F/A-18 CONTROLS RELEASED DEPARTURE RECOVERY FLIGHT TEST EVALUATION

by

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ABSTRACT

The F/A-18 has had a history of numerous departures from controlled flight during operational fleet use. Several of these departures have resulted in mishaps. The current flight manual procedure requires the pilot to neutralize the control stick for departure recovery, however many F/A-18 departures are characterized by high lateral forces making it difficult to maintain neutral longitudinal and lateral control stick position. Recent mishap investigations have questioned the viability of releasing the control stick as a more effective way of maintaining neutral controls thereby reducing recovery times. The Naval Air Warfare Center - Aircraft Division was tasked by Naval Air Systems Command to determine if releasing the control stick during departure recovery would result in any airplane induced control inputs that would delay recovery. Additionally, from the desire to improve departure awareness of all F/A-18 pilots, an assessment was made of the suitability of the test maneuvers for inclusion into an airborne departure recognition and out-of-control flight training syllabus. Testing was conducted using a fleet representative F/A-18D which did not incorporate any non-production emergency recovery devices (i.e. no spin recovery chute). Test maneuvers included both high and low angle of attack departures up to 0.80 IMN. Resultant airplane motions were in many cases violent with lateral acceleration as high as 3.5g and out-of-control oscillations lasting as long as 22 seconds. A variety of recovery techniques were evaluated including: controls released, controls neutralized and released, and hands-on recoveries. This paper discusses the flight test approach, buildup and conduct, test results regarding control stick movement during departure, its effect on departure recovery, and final recommendations regarding recovery from out-of-control flight.

NOMENCLATURE

ACM	Air Combat Maneuvering
AOA (α)	Angle of Attack
ASRM	Automatic Spin Recovery Mode
CAS	Control Augmentation System
CBW	Control-by-Wire
Cl_β	Rolling Moment due to Sideslip, 1/deg
Cn	Yawing Moment
Cn_β	Yawing Moment due to Sideslip (Directional Stability), 1/deg

Cn beta dynamic	$Cn_{\beta} * \cos(\alpha) - \left(\frac{Izz}{Ixx}\right) * Cl_{\beta} * \sin(\alpha)$, 1/deg
FCES	Flight Control Electronics Set
FCC	Flight Control Computer
FCL	FE Plus Centerline Tank Loading
FCS	Flight Control System
FE	Fighter Escort Loading
Fleet	Operational Navy and Marine Corps F/A-18 Squadrons
FRS	Fleet Replacement Squadron
FSD	Full Scale Development
Ixx	Rolling Mass Moment of Inertia, slug-ft^2
Izz	Yawing Mass Moment of Inertia, slug-ft^2
KCAS	Knots Calibrated Air Speed
LEF	Leading Edge Flap
LEX	Leading Edge Extension
NASC	Naval Air Systems Command
NAWC/AD	Naval Air Warfare Center, Aircraft Division, Patuxent River, MD
NATOPS	Naval Air Training and Operating Procedures Standardization Program
NDI	Non-Destructive Inspection
OOC	Out-of-Control
OCF	Out-of-Control Flight
PROM	Programmable Read-Only Memory
PSF	Pounds per Square Inch
QBAR	Dynamic Pressure, lb/ft^2
SRM	Spin Recovery Mode
TEF	Trailing Edge Flap

BACKGROUND

The F/A-18 airplane has a history of departure susceptibility in certain flight regimes since its inception into the fleet. Many of these departures and their characteristics were identified during dedicated FSD, F/A-18B departure resistance, and LEX fence test programs. Test results for these flight test programs are discussed in detail in references 1, 2, and 3. The current flight manual (reference 4) procedure for departure recovery requires the pilot to neutralize the control stick and rudder pedals for recovery. NAWC/AD, McDonnell Aircraft Company, and fleet experience indicate that under most circumstances the resulting motion of the pilot's body during a departure will not allow the pilot to precisely acquire and maintain neutral control stick and rudder pedal position. In some cases, recovery from the departure has apparently been delayed by the inability to apply and maintain neutral controls. A proposal was made by NAWC/AD in December 1990 to modify the recovery procedure to release the control stick and place the feet on the cockpit floor for departure recovery. The "feet on the floor" portion was incorporated into the flight manual, however, NASC required that flight tests be performed to verify that no undesirable control stick transients occurred when the pilot released the stick after departure and that any resulting control stick motion did not adversely affect departure recovery characteristics. Production fatigue strain data was requested so that NASC could assess airplane fatigue life impact should departure demonstrations be incorporated into a fleet departure recognition and OCF training syllabus at the FRS. NAWC/AD was tasked by NASC and a flight test program was performed to validate the controls released departure recovery procedure and to provide a preliminary assessment on the suitability of selected departures for an airborne departure recognition and OCF training syllabus.

TEST OBJECTIVE

The purpose of this evaluation was to validate the controls released departure recovery procedure and to assess the suitability of selected departures for inclusion into an FRS airborne departure recognition and OCF training syllabus.

DESCRIPTION OF TEST AIRPLANE

GENERAL

The F/A-18 (F/A-18A/C single seat and F/A-18B/D dual seat) is a high performance, twin engine, supersonic fighter and attack airplane manufactured by McDonnell Aircraft Company. The airplane is characterized by moderately swept variable camber mid-mounted wings, twin vertical stabilizers mounted forward of the horizontal stabilators and canted outboard 20 deg, a speedbrake located on the upper aft section of the fuselage between the vertical stabilizers and wing leading edge extensions mounted on each side of the fuselage from the wing roots to just forward of the windshield. The airplane is configured with full span leading edge flaps, inboard trailing edge flaps, and outboard ailerons on each wing. The flight control system consists of two digital FCC that utilize a full authority CAS to operate the hydraulically driven control surfaces. The F/A-18 airplane is powered by two General Electric F404-GE-400 augmented turbofan engines each rated at 16,000 pounds maximum uninstalled static sea level thrust. A detailed description of the F/A-18 airplane is contained in the NATOPS flight manual, reference 4. The test airplane for this evaluation was a production F/A-18D Lot X airplane equipped with version 10.1 PROM flight control laws.

FLIGHT CONTROL SYSTEM DESCRIPTION

The FCS in the F/A-18 airplane employs a digital, full authority, high gain CAS as its primary flight control system mode. The CAS mode is AOA and air data scheduled with feedbacks taken from three axis angular rate, two axis linear acceleration, AOA, and air data sensors. Three cross-axis interconnects enhance the flying qualities of the airplane: rolling surface to rudder interconnect to provide better roll coordination, rudder pedal to rolling surfaces interconnect to provide better roll coordination at high angles of attack, and an aileron to collective stabilator interconnect to compensate for an uncommanded pitching moment in the power approach configuration with ailerons drooped. A speedbrake to stabilator interconnect minimizes g transients during speedbrake operation. A departure warning tone (yaw rate and AOA) is available when the flap switch is in the AUTO position. The tone initiates at 25 deg/sec yaw rate and increases in beep frequency up to 45 deg/sec. Above 35 deg AOA and below -7 deg AOA, the tone initiates at a constant frequency and yaw rate warning is no longer available. Above 22 deg AOA, angle of attack feedback is introduced to generate a proportional nose down command which provides an effective increase in stick force cues during low speed and high AOA maneuvering. Inertial decoupling feedback to the stabilator consisting of the product of roll and yaw rate scheduled with air data is incorporated when the flap switch is in the AUTO position. This feedback offsets the pitching moment generated by inertial coupling at high roll rates. Inertia coupling compensation is also used in the yaw axis using the product of pitch and roll rate to command the rudders to counter yaw inertia coupling. Additionally, a SRM is provided and is described below.

