Handling Qualities Related to Stall/Spin Accidents of Supersonic Fighter Aircraft

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This paper reviews the handling qualities that influence the high-angle-of-attack (AOA) behavior of supersonic fighter aircraft in order to obtain a clearer understanding of the causes of stall/spin accidents. The results show that, because modern fighters suffer more serious consequences when control is lost, good handling qualities are essential for safe operation at high AOA. Relaxed static stability used on some fighter aircraft can result in control problems at high AOA due to inertia coupling and the difficulty of a recovery from a deep stall. Indications are that the use of departure/spin resistance and an automatic spin-prevention system will greatly improve the safety record for modern supersonic fighters.

Introduction

HANDLING qualities at high angle of attack (AOA) continue to be an important factor in the safe operation of all types of aircraft. Loss of control at high AOA, leading to departure and spin, has been a historic problem since the early flights of the Wright brothers.[1] Starting with the operation of World War I fighters, many aircraft and lives have been lost due to stall/spin accidents; however, stall/spin maneuvers were sometimes used to escape from an opponent. Due to its low L/D, a spinning aircraft could lose altitude more rapidly (caused by separated airflow) and more safely with the low airspeeds involved, as compared to his pursuer who risked structural failure in attempting to follow in a high-speed dive.

Today modern military fighters are tailored specifically to operate at very high AOA for good combat effectiveness. Because of the demand for increased maneuverability, aerodynamic features and control systems have been devised to provide penetration into AOA ranges two to three times greater than the range of early fighter aircraft. Of particular concern is loss of control when operating at high AOA, resulting in stall/spin accidents. Although some fundamental aerodynamic parameters that underlie the behavior of aircraft at high AOA are reasonably well understood and criteria have been developed to determine the susceptibility of a given configuration to departure and spin problems, the accident record for military fighter aircraft still needs improvement. Over 100 F-4 fighters have been lost due to departure/spin during the development and operation of this internationally used popular aircraft. The more modern fighter aircraft, such as the F-14A, F-15, F-16A, and F/A-18, have much improved stall/spin accident records; however, accidents have occurred for several of these types in the high-AOA range, and these aircraft have yet to be exposed to broader operational use.

This paper examines the handling qualities associated with high-AOA operation with an emphasis on stall/spin accidents of high-performance (supersonic-type) fighters. A clearer understanding of the factors involved could help improve the safety record.

The scope of this paper includes the following: 1) a brief review of the military specifications (MIL SPEC) for the high-AOA portion of the flight envelope, and 2) a look at the high-AOA behavior of several modern supersonic fighter aircraft to focus attention on the need for good handling qualities.

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Discussion

Review of MIL SPEC High-AOA Handling Qualities Requirements

All military aircraft are designed to meet a host of specifications to assure safety of flight and absence of mission limitations as part of the procurement process. Over the years, the requirements for operation in the high-AOA region of the flight envelope have changed considerably both in scope and complexity.

The latest revision, MIL-F-8785C,[2] adequately addresses potential problems of aircraft-and-control system combinations, including higher order dynamics; however, more recent advanced control systems found in new fighter aircraft have again outpaced the existing coverage of handling qualities in the high-AOA area. As indicated in work related to flight safety of augmented aircraft,[3] the door has been opened to alter aircraft handling qualities at high AOA to a greater extent using digital control fly-by-wire (FBW) control systems. Included is the ability to force the aircraft to roll about the stability axis (to reduce unwanted sideslip) and to operate with the center of gravity (c.g.) aft of the normal c.g. range (for reduced aerodynamic drag).

The following handling qualities requirements (from Ref. 2) are of interest for operation in the high-AOA portion of the flight envelope.

Stall Approach

The stall approach shall be accompanied by an easily perceptible warning consisting of shaking of the cockpit controls, buffeting or shaking of the airplane, or a combination of both. An increase in buffeting intensity with further increase in angle of attack shall be sufficiently marked to be noted by the pilot. For many years the lack of adequate high-AOA warning cues has ranked high on the list of pilots' problems in air combat maneuvering (ACM). Pilots desire natural cues that do not place an artificial limit on aircraft performance. As discussed in Ref. 4, pilots in operational squadrons strongly objected to prevention of dangerous flight conditions by using maneuver limiters. Such devices are believed to make an aircraft's maneuvering performance predictable to the enemy. This requirement relates very strongly to flight safety in a dangerous part of the flight envelope.

