F-5E Departure Warning System Algorithm Development and Validation

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Most fighter aircraft exhibit a departure mode that is predictable, repeatable and, therefore, avoidable through the use of warning systems and/or flight control limiters. On the other hand, some aircraft, such as the F-5E, have unique departure/spin-entry mechanisms that are impossible to produce at will, apparently random in occurrence, and extremely difficult to sense by the pilot. Providing a timely and reliable warning of impending departure is a very difficult problem in these latter kinds of aircraft. This paper summarizes the work done to analyze the F-5E departure characteristics, isolate the critical parameters, derive a departure warning algorithm, and flight-validate the system with live air combat maneuvering missions. Results confirmed the combat feasibility of sensing the aircraft's rotational rates, computing the roll-yaw coupled pitch acceleration, which is the essential ingredient of the F-5E departure, and providing the pilot a warning of the presence of a critical magnitude of this intertial pitch acceleration. The algorithm, in an F-5E departure warning system, promises to prevent future inadvertent spin entries, and with appropriate parameter thresholds could be adapted to other aircraft with similar departure mechanisms.

I. Introduction

THE F-5E aircraft has enjoyed a reputation as one of the most aerodynamically honest and forgiving fighters ever built. When configured without wing or centerline stores, it exhibits a high degree of resistance to loss of control, even during aggressive air combat maneuvering. Although the F-5E exhibits this resistance to poststall gyrations (PSG) and spin entries, the aircraft does possess a unique departure "window" through which the pilots have from time to time inadvertently passed, experiencing PSG's and sometimes unrecoverable spins.

The F-5E departure mode is unique because, unlike many other fighters, the aircraft is very tolerant of poststall maneuvering to extreme angles of attack. Although aerodynamic stall of the wing occurs at approximately 23 deg angle of attack, it is commonplace for the aircraft to experience angles of attack of 40–50 deg during air combat maneuvering. During the spin susceptibility tests, momentary excursions to 70 deg were observed with no adverse consequences. A departure from controlled flight requires two key conditions to be met simultaneously; 1) an increasing poststall angle of attack, and 2) a sustained yaw rate of approximately 35 deg/s.

Coordinated rolling maneuvers initiated at medium to high angles of attack can produce these required conditions simultaneously through a well-known phenomenon called roll-yaw coupling. Rolling at medium to high angle of attack requires a high level of body-axis yaw rate in order to maintain coordination (i.e., zero sideslip). This is one of the reasons why the F-5E is most effectively rolled at these angles of attack by using the rudder. Rolling and yawing in-phase combine to produce a nose-up pitch acceleration that will directly produce condition 1, namely, an increasing poststall angle of attack. This is called internal pitch acceleration. The yaw rate required for a coordinated roll can be significant enough to satisfy condition 2, namely, a sustained yaw rate. Both conditions 1 and 2 are brought about by inertial forces. The aerodynamic forces on the aircraft tend to fight these inertial forces under most conditions. There are, however, some "soft spots" in the aerodynamic stability of the F-5E. These soft spots contribute to the existence of a departure window for this aircraft.

The aerodynamic soft spots are depicted in the yaw stability Cn_β and yaw damping Cn_r plots in Fig. 1. The F-5E is directionally unstable in the angle-of-attack regions of about 22–28 deg and above 55 deg. The first-named region includes the maximum lift angle of attack, and the directional looseness has often been used by pilots as a seat-of-the-pants cue of attaining maximum lift. The aircraft normally yaws a very slight but noticeable amount when this angle of attack is encountered. The aircraft does not depart directionally, however, because of other aerodynamically stabilizing characteristics, including yaw damping, as shown in the plot. The aircraft has very strong yaw stability between 30 and 50 deg angle of attack. It is only when the angle of attack is driven above 50 deg (from 50 to 75 deg) that yaw damping is propelling. If the aircraft is allowed to remain in this region a few seconds, a spin will almost certainly develop.

The region around 22–28 deg angle of attack is called the departure window, because the directional looseness in that region allows the aircraft to yaw very readily during high angle of attack rudder rolls. The yaw and roll rates can rapidly couple into an inertial pitch acceleration that, in turn, can very abruptly drive the angle of attack to 50 deg or higher through the window, or out the departure path depicted in Fig. 2.

The significant point is that the departure onset begins in the heart of the air combat envelope, and the cues to the pilot are not significantly different from those associated with normal, hard maneuvering. The maneuver most likely to produce a spin in the F-5E begins with a near-level 3–5 g turn at a nominal airspeed of perhaps 300–350 knots indicated airspeed (KIAS). With the airspeed decreasing through a speed range of 170–260 KIAS, and just as an aerodynamic stall occurs (2–4 g's), apply full top rudder (with or without additional aft stick). As the aircraft rolls, nose-high over the top, inertial coupling may drive the angle of attack to extreme levels (40–60 deg). The airspeed bleeds dramatically, and the aircraft is now at a high angle of attack, with residual yaw rate, and very little aerodynamic stability. If all of this happens, a poststall gyration has just occurred, and a spin will follow immediately if the nose (or angle of attack) is not lowered with a forward stick.

