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PILOT HUMAN FACTORS IN STALL/SPIN ACCIDENTS OF SUPERSONIC FIGHTER AIRCRAFT

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SUMMARY

A study has been made of pilot human factors related to stall/spin accidents of supersonic fighter aircraft. The military specifications for flight at high angles of attack are examined. Several pilot human factors problems related to stall/spin are discussed. These problems include (1) unsatisfactory nonvisual warning cues; (2) the inability of the pilot to quickly determine if the aircraft is spinning out of control, or to recognize the type of spin; (3) the inability of the pilot to decide on and implement the correct spin-recovery technique; (4) the inability of the pilot to move, caused by high angular rotation; and (5) the tendency of pilots to wait too long in deciding to abandon the irrecoverable aircraft. Psycho-physiological phenomena influencing pilot's behavior in stall/spin situations include (1) channelization of sensory inputs, (2) limitations in precisely controlling several muscular inputs, (3) inaccurate judgment of elapsed time, and (4) disorientation of vestibulo-ocular inputs. Results are given of pilot responses to all these problems in the F14A, F16/AB, and F/A-18A aircraft. The use of departure/spin resistance and automatic spin prevention systems incorporated on recent supersonic fighters are discussed. These systems should help to improve the stall/spin accident record with some compromise in maneuverability.

NOMENCLATURE

ACM	air combat maneuvering
AOA	angle of attack
ARI	aileron rudder interconnect
$\bar{c}$	mean aerodynamic chord
C.G.	center of gravity
CAS	command augmentation system
$C_{L_{max}}$	maximum lift coefficient
DFCS	digital flight control system
EBO	eyeballs-out
FCS	flight control system
HUD	head-up display
LEX	leading-edge extension
MIL SPEC	military specifications
MPO	manual pitch override
OVRD	override
RSS	relaxed static stability
SRI	stick rudder interconnect

1. INTRODUCTION

From man's earliest attempts at flight, stall/spin accidents have plagued the development of virtually all types of aircraft. Today, stall/spin accidents are still a serious problem for the military. The problem is accentuated for fighter aircraft by the need to operate at very high angles of attack for good air combat effectiveness.

From the flight mechanics standpoint, the poor stall/spin accident record arises from a combination of several factors: (1) unfavorable aerodynamic (stability and damping) characteristics at high angle of attack (AOA) which cause the aircraft to depart from controlled flight, (2) adverse control-system features which help "trigger" the spin entry, and (3) poor spin recovery characteristics caused by low control effectiveness.

Although the fundamental aerodynamic parameters which underlay the stall/spin problem 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 is still unsatisfactory. Over 100 F-4 aircraft have been lost during the course of development and operation due to out-of-control flight. The record is much improved for modern fighter aircraft such as the F-14, F-15 F-16, and F-18; however, accidents have occurred from flight in the high AOA range and these aircraft have yet to be exposed to broader operational use.

One can intuitively reason that another fundamental part of the stall/spin problem is the pilot's response pattern under very demanding and high-stress flight conditions. The pilot's role in controlling modern supersonic fighter aircraft has changed in that he has been exposed to new phenomena, such as the deep stall, which were not included in his training syllabus. The requirement for a change in his mode of operation is due to several factors: (1) greater emphasis has been placed on multi-role aspects and a diversity of external stores are carried, not only influencing high AOA aircraft behavior, but also demanding a greater versatility from the pilot to carry out his mission successfully; (2) wing planforms designed to provide good lift and maneuverability at very high (AOA) have a gradual stall progression with no sharp g break, thus depriving the pilot of natural stall warning cues; (3) the pilot's "feel" of the aircraft response is masked by the specialized augmentation control systems provided to lessen departure tendencies; (4) the classic steep spin, typical of yesterday's subsonic fighters which required simple recovery techniques (opposite rudder and forward stick) has changed in that modern aircraft may possess several spin modes requiring different control recovery techniques for each; and (5) the long slender features of the supersonic configurations tend to place the pilot farther from the C.G., resulting in large accelerations when high yaw-rate spins occur.

This paper reviews the pilot human factors peculiar to high AOA operation of current supersonic fighter aircraft. A clearer understanding of the pilot's limitations and requirements under high stress situations could help improve the accident record. In turn, the aircraft could be designed to accommodate the pilot rather than requiring the pilot to fit the airplane.

The scope of this paper includes the following: (1) a brief review of the military specifications (MIL SPEC) to point out the handling qualities required in the high AOA flight envelope, (2) a brief background of the peculiarities of human behavior under high stress situations, and (3) an examination of the stall/spin characteristics of several modern supersonic fighter aircraft to pinpoint those areas which affect pilot human factors in a manner tending to cause accidents.

2. BACKGROUND

2.1 Review of MIL SPEC for High AOA Handling Qualities Requirements

The MIL SPEC requirements (Ref. 1) for flight at high AOA are examined briefly to clarify the expected behavior relative to stall/spin characteristics. Areas covered include stall warning, stalls, departures, post-stall gyrations, spins, recoveries, and related characteristics. The requirements are intended to assure safety of flight and absence of mission limitations.

