AUTOMATIC LIMITERS IN AIR FORCE AIRCRAFT FLIGHT CONTROL SYSTEMS

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ABSTRACT

The development of high-gain, full authority electronic flight control systems has enabled aircraft designers to include automatic limiting features in aircraft flight control systems. These limiters can provide maximum usable maneuver envelopes while avoiding undesirable or unsafe regions. Limiters also function reliably, repeatably, and rapidly without the pilot "getting in the loop," allowing him to concentrate on his mission. Initially implemented using analog flight control computers, these concepts are now being transitioned to a new generation of digital computers. This paper examines the use of automatic limiters in the flight control systems of three Air Force aircraft, the F-111, F-16, and B-1B, to increase their resistance to loss of control during maneuvering flight.

INTRODUCTION

Aircraft often have undesirable aerodynamic stability and control characteristics that none of their designers, engineers or pilots would wish to see in the final product. These characteristcs can include uncommanded pitch-ups, as in the F-104, sudden directional divergences or "nose slices", as in the F-4, deep stalls, as in many T-tail aircraft like the Boeing 727, inertial coupling, as in the F-100, and aileron reversal, as in the B-47. These phenomena, usually occurring at high angles of attack (AOA) or high dynamic pressures, may result in loss of control of the aircraft. To avoid these characteristics, warning systems were introduced in the 1950's and early 1960's to alert pilots of dangerous conditions with aural, visual and/or tactile cues. For example, stick and rudder pedal shakers were introduced in aircraft to give pilots a tactile cue of the vehicle's AOA. Some devices were designed to "make" the pilot take the correct action. For example, a stick pusher was used in the F-104 to physically position the pitch controls to prevent departure as the AOA approached stall. However, the effectiveness of these devices proved to be inadequate for a newer generation of high performance aircraft being developed during the late 1960's and 1970's. A new approach was needed to automatically limit AOA through the flight control system and require no pilot action. With this background in mind, the F-111, F-16, and B-1B automatic limiting systems will now be discussed.

The F-111 Aircraft

Aerodynamics -

The high AOA aerodynamic characteristics of the F-111 include a loss of directional stability, adverse yaw from differential stabilator deflection, and high levels of induced drag. Figure 1 shows a typical plot of static directional stability versus AOA. The loss of directional stability results in directional divergences or "nose slices". Figure 2 shows a typical plot of the yaw-due-to-aileron characteristic versus AOA. Note the change from proverse to adverse yaw as AOA increases. The resulting yawing motions at high AOA when roll control is commanded by the pilot increase departure tendancies. Figure 3 shows typical thrust required and available curves. The high levels of drag result in rapid buildup of AOA at slow speeds, increasing total drag levels still further, especially as the aircraft's operating point transitions to the so-called "back side" of the power required curve. The rapid increase in AOA also results in rapidly increasing sink rates. In combination, these characteristics result in departure susceptibility of the F-111.

Flight Control System -

The flight control laws of the F-111 were designed to provide "neutral speed stability" so that speed changes would not require the pilot to continually retrim the aircraft in pitch. Also, the system was designed such that the pilot commanded normal load factor through the pitch stick. As a result, when the aircraft was trimmed in level flight, the pilot received no cues through the control stick as the airspeed changed even though the control system moved the horizontal stabilizers to maintain his trimmed 1g condition. If the pilot did not adjust the throttles precisely to maintain his trim airspeed and the aircraft began to decelerate, the control system allowed the AOA to increase to maintain 1g. If the airspeed got so low and the AOA so high that neutral directional stability was reached, an unexpected loss of control could occur without warning to the pilot. In landing approach configuration, the deceleration could rapidly transition the aircraft to the back side of the power curve where increasing thrust levels are required to maintain flight at lower speeds and where lack of sufficient available thrust would quickly result in high sink rates. Although the F-111 had a rudder pedal shaker triggered by AOA to warn the pilot of excessive AOA conditions, it was not an effective system.To help alleviate the F-111's undesirable flying qualities, a Stall Inhibitor System (SIS) was developed.