Analysis of the operational spin accidents that have occurred to date reveals that the pilots were not aware that inertial roll-yaw coupling was occurring until the departure/spin had developed to the point that recovery was impossible. The tradi-

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tional pilot cues of impending departure are inadequate to alert the F-5E pilot of the onset of inertial coupling. Such indicators as buffet onset, wing rock, sink rate, and nose slice are useful for sensing stall approach and $C_{L_{max}}$, but are of little value as a departure warning. Rapid onset of g's and sudden airspeed loss can be of assistance as an indicator, if the pilot is not otherwise distracted by other flight activities. The pitch acceleration $\dot{Q}$, which produces the large angle-of-attack excursion preceding a departure, is composed of two elements. The aerodynamic component $\dot{Q}_A$ closely follows the control stick commands up to about 30 deg angle of attack, but this tends to resist further increases due to innate longitudinal stability. The inertial component $\dot{Q}_I$ results from the previously described roll-yaw coupling and is the dominating force in the departure. The pilot can only sense the sum of the two components $\dot{Q}$, which is not always exceptionally large. When the aircraft passes through the departure window and enters a poststall gyration, the pilot is unaware because the aircraft appears to be responding to his control inputs. His first indication of departure is the continued motions of the aircraft after the controls are neutralized. The aircraft has, in fact, departed sometime previously. This insidiousness of the departure mechanism has frequently led the pilot to believe that the aircraft departed immediately into a flat spin.

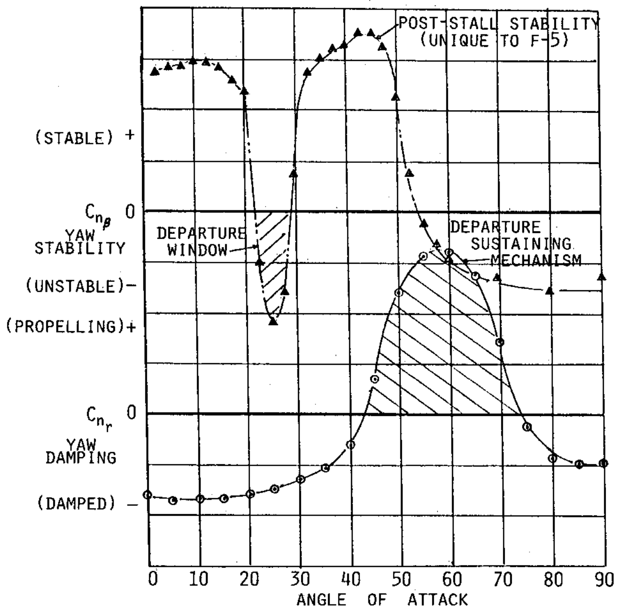

Fig. 1 F-5E aerodynamic stability.

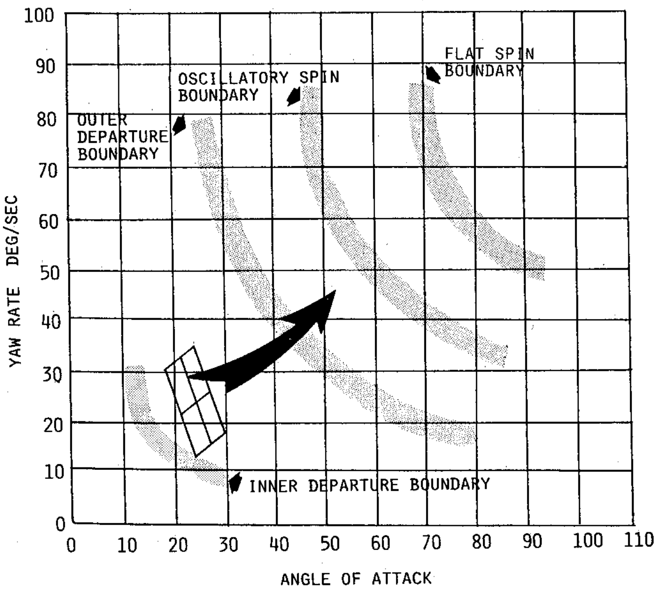

Fig. 2 Departure window.

The Safety Investigation Board, investigating an F-5E spin accident, recognized this problem and recommended that the feasibility of a departure warning device be explored. The U.S. Air Force contracted the development of such a system, and this paper presents the results. The development contract was composed of two phases: the algorithm development phase and the flight validation phase.

II. Phase I—Algorithm Development

Overview

This phase began with an in-depth analysis of available data relevant to F-5E poststall gyrations and spins. All of the flight-test data from the F-5E stall/poststall/susceptibility test were available, and some data from operational spin accidents had been recorded on the Air Combat Maneuvering Instrumentation Range (ACMI) and were studied. Other ACMI data tapes from representative air combat maneuvers were studied, and a large amount of corporate knowledge of F-5E spin characteristics, drawn from involvement in spin-accident investigations as well as the stall/poststall/spin susceptibility test, were brought to bear.

The next step was to consider traditional stall/spin warning systems of other aircraft for possible adaptation of the F-5E. Finding these to be unadaptable, the study homed in on the unique parameters of the F-5E departure mechanism, and a preliminary algorithm was formulated. The algorithm was refined through an iterative process of analytically testing it against the spin-test data and available air combat maneuvering (ACM) data from the ACMI. This ultimately led to a final algorithm proposed for validation in phase II.

Technical Background

It is known that spin departures occur through a combination of aircraft aerodynamic and inertial forces. In many aircraft, the spin entry point is characterized by a major change in the vehicle aerodynamices (a loss of stability) that completely dominates the inertial foces. Such an aerodynamic event can be readily correlated with a range of onset flow conditions. This leads to the classical approach of defining departure boundary in terms of parameters like angle of attack or a combination of angle of attack and yaw rate (R). In the F-4, for example, a tone warning at critical angles of attack assists the pilot in avoiding the angle of attack regime with greatly reduced directional stability. The F-15 has a tone that warns the pilot of a critical threshold of yaw rate, and the F-18 has a warning tone for both yaw and angle of attack.