Warning cues. Warning or indication of approach to stall, loss of aircraft control, and incipient spin shall be clear and unambiguous. For many years the lack of adequate high AOA 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. 2, 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. Admittedly, this requirement is difficult to quantify and relates very strongly to flight safety in a dangerous part of the flight envelope. Providing adequate warning cues may be only one solution to the problem. Another is to provide good aircraft characteristics such that the pilot can maneuver without concern for loss of control due to stall, departure, or spin.

Stall characteristics. In unaccelerated stalls the magnitude of uncommanded rolling, yawing, and pitching motions are 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 continues to be a difficult area for the pilot to cope with.

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 deserves increased emphasis. As will be discussed later, highly specialized control-movement techniques are required for deep stall recoveries.

Departure from controlled flight. The aircraft shall be resistant to departure from controlled flight, post-stall 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 post-stall gyrations and spins. These requirements state the following: *(a) Proper recovery technique must be readily ascertained by the pilot and simple and easy to apply under the motions encountered, (b) a single technique shall provide prompt recovery from all post-stall gyrations and incipient spins, (c) avoidance of spin reversal or adverse mode change shall not depend on precise pilot control timing or deflection, (d) safe and consistent recovery and pullouts shall be accomplished with acceptable control forces, and (e) recovery should be specified in terms of allowable altitude loss or* *number of turns.* These are relatively new requirements and although difficult to design into an aircraft, could provide needed flight safety improvements.

2.2 Identification of Pilot Human Factors Related to Stall/Spin

In recent years, increased emphasis has been given to develop fighter aircraft specifically tailored to maneuver at very high AOA. The manufacturers and test agencies have gone to great lengths to provide aircraft which can be flown safely over a wide AOA and sideslip range. In spite of best efforts, accident records show that operational pilots can lose control during aggressive maneuvering. In a very comprehensive survey of operational commands and squadrons (Ref. 2), it was noted that although high AOA maneuvering in combat was not considered a primary tactic, it should not limit the use of the aircraft. A digest of pilots' comments on high AOA flying characteristics obtained from operational units of fighter squadrons is given in Table 1. Without going into detail for each aircraft, in general, the pilots were satisfied with the departure characteristics but not the warning cues inherent in many of these supersonic fighter designs.

TABLE 1. DIGEST OF PILOT COMMENTS ON SUPERSONIC FIGHTER AIRCRAFT HIGH-AOA FLYING CHARACTERISTICS (from Ref. 2)

Aircraft	Overall high AOA F.Q.	Departure characteristics	Cues	Other
F-4C,D,E	Acceptable to good for fighter Departure hazard for ground attack Good control effectiveness Must change control technique to rudder maneuvering	Strong adverse yaw Abrupt nose slice/roll Predictable-repeatable Recoverable (if sufficient altitude	α: Buffet (poor, early, heavy) Stick position V: Stick force Dig-in Opt. turn: Aircraft buzz	Force harmony problems at low dynamic pressure Can over-rotate or over-g Roll SAS turned off
F-4E (Leading edge slat)	Excellent Better separation between $C_{L_{max}}$ and departure α Less roll rate capability Use aileron and rudder to roll	Reduced adverse yaw Departure resistant Roll departure Somewhat unpredictable at very high α Recovers quickly	α: Buffet (good, steady increase) Aural tone Stick position V: Buffet increase Stick force Opt. turn: Aircraft buzz	Roll SAS turned off
F-5E	Excellent Can point aircraft at very low speeds Never worry about α Loose aileron roll power — must use rudder maneuvering	Departure resistant Rudder induced high yaw rate Difficult to recover	α: Buffet; stick position V: Flap horn Opt. turn: Buffet	No roll rate CAS Full aft stick — max α Centerline stores degrade stability significantly
F-14A	Good — "honest" High control power Requires rudder maneuvering	Adverse aileron yaw Departure resistant Yaw/roll departure Severity is speed dependent	Generally poor Buffet Stick position Stick force	Main problem with asymmetric thrust PCAS turned off at high α
F-15A	Excellent High longitudinal control power Some worry about over-g SRI makes airplane consistent and repeatable Can override SRI	Departure resistant Nose slice Recover hands off Auto roll if inverted	α: Mild wing rock decreasing roll power nose drop at stall Opt. turn: Light buffet	Constant Fs/g longitudinal CAS PCAS turned off at high α SRI provides all stick maneuvers $p\alpha \rightarrow \delta_r$ causes inverted auto roll
F-16A	Excellent maneuvering Maneuver with abandon: no worry about g or departure Tendency to excessive use of high α because of poor cues Limiters "take over control," save poorly skilled pilot, restrict highly skilled pilot	Departure preventing system Can be tricked into Lat/Dir departure g-overshoot Super stall Automatic anti-spin system Recovery sometimes difficult	None No stick cues No buffet No artifical cues	Constant F_s/n CAS SRI provides all stick maneuvering Maneuver limits on n, α, p Need limit changes with stores

In the following, several basic pilot human factors problems are discussed to obtain a clearer understanding of the reasons for continued stall/spin accidents.