Stall Inhibitor System -

The F-111 SIS was designed to prevent departures at high angles of attack where loss of directional stability occurs and to reduce the chance that high sink rates could develop quickly, especially at low altitudes. A simplified functional block diagram of the SIS control laws is shown in figure 4. AOA feedback was added to cancel commands from the pilot and command augmentation system (CAS) that would otherwise have increased AOA. The SIS functions through the original series pitch damper in the stability augmentation system (SAS). By summing AOA and washed-out pitch rate, a signal is generated to command the pitch damper servo in the nose down direction. The signal is gain scheduled as a function of AOA to reduce the command augmentation authority and increase the stick force required for the pilot to increase AOA further. The net effect is to decrease the nose up stabilizer authority available through the flight control system as AOA increases and make approaching a stability limit noticeable to the pilot through control stick cues.

The SIS also contains a sideslip angle reducer function that acts through the yaw damper to minimize sideslip angle. A simplified block diagram of this function is shown in figure 5. Roll rate and yaw rate signals are combined into a pseudo-sideslip angle rate signal and used to command the rudder to minimize sideslip angle during rolling maneuvers. Additionally, a differential stabilizer position signal is used to command rudder in the proper sense to compensate for the adverse yaw characteristic and coordinate the roll or turn, functioning as an aileron-to-rudder interconnect (ARI). These signals are also scheduled as a function of AOA.

The F-16 Aircraft

Aerodynamics -

Significant F-16 airframe characteristics include both an unstable slope to its pitching moment curve and a loss of directional stability at high AOA, as shown in figures 6 and 7, respectively. These characteristics result in departure susceptibility if the pilot attempts to maneuver in that region. The F-16 can also stabilize at an extremely high AOA after a departure, called a "deep stall" condition, from which recovery may not be possible. As a result, the contractor included AOA limiting in the flight control system from the beginning to avoid the high AOA conditions where these undesirable aerodynamic characteristics would be encountered.

Also, since the F-16 airframe was designed to be statically unstable in pitch at subsonic Mach numbers, the flight control system must stabilize as well as control the aircraft with the all-moving horizontal tails. As a consequence, during high roll rate maneuvers at high angles of attack, there may be insufficient nose-down restoring moments available from the horizontal tails to counter inertially generated nose-up moments. Figure 8 shows the trend in the inertial coupling tendency as AOA increases. This roll-pitch coupling phenomenon resulted in the development of a roll rate limiter that will be discussed shortly.

Flight Control System -

The F-16 flight control system also created some unique characteristics because of the control laws adopted. In the pitch axis, the F-16 was designed to have neutral speed stability for up-and-away flight, similar to the F-111 design. It therefore could also achieve low speeds and high AOA's without cues to the pilot through the cockpit controls. The lack of cues to the pilot was also aggravated by the use of a force-sensing side stick controller without noticable motion. In the roll axis, the system was designed to roll the aircraft in response to lateral pilot commands applied to the side stick controller. The command resulted in differential deflection of the wing flaperons and horizontal tails, and coordinated deflection of the rudder through an ARI to minimize sideslip angle. However, F-16 pilots originally trained in aircraft like the F-4 were taught to roll at high AOA with rudder commands rather than lateral stick commands to avoid departures due to adverse yaw from ailerons and differential tails. When they rolled the F-16 at high AOA with rudder, the aircraft often departed. Why? As expected, the rudder pedal command generated sideslip angle which in turn caused the aircraft to roll. However, as long as the pilot avoided lateral stick commands, the flight control system assumed the pilot wanted zero roll rate and commanded differential flaperon and horizontal tail deflections to stop the roll. The net result was control surface positions that are "pro-spin" and that caused loss of control.

The F-16 flight control laws were initially developed and tested for several air-to-air external weapons loadings including missiles, ECM pods and external fuel tanks. However, F-16 missions gradually evolved into ones that were also largely air-to-ground, and the complement of heavy external stores with which the F-16 was to remain departure resistant expanded significantly. The inertial and aerodynamic effects of these stores aggravated the roll coupling tendencies that had been noted with the air-to-air configurations. As a result, the automatic limiters were made dual mode. That is, they had one set of control laws and gains for air-to-air loadings and another, more restrictive set, for the air-to-ground loadings. The appropriate limiter mode was selected by the pilot with a switch in the cockpit.