In aircraft that are well-behaved aerodynamically at stall, like the F-5E, the spin departure is caused by inertial coupling. In this case, the subsequent analysis shows that the use of angle of attack and yaw rate as correlation parameters does not give a precise enough boundary to use in an automatic warning system. Therefore, a reliable self-contained inertia-based system has been proposed. It should be noted that although the F-5E aircraft has been the target of this study, the approach and findings would be applicable to any aerodynamically well-behaved aircraft whose spin susceptibility by inertial coupling. A thorough review and analysis of available handling qualities data for the F-5E led to the following summary assessment of its departure and warning characteristics.

The F-5E is resistant to departure even in aggressive maneuvering, and departure warning is adequate for most types of air combat maneuvering. The F-5E is at least resistant to departure in maneuvers involving sustained rudder-roll maneuvers at near-stall or poststall angles of attack. Departures are developed if the maneuver control inputs occur in phase with the natural motions of the aircraft—this phasing creates an uncommanded pitch acceleration that develops through inertial coupling.

This departure mode provides inadequate warning to the pilot, since he cannot distinguish between the expected response to his control and the effects of inertial coupling; and unless this departure is sensed immediately and proper recovery controls applied, the aircraft will progress rapidly into a spin. Recovery from a developed spin is highly unlikely.

Classical Analysis Approach

Historically, departure and spin boundaries have been defined in terms of angle of attack and yaw rate. Analytically (simulation), those boundaries are established as follows: set of initial conditions of alpha angle-of-attack and yaw rate R are picked with all other angles and rates put at zero. Then a six-degree-of-freedom simulation is initiated and evaluated. If after two turns α is less than α_s, then the initial conditions are deemed "no spin." If after two turns α is greater than α_s, the conditions are "spin", and if α remains greater than α_s indefinitely, then the initial conditions result in a steady-state spin. A series of entry conditions are plotted and a theoretical spin boundary is established, as shown in Fig. 3. The "perfect" correlation of this theoretical analysis provides initial spin boundaries against which flight-test data can be compared. Note that each boundary extends to two extremes on this plot: maximum yaw rate with the associated angle of attack, and maximum angle of attack with an associated yaw rate. The notional figure shows perfect correlation. In actual flight test, maximum values of α and R are tabulated during a maneuver. They are plotted and designated as falling into one of three categories: no departure, PSG or departure, and spin.

Analytical Approach

With the F-5E, as previously shown in Fig. 2, there are combinations of angle of attack and yaw rate that roughly define departure boundaries. However, they are not useful for incorporation into a departure-warning algorithm. The inner departure boundary is too restrictive and would lead to many false warnings if it was used. This boundary lies in the heart of the air combat envelope and 99 times out of a hundred, crossing it is no problem whatsoever. On the other hand, the outer departure boundary is not reachable with aft stick alone. And when it is breached through inertial coupling, a poststall gyration is virtually assured. If it was used as the warning boundary, it would be too late. It would merely advise the pilot that he had just departed.

Since the F-5E departure onsets through the previously described window, the search for the best algorithm parameters was then concentrated around the departure onset conditions. Again, in terms of angle of attack and yaw rate, there was no clear distinction between those few maneuvers that progressed to departure and the remaining majority that were normal, well-controlled tactical maneuvers.

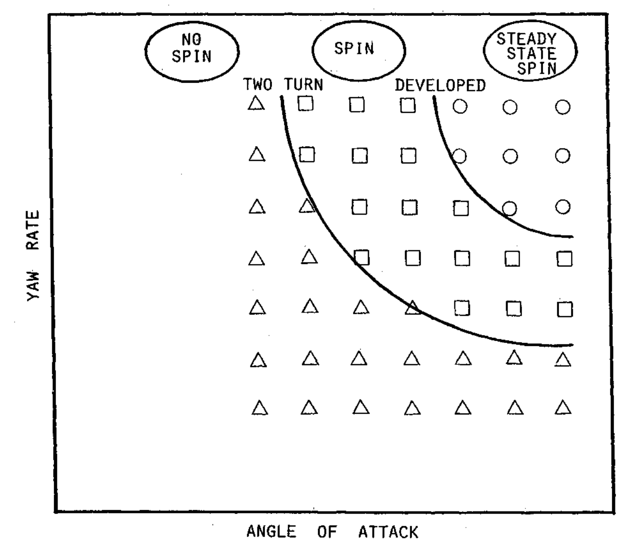

Fig. 3 Analytical spin boundaries.

Attention was then turned to rates and accelerations that not only could be more reliably measured, but also showed indications of correlating well with departure tendencies. Yaw rate R, pitch rate Q, and inertial pitch acceleration $\dot{Q}_I$ were identified as the most promising set of parameters. Of these parameters, $\dot{Q}_I$ is the only one requiring brief explanation and definition. However, it should be emphasized that $\dot{Q}_I$ is a readily available quantity defined in an orthodox way.

The rectilinear Newtonian equation of motion, simply put, equates the applied force to the product of mass and acceleration. The rotational Newtonian equation for pure pitching motion of a symmetrically loaded aircraft with no engine gyroscopic effects is:

$$M = Iy\dot{Q}$$

where M is the aerodynamic pitching moment, Iy the pitch inertia, and $\dot{Q}$ the pitch acceleration.