Collective deflection of the stabilators, leading edge flaps, trailing edge flaps, aileron droop (power approach), and rudder toe-in (power approach) provide longitudinal control. Collective flap scheduling, as a function of AOA and Mach, is designed to minimize drag during cruise, improve departure resistance during maneuvering and provide flap load alleviation at elevated Nz. Differential deflection of the stabilators, ailerons, LEF and TEF, along with synchronous deflection of the rudders provide lateral-directional control.

The longitudinal and lateral mechanical components of the FCS are comprised of the following: cockpit control stick, longitudinal and lateral feel springs, longitudinal trim actuator, linkage and cables between the control stick and stabilator servo actuators, and an electromechanical ratio changer which adjusts the stick to stabilator gearing while in the mechanical backup mode. Longitudinal and lateral spring cartridges provide control stick forces to the pilot. A counter weight is provided in the longitudinal axis to counter control stick inertial forces encountered during a catapult launch. An eddy current damper is provided to add an additional lateral stick force increment as a function of lateral stick rate. The control stick is duplicated in the aft cockpit of the two-place airplane and is connected to the forward stick via mechanical control linkages. The mechanical linkage allows the control stick position sensors to sense pilot stick commands from either cockpit. Longitudinal and lateral control stick movement in either cockpit will move the control stick in the other cockpit. Linkages and cables connect the pilot's control stick and stabilators while in the mechanical mode. Design longitudinal and lateral breakout plus friction and stick force gradients are presented in table I.

Table I
CONTROL STICK CHARACTERISTICS

Direction	Breakout plus Friction (lb)	Stick Force Gradient (lb/in)
Longitudinal	± 3.0	7.4
Lateral	± 2.0	3.7

SPIN RECOVERY SYSTEM

A spin recovery system is incorporated into the FCS of the F/A-18. When engaged in either the automatic or manual SRM, the spin mode control laws remove all angular rate and linear acceleration feedbacks, control surface interconnects and provides the pilot with full aileron, rudder, and stabilator authority. The LEF are commanded to 34 deg leading edge down and the TEF are commanded to 0 deg. Spin recovery arrows are displayed on the DDI to indicate proper direction for application of lateral stick for recovery. When the cockpit mounted spin recovery switch is in the NORM position, the ASRM will engage when the following conditions are met: airspeed 120 ± 15 kts, and filtered yaw rate over 15 deg/sec. Engagement of the ASRM is delayed by a 7.2 sec lag filter placed on yaw rate. This is designed to prevent engagement during momentary yaw rate excursions. Once ASRM engages, the yaw rate lag filter reduces to 3.2 sec to prevent overcontrol and reduce the possibility of entering a progressive spin during recovery. With ASRM engaged, the spin mode control laws will be provided only when lateral control stick is placed in the direction of the spin recovery arrows. The direction of the spin recovery arrow is determined by yaw rate and Nz. With a left filtered yaw rate over 15 deg/sec and positive filtered Nz or a right filtered yaw rate over 15 deg/sec with negative filtered Nz, a left arrow will be displayed. The same logic can be applied to the right arrow. A 3.2 sec lag filter is also applied to Nz and is designed to prevent frequent reversals of the spin recovery arrows. Application of lateral stick opposite of the arrow will result in the FCS reverting to normal CAS scheduling. The flaps remain in the recovery positions and the spin recovery arrow remains displayed until the product of production and filtered yaw rate is less than 225 $(deg/sec)^2$ or airspeed exceeds 239 kts. The 121 kt to 239 kt hysteresis in the airspeed logic is necessary due to fluctuations in pitot-static system pressures during oscillatory spins.

Placing the spin recovery switch in the RCVY position will engage the manual SRM when airspeed is 120 ± 15 kts regardless of yaw rate. The spin mode control laws are engaged as long as the airspeed criteria is met providing full control authority regardless of spin recovery arrow display. In the manual SRM full authority pro-spin controls can be applied if lateral stick is applied opposite the spin recovery arrow. The spin recovery arrows will be displayed if filtered yaw rate (3.2 sec lag filter) is over 15 deg/sec. The logic for spin arrow direction is the same as with ASRM. With the spin recovery switch in the RCVY position, the flight controls will revert to CAS when airspeed exceeds 239 kts.

Flight test and fleet experience have demonstrated that the arrows may cycle rapidly during highly oscillatory departures or spins if the airspeed and yaw rate criteria is met but filtered Nz cycles between positive and negative. During highly oscillatory spins, the arrow can momentarily disappear when production yaw rate crosses zero. Additionally, during recovery from intermediate and high yaw rate spins, removal of the spin recovery arrows may be delayed as filtered yaw rate decreases, when actual production yaw rate is at or near zero.

SINGLE VS. TWO SEAT AERODYNAMIC DIFFERENCES

While a major effort was made during F/A-18 FSD to develop control laws to increase departure resistance in the F/A-18, significant differences remain between single seat and two seat configurations. The two seat configuration has demonstrated through fleet experience and references 2 and 3 flight tests to exhibit significantly less departure resistance than the single seat configuration. The only external difference between the two configurations is the enlarged canopy to accommodate the second seat. Departure resistance decreases further in loadings that utilize the centerline tank which is mounted forward of the airplane CG. Although the centerline tank loading is the most departure prone, it is the configuration of choice for ACM training as a compromise between performance and fuel considerations. Areas of departure susceptibility include: (1) rolling maneuvers at less than 0.7M between 30 and 35 deg, (2) full rudder pedal inputs at less than 250 KCAS and less than 10 deg AOA, and (3) rolling maneuvers at high subsonic Mach and high AOA (reference 5). Reference 5 identified factors which contribute to F/A-18 departures at both low (less than 10 deg) and high AOA.