Angle of Attack Limiter -

Figure 9 shows a simplified block diagram of the F-16 AOA limiter control laws. Angle of attack is measured, combined with washed out pitch rate for rate anticipation, and fed back to the horizontal tails through two paths that are switched on at different AOA's and gain scheduled. These two paths result in the two-slope characteristic of the AOA/Load Factor boundary shown in figure 10. Also shown in figure 9 are the F-16's command path integrator and load factor feedback path (to make it a "G" command system), the pitch rate feedback path (for improved damping), and the proportional AOA feedback path (to stabilize the F-16 airframe) in the basic control laws.

Roll Rate/Rudder Command Limiters -

Figure 11 shows a simplified block diagram of the roll rate command limiter. The roll rate limiter controls the maximum roll rate the pilot can command as a function of AOA, dynamic pressure, and horizontal tail deflection. As maximum roll rate is reduced, the inertial coupling tendency is reduced. The rudder command limiter was incorporated to limit the pilot's ability to command rudder at high AOA where the adverse yaw characteristcs of the roll control surfaces are especially strong contributors to departure susceptibility. Figure 12 shows the rudder command limiter boundary. Here, the maximum rudder command is reduced as AOA increases beyond a critical value. Therefore, if the pilot wants to achieve a high roll rate there, he must use the lateral stick commands that the roll control laws were designed to use. Additionally, figures 10 and 12 show how the AOA and rudder command limiters, respectively, vary as roll rate increases to further control roll coupling tendencies.

The B-1B Aircraft

Aerodynamics -

The aerodynamic characteristic of the B-1 airframe that results in the need for departure prevention is a sudden change from stability to instability in pitch at high AOA. Passing the point of neutral stability results in an uncommanded pitch-up to excessive angles of attack and departure from controlled flight. A typical pitching moment curve is shown in figure 13. In this case, stall AOA is defined by a stability characteristic rather than by a sudden loss of wing lift. The B-1A design included a warning system that consisted of a stick shaker, horn and light to alert the pilot of impending loss of control. The warnings were triggered by the Central Air Data Computer (CADC) at an AOA that was 80% of the stall AOA, which was the AOA at which neutral stability occurred. The CADC computed stall AOA continuously based on wing sweep, flap/slat position, center of gravity location, and Mach number. This 20% loss of usable AOA envelope was not a serious problem for the B-1A because its operating weight range and Mach/altitude envelope did not require AOA's in this region during cruise and maneuver.

The B-1B has an almost identical external aerodynamic configuration as the B-1A. The pitch-up tendency from the unstable pitching moment break still exists. However, the B-1B operating weight range has increased relative to that of the B-1A due to the incorporation of additional fuel, new weapons, and structural modifications to accomodate these changes. Consequently, the AOA's necessary for the B-1B to cruise, climb and maneuver are significantly higher than those needed by the B-1A and include AOA's beyond the point of neutral stability. Rather than modify the B-1B airframe aerodynamics, the Air Force decided to apply the concepts of a Stall Inhibitor System (SIS) and Stability Enhancement Function (SEF) to the B-1B.

Flight Control System -
The B-1B's flight control system is basically unchanged from that of the B-1A. There are parallel mechanical and electrical command paths that are mechanically summed prior to the surface actuators. The Stability and Control Augmentation System (SCAS) provides improved damping through pitch, roll and yaw rate feedbacks. The SCAS servo commands are summed mechanically with the mechanical and electrical commands from the crew. There is a roll/yaw interconnect to coordinate turns. Flying qualities and the feel of the aircraft to the pilot are significantly influenced by mechanical system nonlinearities and rigging tolerances.