Need for satisfactory warning cues. A prioritized list of high AOA cues is given in Table 2 (from Ref. 3). Assuming that the operational pilot will maneuver up through maximum lift capability, tactile (nonvisual) cues can be an important source of information when aggressively pursuing an opponent. As noted previously in Table 1, most modern supersonic aircraft do not have adequate nonvisual warning cues and other alternatives may be required. Pilots require cues to be consistent and repeatable regardless of aircraft configuration. They want to approach the limit of controllability without going over a precipice. In general, currently used artificial cues (aural tones and panel lights) receive lower priority in signaling the brain of impending disaster and tend to be ignored under high stress situations.

TABLE 2. HIGH-ANGLE-OF-ATTACK CUES (from Ref. 3)

Cue	Considerations
	Normally natural cues
Buffet	Useful head-up Should be gradually increasing with angle of attack May interfere with ACM tracking if too severe Can be implemented artificially — stick shaker Possible to confuse stall buffet with flap or Mach buffet
Airframe vibration	Useful head-up or down Not easily designed-in — may be very subtle or very prominent Can be masked by turbulence
Uncommanded motion	May be in the form of wing rock, porpoising, pitch-up, g-break, adverse yaw, etc. May interfere with tracking or create hazard if at low altitude May involve a change in technique, e.g., feet-on-floor to stick-and-rudder to rudder only
Stick force	Usually more associated with IAS or, in some case, n_z Useful head-up Can be implemented artificially — $\bar{q}$-bellows, stick pusher Can be in various forms — stick lightening, control "mushiness," loss of effectiveness, etc.
Stick displacement	Relates remaining control authority Useful for indicating trim condition (if parallel trim involved)
	Normally artificial cues
Angle of attack gauge	Direct indication of angle of attack Direct scan required whether on panel or on HUD Angle-of-attack signal can be augmented to account for rate of onset — add $\dot{\alpha}$ or $\dot{\theta}$ Other gages used as indirect indicators of angle of attack — trim position, IAS
Aural	Commonly used in artificial warning systems May be difficult for pilot to assimilate in presence of other aural cues or information More useful if a graduation in tone Natural aural cues are also commonly used in supporting roles — wing noise relates to IAS or noise level used to distinguish Mach buffet from stall buffet

Awareness of out-of-control situations. Pilots may have difficulty in determining if an out-of-control situation is indeed a spin and, if so, whether it is upright or inverted. As noted in a recent Navy spin training instruction manual: ". . . the disorienting and physiological debilitating effects of sudden, unexpected, and often violent aircraft departure are at best confusing and at worst fatal . . ." Many pilots lack confidence to fly to high AOA limits because of uncertainty of proper analysis of aircraft motions. Clearly, the out-of-control modes are more complex in modern aircraft and pilots may not have received training to recognize all modes.

A flat upright spin on modern fighters can feel somewhat similar to an inverted spin because of the large eyeballs-out (EBO) translational acceleration. The pilot must look at several sensor inputs to determine the spin mode. If the turn needle is pegged, AOA is at the upper limit, and the airspeed is low, then the aircraft is in an upright spin. The pilot must make a proper judgment when the turn needle and AOA are pegged, but airspeed is greater than 200 knots. In this case the aircraft is *not* in a spin but in a tight-turn spiral.

Use of correct spin-recovery technique. The primary human factors problem in spin recovery is that the pilot is called upon to provide unusual control inputs that are not part of his normal reflex action. He must be prepared beforehand psychologically and physiologically by repeatedly fantasizing the correct control procedures in order to perform satisfactorily in a high stress situation.

Once a recognized spin has started, pilot workload rises rapidly and confusion can set in, even under training conditions. As discussed in Ref. 4, a marked reduction in mental capacity of reception occurs and only one source of sensory information may be perceived and used effectively. Each aircraft requires specific pilot control actions that must be accomplished quickly to minimize yaw rate buildup. Under stress the brain tends to accept only one input at a time (see Ref. 5), and decisionmaking processes may degrade. The pilot must select the correct control input to effect recovery and relegate other items (adjustment of engine power, trim, selection of augmentation system switches, etc.) to reflex action.

Timing of control inputs and holding the controls at the *full* deflection for a sufficient period of time is necessary. As noted in Ref. 4, the ability to control multiple muscular actions may decrease and the pilot would be unaware that the stick has drifted away from the full anti-spin position.

It has been established (Ref. 4) that one's internal chronometer changes under stress, such that judgment of time becomes inaccurate. In one case, the pilot reported that he had snapped the controls to the recovery position smoothly in 1 sec, while the telemetered data showed it took 5 sec and that the action was jerky. This action indicated that time had been shrunk by a factor of 5. In another case the pilot bitterly reported that the aircraft was extremely unresponsive to his recovery inputs even after holding anti-spin control positions for 20 sec. The time history records showed that recovery had occurred in 4 sec, thus indicating that time had appeared to *expand* by a factor of 5. Put another way, the pilot thinks he has held anti-spin controls in for a period of 20 sec (required by several aircraft with large inertias) when, in fact, he has applied the controls for only 4 sec.