It was observed that the departures of the F-5E occurred when rotation about other axes, namely roll and yaw rates (P and R, respectively), were in phase with and additive to pitch acceleration. The full equation that includes these effects is

$$\dot{Q} = \frac{My}{Ix} + \frac{Iz - Ix}{Iy} \times PR + \frac{Ixz}{Iy}(R^2 - P^2)$$

where Iz and Ix are the yaw and roll inertias, and Ixz is the cross inertia. In the F-5E, Ixz is very small and so the third term is neglected. Because My is the aerodynamic contributor, we can break out the inertial and aerodynamic components of the functions as follows:

$$\dot{Q} = \dot{Q}_{\text{aero}} + \dot{Q}_I \text{ (inertial)}$$

$\dot{Q}_I$, quite simply, is pitch acceleration due to roll and yaw rates, commonly called roll-yaw coupling or inertial coupling. $\dot{Q}_I$ can be computed by the product of P and R and a constant. A review of all maneuvers conducted in the F-5E spin susceptibility test revealed that all departures were preceded by a significant value of the inertial pitch acceleration parameter. A cross plot of $\dot{Q}_I$ and angle of attack showed that a 30 deg/s^2 threshold would provide warning for nearly all PSG's and spin maneuvers. Of particular concern, however, were several mild PSG and no-departure maneuvers preceded by greater than 30 deg/s^2 $\dot{Q}_I$, which would constitute false warnings. Further analysis of these points, however, revealed that all occurred at relatively high airspeeds and would be eliminated by a velocity inhibit function of about 200 KIAS.

Data analysis of flight-test maneuvers also indicated that yaw rate and pitch rate thresholds would be good backup warning cues to inertial pitch acceleration. It appeared that 25 deg/s yaw rate and 20 deg/s pitch rate were the proper values, and they were included in the algorithm.

The derived departure warning system (DWS) algorithm was set as follows:

$$\dot{Q}_I = K_1\, P \times R \geq 30 \text{ deg/s}^2, \quad R \geq 25 \text{ deg/s}, \quad Q \geq 20 \text{ deg/s}$$

The airspeed inhibit logic was set at 210 KIAS because it could conveniently use an existing flap programming airspeed signal from the aircraft's central air data computer. K_1 is about 0.98–1.01 for a wide range of loading conditions.

Application of the Algorithm

The developed algorithm was then analytically applied to a series of actual aircraft event-time histories. Samples of these are shown in Figs. 4–7. On these figures, the warning tone and

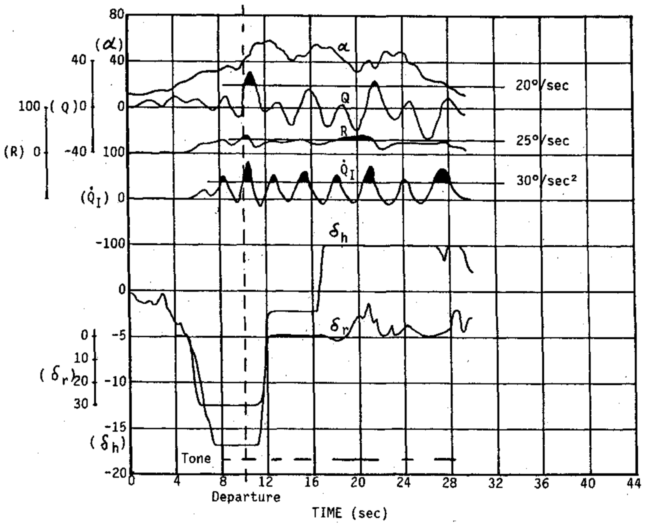

Fig. 4 Poststall gyration maneuver time history, example 1.

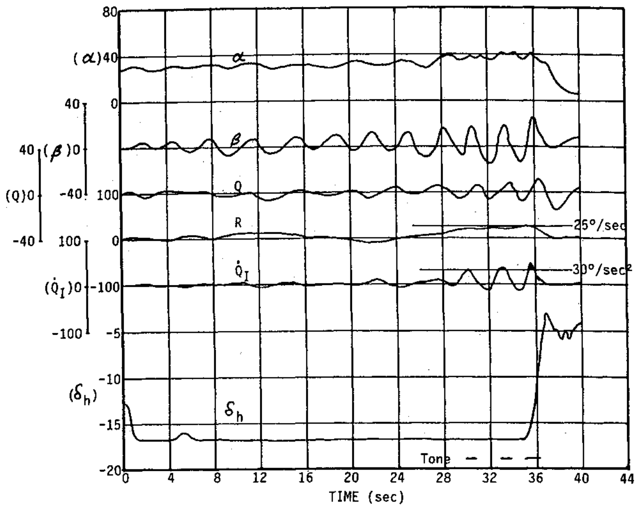

Fig. 7 Prolonged aft-stick stall time history.

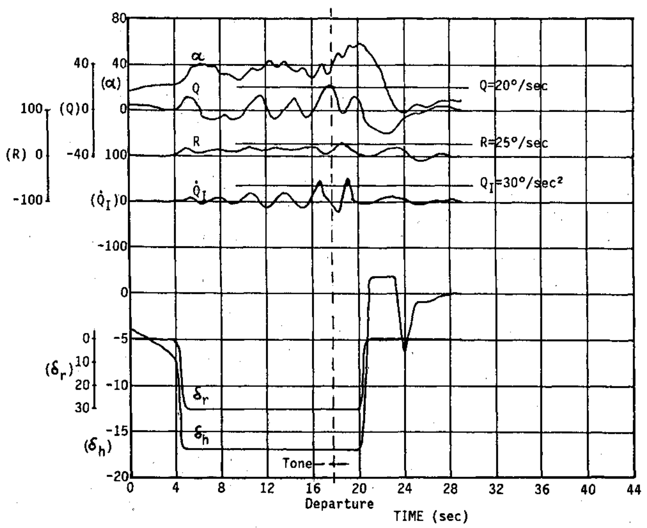

Fig. 5 Poststall gyration maneuver time history, example 2.