Stall Inhibitor/Stability Enhancement Systems -

Why both a SIS and SEF? The SIS concept was based on the F-111 SIS that had already been developed and with which the Strategic Air Command (SAC) pilots were familiar. The B-1B SIS was to automatically limit AOA to prevent exceeding the stall AOA (neutral stability) and open the usable AOA envelope by triggering the horn and light stall warnings at 95% of stall AOA rather than at 80%. It was judged to be a low risk approach because of the F-111 experience as well as the availability of B-1A flight test data at angles of attack up to the stall AOA. Although SIS does not allow the B-1B to fly at AOA's beyond neutral stability, it does enlarge the usable AOA envelope, thus providing enhanced maneuverability at heavy weights with improved departure protection. The SEF, on the other hand, was designed to allow operation at AOA's where the B-1B was unstable in pitch and automatically limit AOA to prevent departure. This was done using techniques similar to those successfully applied to the F-111 and F-16. SEF AOA limits are based on factors including remaining stabilizer control authority, turbulence and gust response characteristics, and magnitude of overshoots of the AOA limit. SEF development had higher risks because aerodynamic data was needed at AOA's where the B-1A had not been flown during its flight test program and where confidence in the accuracy of the wind tunnel data base was relatively low.

Figure 14 shows a simplified block diagram of the SIS/SEF control laws. Functionally, SIS and SEF are identical. The only difference between the SIS and SEF implementations is in the computation of AOA limits in the CADC. AOA and AOA rate are used to generate a "standardized" AOA signal that is adjusted to account for the effects of wing sweep, flap/slat position, Mach number, etc. and fed back through gain scheduling to the SCAS servo and to the stabilizers. The standardized AOA varies from zero at zero lift to 1.0 at the AOA limit. The same signal is used in the command limiter to reduce the pilot's authority to command the stabilizers and provide increasing stick force cues as AOA increases. Although pitch rate feedback for damping was part of the original SCAS design, additional pitch rate feedback is added at high AOA's by SIS/SEF. Both SIS and SEF were designed to solve a pitch axis problem and no features have been included to address combined axis issues such as inertial coupling.

Summary of Common Characteristics

As you may have already perceived from the descriptions above, there are several features that all three automatic limiting concepts have in common. All three include AOA feedback, anticipation with either pitch rate or AOA rate feedback, and pilot command limiting for increasing stick force cues. All three concepts gradually phase out the pilot's ability to increase AOA further as AOA increases. Perhaps less obvious, each aircraft also has an ARI (or roll/yaw interconnect), either as part of the limiters or as part of the basic flight control laws. From simulation and flight test results, it is also known that all three limiter concepts can be defeated, usually by combinations of low airspeeds, high pitch, roll or yaw rates, large stick deflections or high stick force commands, and damper servo or stabilizer/horizontal tail rate or authority saturation.

Considerations For Future Application

Now I would like to discuss several issues related to the application of automatic limiters to future aircraft. What follows will be based primarily on my experience and interpretation of past results from the three aircraft limiters described above. Although the emphasis of this paper has been on three military aircraft, I believe automatic limiters and most of the considerations to follow are applicable to transport and commercial applications as well.

Limiters or Aerodynamic Modifications?- Automatic limiters applied to the F-111, F-16 and B-1B aircraft addressed specific problems that existed due to their aerodynamic, flight control and mission characteristics. They were developed because alternative airframe modifications would have been too costly and to provide maximum usable flight envelopes within which the aircraft could perform its required missions satisfactorily. In military aircraft at least, a departure resistant vehicle without any automatic limiters (or flight manual restrictions for that matter) would be preferable to one with the same level of departure resistance achieved through automatic limiters. This would be especially true if the limiters reduced the aircraft's usable flight envelope. But in the early stages of air vehicle development, actual flight characteristics and limitations are usually not known accurately. Once identified, however, it would be preferable to make those limits transparent to the pilot through the flight control system, allowing him to make the most of his aircraft's maneuver performance without flight manual restrictions diverting his attention from his primary mission.

Performance Impacts?- Some have argued that automatic limiting takes away flight envelope that would otherwise result in better maneuvering performance. For example, AOA limiting could prevent the pilot from flying at high lift coefficients where his turn rates would be higher (see figure 15). However, one must differentiate between theoretical and usable envelopes. In the B-1B case, figure 13 showed that the lift curve peaked well beyond the stall AOA where neutral stability occurred. However, maximum lift was only a theoretical value since it could not be reached without loss of control. Either the pilot had to limit the aircraft to the stall AOA or an automatic system had to do it. For the SEF equipped B-1B's, automatic limiting was necessary to allow safe use of the lift available at AOA's in the unstable flight regime. Also, since the consequence of exceeding AOA limits is often loss of control, safety margins must be included in flight manual limits to allow for pilot reaction time. Thus, AOA limits observed manually will be lower than true aerodynamic limits by some margin related to the pilot's ability to recognize his situation and react properly. Since they react faster, automatic limiters allow these safety margins to be minimal, thus giving up less of the theoretical flight envelope. In summary, properly designed automatic limiters should take away less performance capability from the pilot than he would lose anyway by observing flight manual restrictions if the limiters weren't there.