HIGH AOA

The departure resistance parameter, Cn beta dynamic is a measure of available restoring angular yaw acceleration for neutral controls when an aircraft is perturbed in sideslip. A comparison between the single and two seat F/A-18 is shown in figure 1:

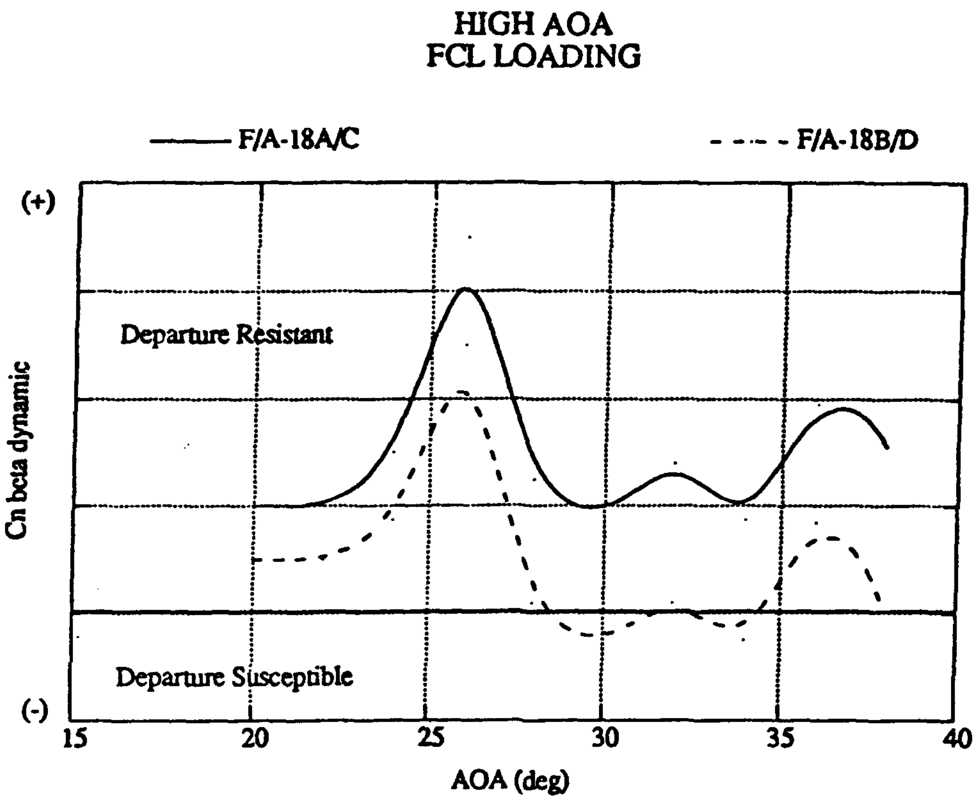

Figure 1
F/A-18 HIGH AOA DEPARTURE SUSCEPTIBILITY COMPARISON

From 20 to 25 degrees AOA, departure resistance for the single seat F/A-18A/C increases due to the effects of increased directional stability (Cn_β) as a function of AOA. Above 25 degrees AOA, however, a decrease in Cn_β due to vertical tail blanking results in a corresponding decrease in departure resistance. The two seat F/A-18B/D departure resistance characteristics follow the same general trend as the single seat, however, around 30 to 35 degrees AOA, the aircraft become departure susceptible. The differences observed between the single and two seat departure resistance can be explained by the effects of the two place canopy where increased vertical surface area forward of the CG results in an overall destabilizing effect.

LOW AOA

The two predominate factors affecting yaw acceleration (departure susceptibility) at low AOA are the amount of rudder available and directional stability as shown in figure 2.

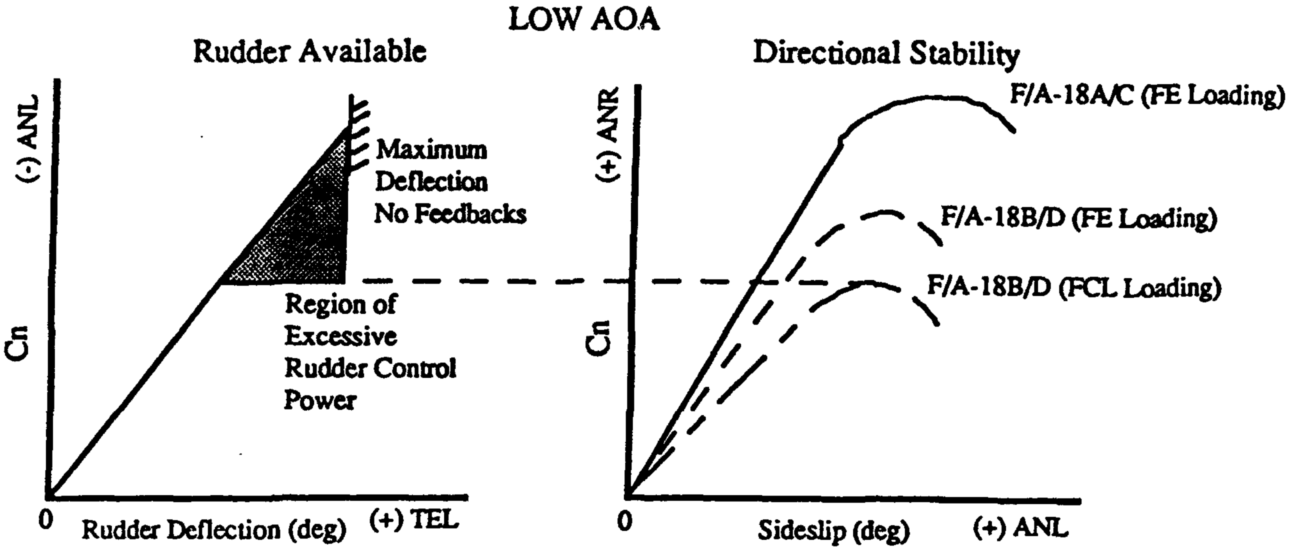

Figure 2
COMPARISON OF RUDDER CONTROL AVAILABLE VS. DIRECTIONAL STABILITY

Directional stability differences between the single seat and two seat F/A-18 in the FE loading (FCL less centerline tank) are due to the destabilizing effects of the two place canopy as discussed for the high AOA case. Addition of the centerline tank in the FCL loading increases vertical surface area forward of the CG and thus further degrades yaw restoring moment due to sideslip. Relating the maximum amount of restoring yawing moment (directional stability) to rudder available results in a region of excessive rudder control power. Thus large rudder inputs applied in this region overpowers the directional stability restoring effects and results in a subsequent departure from controlled flight.

OUT-OF-CONTROL CHARACTERISTICS

DEPARTURES

As previously discussed, the F/A-18 FCS incorporates a number of features which augment the airplane's natural departure and spin resistance. In CAS mode, exceptional maneuvering capability exists throughout the operational flight envelope; however in certain flight regimes reduction of lateral and directional stability significantly reduces departure resistance. At high AOA, yaw CAS allows aggressive maneuvering up to the departure warning tone at 35 deg AOA, however lateral-directional stability weakens significantly in the mid-AOA range making departure much more likely with aggressive maneuvering in these flight conditions. At low AOA in the -5 to 10 deg range, high rudder control power and control law scheduling makes the airplane very susceptible to departures with large rudder pedal or partial cross control inputs. As discussed above, the F/A-18 two-seat and/or centerline tank configurations further aggravate these situations. Previous flight test has shown that typical F/A-18 departures occur with little or no warning as a yaw divergence (nose slice) followed by an uncommanded roll in the same direction. Normally, departures in the F/A-18 will exhibit random oscillations until sideslip and yaw rate subside, followed quickly by a nose low recovery with airspeed rapidly accelerating. If recovery is not evident after several seconds of random post-departure oscillations, the airplane may have entered a spin or AOA Hangup/Falling Leaf mode and further pilot action will be required to effect recovery.