Stall Characteristics

In unaccelerated stalls the magnitude of uncommanded rolling, yawing, and pitching motions is left to be defined by the procuring agency. In addition, it is desired that no pitch-up tendencies occur in unaccelerated flight; however, mild nose-up tendencies are permitted in accelerated flight if the operational effectiveness of the airplane is not compromised. Pitch-up can occur from many causes (i.e., outer panel stall, inertial coupling, etc.), and it can be a difficult problem area if pitch control effectiveness is reduced at high AOA.

Stall Prevention and Recovery

It shall be possible to prevent the stall by moderate use of pitch control alone at the onset of the stall warning. It shall be possible to recover from a stall by simple use of the pitch, roll, and yaw controls. In straight flight stalls, pitch control power shall be sufficient to recover from any attainable AOA. The consequences of inadequate pitch control on pilot performance can be severe and deserve increased emphasis. As discussed later, highly specialized control-movement techniques may be required for deep stall recoveries.

Departure from Controlled Flight

The aircraft shall be resistant to departure from controlled flight, poststall gyrations, and spins. It is further stated that the pilot should be able to arrest any uncommanded motion by simple control, although no definition is given of what constitutes simple control. In addition, adequate warning of approach to departure shall be provided.

These requirements must meet pilot-centered criteria, are difficult to quantify, and may differ widely in application to specific aircraft.

Recovery from Poststall Gyrations and Spins

These requirements state the following: 1) Proper recovery techniques must be readily ascertained by the pilot and simple and easy to apply under the motions encountered, 2) a single technique shall provide prompt recovery from all poststall gyrations and incipient spins, 3) avoidance of spin reversal or adverse mode change shall not depend on precise pilot control timing or deflection, 4) safe and consistent recovery and pullouts shall be accomplished with acceptable control forces, and 5) recovery should be specified in terms of allowable altitude loss or number of turns.

Stall and High Angle of Attack (RSS Pitch Axis Control Power)

In any airplane normal state or failure state...for all angles of attack from zero lift to—with full nose-down control, the airplane shall exhibit a net nose-down pitching moment of sufficient magnitude to generate—rad/sec^2 nose-down angular acceleration.

Operation in the stall and high-AOA range is critical for aircraft with relaxed static stability (RSS) because of limited available control power to pitch the aircraft nose down and prevent entry into a deep stall from which recovery may not be possible. In effect, the amount of instability operationally acceptable may be set by pitch control power.

Rolling Maneuvers (RSS Pitch Axis Control Power)

In the rolling maneuvers specified...and for at least successive maximum performance bank to bank rolls between—and—deg of bank angle,...the control authority, rate, and hinge moment capability shall be sufficient to prevent divergence or loss of control.... Rolling (bank-to-bank) maneuvers can be critical for RSS aircraft because inertia coupling tends to increase AOA and add to any unstable aerodynamic pitching moments. The pilot may use wing rocking for evasive action in air combat, or to signal an intention to break off or end practice air-combat maneuvers.

Summary of High-AOA Handling Qualities for Fighter Aircraft

In recent years, increased emphasis has been given to developing fighter aircraft specifically tailored to maneuver at very high AOA. The manufacturers and test agencies have gone to great lengths to provide aircraft that can be flown safely over a wide AOA and sideslip range. In spite of the best efforts, accident records show that operational pilots can lose control during aggressive maneuvering. In a very comprehensive survey of operational commands and squadrons,[4] it was noted that, although high AOA maneuvering in combat was not considered a primary tactic, it also should not limit use of the aircraft. Pilots' comments on high-AOA flying characteristics obtained from operational units of fighter squadrons flying F-4, F-5, F-14, F-15, and F-16 aircraft indicate that, in general, the pilots were satisfied with the overall high-AOA flying qualities and the departure characteristics, but not with the warning cues inherent in most of these supersonic fighter designs. Many factors interact to influence the pilot's acceptance of controllability, and safe operation at high AOA depends to a great extent on individual pilot skill and judgment.

Results for Specific Aircraft

In the following section, examples from the operation of specific aircraft are given to illustrate the importance of satisfactory high-AOA handling qualities outlined in the previous section.

High-AOA Flight Characteristics for F-14A

As noted in the pilot's flight manual, in the cruise (clean) configuration the aircraft does not exhibit a classic aerodynamic stall ("*g*" break), and to the pilot the stall is not perceptible. Lift curve characteristics shown in Fig. 1 indicate that a directional divergence and roll reversal start to occur slightly above 15-deg AOA. Buffet starts at 14 deg, increasing to moderate at 17 deg, and then decreases to light buffet at 24-deg AOA. (NOT considered satisfactory stall warning.) (See Ref. 5).