Another complicating factor is that the pilot must recognize and anticipate spin recovery to apply correct control movement to avoid a secondary spin. It is important that the pilot uses correct sensory feedback to determine if recovery from the spin is imminent. In addition, he must possess "fluid intelligence" to be able to quickly change the recovery process in the event that a modification in technique is required.

Recently, there has been increased use of visual displays to aid the pilot in determining correct anti-spin control procedures. These visual inputs must be used with caution. Studies have shown (see Ref. 6) that vestibulo-ocular disorientation can occur in prolonged spins. Results show that in the roll plane of the skull there is limited capability for optokinetic following. Consequently, misleading vestibular signals arising from prolonged rotation drive an inappropriate oculomotor response. Pilots have reported that with high yaw-rate spins (180°/sec), a "wagon wheel" effect can occur, where the large black squares (earth reference) and cardinal headings on the HUD appear to move in a direction contrary to that of the spin. Additional research is needed in this area.

Effect of high rotation rates on recovery. As indicated earlier, the design of modern fighters tends to place the pilot farther forward from the C.G., subjecting the pilot to relatively large longitudinal accelerations in high yaw-rate spins. These forces cause additional pilot anxiety because of concern for escape which may take number one priority in the pilot's mind and cause inappropriate control recovery action. In addition, records show that under high accelerations full right lateral control input is very difficult to maintain (see Ref. 4). In fact, some cockpit restraint systems may allow the pilot to be displaced, such that correct control positions for recovery may not be physiologically possible.

Finally, the high EBO acceleration tends to pool the blood at the extremities, making it very painful to exert appreciable forces on the controls. The predominating factor in discussions with pilots on spin-recovery techniques is to keep it *simple*. The ideal recovery technique from the pilot's standpoint is to neutralize or release all controls — a simple reflex action which is easy to carry out, particularly during high accelerations.

Judgment of performance (altitude) margins. Another human factors problem may occur when it is necessary to leave an aircraft after an irrecoverable out-of-control situation has developed. Modern fighter designs tend to have high descent rates and may require a relatively large number of turns (8-10) for spin recovery. In addition, there can be excessive altitude loss in recovery, after the spin is stopped. The foregoing factors may be difficult for the pilot to judge accurately and unless he is preprogrammed and strongly motivated to initiate ejection at a set altitude, there is a great tendency to delay ejection. Part of the problem, particularly with test pilots, is pride: loss of the test aircraft can ruin the total program. In training missions, the motivation to stay with the aircraft is also strong: the student pilot wants to recover for fear of losing points with the instructor pilot. Equally catastrophic is when the instructor pilot has allowed the student pilot to go too far and must save face by coming home with the aircraft. Finally, because the forces and accelerations have shifted the pilot's position away from an idealized ejection posture, the pilot may delay ejection hoping to achieve a more favorable body position.

3. DISCUSSION

3.1 Results for Specific Aircraft

Several of the pilot human factors problems previously discussed are reviewed for specific aircraft in this section.

High AOA flight characteristics for F-14A. This aircraft illustrates spin-recovery problems when the pilot is placed far forward (22 ft) from the C.G. 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 no stall is perceptible. Lift curve characteristics shown in Fig. 1 indicate that a directional divergence and roll reversal start to occur slightly above 15° AOA. Buffet starts at 14°, increasing to moderate at 17°, and then decreases to light buffet at 24° AOA (*not* considered satisfactory stall warning; see Ref. 2).

Aircraft response to pilot control inputs becomes more difficult to predict above 20° 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. Sink rate may increase to 9000 ft/min and loss of 5000 ft altitude is typical in recovery from high AOA flight.

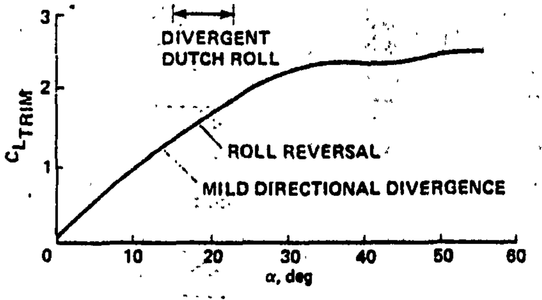

Fig. 1. F-14A trimmed lift curve (from Ref. 2).

In the takeoff/landing configuration, at 28° AOA, the stall is characterized by divergent wing rock and yaw excursions. Yaw angles may reach 25° and roll angles 90° within 6 sec 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. One can appreciate the need for a good pilot indoctrination to fly this type of aircraft at high AOA.

Although the F-14A is basically departure resistant, departures can occur during maneuvers combining rolling with high AOA. Departure is described as a snap roll, or a 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 stick opposite to the direction of roll will aggravate departure.

Departure recovery requires precise control positioning and timing. The pilot's flight manual states that pilots should 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 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 rudders must be moved in the opposite direction. When roll/yaw stops, pilots should 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 controlled flight. As noted previously, in a high stress situation, the pilot's ability to control multiple muscular actions may decrease, particularly when exposed to strong forces (discussed next).