SPIN MODES

Four spin modes of the F/A-18 have been identified during previous flight test. The low yaw rate spin mode is characterized by AOA in the 50 to 60 deg range and a very low oscillatory yaw rate (less than 40 deg/sec). Asymmetric thrust and/or asymmetric store loadings significantly increase the airplanes susceptibility to the low yaw rate spin. The intermediate yaw rate spin mode is likely with moderate to large lateral asymmetry and is characterized by higher average yaw rates (20 to 80 deg/sec) with AOA typically varying between 40 and 80 deg and bank angle excursions of ± 60 deg or more. The high yaw rate spin mode exhibits yaw rates from 100 to 140 deg/second and AOA in the 80 to 90 deg range, and is best described as a smooth flat spin. Entry into this mode is possible only with sustained full pro-spin lateral stick with the spin recovery switch in RCVY, or with very large lateral asymmetry. The inverted spin mode, likely only with full pro-spin controls, exhibits a yaw rate of approximately 30 deg/second and up to -50 deg AOA. For all spin modes, recovery with spin recovery mode engaged and lateral stick applied in the direction of the spin arrow will begin immediately, but may take up to one turn to become apparent.

AOA HANGUP / FALLING MODE

The airplane exhibits a weak nose-down pitching moment capability in the 45 to 55 deg AOA region which is further reduced with an aft CG and/or external store loading. An AOA Hangup mode has been exhibited with these conditions where AOA stabilizes in a high positive or negative region and roll, yaw and pitch oscillations develop with no sustained rotation in one direction. This mode may be encountered during departure recovery, during the final stages of spin recovery, or near zero airspeed (vertical) maneuvers. Recovery from an AOA Hangup requires full forward or aft stick to maintain full nose down stabilator deflection until sufficient pitching moment can develop to break the AOA. A much more dynamic version of the AOA Hangup is the Falling Leaf mode, which may develop during any highly oscillatory departure and may be encountered over a wide CG range. This mode exhibits cyclic oscillations in roll, yaw and pitch with AOA ranging from approximately -5 to 55 deg and airspeed indications from 48 to 200 KCAS. Recovery from the Falling Leaf Mode requires sustained application of full forward stick to maintain full nose down stabilator throughout the oscillation to break the AOA.

CURRENT OOC RECOVERY PROCEDURE

The existing NATOPS flight manual procedure calls for the following actions to be memorized and performed when out-of-control:

1. Controls - NEUTRAL/FEET OFF RUDDERS/SPEEDBRAKE IN

If still out-of-control -

2. Throttles - IDLE
3. Altitude, AOA, airspeed, yaw rate, and DDI - CHECK
   Determine if in a SPIN or AOA HANGUP

If SPIN confirmed and command arrow present -

4. Full lateral stick - WITH ARROW

If SPIN confirmed and command arrow not present -

4. Spin recovery switch - RCVY
5. Full lateral stick - WITH ARROW

If AOA HANGUP or when yaw rate stops (no command arrow) -

4. Lateral stick - SMOOTHLY NEUTRAL
5. Spin recovery switch - CHECK NORM
6. Longitudinal stick: -
   - FULL FWD IF AOA POSITIVE
   - FULL AFT IF AOA NEGATIVE

7. Throttles - MIL or MAX
8. Above 150 knots - ROLL UPRIGHT AND RECOVER

If passing 10,000 AGL with no indication of recovery -

9. Eject

The major objective of this test was to evaluate controls released versus controls neutralized and maintained (hands-on) recoveries. Since no recent departure testing had been performed and a fairly high occurrence of mishaps resulting from OCF continued, the overall suitability, clarity and utility of the above procedure and the associated flight manual discussion was also evaluated.

TEST PLANNING

TEST MANEUVERS

Certain limitations existed on the test program from the initial phases of test planning. The most important one was that no two seat F/A-18 asset existed with a spin recovery chute and/or emergency electric / hydraulic systems available. Until this evaluation, no F/A-18 intentional departure testing had been conducted without emergency recovery devices installed. No intentional departure testing had ever been conducted on the two seat airplane with or without emergency recovery devices installed. This significantly impacted test planning and the overall direction of the flight test program. Test points were selected from a pool of maneuvers from previous test programs (references 2, 3, and 6) that resulted in departures . The criteria for selecting each test maneuver were that: (1) each departure was demonstrated in flight during previous test programs and (2) each had an easy entry and a positive recovery. The second criteria was important because in addition to the primary objective of validating controls released recoveries, the development of an airborne departure recognition and OCF training syllabus was a priority. Three recovery techniques were performed during the evaluation: (1) controls released, (2) controls neutralized and released, and (3) controls neutralized and maintained (hands-on). All recovery inputs were initiated at departure recognition which was defined by a lack of response to control inputs, an uncommanded nose reversal, and an accelerating departure warning tone. Three types of entry maneuvers were performed: type A high AOA, type B low AOA, and type C high energy and low AOA. A table of test maneuvers by type is described in Table II.

Table II
TEST MANEUVER DESCRIPTIONS

Test Type	Description	Altitude (ft MSL)	Airspeed (KCAS)	QBAR (psf)	AOA (deg)	Control Input (1)
Type A						
A1	Roll Over	35,000	170	94.4	32	Full lateral stick opposite direction of turn (8 sec)
A2	Roll Over	35,000	210	142.8	32	Full lateral stick opposite direction of turn (8 sec)
A3	Roll Over	35,000	180	105.4	33	Full rudder opposite direction of turn (14 sec)
A4	Roll Reversal	35,000	255	195.7	23	Roll using full rudder to 120 deg bank, then full opposite rudder (3 sec)
A5	Roll Under	35,000	235	170.8	31	Full lateral stick and full rudder in direction of turn (4 sec)
Type B						
B1	Unloaded Entry	35,000	210	142.8	-2	Full rudder (4 sec)
B2	Unloaded Entry	35,000	185	109.3	5	1/2 lateral stick/ full opposite rudder (4 sec)
B3	Unloaded Entry	35,000	210	142.8	2	Full lateral stick/ full opposite rudder (4 sec)
Type C						
C1	Level Entry	30,000	305(.8)	281.0	Level	Abrupt full cross control
C2	Unloaded Entry	30,000	305(.8)	281.0	A/R	Full coordinated with 2 inches forward stick (4 sec)

Note: (1) Times listed are maximum time available to effect a departure.

High sideloads were expected during the type C departures and therefore extensive planning occurred to ensure that vertical tail, centerline tank attachment, and engine mount loads were not exceeded. Production fatigue strain data were monitored to ensure vertical tail loads were not exceeded during the buildup in QBAR. Lateral acceleration was monitored to ensure predicted load limits for the engine mounts were not exceeded. To ensure centerline tank attachment integrity, all centerline pylon to aircraft hardware was removed and replaced with new hardware. Non-destructive inspection of all attachment hardware was completed prior to installation. Breakout torque data of the centerline pylon attachment bolts was gathered post-flight and damage was assumed if the torque was less than 40% of its' original pre-flight value. All departure maneuvers were conducted with the centerline tank empty to reduce the inertial component of the loads acting on the pylon to airplane attachment bolts.

The test loading (FCL), shown in figure 3, was chosen because previous flight test had demonstrated this loading to be one of the least departure resistant loadings that was also fleet representative. CATM-7's on stations 4 and 6, while mission representative, were removed to ensure that the CG remained forward of the flight clearance limit (23.5% MAC).