Aircraft response to pilot control inputs become more difficult to predict above 20-deg AOA. Pitching moment due to sideslip changes magnitude and sign as AOA is increased. Excessive or prolonged use of lateral stick deflection can cause departure, and recovery from high-AOA flight requires the pilot to use rudder alone. The sink rate may increase to 9000 ft/min and a loss of 5000 ft altitude is typical in recovery from high-AOA flight.

In the takeoff/landing configuration, at 28-deg AOA, the stall is characterized by divergent wing rock and yaw excursions. Yaw angles may reach 25 deg and roll angles 90 deg within 6 s if the stick is held back. If the stall condition is momentarily penetrated, 1000 ft of altitude is required for recovery. The stall warning and stalling characteristics of the F-14A are typical of high-performance fighter aircraft and good pilot indoctrination is essential to fly this type of aircraft safely at high AOA.

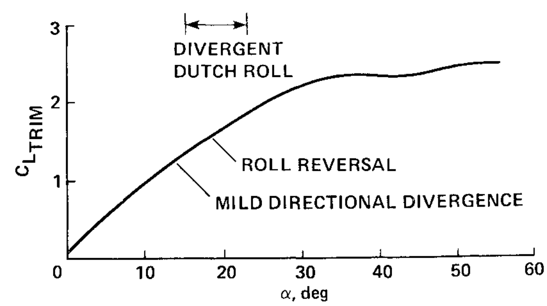

Fig. 1 F-14A trimmed lift curve (from Ref. 5).

Although the F-14A is departure-resistant, departures can occur during maneuvers combining rolling with high AOA. Departure is described as a snap roll, or series of snap rolls, opposite to the direction of desired turn or lateral stick input. Since the departure is "triggered" by adverse sideslip generated by the differential rolling tail, using the stick opposite to the direction of the roll (which is an instinctive reaction) will aggravate departure.

Departure recovery requires precise control positioning and timing. The pilot's flight manual states for departure recovery to neutralize rudders and lateral stick and push stick forward slowly to trim position or slightly forward of trim, to reduce AOA to 17 units or less. Pushing the stick forward rapidly during a departure can result in increasingly oscillatory pitch-and-roll motions. If recovery is not eminent, lateral stick must be moved slowly in the direction of roll and yaw, and the rudders are moved in the direction opposite to roll and yaw. When roll/yaw stops, immediately neutralize lateral control and rudders.

The foregoing departure recovery procedures illustrate the need for precise, well-timed control movements to prevent further deterioration from controled flight. One could question whether the foregoing technique meets the "simple application of pilot control" outlined in the MIL SPEC.[2]

It is important that the pilot appreciates the need to effect recovery quickly before the yaw rate builds up. Because the F-14A was designed for carrier operation, the cockpit is located relatively far forward (22 ft ahead of the c.g.) for good downward visibility. This results in large longitudinal accelerations with increase in yaw rate as shown in Fig. 2.[5] Centrifuge tests of the F-14A configuration showed the following:

1) At -3 g Eye Balls Out (EBO), the pilot could operate flight controls but could not reach the overhead ejection handle.

2) At -5.5 g EBO, the pilot could think and see, but could not move the flight controls due to pain caused by blood pooling in the extremities.

In addition to the longitudinal EBO forces, large cockpit lateral accelerations can build up when a rapid onset of yaw rate induces a large sideslip angle (shown in Fig. 3). This is caused by loss of directional stability (C_{N_β}) beyond $\alpha = 14$ deg. Recovery procedures may be difficult to accomplish because of the inadequacy of the lateral seat restraint system. In fact, the pilot can be displaced sideways such that his helmet is against the canopy and he may not be able to reach the engine controls momentarily. This aspect of controllability is not covered explicitly in the MIL SPEC's[2] high-AOA requirements.

As noted in Ref. 5, ... For a test pilot who purposely causes the aircraft to depart, knows which direction it will go, has a yaw rate gage, and has practiced the maneuver on the simulator, recovery from this maneuver was possible. For the fleet pilot who encounters this departure unexpectedly, recovery would not be certain.

