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F/A-18E/F Super Hornet High-Angle-of-Attack Control Law Development and Testing

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The Boeing F/A-18E/F Super Hornet completed the high-angle-of-attack (HiAOA) flight test program in the spring of 1999 as part of the airplane's three-year engineering and manufacturing development flight-test effort. Building on the success of F/A-18 Hornets serving world-wide, the design of the much larger Super Hornet sought to improve on the original Hornet's positive attributes and correct those characteristics where 20 years of experience indicated room for improvement. Beginning with the design history and objectives, details of the HiAOA flight control law development and testing are presented, concentrating on those aspects where particular challenges were faced. Successes and failures of the initial design are specifically covered, as well as the refinements necessary to achieve fully the program's design goals.

Introduction

ON 3 May 2000, the F/A-18 E/F Super Hornet and the government industry team responsible for its development were awarded the 2000 Collier Trophy in recognition of the program's achievements. Improvements to the capabilities and safety of the airplane at high angle of attack (HiAOA) were prominent among the cited achievements. Furthermore, with the delivery of Super Hornets to U.S. Navy squadrons in the spring of 2000, fleet users who were previously skeptical of the airplane's value have rapidly been converted to advocates. Improvements to HiAOA agility and safety have been among pilots' favorite features.

Super Hornet's Heritage

The heritage Hornet (F/A-18 Models A–D) is unique among the first generation of fly-by-wire aircraft developed and fielded in the late 1970s, and it has become the world's benchmark for HiAOA fighters. In an era when most fly-by-wire airplanes were imposing angle-of-attack (AOA) limiters, the clean F/A-18 was cleared to operate to its full aerodynamic capability. In contrast, aircraft such as the F-16 and Mirage 2000 implemented AOA limiters within their control laws to avoid out-of-control-flight (OOCF) losses due to departure, spin, or deep stall. Furthermore, as a research subject, the heritage Hornet has become the common reference for HiAOA papers, and the Hornet was the airplane of choice for NASA's High-Angle-of-Attack Research Vehicle (HARV) (for example, see any of dozens of papers published in *High Angle of Attack Technology Conference Proceedings*, NASA CP-3149, 1990, or CP-3137, 1992).

Fleet and international experience with the heritage Hornet has, however, revealed room for improvements to both its safety and its HiAOA capabilities.

Maneuvering restrictions associated with wing stores impose significant constraints on the fleet operator. Because of adverse departure characteristics with wing stores, the flight manual restricts the AOA for most of the permissible loadings. Consequently, the unlimited AOA capability is really only available for training loadings. Fleet operators are faced with restrictions that change with the weapons load and may change during the course of a flight. These restrictions are not automatically implemented in the flight control system, but demand careful recall and attention on the part of the pilot.

OOCF accounts for 17% of U.S. Hornet losses. According to the Naval Safety Center, sustained OOCF or low-altitude departures were responsible for 19 of 109 Class A mishaps (1980–1998). The most common OOCF mode is a falling-leaf limit-cycle oscillation characterized by in-phase roll and yaw, which creates a nose-up inertial coupling moment in excess of the available nose-down aerodynamic moment. Falling-leaf entry typically occurs from a nose-high attitude at low airspeed, with the worst recoveries associated with aft c.g. or heavy wing store loadings. Spins are less prevalent than the falling leaf, usually resulting from exceeding AOA limits with large lateral weight asymmetries.

The flight control system (FCS) incorporates an automatic spin detection and recovery mode. Spin mode enables when the airspeed decreases below 120 knots calibrated airspeed (KCAS) and filtered yaw rate exceeds 15 deg/s. (Filtering prevents spurious activation of the automatic spin mode. The pilot may manually bypass the filtered yaw rate requirement by means of a cockpit 'manual spin recovery' switch.) Once enabled, spin mode overwrites the pilot's principal displays with a large left or right spin arrow, indicating the required lateral control input. Deflection of the pilot's stick in the indicated direction engages the mode, disabling all FCS feedback loops, and providing full control throw in all axes. Antispin yaw control power predominantly comes from adverse yaw generated by differential deflection of the stabilators and ailerons. Spin mode deactivates and normal feedback operation returns whenever the stick is returned to neutral, the airspeed increases above 245 KCAS, or the filtered yaw rate decreases below the threshold.