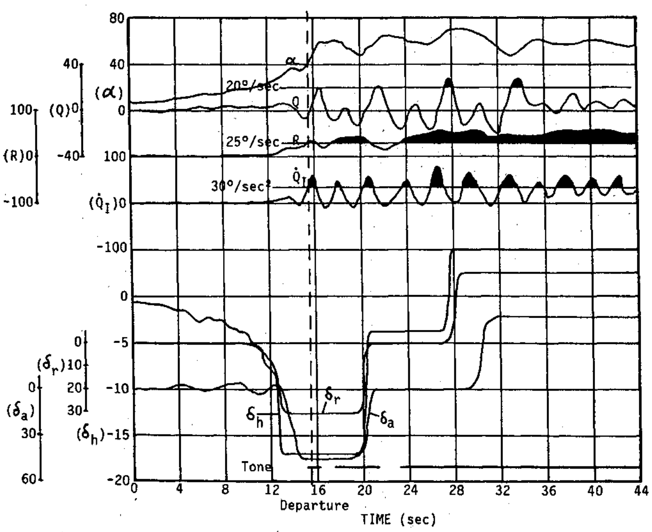

Fig. 6 Flat spin time history.

the parameter value generating the tone are shown. Each event is discussed in detail below.

Poststall Gyration Maneuver Time History, Example 1

The maneuver began as a 3 g, windup turn at 260 KIAS. Full rudder was applied at the stall (200 KIAS) and full aft stick followed 1.5 s later. It coupled quickly and $\dot{Q}_I$ would have triggered a tone about 2 s after full rudder application. Between 2 and 2.5 s later, $\dot{Q}_I$, Q, and R all have reached tone threshold level as the AOA is driving up to near 60 deg. This maneuver was recovered aerodynamically; however, coupling prolonged that PSG an uncomfortably long time. It should be noted that the DWS tone would have sounded, quite validly, at intervals throughout the recovery. Had prompt and full attention not been given to recovery, this maneuver would almost certainly have progressed to a nonrecoverable flat spin.

Poststall Gyration Maneuver Time History, Example 2

This time history is a maneuver with very aggressive control inputs (full aft stick, full rudder), and that initially has virtually no coupling. Even though angle of attack is frequently above 40 deg during the first 12 s and sideslip is diverging, yaw rate is low and there would be no tone. After 12.5 s of control application, sufficient coupling occurs to actuate the tone, and rightly so, as angle of attack is driven up to near 60 deg. This maneuver recovered immediately when rudder was neutralized and the stick was moved forward. It is significant that yaw rate, the traditional spin indicator, was never greater than about 25 deg/s. $\dot{Q}_I$ was the first and best indicator of impending departure.

Flat Spin Time History

The maneuver was a full cross control input at 180 KIAS and 2 g's as stall angle of attack was reached. As can be seen in the region from 20 to 27 s, the aircraft has 30–50 deg/s yaw rate with angles of attack from 50 to 70 deg, and so is unquestionably departed. $\dot{Q}_I$ provides the first warning at 15.5 s (5 s before the actual departure), the DWS tone is off until 16.5 s when Q turns it on, and then yaw rate, which exceeds the limit at 17.5 s, sustains the warning until about 22 s when Q reduces below the threshold. At 23 s, yaw rate and $\dot{Q}_I$ turn the tone on for the remainder of the maneuver.

Prolonged Aft-Stick Stall Time History

The following is a full aft stick, 1 g stall with rudders neutral and ailerons used as necessary to attempt to hold wings level. In this maneuver, the full aft-stick stall is maintained for a significant time. The aircraft resists actual departure for most of the time; however, at the end of the maneuver, the roll and yaw rates begin to couple in phase with the aircraft motion, and $\dot{Q}_I$ provides excellent warning of a potential departure.

The data analysis of Phase I revealed that some of the spins that have occurred in the F-5E history could have been avoided if a timely departure warning system would have provided the necessary cue to the pilot. The algorithm derived for the proposed departure warning system would have provided the necessary cue to the pilot for all of the PSG's/spins encountered in the flight-test program, and very probably many of the inadvertent spins that resulted in accidents. The proposed warning thresholds and the airspeed inhibit function promised to minimize nuisance/false warnings. The algorithm was ready for flight validation.

III. Phase II—Flight Validation

Overview

Validation of the DWS algorithm through the use of the ACMI range was chosen as an alternative to installing test hardware in the aircraft. The primary reason for performing the validation in this manner was to avoid taking any aircraft out of service for system installation. Also, using the ACMI allowed adjustments to the algorithm thresholds without the need for any access to the aircraft. All of the required sensors are present in the ACMI pod, and the DWS algorithm can be programmed into the ACMI ground-station software. The flight data of an aircraft maneuvering on the range can be flagged to indicate all cases where a DWS threshold is reached, and careful, detailed postflight analysis can be performed with the engineering data printouts.

ACMI Programming

The Airborne Instrumentation Subsystem (AIS) was reviewed and analyzed to determine that all required parameters were available and within the range and accuracies necessary for the DWS algorithm. Of prime interest was the rate-gyros package that provides the aircraft rates of motion about each stability axis. The analysis confirmed that the AIS rate gyros are nearly identical in capability and accuracy to the package proposed for use in the DWS. A mathematical transformation was incorporated into the ACMI software to compensate for the gyro package location at the aircraft wingtip vice, the aircraft center of gravity. All other flight parameters necessary for the flight validiation were found to be available and within acceptable ranges and accuracies.

Validation Procedures

The ACMI software was modified to include the DWS algorithm. The tone that normally sounds to signal a missile launch was programmed to be the DWS warning tone, actuated when any one of the three parameters reached the critical threshold value. This tone was transmitted on an open, unused uhf radio frequency, which could be heard in the Display and Debriefing Subsystem (DDS) control room, but not on the fighters' working frequency. Also, the Control and Computation Subsystem (CCS) tape was marked such that an alphanumeric printout of the CCS data would include a flag at the point of tone activation. The alphanumeric printout presented a breakout of each of the key parameters in 3–5 samples/s data flow such that it could be determined which parameter activated the tone and the values of other key parameters could be assessed. The normal procedure was to view a flight in real time from the DDS control room. If the DWS tone sounded during any portion of the flight, the time sequence number was noted, and a digital printout of the corresponding CCS time slice was taken for close analysis. Also, after some missions, the mission pilots reviewed the DDS tapes and were interviewed for their assessments of tone-generating maneuvers, i.e., were the tones valid, and would a tone have been a help, hindrance, or of neutral value?