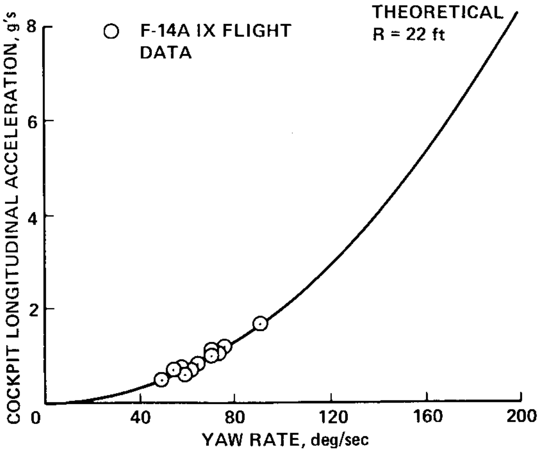

Fig. 2 Variation of acceleration with yaw rate (F-14A) (from Ref. 5).

A part of the departure and recovery problem for twin-engine aircraft is that the pilot has difficulty in determining engine power status during departures and spins. Currently used engine sensors require too much pilot analysis to determine to what degree engine thrust asymmetry has occurred. This adds appreciably to the pilot's workload during a high-stress situation.

Summing up for the F-14A, although the aircraft is basically departure- and spin-resistant, a number of stall/spin accidents have occurred because of poor warning cues and inherent pilot limitations in analyzing the out-of-control mode, and applying correct antideparture/spin control procedures. Because the pilot is so vulnerable to the debilitating centrifugal acceleration effects, this aircraft would have benefited greatly from an automatic spin-prevention system.

High-AOA Characteristics for F-16A/B

This aircraft illustrates the need for unusual stall recovery techniques. It is noteworthy that no spin accidents have occurred for this aircraft. It has been made spin-resistant by using a system that detects a threshold yaw rate and automatically applies ailerons with, and rudder against, the spin. (Several aircraft have been lost, however, due to certain handling qualities deficiencies discussed next.)

Similar to other fighter aircraft that operate at high AOA, the F-16 can encounter coupling control problems from kinematic and inertial effects. Kinematic coupling occurs when an aircraft is flying at high AOA and is rolled about its body axis converting AOA to sideslip angle. Because large amounts of sideslip may affect stall departure adversely, the control system can be programmed to roll the aircraft more nearly around the stability axis (velocity vector). This, in turn, may lead to problems if the pilot uses excessive rudder in coordinating a roll maneuver because the proverse yaw (sideslip) generated can couple to produce increases in AOA that can lead to an uncontrolled pitch-up if the available nose-down pitch control power is exceeded.

In addition, inertial coupling can be severe when the aircraft is rolled rapidly about its velocity vector at high AOA. Inertial coupling results in a nose-up pitching moment as the relatively fuselage-heavy mass distribution tries to align itself in the proper relationship with the velocity vector. As would be expected, the magnitude of nose-up pitching moment increases with increase in AOA and roll rate. The effects of coupling are more serious for aircraft with low or negative pitch stability and can result in loss of AOA control as noted in Ref. 3. An F-16 airplane was lost as a result of performing successive wing rocks in a 2-3-g turn at an altitude of about 6000-ft and 430 knots. The pilot safely ejected after a sudden pitch-up. This out-of-control roll behavior violates the MIL SPEC requirements and the obvious "fix" was to limit roll rate as a function of AOA.

The lift characteristics of the F-16 (Fig. 4) show an initial break in lift curve slope at 20-deg AOA due to outer wing-panel stall. The highly swept wing-body strake continues to increase lift up to and beyond $C_{L_{max}}$ at 35-deg AOA.

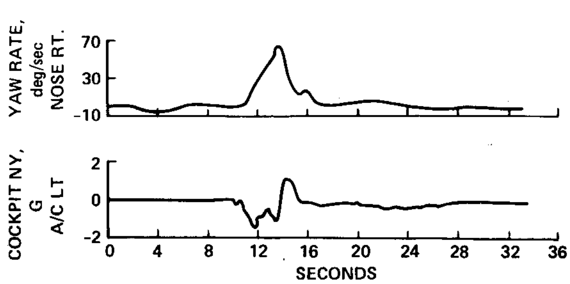

Fig. 3 Cockpit lateral acceleration at high yaw rate (F-14A) (from Ref. 5).