STATION

1	2	3	4	5	6	7	8	9
CATM-9	CLEAN	CLEAN	LAU-116	EXT FUEL TANK	LAU-116	CLEAN	CLEAN	CATM-9

Figure 3
TEST LOADING

SIMULATION

The NAWC/AD manned flight simulator was used extensively during test planning. Although all test departures had been experienced previously in flight, all but one (maneuver C1) of the departures had been performed in an F/A-18B which has a significant difference in pitch inertia as well as a much more aft CG position. In addition to test planning and the development of the test maneuver entry technique, the simulator was used as an engineer training device to develop ground station communication protocol, and practice out-of-control mode recognition.

A study was conducted to develop predictions for stick dynamics during departures throughout the F/A-18 flight envelope. A stick model was developed and is presented below in figure 4.

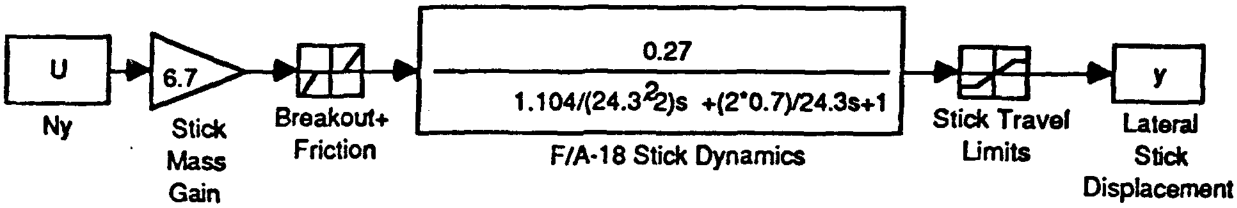

Figure 4
Lateral Stick Model Block Diagram

Assumptions established in the beginning of the study were:

a. The stick deflection simulation model did not consider the mass below the "pivot point" (i.e. the combined mass of linkages and pushrods under the cockpit floor).
b. Weight and inertia values were doubled to account for the effect of modeling stick movement in an F/A-18D (front and aft seat control sticks).
c. Lateral stick breakout plus friction and force gradient (linear variation assumed) was in accordance with table I. Deflection limits were set to ± 3 inches.
d. Lateral stick damping ratio was set to 0.7. The undamped natural frequency of the lateral stick was set to 24.3 Hz.
e. Measured lateral stick weight was 3.4 pounds for a production assembly unit. Inertia about the pivot point was 0.552 lb-in-s^2.

Although assumptions a and b were not valid, the model still provided a "worst case" situation in that modeled stick inertia was much lower than the actual airplane assembly and hence predicted stick movement would be more sensitive to the effects of Ny. A typical comparison of lateral stick deflection due to production Ny between flight test data and predicted simulation results is shown in figure 5.

CONTROLS FREE

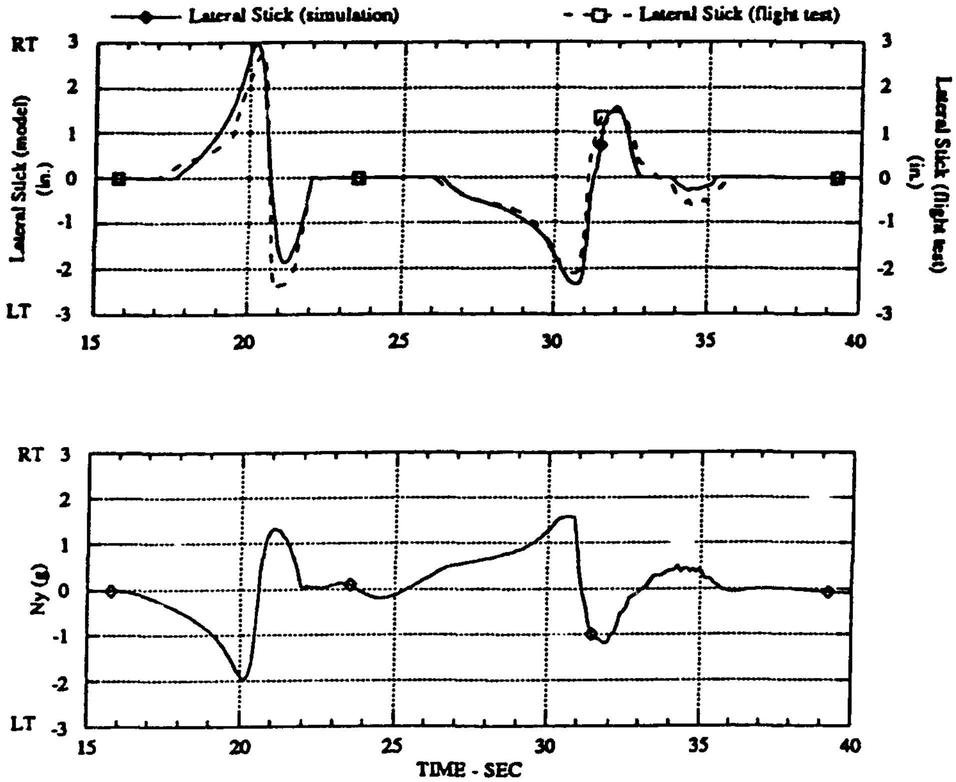

Figure 5
LATERAL STICK DEFLECTION DUE TO NY
FLIGHT TEST COMPARISON WITH MODEL

Figure 5 demonstrates that the model predictions were similar to results obtained during flight test. Pre-flight test modeling of uncommanded lateral stick movement during departures was important in providing a better understanding of what would be encountered in flight, however the results of the study were not considered to have an effect on safety of flight planning because the primary purpose of the program was to determine the stick movement and evaluate its' effects on departure recovery. The results of the flight test could then be used to validate the model for use in predicting stick dynamics throughout the full envelope during a hands-off departure recovery.

FLIGHT TEST

CONDUCT

Flight test was completed at NAWC/AD during April and May 1992. Ten data flights were completed during which 110 test maneuvers were performed and 67 departures resulted. Two NAWC/AD test pilots who had completed the simulator buildup alternated in the front seat for all flights; the aft seat was occupied by several fleet experienced test pilots chosen for their FRS instructor backgrounds. During the initial test flights, all departure entry and recovery control inputs were made from the front seat. During later flights, maneuvers were performed from both the front and aft seats. All test flights were accompanied by a chase aircraft manned with a dedicated airborne photographer. Ground, HUD and airborne chase video documentation was obtained for all test maneuvers. In addition to standard flying qualities data, production fatigue strain and Ny data were monitored real-time to ensure that vertical tail and engine mount limit loads were not exceeded.

DEPARTURES

TYPE A

Type A entry maneuvers (AOA's between 23 and 33 deg) showed limited success in producing departures. Most maneuvers resulted in high AOA rudder rolls that were controlled throughout the duration of required control input times. During the roll-under maneuvers, airspeed remained high enough to prevent departure. During the roll-over maneuvers, occasional benign departures were experienced as a slight nose slice with approximately 28 deg/sec yaw rate and 11 to 25 deg sideslip. Substantial warning in the form of vortex rumble and sideforce preceded the departure and recovery was immediate as controls were released. As testing progressed, maneuver technique was amended to investigate AOA ramping, airspeed bleed and pitch rate effects on departure in hopes of attaining optimal entry conditions. Limited success was achieved as the airplane showed excellent departure resistance in the high AOA/low airspeed entry maneuver conditions.