Spin mode, as implemented in the heritage Hornet, has been a mixed blessing. The system is prone to false alarms, particularly during a falling leaf, where the high oscillatory roll and yaw rates convince the system that a spin is present. In this case, the spin display enables, toggling the arrow left and right with oscillating

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direction with the yaw rate. If the pilot misdiagnoses the mode and chases the arrow, the resulting control inputs feed the falling leaf.

Deficiencies in the implementation are presently addressed by pilot training. Three lengthy flight manual procedures, which are memory items, detail the pilot's response to departure, falling leaf, or spin. A decision tree determines which of the procedures is to be followed. This complexity is burdensome, and because few pilots have direct experience with the falling leaf, it remains shrouded in mystery. Because of the disorienting nature of OOCF and awkward recovery procedures, pilots have not consistently recovered the airplane.

Finally, the weight constraints of shipboard operations and the advent of large, heavy precision munitions have dramatically increased the frequency of large asymmetric external loadings. Modest asymmetries increase the departure and spin susceptibility and come with undesirable flight manual limitations on the maneuverability. Large asymmetries impose severe limitations, which must be rigidly observed, thereby reducing the airplane's safety and operational flexibility.

Requirements and Objectives

The requirements imposed on the F/A-18 E/F were daunting. (The E model is single place; the F model is two place. The sail area of the two-place canopy forward of the c.g. is directionally destabilizing and responsible for significant limitations on the early two-place B and D models.) The U.S. Navy needed a Hornet that was 25% larger, but that retained the agility and maneuverability of the smaller airplane. Furthermore, there was a strong desire to improve on the older Hornet's capabilities in the HiAOA regime. Although the airplane was not developed to field a better HiAOA machine, both the U.S. Navy and the contractor recognized that improvements to the HiAOA flying qualities would result in a safer and more lethal fighter.

HiAOA enhancements fell into two categories. First, improvements in the maneuvering performance and operational flexibility were desired. Second, the design needed to decrease the susceptibility to departure and out-of-control mishaps. U.S. Navy tactical aircraft design philosophy expressed the desired improvements: 1) highly departure resistant (not necessarily departure proof); 2) fully recoverable from all HiAOA, departure, and spin conditions; 3) possess sufficient nose-down pitch control power to recover from HiAOA (no deep stall); 4) no AOA limiters except for terminal phases of flight or heavy external store loadings beyond those required for the design missions; 5) capable of generating tactically significant roll and yaw rates at HiAOA while still providing sufficient departure resistance; 6) sufficient pilot cues of degrading characteristics.

This design philosophy was intended to provide the requisite capability for the full range of design missions, as well as adequate flying qualities and maneuverability for off-design configurations and missions. The following detailed requirements further expressed this philosophy:

1) For departure resistance, below the maximum lift coefficient, pilot control inputs could not cause departure. Furthermore, the airplane could not exhibit any uncommanded motions that could not be arrested promptly by simple control application or by release of the flight controls.

2) For spin recovery, a straightforward spin recovery technique was required that accomplished spin recovery within two turns.

3) For lateral weight asymmetry, the E/F-model limits were to be as good as or better than those defined for the F/A-18 C/D.

4) For F-model restrictions, the same maneuvering envelope was to apply to the E and F models.

Beyond the preceding formal requirements, the U.S. Navy and Boeing agreed that careful use of the available control power could also achieve further improvements to the safety and flexibility of the airplane. Specifically, the design group sought to eliminate altogether the OOCF modes that have led to the loss of heritage Hornets. Additionally, improvements to the spin recovery system and procedures seemed within easy grasp.