The pitching moment characteristics associated with these lift characteristics are of special interest (Fig. 5, from Ref. 6). Note the mild pitch static instability in the lower AOA range for the nominal c.g. position of 0.35*c* (typical for relaxed static stability—RSS), and that a stable trim point exists in the high-AOA range around 60 deg. An important point of interest is that once an AOA of approximately 50 deg is exceeded, relatively low pitch control power exists to retrim the aircraft to a lower AOA value. Because of the good lift characteristics (flat lift curve top), the aircraft may be flown to very high AOA where departures may occur; therefore, AOA is limited artificially to values below 25 deg by automatically applying nose-down stabilizer control. The effectiveness of this technique is limited by the nose-down pitch control power available. For tail-aft aircraft that employ RSS (such as the F-16), sufficient nose-down pitch control power may be basically difficult to obtain at high AOA if the tail operates in the separated flow wing wake. An excellent discussion of the mechanics of departure for fighter aircraft with RSS is given in Ref. 6. An alpha limiter, such as used on the F-16, can be defeated in prolonged vertical climbs to zero airspeed where high AOA is produced during the "fall-through." As noted subsequently, this can be very perplexing for the pilot, and several accidents have resulted because of the unusual control inputs required for recovery and the lack of previous exposure.

The flight manual for the F-16A/B aircraft discusses the out-of-control recovery procedures illustrating potential handling qualities problems. The upright deep stall is characterized by a 1-*g* load factor, AOA pegged at 32 deg, and an airspeed reading between 50-150 knots. With rearward c.g. locations, where the deep stall is oscillatory in pitch, the AOA may vary ±30 deg with some roll oscillations. Oscillatory deep stalls can be deceptive in that the nose may drop below the horizon giving the appearance of self-recovery. As noted in Ref. 7, the deep stall ride qualities are unique in that the aircraft is very quiet, with gentle buffet, and no apparent forward motion. The pilot must not be lulled into a complacent attitude however, since the sink rate is approximately 400 ft/s and many of the deep stall situations have occurred during low-altitude maneuvering.

The recovery procedures from the deep stall are certainly not classic and demand a well-disciplined approach. The aircraft is essentially "locked in" to the high-AOA trim point, and full nose-down stabilizer pitching moment is insufficient to overcome the basic stability; however, the aircraft can be "rocked" out of the deep stall. This is done by using the total available pitching moment control [full nose-down to full nose-up (see Fig. 5)] in phase with the residual pitch oscillatory motions. The pilot must hold the manual pitch override (MPO) switch in override (OVRD) giving the pilot full tail travel, speed brakes must be extended, and AFT (fuel) FEED selected. Since most deep stalls are oscillatory in roll and yaw also, it may be difficult for the pilot to ascertain a change in pitch attitude with the aircraft banked. The instructions note that if no increase in attitude is discerned (with full pitch control), the pilot should wait 3 s and then apply full reverse control. If the nose does not continue down with full forward stick, but reverses and starts up, full back stick must be applied to continue rocking the aircraft. The pitch oscillation has a period of approximately 3 s and the pilot is warned that rapid cycling of the control will be ineffective.

The foregoing deep stall recovery procedure, although effective in principle, requires good timing and patience from the pilot. Although the recovery method is not difficult to carry out physiologically, the unusual control inputs and timing required may cause some pilots to essentially "give up." Previous exposure to this situation can obviously improve pilot proficiency and confidence. The ability to achieve success on the first try is not good, as indicated by the fact that 75% of visiting European F-16 pilots failed when tested in a two-place F-16 aircraft.

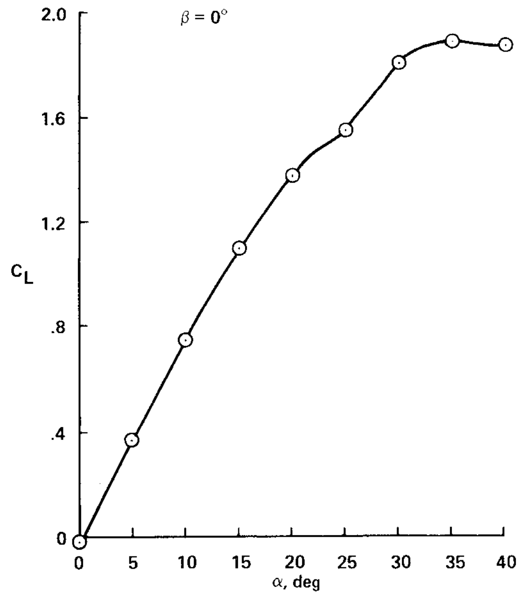

Fig. 4 Untrimmed lift characteristics of F-16A configuration.[6]