The validation was conducted in a one-week time period during which the F-5E Aggressors were flying on the ACMI range about two to five missions per day. The missions were usually 2 vs 1, with three F-5E's, two F-5E's, and one F-15, or two F-5E's and one F-16. The pilot skill level varied from 15–20 h in the aircraft to several hundreds of hours of aggressor experience. In addition to the live missions flown during the week of validation, several tapes from missions flown the three weeks prior were screened and analyzed in the same fashion as the live missions. In all, 36 F-5E sorties were evaluated using the above procedures.

Aircraft Configuration

The aircraft were flown without any pylons or stores on the wings or fuselage. Each aircraft had an ACMI pod on one wingtip missile launcher rail and, in some cases, a training AIM-9 missile (inert) on the other. Aircraft center of gravity (c.g.) was approximately 18.5–19.0% mean aerodynamic chord (MAC), which is the ammo-fired, aft c.g. location. Previous tests of the aircraft have shown this c.g. to be more prone to departure than the more forward, ammo-in location of 13.0–13.5% MAC.

Test Objectives

The objectives of the validation phase were as follows:

1) Evaluate the baseline DWS algorithm against the following criteria: a) provide consistent indication when postsall conditions conducive to departure from controlled flight are occurring; b) provide warning of PSG/spin early enough to allow the pilot to recognize the warning, evaluate the flight conditions, and take recovery action in time to be effective; c) provide minimum of false warnings or to minimize the duration of false warnings that do occur.

2) Identify and implement required improvements to the baseline DWS algorithm.

There were two major concerns that needed to be addressed in the validation phase. First was the concern that the DWS tone would activate too readily and too frequently to be credible to the pilots. Too many false warnings would lead to the tone being ignored or turned off. Second, there was the concern that the system would not consistently give timely warning of conditions that could rapidly lead to departure/spin. Departures or spins were neither anticipated nor desired during this validation in order to address this concern. Rather, the conditions under which the tone was triggered were to be compared to fully documented conditions encountered in the spin susceptibility tests from which PSG's and spins developed. The ultimate goal was to fine-tune and verify system performance such that every warning tone was worthy of pilot attention and, conversely, every flight condition that was vulnerable to PSG/spin would trigger a warning tone.

IV. Test Results

A total of 36 sorties, flown by 29 different pilots, were evaluated with the DWS algorithm. The maneuvering was aggressive and frequently reached and exceeded maximum wing lift performance, often in conjunction with aircraft rolling and yawing. A diversity of control techniques were observed, which produced aircraft motions sufficient to trigger DWS tones from each of the algorithm parameters.

Early in the validation effort, it was obvious that the tone was activating far too frequently by the pitch-rate parameter. For the first three missions screened, it was not uncommon to have a warning tone sound 10–12 times during a hard turn or straight-ahead pullup. Although the aircraft were being maneuvered very aggressively, it was clear from the DDS monitor, the alphanumeric printouts, and pilot debriefs, that the majority of the tones were unnecessary. The pitch-rate parameter of the algorithm was, therefore, adjusted from 20 to 30 deg/s. Previously flown mission tapes were then replayed with the adjusted algorithm, as were all subsequent live missions. This produced a dramatic reduction in false tone activations.

Twenty-two of the 36 sorties screened had no tones generated at all, even though each of these sorties had some periods of aggressive high-g, high angle of attack, low-airspeed maneuvering. Of the 14 sorties that experienced DWS warning tones, the number of activations per flight varied from one to five. A total of 29 tone activations were observed. Two were first activated by inertial pitch acceleration ($\dot{Q}_I$), five were activated by yaw rate (R), and the remaining 22 were produced by pitch rate. One of those first activated by $\dot{Q}_I$ immediately progressed to a tone-producing 34 deg/s pitch rate and resulted in an angle-of-attack excursion to 47 deg. The other was not accompanied or followed by any significant aircraft motions. All of those that were first activated by R were immediately followed by a significant amount of inertial pitch acceleration. Three produced $\dot{Q}_I$ tones, and the other two were only slightly under the threshold at 25 and 27 deg/s^2.

Most of the tones activated by pitch rate were due to pitch pulses generated by the pilot. About half had some amount of $\dot{Q}_I$ just prior, which assisted in generating the pitch rate. One, and possibly two, had significant $\dot{Q}_I$ as a driving force. In these cases, the pitch rate warning was a valid indicator of inertial coupling, which was substantial, but not of tone-generating magnitude by itself.

These tests reaffirmed that large rudder inputs, to induce roll at high angles of attack, can produce significant inertial roll-yaw coupling into pitch acceleration if the natural motions of the aircraft become "in-phase" with the commanded inputs. A pilot who stated that he had been using a lot of rudder on recent missions accounted for four of the five yaw-rate activated warning tones. Two of these generated tone-producing pitch accelerations (32 and 40 deg/s^2) and two generated only slightly smaller $\dot{Q}_I$ (25 and 27 deg/s^2). The pilot stated that he felt like the aircraft was well under control at all times. That is not surprising since in each of his tone-generating maneuvers, the motions damped out and/or he terminated the aggravating control inputs prior to a departure. One of his rudder rolls (270 deg in duration) coupled strongly to produce a 34 deg/s pitch rate and an angle of attack excursion to 42 deg. This one had all of the earmarks of a departure; but fortunately, the roll was reversed and the coupling cancelled prior to any further increases in angle of attack and yaw rate.