Increased Complexity?- Developing automatic limiters for retrofit to an existing aircraft, such as the F-111 and B-1B, will always present unique challenges and can be expected to increase system complexity. For example, the existing electrical and mechanical flight control systems must be thoroughly understood or errors in modelling the existing system will result in a poor limiter design. What is worse is that the unsatisfactory nature of the design may not become apparent until flight testing has started, requiring multiple iterations of redesign, hardware/software modification and flight test. Mechanical control linkages have been particularly difficult to understand accurately so that new electronic limiter functions could effectively compensate for their effects. In some cases, additional data must be provided to the flight control computer, such as AOA or aileron position, requiring new sensors, wiring and interface connectors. In contrast, modern fly-by-wire flight control systems have far fewer mechanical components and implement control laws through software. Providing that the memory and through-put reserves of the computer are adequate, incorporating automatic limiting should not increase complexity significantly at the system level. That is, the necessary signals for aircaft states, such as AOA, pitch rate, yaw rate, etc, should already be available to the flight control computer, and the revised software will still reside in the same computer or computers that were in the original system. The software will become more complex, however, as the control laws are revised to include the automatic limiting logic and as further refinements are made based on flight test results. Quality assurance of the flight control software becomes a significant challenge as these changes are made since error-free execution is essential to safe flight.

Cost/Schedule Impacts?- Experience with the F-111, F-16 and B-1B programs does indicate that limiter development can have an adverse impact on program costs and schedules. Somewhere between twenty-four and forty-eight months have been needed to conduct initial analyses and ground based simulations, build prototype hardware for flight test, conduct flight test verification, make modifications to recover from design errors, and deliver initial production units. For the F-111 and B-1B, these efforts were not part of the initial full scale development program at all, and for the F-16, the scope of the effort turned out to be far more time consuming and complex than initially anticipated. Future planning should take this history into account and not be overly success oriented.

More Hazardous to Test?- Flight testing of automatic limiter systems should be no more hazardous than traditional high AOA testing to explore the extremes of an aircraft's flight envelope. At the Air Force

Flight Test Center at Edwards AFB in California, any hazardous testing requires that extra precautions be taken, such as using spin recovery parachutes, backup electrical and hydraulic power sources, special instrumentation, safety chase aircraft, and a methodical build-up approach from less critical to more critical conditions. Close matches between flight test results and simulator/analytical predictions are also often required before proceeding. Because flight safety will always have priority, it will be difficult to predict how long any hazardous testing will take to complete, whether automatic limiting is part of the aircraft system or not.

Crutches for Poor Design?- Automatic limiters should never be used as crutches for poor design. Early in the design stage, the objective should be to meet all flight critical requirements, including departure resistance, through good aerodynamic design features, such as stable pitching moment breaks and good control effectiveness at high AOA, and without the need for limiting. However, there are always uncertainties in the development process, and the final vehicle configuration is a compromise among often conflicting requirements of different disciplines. Therefore, it would be expedient to build into the flight control laws from the very beginning the capability to make use of automatic limiting features. This is becoming easier to do in the software of digital flight control computers than it was in the past in the hardware of electrical analog computer or hydromechanical systems.