It is important that the pilot appreciates the need to effect recovery quickly before yaw rate builds up. Because the cockpit is located 22 ft ahead of the C.G., large longitudinal accelerations occur with an increase in yaw rate, as shown in Fig. 2 (from Ref. 7). Centrifuge tests of the F-14A configuration showed the following:

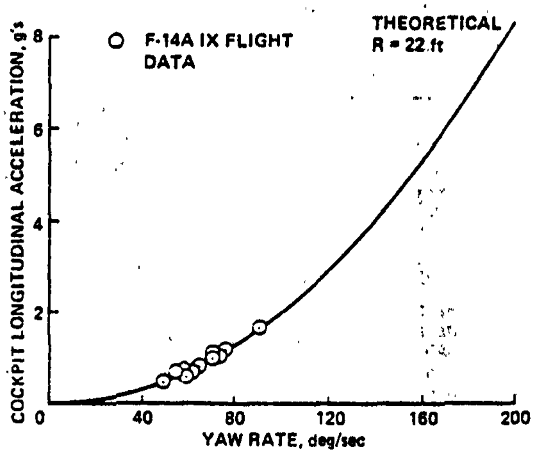

Fig. 2. Variation of acceleration with yaw rate (F-14A; from Ref. 7).

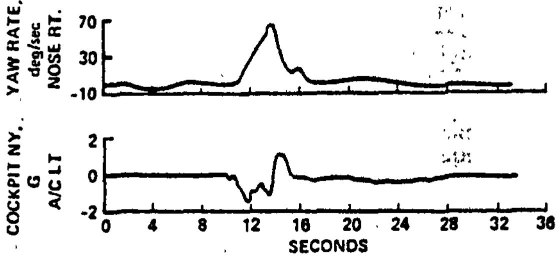

Fig. 3. Cockpit lateral acceleration at high yaw rate (F-14A; from Ref. 7).

1. At -3 g 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 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). 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.

Part of the 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 analyzing by the pilot to determine to what degree engine thrust asymmetry has occurred. This adds appreciably to the pilot's workload during a high stress situation.

As noted in Ref. 7, "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."

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

High AOA characteristics for F-16A/B. This aircraft illustrates the need for unusual stall-recovery techniques by the pilot. 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 the spin and rudder against the spin.

The lift characteristics of this configuration show an initial break in lift curve slope at 20° AOA, resulting from outer wing panel stall (Fig. 4). The highly swept wing-body strake continues to increase lift up to a $C_{L_{max}}$ at 35° AOA (Ref. 8). The pitching-moment characteristics associated with these lift characteristics are shown in Fig. 5 (obtained from Ref. 8). Note that mild pitch static instability occurs in the lower AOA range for the nominal C.G. position of 0.35 $\bar{c}$ and that a stable trim point exists in the high AOA range at approximately 60°. An important point of interest is that relatively low pitch-control power exists to retrim the aircraft to a lower AOA value. Because the aircraft could be flown to very high AOA where departures may occur, the AOA is limited artificially to values below 25° by automatically applying nose-down stabilizer control. The effectiveness of this technique is limited by the nose-down pitch-control power available. For aircraft which employ relaxed static stability (RSS) (such as the F-16A), sufficient nose-down pitch control is basically difficult to obtain. Thus, even with an alpha limiter employed, an operational pilot in ACM can depart the aircraft; several accidents have resulted from the deep stall hang-ups.

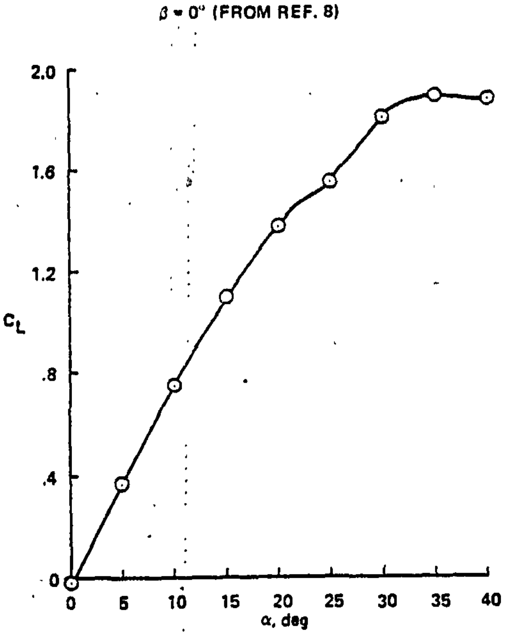

Fig. 4. Untrimmed lift characteristics of F-16A configuration.