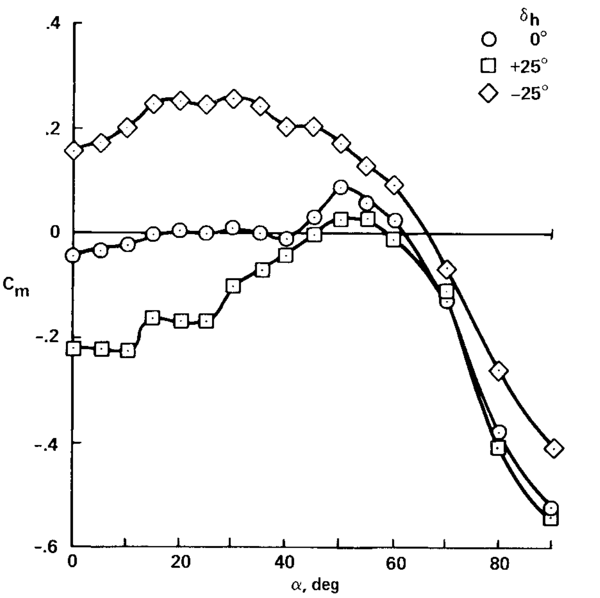

Fig. 5 Variation of pitching moment for various stability stabilizer deflections, e.g., at 0.35c. F-16 configuration (from Ref. 6).

Further, as noted in Ref. 8, the use of an MPO switch may have questionable operational utility: ...The MPO was an effective upright deep stall recovery device when utilized properly.... However, the ability of the operational pilot to properly and readily adapt to the usage of the MPO remains a concern. During flight tests with pilots who were extremely familiar with the deep stall environment, as many as four total cycles of the stick were required before an effective cycle was achieved. The primary difficulty encountered involved improper phasing with existing pitch oscillations. Proper phasing became much more difficult when severe roll oscillations existed. The rolling tendency (to as much as 90 deg bank angle) masked the pitching motion of the aircraft.

In summary, RSS used on the F-16 aircraft can aggravate pilot control problems at high AOA, resulting in deep stall. The pilot must provide a properly phased pitch control oscillation technique (which violates the "simple" rule) to effect recovery. In addition, kinematic and inertia coupling can lead to high-AOA flying quality problems if roll rate is not limited.

Results for F/A-18

This aircraft is used to exemplify potential problems for the pilot when advanced fight control systems are used to provide departure/spin resistance and automatic spin recovery. A primary design goal for this aircraft was to provide the operational pilot with an unrestricted maneuvering capability (no AOA limiter) in the high-AOA range. The F/A-18 incorporates a highly sophisticated, full-authority, digital flight control system programmed to enhance high-AOA flight characteristics. As noted in Ref. 9, departure/spin resistance is obtained by scheduling the maneuvering flaps (both leading and trailing edges) with AOA and Mach number and by reducing differential tail and aileron authority at high AOA to reduce adverse yaw. An aileron-rudder interconnect (ARI) feature provides a proverse yaw contribution to improve roll coordination. A rudder pedal-to-roll interconnect reduces proverse yaw during rudder (only) rolls. Kinematic coupling (interchange of AOA and sideslip) is minimized by rolling about the stability axis and roll-to-pitch feedbacks are used to reduce inertia coupling effects. These features, some of which are unique to the F/A-18, reduce coupling without seriously sacrificing maneuverability. An automatic spin recovery mode logic was designed into the control system to establish yaw rate engagement thresholds that were not so low as to reduce departure/spin resistance, but not so high as to prevent recovery from a spin.

Unfortunately, during Initial Operational Test and Evaluation (OTE) on November 14, 1980, the first unintentional F/A-18 out-of-control experience happened to an operational pilot. The departure occurred during "yo-yo" (pull up, push down) maneuvers at about 20,000 ft. Although the pilot applied correct antispin-control inputs, recovery could not be obtained, and the pilot ejected safely below 10,000 ft. The fact that the departure occurred so easily, and it was apparently impossible to recover, further serves to illustrate handling quality problems when the pilot is confronted with an unexpected out-of-control situation.