TYPE B

Type B unloaded entry maneuvers provided consistent departures during all attempts. Departure warning was good for all entry maneuvers of this type with sideforce and vortex rumble building steadily as sideslip increased to the point of departure. Departures of this type were characterized by an initial roll off that was fairly abrupt and resulted in Ny of up to 2.5 g. Several yaw and roll reversals resulted along with large excursions in AOA (+100 to -70 deg) and airspeed (48 to 215 KCAS). The length and severity of these departures showed strong relation to pitch rate during maneuver entry along with the rate of control application. Consequently, an apparent randomness was exhibited with some departures lasting only 4 seconds and others up to 22 seconds. Maximum altitude loss was 9,000 ft. Numerous "false" recoveries were exhibited where AOA, yaw rate and airspeed all indicated that recovery was imminent while sideslip (not visible to the pilot) was substantial and the departure continued. An example is shown in figure 6. At least three occurrences of the falling leaf mode were encountered from type B maneuver entries that were self-recovering with controls released. All had similar roll, yaw and pitch oscillations but were different in their level of stabilization and length. An example of the falling leaf mode is shown in figure 7.

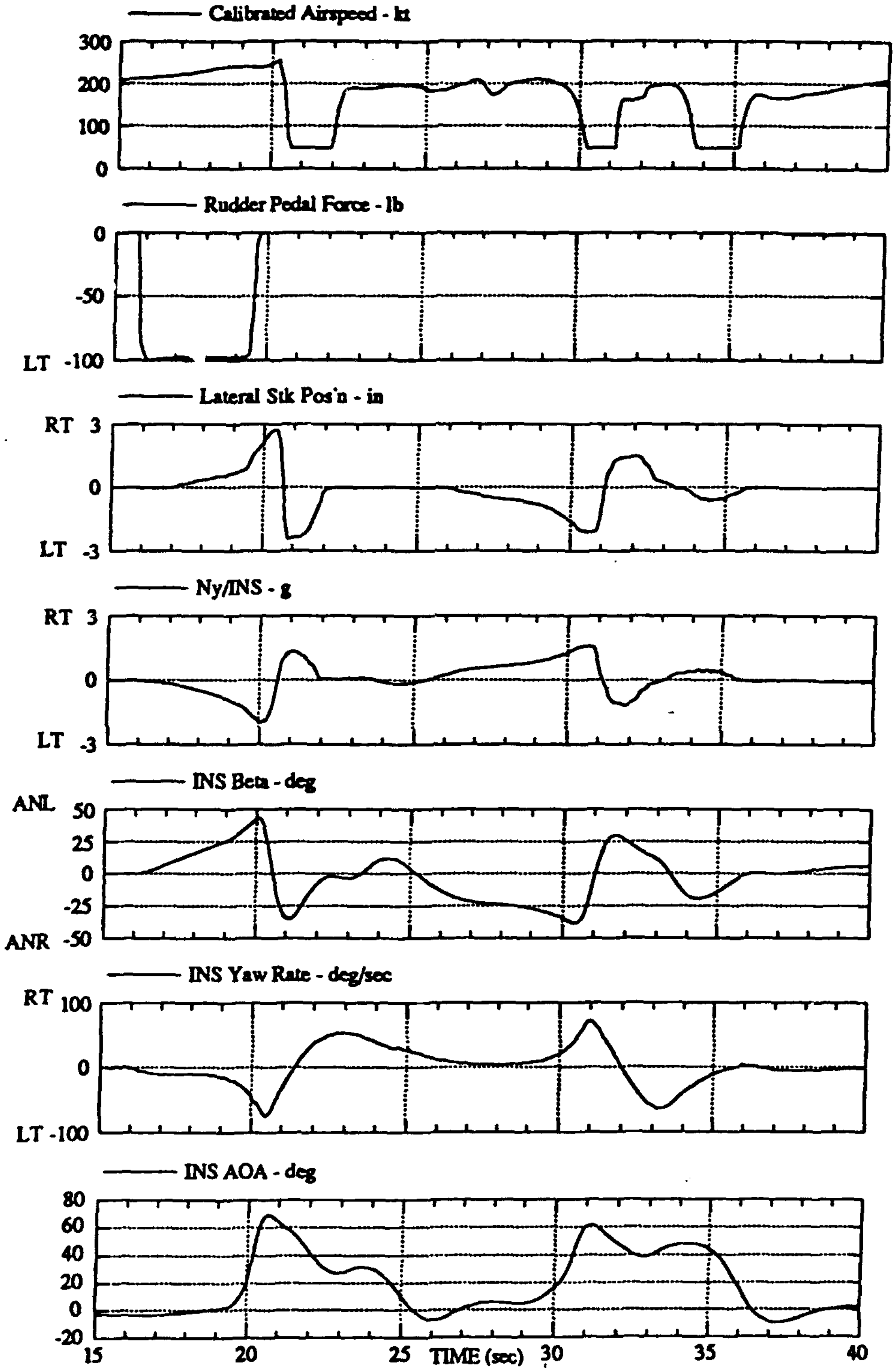

Figure 6
TIME HISTORY OF A TYPE B "FALSE RECOVERY"