An excellent discussion of the mechanics of departure for fighter aircraft with relaxed static stability is given in Ref. 8. The alpha limiter can be defeated if the pilot uses high roll rates where sufficient nose-up inertia coupling moments are generated to overpower the available nose-down control moment. The available full nose-down moment could also be used in recovery from prolonged vertical climbs to zero airspeed where high AOA conditions result during the fall-through phase. Thus, the alpha limiter can be "fooled" with normal evasive maneuvering by operational pilots, resulting in a deep stall condition. As noted later, this can be very perplexing for the pilot because of the unusual control inputs *required and the lack of previous exposure.*

The flight manual for the F-16A/B aircraft discusses the out-of-control recovery procedures, illustrating pertinent pilot human factors problems. The upright deep stall is characterized by a 1-g load factor, an AOA pegged at 32°, and an airspeed reading between 50 and 150 knots. With rearward C.G. locations, the deep stall is oscillatory in pitch, and the AOA may vary ±30° with some roll oscillations. Oscillatory deep stalls can be deceptive because *the nose may drop below* the horizon, giving the appearance of self-recovery. As noted in Ref. 9, 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/sec and many of the deep stall situations have occurred during low-altitude maneuvering.

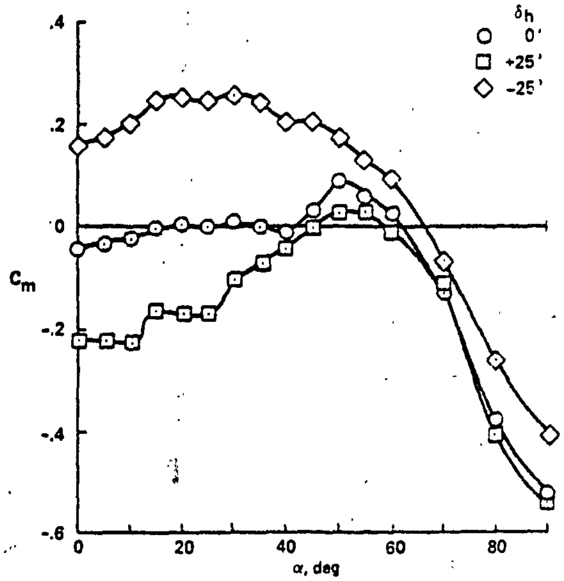

Fig. 5. Variation of pitching moment with α for various stabilator deflections (F-16A configuration; from Ref. 8). C.G. is at 0.35 $\bar{c}$.

The recovery procedures from the deep stall are certainly not classic and demand a well-disciplined approach. Because the aircraft is locked into the high AOA trim point by a stable pitch stability situation, full nose-down stabilizer deflection will not 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 (Fig. 5) in phase with the residual pitch oscillatory motions. The pilot must (1) hold the manual pitch override (MPO) switch in override (OVRD), giving the pilot full tail travel; (2) extend the speed brakes; and (3) select the AFT (Fuel) FEED mode. 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 sec and 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 sec 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 physiologically to carry out, the unusual control inputs required may cause some pilots to give up. Exposure to this situation can obviously improve pilot proficiency and confidence. The ability to achieve success on the first try is not good; 75% of visiting European F-16 pilots failed when tested in a two-place F-16 aircraft. Further, as noted in Ref. 10, 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° bank angle) masked the pitching motion of the aircraft."

In summary, RSS used on fighter aircraft can result in pilot control problems at high AOA due to deep-stall trim. The pilot must provide a properly phased pitch-control oscillation technique (which violates the *simple* rule) to effect recovery during a period of high psychological stress.

Results for F/A-18A. This aircraft is used to exemplify potential problems for the pilot when advanced flight-control systems are used to provide departure/spin resistance and automatic spin recovery. A primary design goal was to provide the operational pilot with an unrestricted maneuvering capability (no AOA limiter used) in the high AOA range. The F/A-18A incorporates a highly sophisticated, full-authority, digital flight-control system programmed to enhance high AOA flight characteristics. As noted in Ref. 11, departure/spin resistance is obtained by scheduling the maneuvering flaps (both leading- and trailing-edge flaps) with AOA Mach number and by reducing differential tail and aileron authority at high AOA to reduce adverse yaw. An aileron rudder interconnect (ARI)-like feature provides a favorable (proverse) yaw contribution to improve roll coordination. A rudder pedal to roll interconnect reduces proverse yaw during rudder-only rolls. The roll control systems minimize kinematic coupling (the interchange of AOA and sideslip) by rolling about the stability axis. Roll-to-pitch feedbacks are used to reduce inertia-coupling effects. These features, some of which are unique to the F/A-18A, will be common to future aircraft designs to produce roll about the velocity vector and hence reduce sideslip in high AOA maneuvers without sacrificing maneuverability. As noted in Ref. 2, this could result in more yaw than roll at high AOA, and pilots may experience difficulty in detecting nose slice departure. In piloted simulator tests, application of recovery control was too late to prevent departure. An automatic spin-recovery mode logic was designed into the control system to establish yaw-rate engagement thresholds which 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 on Nov. 14, 1980, the first unintentional F-18A out-of-control experience happened to an operational pilot. The departure occurred during yo-yo maneuvers at about 20,000 ft. Although the pilot applied correct anti-spin-control inputs, recovery could not be obtained, and the pilot ejected safely below 10,000 ft. The facts that the departure occurred so easily and was apparently impossible to recover from further illustrate pilot problems when confronted with an unexpected out-of-control situation.