To examine whether the pilot had adequate warning of the approach to departure, it is noted[10] that as AOA is increased through about 10 deg, a medium-frequency, low-amplitude buffet can be felt by the pilot. Further increases in AOA result in increased airframe buffeting with decreased frequency; however, these changes are subtle, spread out over a wide-AOA range, and generally do not serve as an adequate warning. As AOA exceeds 50-60 deg, the pilot can hear a loud recurring noise associated with the shed vortex from the leading edge extension (LEX). This noise is not effective for warning, because it occurs at an AOA too far above $C_{L_{max}}$ (35-40 deg). Because the aircraft has weak natural warning cues, artificial AOA cues are provided using computers. The various artificial cues provided by the AOA feedback loops are shown in Fig. 6 (from Ref. 9). The most significant of these cues may be in the pitch control where, above 15-deg AOA, much larger pull forces are required. As 35-deg AOA is reached pilots may use two hands on the stick, which should serve as a very effective cue for out-of-the-cockpit flying.

Looking next at the spin characteristics of the F/A-18, as described in Ref. 10, it was noted by the pilot in the November 1980 accident that the spin yaw rate was very low; in fact, so low as was found in subsequent investigations to prevent automatic engagement of the spin recovery mode (which provides full control authority). (This low yaw rate spin mode was not predicted by model tests.) Thus, the flight control system (FCS) remained in the limited authority command augmentation mode, and the pilot was left with low antispin yaw control power—a factor that must have been very perplexing to the

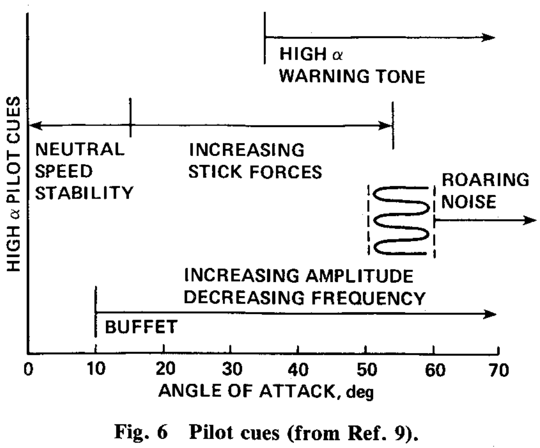

Fig. 6 Pilot cues (from Ref. 9).

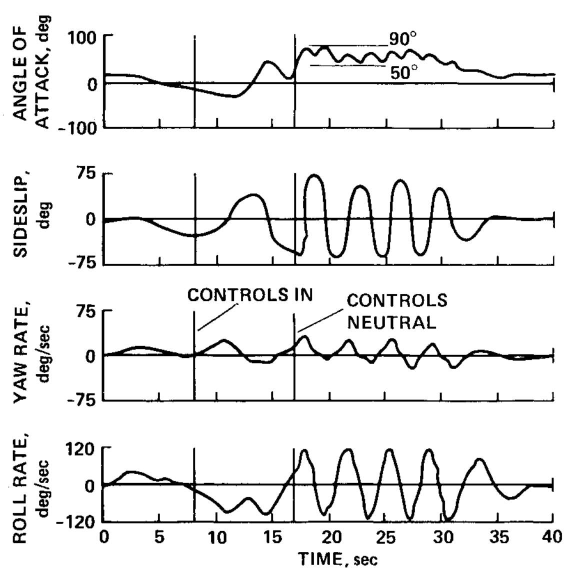

Fig. 7 F/A-18 "falling leaf" (from Ref. 11). Rudder-only inverted spin attempt.

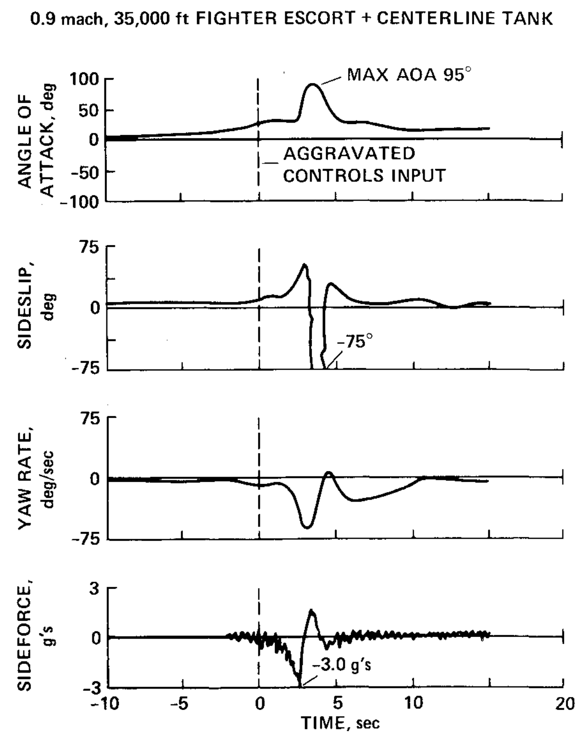

Fig. 8 F/A-18 high-Mach departure.