If rudder is applied at higher airspeeds and medium angles of attack, the yaw rate is not very great, but the roll rate can be dramatic. One such maneuver had a yaw rate of only 16 deg/s, but experienced a very abrupt and large roll rate (113 deg/s). This example generated an inertial pitch acceleration of 34 deg/s^2 and an angle-of-attack excursion to 47 deg. There was an associated, nearly instantaneous, onset of two incremental g's, and an equally rapid bleedoff of indicated airspeed of 76 knots (193–117). Fortunately, a sustaining yaw rate was not present and recovery was quite rapid.

V. Analysis

Assessment of $\dot{Q}_I$ Tone Threshold

There were two maneuvers observed in which inertial pitch acceleration was unquestionably the parameter that first triggered a warning tone. There were three, and possibly four other $\dot{Q}_I$ activations that were preceded by yaw-rate warnings. For the one tone in question, it could not definitely be determined which parameter activated the tone. The digital printout showed both R and $\dot{Q}_I$ at high values, but did not capture the instant that one or both exceeded the threshold.

In each case, the sequence began with yaw rate (rudder roll) that coupled with roll rate to produce the pitch acceleration. A reactive pitch rate and increase in angle of attack followed. The magnitude of the resulting pitch rates and angle-of-attack excursions was not always proportional to the pitch acceleration. Sometimes the acceleration was resisted by aerodynamic forces or natural damping of the aircraft.

Previous experience with the aircraft has confirmed that departures occur only when the various forces acting on the aircraft are in phase with, or at least not strongly resisting, the inertial pitch acceleration. It is the author's judgment that each of the warning tones generated by $\dot{Q}_I$ in this validation sampling was the result of pitch acceleration of sufficient magnitude to be of concern to the pilot.

On the other hand, the data were examined to determine if there were cases of strong inertial coupling below threshold level, but strong enough to be of concern. There were five instances in which $\dot{Q}_I$ was between 25 and 30 deg/s^2. Two of these were preceded by an R-generated tone. The other three were not accompanied by any warning tones. Two of these had no significant aircraft motions. The other had an angle-of-attack excursion from 30 to 44 deg at a slow rate, while yaw rate persisted between 15 and 20 deg/s for about 3 s. Airspeed was only 110–115 knots, and the aircraft was wallowing about all axes, but was not close to departure. This latter case and one other did, in fact, ultimately result in warning tones ($\dot{Q}_I$ in this case and Q in the other) within 4 s of their peak values.

From this analysis, it was concluded that $\dot{Q}_I$ is, indeed, a key indicator of departure vulnerability. Also, the threshold value of 30 deg/s^2 is correct.

Assessment of the R-Tone Threshold

Using the same logic, the first consideration was to ask if the threshold was too low. Yaw rate activated the tone only four and possibly five times. The uncertain case was previously discussed under the $\dot{Q}_I$ analysis. In each of these, yaw rate was the precursor to significant roll-yaw coupling. In three cases, it precipitated tone-generating $\dot{Q}_I$, and in the other two, 25 deg/s^2 or more of $\dot{Q}_I$ followed. In summary, each tone generated by yaw rate was a valid warning of significant aircraft roll-yaw coupling, which should be of concern to the pilot.

Analysis of data to determine if the threshold was set low enough revealed five instances of yaw rate between 20 and 25 deg/s, i.e., just under the threshold.

One of these resulted in an immediate tone-producing inertial pitch acceleration of 36 deg/s^2. Thus, it would have been a valid, but redundant, warning. The other four examples were accompanied by fairly strong inertial coupling ($\dot{Q}_I = 15$–27 deg/s^2), but no significant angle-of-attack excursions, airspeed losses, g onsets, etc. A warning would have been unnecessary.

In summary, the data confirmed that yaw rate is a valid indicator of departure vulnerability, and is correctly set at 25 deg/s.

Assessment of the Q-Tone Threshold

The pitch-rate parameter was the most frequent generator of warning tones. Early in the test phase, the warning threshold was adjusted upward from 20 to 30 deg/s. With the readjusted threshold, there were still 22 tone activations due to pitch rate only. One to two of these were judged to be valid warnings, and another five to six were optional. The others were judged to be unnecessary. The two deemed to be valid were so judged because the pitch rate was generated by substantial inertial pitch acceleration, although less than threshold level $\dot{Q}_I$.

Adjusting the pitch-rate threshold upward would screen out most of the unnecessary tones. However, those that were judged to be valid would also be eliminated because their peak values of Q were just above the threshold at 30 to 31 deg/s. There were only two pitch rates observed at 35 deg/s or greater, neither of which were necessary warnings. If the threshold were set at 32 deg/s, seven of the pitch-rate warning tones would have been allowed. If it were set at 35 deg/s, only two tones would have occurred due to pitch rate alone.

Another possible option is to remove the pitch-rate parameter from the DWS algorithm entirely. Rationale for this action would say that pure pitch rate, due to an aft-stick pulse by the pilot, is noncritical in the F-5E, and a warning of high rates is unnecessary. This is true. Pitch rates driven by inertial pitch acceleration are the critical kind, but those will be identified by an inertial pitch acceleration warning tone, if they are sufficiently strong to be of concern. Pitch rate in the algorithm, however, provides a good backup or confirming warning. Also, spin-test data show that as a departure progresses to a spin, pitch-rate warnings tends to fill in the gaps between surges of inertial pitch acceleration, and would reinforce the urgency of the warning.

The author concludes that the pitch-rate threshold, as presently set, is a bit too sensitive and generates an excessive number of false warnings. Pitch rate should remain in the algorithm, however, because it augments and reinforces the inertial pitch acceleration warnings. The pitch-rate threshold should be reset to 35 deg/s.