Looking first to examine whether the pilot had adequate warning of the approach to departure, it is noted (Ref. 11) that as AOA is increased beyond 10°, a medium-frequency, low-amplitude buffet can be felt by the pilot. Further increases in AOA result in increased airframe buffet with decreased frequency; however, these changes are subtle, spread out over a wide AOA range, and generally do not serve as an adequate AOA indication. As AOA exceeds 50° to 60° 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 AOA for $C_{L_{max}}$ (35° to 40°). Because the aircraft has weak natural warning cues, artificial AOA cues are provided through computers. The various artificial cues provided by the AOA feedback loops are shown in Fig. 6 (from Ref. 11). The most significant of these cues may be in the pitch control, where above 15° AOA much larger pull stick forces are required. As 35° AOA is reached, most pilots 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-18A aircraft, as described in Ref. 12, it was noted by the pilot in the Nov. 1980 accident that the spin yaw rate was very low; in fact, so low as 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 (CAS) mode, and the pilot was left with low anti-spin yaw control power. This factor must have been very perplexing to the 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 (Ref. 11). A low yaw rate, less than 50°/sec, relatively smooth with some pitch and roll tendencies and a rate of descent of 21,000 ft/min — recovery could be effected in less than one turn. An intermediate-mode yaw rate (20°/sec to 80°/sec) resulted in much more violent oscillations about all axes. This was very disorienting to the pilot because of the changing yaw rates and the execution of a 360° roll while continuing to spin in the established direction. The high yaw-rate

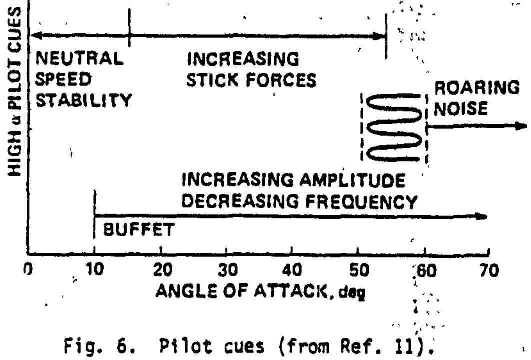

Fig. 6. Pilot cues (from Ref. 11).

spin (110°/sec to 140°/sec) occurred at AOA up to 95°, and was smooth and flat with only small oscillations. Unlike the other modes, EBO accelerations become uncomfortable (but not disorienting), -3.5 g maximum, with recovery in less than three turns.

Looking further at out-of-control modes which may have confronted the pilot in the 1980 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° to 55°, the pilot experiences a very slow nose-down, pitch recovery with full forward stick. As noted in Ref. 13, "Time to recover was excessive and loss of altitude could exceed 8000 ft. Recovery was achieved with full forward stick and extreme patience . . ."

Another variation of this AOA hang-up was termed a "falling leaf maneuver" because of the oscillations in sideslip, roll rate, and pitch rate which 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. 13, this oscillatory falling-leaf mode was the most probable cause of the 1980 accident.

Whenever extreme patience is demanded from the pilot to effect recovery, pilot response patterns are difficult to predict. As discussed previously, judgment of time during periods of high stress can be seriously inaccurate. Because the pilot is not aware of this infirmity, given the option, ejection might appear to be the only solution.

To deal with the foregoing type of departure problems, an improved automatic spin mode logic was incorporated. A unique feature of this system is that it provides full anti-spin control authority only if the pilot moves the lateral stick in the correct direction (with the spin). If the pilot applies pro-spin stick, the digital flight control system (DFCS) reverts back to the CAS mode which, in effect, negates his input.

The use of direct command signals to aid the pilot in out-of-control situations has merit, since as noted previously, under high stress conditions the mind tends to perceive and use only one channel or source of information. Equally effective might be a voice command, based on a model-following system and software logic which analyzes the state of the aircraft's motions and verbally instructs the pilot as to the correct control positions for recovery.

Another example where the pilot was exposed to large lateral side forces occurred during departure tests at medium AOA when aggravated (pro-spin) controls were applied (see Ref. 13). As shown in Fig. 8, extremely high side forces (up to 3 g laterally) were associated with the very large sideslip angles (over 75°) that occurred in this high subsonic (M = 0.9) departure. As previously discussed for the F-14A aircraft, 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 flightpath divergence with suitable control law logic.

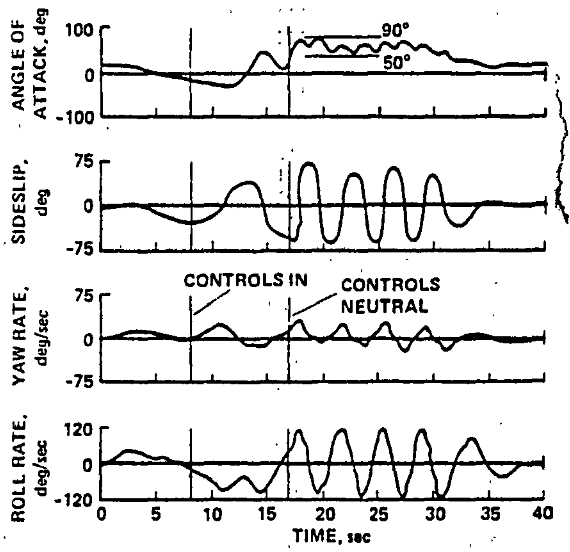

Fig. 7. F/A-18A "falling-leaf" (from Ref. 13), rudder-only inverted spin attempt.