operational pilot since previous flight testing had shown the aircraft to be extremely difficult to depart, nearly impossible to spin, and rapid in spin recovery. Subsequent flight spin tests revealed three spin modes, not always distinct.[10] At a low yaw rate, less than 50 deg/s, motions were relatively smooth with some pitch and roll tendencies and a rate of descent of 21,000 ft/min, and recovery could be effected in less than one turn. An intermediate mode-yaw rate of 20-80 deg/s was much more violent; oscillations about all axes were very disorienting to the pilot because of changing yaw rates and the execution of a 360-deg roll while continuing to spin in the established direction. The high yaw rate spin (110-140 deg/s) which occurred at AOA up to 95 deg was smooth and flat with only small oscillations; unlike the other modes, EBO accelerations become uncomfortable (but not disorienting), $-3.5g$ max, with recovery in less than three turns.

Looking further at out-of-control modes that may have confronted the pilot in the 1980 OTE accident, flight tests identified what was termed an AOA "hang-up" in low-speed flight with rear c.g. loadings. This condition was encountered from near-vertical, low-speed stalls or occasionally following spin recovery. In the AOA range of 45-55 deg, the pilot is confronted with a very slow nose-down pitch recovery even with full-forward stick. A variation of this AOA "hang-up" was termed a "falling-leaf" maneuver because of the oscillations in sideslip, roll rate, and pitch rate that occur during descent. The magnitude of the oscillations shown in the time history data of Fig. 7 would cause additional anxiety for the pilot because of the excessive time required for pitch-down, and the large altitude loss. In addition, lateral control appeared to be ineffective in damping the roll oscillations. As noted in Ref. 11, this oscillatory "falling-leaf" mode was the most probable cause of the 1980 accident. Limiting rearward c.g. location would alleviate the tendency for AOA "hang-up."

To deal with the foregoing departure problems, an improved automatic spin mode logic was incorporated into the F/A-18. A unique feature of this system is that it provides full antispin control authority only if the pilot moves the lateral stick in the correct direction (with the spin). If the pilot applies prospin stick, the DFCS reverts back to the command augmentation mode which, in effect, negates his input.

Another example where the pilot was exposed to large lateral side forces occurred during departure tests at medium AOA when aggravated (prospin) controls were applied.[11] As shown in Fig. 8, extremely high side forces (up to $3g$'s laterally) were associated with the very large sideslip angles (over 75 deg) that occurred in this high subsonic ($M=0.9$) departure. As previously discussed for the F-14A, the pilot is at an extreme disadvantage to provide precise control positioning to effect recovery. Fortunately, in this case, recovery was readily accomplished with neutral controls. It would be prudent to protect the operational pilot from this type of flight-path divergence by suitable control law logic.

In summary, the F/A-18 has achieved good handling qualities and maneuvering capability at high AOA by advanced control system logic. Although some unique and unexpected high-AOA problems were encountered in early testing, because of protective features in the FCS logic, it would be expected that fewer stall/spin accidents due to pilot error will occur during the operational life of this type of aircraft.

Concluding Remarks

This paper emphasizes that, because modern supersonic fighters suffer serious consequences when control is lost, good handling qualities are essential for safe operation at high angles of attack (AOA). Although the MIL SPEC for flying qualities has greatly improved requirements for high-AOA flight, their qualitative nature and lack of coverage for the effects of advanced control systems suggest that further improvement is needed.

Relaxed static stability used on some fighter aircraft can result in handling quality problems at high AOA. This is because of the inherent limitations in available nose-down pitch control power needed to prevent pitch-up during inertia-coupled roll maneuvers and recovery from deep stall.

Because modern fighter aircraft continue to be lost due to unanticipated stall/spin problems, departure/spin resistance and automatic spin-prevention systems should be provided for future fighter designs. Indications are that these systems will greatly improve the safety record without seriously sacrificing high-AOA maneuverability. Continued emphasis should be given to improved high-AOA aerodynamic and design criteria to lessen systems requirements.

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