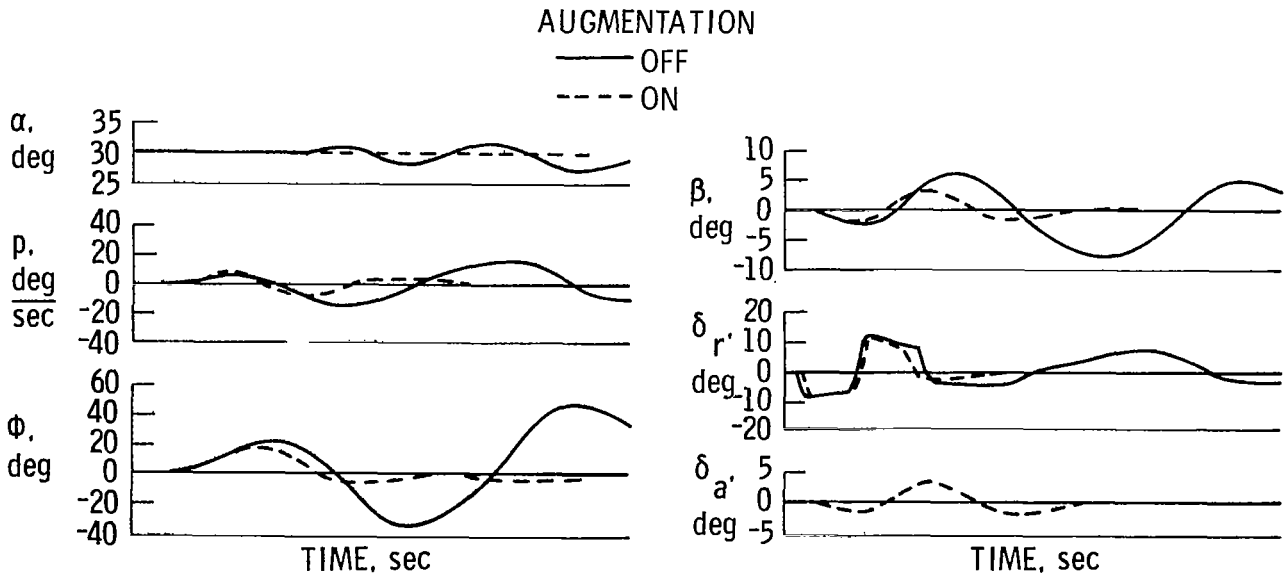


Figure 12.- Effect of augmentation on response to rudder doublet at $\alpha = 30^\circ$.