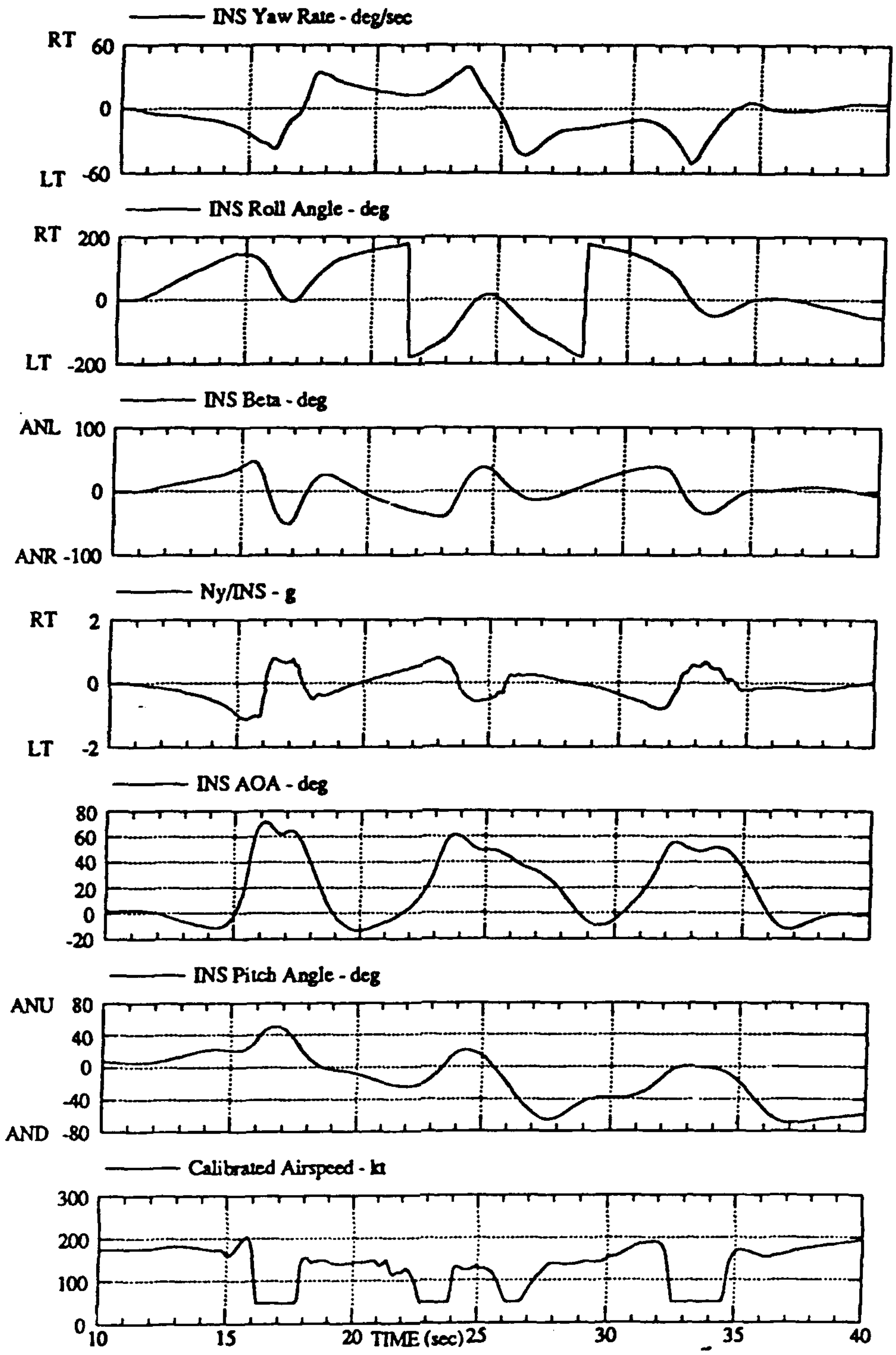

Figure 7
TIME HISTORY OF A "FALLING LEAF" EXTENDED DEPARTURE

TYPE C

Type C roll-coupled departures can best be described as quick, violent departures with little warning and a speedy recovery. The combination of rapid roll and yaw during maneuver entry somewhat masked vortex rumble and sideforce buildup, however the departure warning tone sounded as approximately 1 1/2 rolls were completed. As the airplane departed, the large sideslip buildup generated a slight roll hesitation followed quickly by a violent roll reversal and massive AOA spike. Excursions up to 100 deg AOA and Ny in the range of 0.6 to 3.5 g were exhibited using both coordinated and cross-controlled entry maneuvers. Recoveries were rapid and no extended departures were observed. Since the high lateral loads generated forced flight termination for centerline fuel tank inspection, these maneuvers were the last test points to be completed during each flight.

RECOVERY TECHNIQUE

Controls released, controls neutralized and released, and hands-on departure recovery procedures were evaluated with both aircrew harnesses locked throughout the maneuver. During controls released technique departures, the control stick movement was a direct function of N_y in the lateral axis (up to maximum deflection of 3 inches at 3.5g Ny) but the stick did not move significantly in the longitudinal axis. When Ny subsided, the control stick exhibited positive centering characteristics. No impact of lateral stick movement on the extent or severity of departure was evident. A time history of lateral control stick movement during departure is presented in figure 5. Lateral stick movement during hands-on recoveries was significantly less than controls released, however the test team felt that the hands-on recoveries were unrepresentative of actual fleet conditions since the pilot was expecting the departure and his harness was locked. Pilot comments during flight test indicated that the controls released technique was preferred due to the ability of the pilot to brace his body during departure more effectively, simplicity in technique and an overall increase in situational awareness.

CONCLUSIONS AND RECOMMENDATIONS

CONTROLS RELEASED VS CONTROLS NEUTRALIZED

The unanimous opinion of all test team members was that controls released departure recovery was preferable to controls neutralized departure recovery. Five important factors supported this conclusion. First, although the control stick moved significantly under Ny when released, no prolonged departures or adverse airplane response could be contributed to this movement. Average altitude loss with controls released was 3,100 ft compared to 5,000 ft with controls neutralized and released. Second, despite lateral movement only small longitudinal control stick displacement was observed. Inadvertent longitudinal stick input while attempting to hold controls neutral during departure has long been suspected as a major contributor to prolonged departures and past mishaps. During flight test, all departures were performed with the aircrew harnesses locked. Fleet pilots rarely fly with the harness locked as it restricts aft visibility, and with the harness unlocked the probability of inadvertent lateral or, more importantly, inadvertent longitudinal stick is greatly increased because of the pilot's body motion during departure. Third, the action of releasing the control stick is simple. Neutralizing the control stick requires pilot attention and "heads down" in order to sight and feel for the correct initial position and then maintain this position. Releasing the control stick helps to keep the pilot "heads up" to scan altitude, AOA, airspeed and yaw rate as the out-of-control procedure calls for. Increased situational awareness and therefore timely recognition of a stabilized OOC mode, impending recovery or ejection altitude is more probable. Fourth, releasing the control stick frees the right hand and allows the pilot to grab the canopy rail handle to help brace his body. This braced position with head up may help maintain proper body position should ejection become necessary. Finally, removing the pilot's hand from the control stick effectively increases his reaction time to input lateral stick if a command spin arrow is displayed. With controls released, a more resolute decision must be made to grasp the control stick and displace it laterally.

FLEET DEPARTURE TRAINING MANEUVERS

In an effort to determine the suitability of flight test departures for inclusion into an airborne departure recognition and OCF training syllabus, the following questions were asked:

a. *Does the entry maneuver produce a departure?* Virtually all of the high AOA entry maneuvers were unsuccessful in producing classic nose slice departures. Departures that were exhibited in these conditions were simple ballistic departures or slight nose slices that recovered immediately when controls were released. No beneficial fleet training would be gained from these maneuvers as many F/A-18 pilots experience these types of departures during routine ACM. The balance of the entry maneuvers, with low or unloaded AOA, were quite different and definitely met the criteria of repeatable departure.

b. *Does the entry maneuver produce an easily recoverable and safe departure where altitude loss is acceptable?* All flight test departures were recovered within an acceptable altitude loss, but a randomness was exhibited as to when or if the recovery conditions would always be met. Departure recovery times varied significantly from 4 to 22 seconds. During several extended departures, "false" recoveries were observed where AOA and airspeed were within recovery parameters and yaw rate had subsided but substantial sideslip existed and the airplane re-departed (figure 6). Such maneuvers would not be suitable for fleet training.

c. *Has the maneuver exhibited, or does the maneuver show the potential to develop into an AOA Hangup, Falling Leaf or Spin?* Confidence in overall recoverability became questionable for all maneuvers when a falling leaf mode developed during a B2 departure (figure 7). Maneuvers showing potential of a stabilized OOC mode were not desired for inclusion into a fleet departure training syllabus.

d. *Does the entry maneuver produce a repeatable departure where airplane motions are similar despite reasonable deviations in entry conditions?* Substantial variation in length of departure, airplane motion and altitude loss was apparent due to small changes in pitch attitude and pitch rate during maneuver entry. Only maneuvers that were fairly insensitive to reasonable deviations in entry parameters were desired for fleet training.

e. *Does the entry maneuver produce an excessively violent or disorienting departure?* All maneuvers which provided consistent departures (types B & C) produced high pitch, roll and yaw rates along with significant sideforces. None were substantially more disorienting or violent then similar maneuvers experienced by all Navy jet pilots in other airplane types during flight training.

f. *Does the entry maneuver produce loads approaching the structural limits of the airplane?* Type A & B departures did not exhibit high lateral loads (type A N_{ymax} of 0.8 g and type B N_{ymax} of 2.5 g.) whereas both type C departures produced N_y (3.5 g N_y) approaching the engine mount limits. N_z and N_x loads were moderate for all departures.