Impacts on Analytical/Simulation Modelling?- The development of effective automatic limiting systems requires accurate modelling of aerodynamic and flight control hardware and software characteristics. If cost and schedule considerations during the development process result in reductions in the scope of wind tunnel testing or efforts to adjust analytical and simulator data bases to match flight test results, the limiter development process (and flight control system development in general) will be more difficult, costly and lengthy. Also, good data and ground-based simulation facilities are needed because of the dependence on piloted simulations to evaluate limiter concepts before hardware and software are built for flight test evaluation. For these simulations to provide results that are truly applicable to the flight test air vehicle, the simulation must have the highest possible fidelity in the aerodynamic and flight control system modelling, cockpit controls and displays, and visual display system. Finally, although more expensive than ground-based simulation, inflight simulation should be used to verify ground-based simulator results during proof of concept testing. Inflight simulators, such as the NT-33, Total Inflight Simulator (TIFS) and the new Variable stability Inflight Simulator Test Aircraft (VISTA), can reduce development risk because they place evaluation pilots in a "seat-of-the-pants" environment closer to what they actually will experience in the flight test aircraft.

Conclusions

In conclusion, automatic limiting features have been successfully used in U.S. Air Force aircraft. These features have increased flight safety and enabled pilots to make more effective use of their aircraft. Consequently, fewer flight manual restrictions have been necessary than would otherwise be required. While air vehicles that achieve superior mission performance through aerodynamic means alone should continue to be a design objective, automatic limiting is a viable alternative that has sometimes been found preferable to airframe modifications. As new aircraft designs are pushed to the limits of aerodynamic, propulsion, and flight control technology, it would be prudent to include provisions for automatic limiting in the flight control laws early in the design and development process. With the trends in digital flight control computer technology, this is getting easier to do within reasonable memory and through-put requirements. Finally, proper design of automatic limiters can provide maximum usable maneuver envelopes without significant loss of maneuvering performance.