Adequacy of the Warning Tone

Timeliness

From this data sample, all of the valid warning tones were sounded sufficiently in advance of a departure to allow recovery action. There were no departures from controlled flight experience, although a few maneuvers placed the aircraft in the highly vulnerable flight conditions from which departure was a distinct possibility. These were usually terminated by a cessation or reversal of the rolling and yawing that generated the strong coupling. Of the maneuvers considered most vulnerable to departure, the warning tone sounded 1–2 s prior to the large g onset/angle-of-attack excursion. Spin-test data have previously shown that there is an additional 5–7 s after the angle-of-attack excursion during which recovery is possible, if control action is taken, before the aircraft progresses to an unrecoverable spin mode.

Duration

One maneuver, which was a 360 deg, high-g rudder roll, produced a valid warning tone from yaw rate and inertial pitch acceleration of approximately 3 s duration. Two other maneuvers, also rudder rolls with inertial coupling, had warning tones of approximatley 2 s duration. All other tones experienced were 1 s or less beeps. These results were precisely as expected. The initial tones are short beeps, but as the maneuver progresses in severity, the tone duration extends until it becomes near continuous in a poststall gyration/spin.

VI. Analysis of MXU-553 Data of 1983 F-5E Spin Accident

Data recovered from the MXU-553 recorder aboard a recent spin mishap aircraft included roll and yaw rates. Inertial pitch acceleration could be computed from these values, and departure warning system tone thresholds could readily be observed. The MXU-553 data also included the horizontal stabilator position, which was helpful in assessing when the pilot sensed the out-of-control situation and applied recovery controls. Figure 8 is a plot of all recorded parameters, plus the computed $\dot{Q}_I$.

Departure occurred at time 29 s. This judgment is based on the large airspeed loss (180 KIAS down to 100 KIAS or less) and the upward trend in angle of attack. (Unfortunately, the angle of attack data trace dropped out from that point forward.) It can be seen that the departure warning tone would have sounded just after time 27 s, triggered by both $\dot{Q}_I$ and yaw rate. The tone comes on again after the aircraft departs, and with the exception of one small break at time 30 s, remains on thereafter.

It can be seen that the control stick was full aft at about 5–6 s intervals and was neutral to slightly forward in-between times. This correlates with the pilot's recollection of doing a series of loaded rudder rolls with an unload in between rolls. The pilot has stated his belief that he sensed the departure, in the form of a "roll hesitation" at about time 29–30 s, and put in recovery controls at 31 s. It is suggested by the author that the roll hesitation sensed by the pilot was, in fact, at times 36–37 s, and recovery controls were applied at time 39 s. The first time the stick is full forward is 39 s, which correlates with antispin recovery. Furthermore, if antispin controls were applied at 31 s, it is difficult to comprehend the full aft stick application at time 37 s. This is not to criticize the pilot. It is to point out the extreme difficulty of sensing the actual aircraft departure. Comparing the MXU-553 data with numerous data samples from the spin susceptibility tests of similar departures, it is suggested that the mishap aircraft could have been recovered areodynamically if recovery had been initiated by time 31 s. The tone at time 27 s and again at 29 s would have prompted the pilot to take prompt recovery action, and this accident could have been avoided.

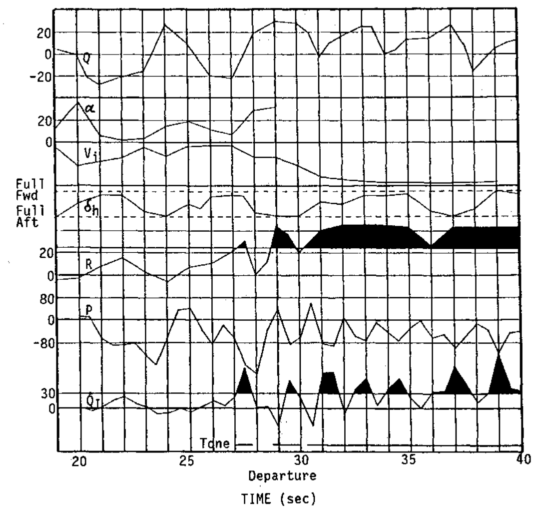

Fig. 8 MXU-553 data of spin accident.

VII. Conclusions and Summary

A sufficient number of air combat training missions were observed to properly evaluate the DWS algorithm. Each of the 36 sorties observed had examples of aggressive maneuvering with large excursions of airspeed, angle of attack, and g's. There was a diversity of control techniques observed that provided discrete examples of each of the different ways the warning tone can be actuated. Increasing the sample size would not provide significantly new data, but would repeat and reinforce that which was collected.

Inertial pitch acceleration $\dot{Q}_I$, and yaw rate R, were found to be valid parameters for the DWS algorithm, and the threshold values are properly set. Pitch rate is also a beneficial parameter, but the threshold value should be reset to 35 deg/s. This will retain the backup warning for large pitch rates generated by strong inertial pitch acceleration. The pitch rate always lags the acceleration; thus, if each parameter is of tone-generating magnitude, the duration of the tone will be extended for greater emphasis if the conditions worsen.

The DNS is a valid indicator of inertial pitch acceleration and the resulting aircraft motions, which can quickly progress to a poststall gyration or spin. In the vast majority of cases of roll-yaw coupling, the inherent aerodynamic stability and damping of the aircraft wash out the resulting motions, and the aircraft remains under control. However, the pilot must be aware each time this departure-producing acceleration is experienced, and must take prompt action to assure the aircraft is indeed controllable. The DWS can reliably provide that awareness through a distinctive warning signal to the pilot.

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