Overall, no flight test departure maneuvers were deemed suitable for inclusion into an airborne departure recognition and OCF training syllabus.

NATOPS FLIGHT MANUAL CHANGE RECOMMENDATIONS

SHORTCOMINGS WITH EXISTING OOC RECOVERY PROCEDURE

From flight test results and analysis of past departure mishap reports, the following concerns related to the existing NATOPS out-of-control recovery procedure and associated discussion arose:

a. The most significant warnings of impending departure; sideforce and audible vortex rumble, were not included in the NATOPS discussion.
b. The procedure was too centered on spin recovery. Many fleet pilots were expecting spin entry even when the probability of entering a spin was unlikely. The more likely airplane motions following departure were random oscillations followed by recovery or perhaps entry into a transitory falling leaf mode.
c. Too little emphasis was given to visual confirmation of a spin through yaw rate, turn needle, AOA and airspeed. Many fleet pilots thought of the digital CBW FCS of the F/A-18 as magic and when presented with a command spin arrow, whether erroneous or not, believed that a spin was confirmed.
d. The distinction between AOA hangup and falling leaf modes was not clear within the NATOPS discussion. Fleet pilots were expecting stabilized, not large amplitude, oscillatory AOA in a Falling Leaf mode and therefore not reacting with full forward stick.
e. The stated recovery airspeed of 150 knots was not accurate. Also, other critical flight parameters necessary for recovery (sideslip, yaw rate and AOA) were not adequately discussed nor included in the recovery procedure.

RECOMMENDED OOC RECOVERY PROCEDURE AND DISCUSSION

The recommended new NATOPS flight manual procedures, split into an OOC recovery and spin recovery procedure follow:

Out-of-Control Recovery
1. Controls - RELEASE/FEET OFF RUDDERS/SPEEDBRAKE IN

If still out-of-control -

2. Throttles - IDLE
3. Altitude, AOA, airspeed and yaw rate - CHECK

If positive AOA HANGUP or FALLING LEAF MODE develops -

4. Longitudinal stick - FULL FWD

If negative AOA HANGUP develops -

5. Longitudinal stick - FULL AFT

With AOA and yaw rate tones removed, sideforce subsided and airspeed accelerating above 180 knots -

6. Throttles - MIL or MAX
7. ROLL UPRIGHT AND RECOVER

If passing 10,000 feet AGL with no indication of recovery -

8. Eject

Spin Recovery

If out-of-control with sustained yaw rate -

1. DDI - CHECK

With command arrow present -

2. Lateral stick - FULL WITH ARROW

With command arrow not present -

3. Spin recovery switch - RCVY
4. Lateral stick - FULL WITH ARROW

When yaw rate stops -

5. Lateral stick - SMOOTHLY NEUTRAL AND RELEASE
6. Spin recovery switch - CHECK NORM

If positive AOA HANGUP or FALLING LEAF MODE develops -

7. Longitudinal stick - FULL FWD

If negative AOA HANGUP develops -

8. Longitudinal stick - FULL AFT

With AOA and yaw rate tones removed, sideforce subsided and airspeed accelerating above 180 knots -

9. Throttles - MIL or MAX
10. ROLL UPRIGHT AND RECOVER

If passing 10,000 ft AGL with no indication of recovery -

11. Eject

Splitting the previous NATOPS procedure provides the fleet pilot with a more straightforward course of action to deal with the random oscillations that will likely occur upon departure with normal airplane loading. Additionally, splitting the procedure provides a break in the memorized procedure that along with emphasis on visual confirmation of a sustained yaw rate forces the pilot away from simply using the command arrows as spin confirmation. These changes should help prevent the application of premature or incorrect anti-spin control inputs when a spin does not exist. Perhaps the most significant change was the inclusion of recovery conditions. Flight test indicated that only when AOA and yaw tones were removed, sideforce had subsided and airspeed was accelerating above 180 KCAS, the airplane was recovered. As discussed, several "false" recoveries were exhibited where although no tones were present, airspeed was well in excess of 150 KCAS, sideslip was ramping in excess of 35 deg and the airplane was still very much OOC. Since no cockpit indications of sideslip are presented in the F/A-18, sideforce, which in the above situation was increasing to approximately 1.5 g, was a critical factor in pilot recognition of recovery. Finally, associated NATOPS discussion was added to more clearly distinguish the falling leaf mode from the more static and less likely AOA hangup mode along with a more in-depth description of vortex rumble and sideforce as departure warning cues.

SUMMARY

The proposed controls released departure recovery procedure, standing alone, will probably not have a significant impact in the fleet departure mishap rate since many fleet departures occur at fairly low altitudes where recovery prior to ejection altitude is unlikely. The more important benefits of this flight test will undoubtedly come in the form of training through NATOPS discussion, procedure clarification and fleet FRS briefings aimed to increase the community's overall departure awareness. Although a more hands on method of dissemination through fleet departure training flights was desired, the maneuvers tested were clearly not suitable due to a high degree of unpredictability. For the long term, only departure prevention will save jets. Research into modified F/A-18 flight control laws along with the incorporation of a cockpit sideslip warning tone is ongoing and appears to show promise. Pilot awareness and airplane improvements, together with periodic flight test from review of fleet problems will continue to provide F/A-18 pilots with the knowledge, hardware and procedure necessary to maneuver safely and aggressively throughout the airplane envelope.

REFERENCES

1. White LCDR, et al.: "F/TF/A-18A Airplane Board of Inspection Survey Flying Qualities, Propulsion Systems, Air Vehicle System, and Air Vehicle Subsystem Trials"; SA-25R-83, 2 May 1983.

2. Shows MAJ R.J., Mumfrey G.D.: "Evaluation of the F/A-18B Airplane Departure Resistance and High Angle of Attack Flying Qualities"; SA-141R-86, 9 Feb. 1987.

3. Magnusson F., Wilcutt MAJ: "Handling Qualities and Performance Evaluation of the F/A-18A/B with Leading Edge Extension Fences Installed"; SA-97R-88, 2 Nov. 1990.

4. NATOPS Flight Manual A1-F18AC-NFM-000 for the F/A-18A/B/C/D, 15 Jan 1991.

5. Heller M.J., et al.: "TF/A-18 Stability and Control Improvement Study"; MDC B2473, 21 Nov. 1990.

6. McDonnell Aircraft Company Test Work Description Number FMR06.01-001, "F/A-18B Reconnaissance Stability and Control Flight Test", 5 Dec. 1990.