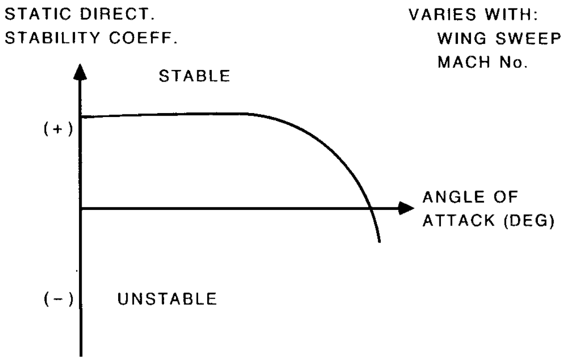

FIGURE 1. F-111 DIRECTIONAL STABILITY CHARACTERISTICS

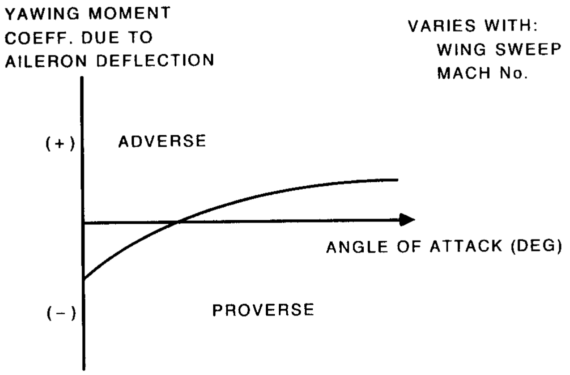

FIGURE 2. F-111 YAW-DUE-TO-AILERON CHARACTERISTICS

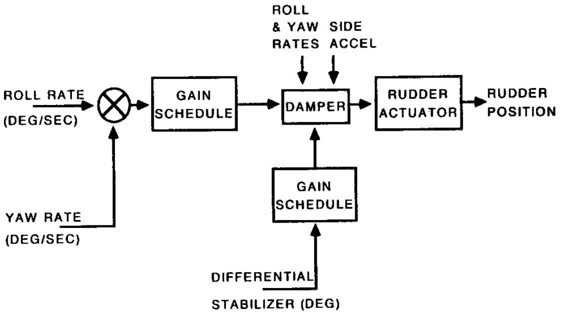

FIGURE 5. F-111 YAW AXIS SIS FUNCTIONAL DIAGRAM

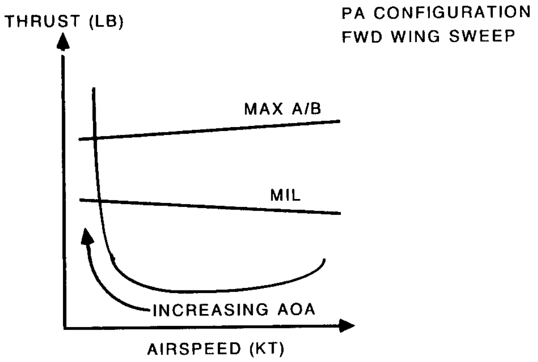

FIGURE 3. F-111 THRUST REQUIRED/AVAILABLE CURVES

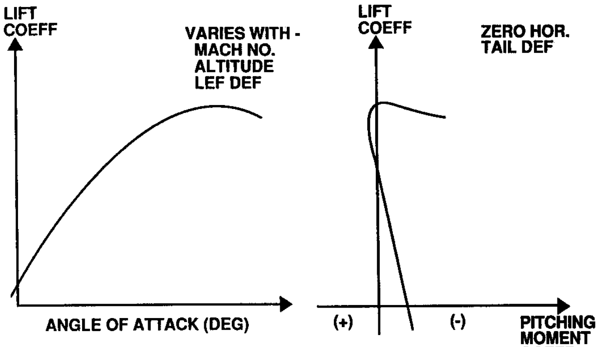

FIGURE 6. F-16 LONGITUDINAL CHARACTERISTICS

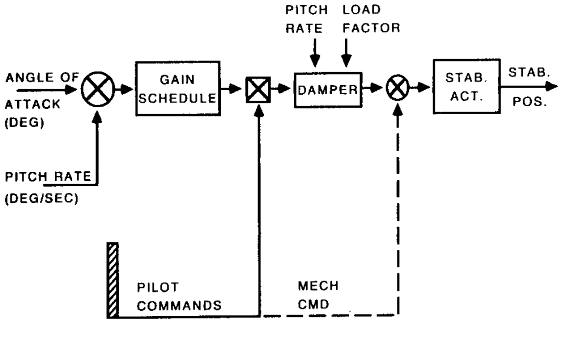

FIGURE 4. F-111 PITCH AXIS SIS FUNCTIONAL DIAGRAM

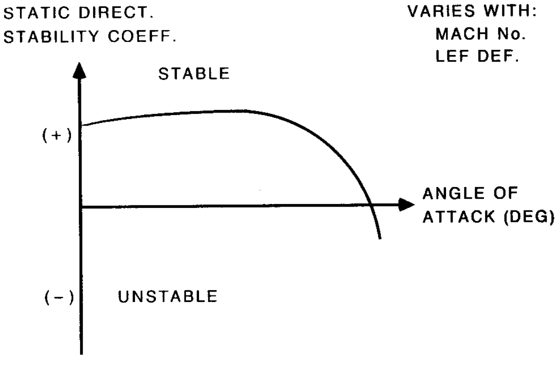

FIGURE 7. F-16 DIRECTIONAL STABILITY CHARACTERISTICS