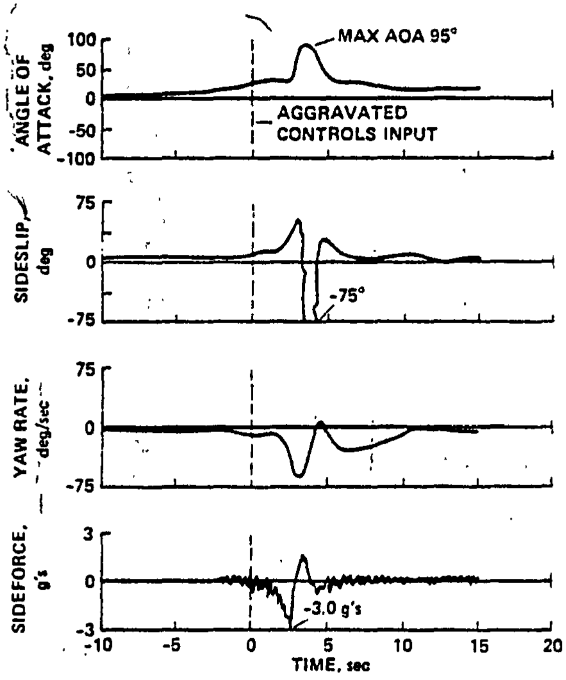

Fig. 8. F/A-18A high Mach departure; Mach = 0.9; 35,000 ft fighter escort + centerline tank.

In summary, the F/A-18A aircraft represents an advanced high-performance fighter aircraft providing the pilot with unrestricted maneuvering capability at high AOA. Although some unique and unexpected high AOA problems were encountered in early testing, because of improvements made 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 aircraft.

5. CONCLUSIONS

A review of pilot human factors related to stall/spin accidents of supersonic fighter aircraft indicates the following:

1. To improve the stall/spin accident record, a better understanding is needed of fundamental human factors which limit the operational pilot's ability to perform satisfactorily in the high stress environment associated with air combat maneuvering at very high AOA.

2. The primary human factors problem is that the pilot is called upon to provide unusual control functions that are not part of his normal reflex action in an environment where his psycho-physiological processes are degraded.

3. Several serious psycho-physiological phenomena influencing the pilot's behavior in stall/spin situations include: (1) channelization of sensory inputs (one thought at a time); (2) limitations in precisely controlling several muscular inputs; (3) inability to accurately judge passage of time; and (4) disorientation of vestibulo-ocular inputs.

4. Key human factors related items which influence the pilot's ability to operate successfully in the high AOA part of the flight envelope include (1) the need for tactile (nonvisual) warning cues to sense margins from out-of-control flight; (2) a means for quickly identifying out-of-control situations; (3) stall/spin recovery techniques which are simple for the pilot to execute; (4) an improved crew restraint system to alleviate large translational forces in departures and spins; and (5) motivation schemes to facilitate timely ejection.

5. Because the latest supersonic fighter aircraft provide the pilot with greatly increased capability for high AOA maneuvering, departure/spin resistance and automatic spin prevention systems are needed to provide additional protection from out-of-control flight. These systems, including the use of graphic displays and voice command information for departure/spin recovery assistance, and improved engine-status information for twin engine aircraft, will undoubtedly improve the stall/spin accident record; however, more operational experience is needed to optimize these concepts for the fighter pilot with an acceptable reduction in maneuverability and minimum increase in aircraft cost and complexity.

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16. Abstract

A study has been made of pilot human factors related to stall/spin accidents of supersonic fighter aircraft. The military specifications for flight at high angles of attack are examined. Several pilot human factors problems related to stall/spin are discussed. These problems include (1) unsatisfactory nonvisual warning cues; (2) the inability of the pilot to quickly determine if the aircraft is spinning out of control, or to recognize the type of spin; (3) the inability of the pilot to decide on and implement the correct spin-recovery technique; (4) the inability of the pilot to move, caused by high angular rotation; and (5) the tendency of pilots to wait too long in deciding to abandon the irrecoverable aircraft. Psycho-physiological phenomena influencing pilot's behavior in stall/spin situations include (1) channelization of sensory inputs, (2) limitations in precisely controlling several muscular inputs, (3) inaccurate judgment of elapsed time, and (4) disorientation of vestibulo-ocular inputs. Results are given of pilot responses to all these problems in the F14A, F16/AB, and F/A-18A aircraft. The use of departure/spin resistance and automatic spin prevention systems incorporated on recent supersonic fighters are discussed. These systems should help to improve the stall/spin accident record with some compromise in maneuverability.

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