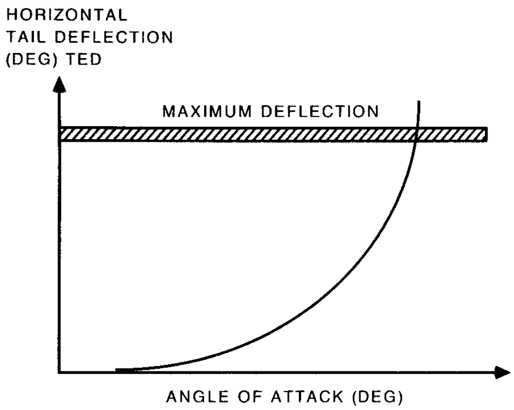

FIGURE 8. F-16 ROLL COUPLING CHARACTERISTIC

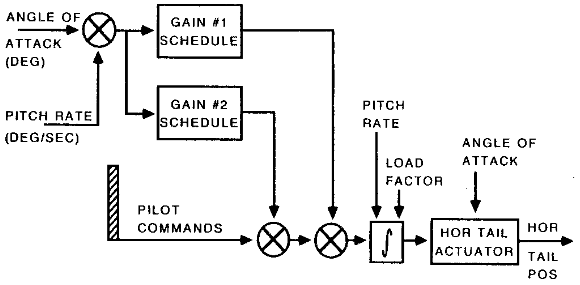

FIGURE 9. F-16 AOA LIMITER BLOCK DIAGRAM

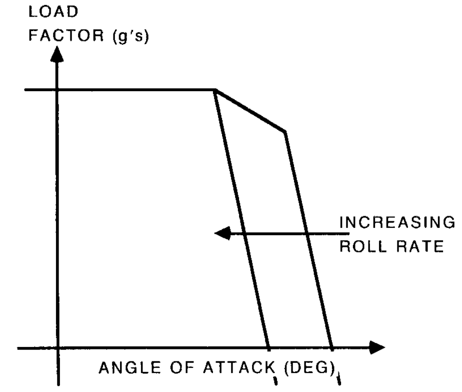

FIGURE 10. F-16 ANGLE OF ATTACK/LOAD FACTOR LIMITER

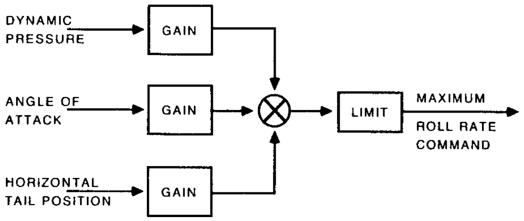

FIGURE 11. F-16 ROLL RATE COMMAND LIMITER

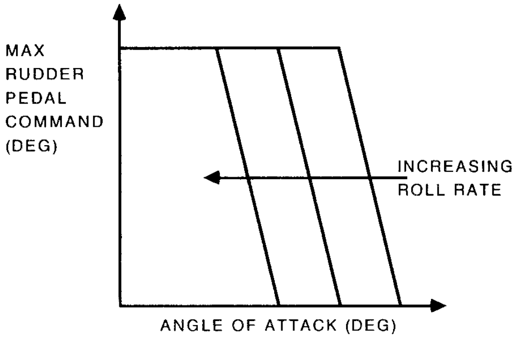

FIGURE 12. F-16 RUDDER COMMAND LIMITER

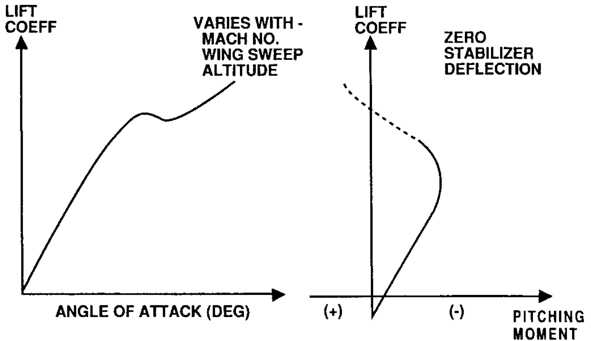

FIGURE 13. B-1B LONGITUDINAL CHARACTERISTICS

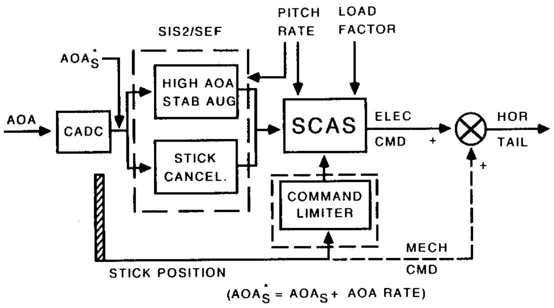

FIGURE 14. B-1B SIS/SEF BLOCK DIAGRAM

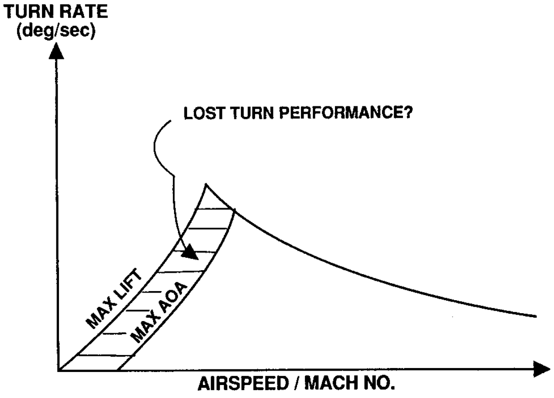

FIGURE 15. POSSIBLE TURN PERFORMANCE IMPACT