Design Features

General Features

Superficially, the E/F models appear to be a photographic enlargement of the heritage Hornet models (Fig. 1). The weight and wing area both grew by 25%. Control surface layout is similar, increasing more than 25% to achieve the maneuverability goals with the larger airframe.

Several features significantly change the HiAOA character of the airplane. First, unlike the earlier models, which were positively stable, the E/F is unstable for most of the allowable c.g. locations. Static margin reductions provide improved maneuvering and carrier landing performance. Next, the mechanical backup to the FCS was removed for weight reduction and improved maintainability. Otherwise, the E/F's FCS hardware architecture is nearly identical to the heritage Hornet's quad-redundant control authority system (CAS), albeit with different gains. Changes to the planform include a snag on the wing leading edge to enhance rolling performance on approach and a broader, shorter leading-edge extension (LEX) for improved HiAOA lift. Speed-brake functionality is now provided by the deflection of all FCS surfaces and two LEX-mounted spoilers. These spoilers also improve nose-down control power at HiAOA.

The E/F's HiAOA control laws build on the earlier models' FCS architecture, incorporating several new features in pursuit of the design objectives. Space permits mention of only those features that had a prominent role in the results.

HiAOA directional stability is significantly improved by use of the ailerons and the differential stabilators as primary yaw control devices at some flight conditions. Their power in the yaw axis is attributed to two complementary effects. First, both sets of surfaces generate considerable adverse yaw, so that a roll command away from the sideslip generates a restoring moment. Second, any resulting body-axis roll kinematically reduces sideslip. Hence, deflection of the rolling surfaces augments both the directional stability and increases the apparent dihedral.

Sideslip and sideslip rate feedbacks were incorporated in the original Super Hornet design and are discussed hereafter, as are improvements to the spin mode. Other features introduced to address problems uncovered by flight test will be discussed later. Finally, a direct proverse sideslip command capability was added late in the program to augment the roll performance.[1]

Sideslip and Sideslip Rate Feedbacks

The E/F generates direct control of sideslip (beta) and sideslip rate (beta-dot) by feeding those signals to the ailerons and differential stabilator. The sideslip feedback works primarily to increase lateral stability in the 30–35 deg AOA region, an area susceptible to departure for the heritage Hornet. The sideslip rate works to dampen the

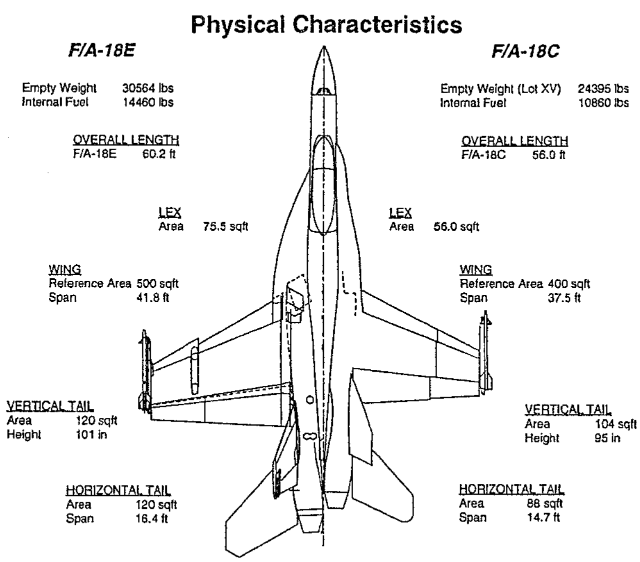

Fig. 1 Planform comparison of E/F to earlier models.

Dutch roll mode, which was necessary to achieve adequate system stability. Increased Dutch roll damping had a fortunate secondary benefit of eliminating the falling leaf mode, which is an exaggerated form of in-phase Dutch roll motion.[2]

These feedbacks introduced one architectural complication. A quad-redundant yaw rate signal is integral to the FCS of all models. However, the single inertial navigation system (INS) provides simplex beta and beta-dot signals. Consequently, the FCS reliability requirements dictated that adequate HiAOA handling be retained with the less reliable INS failed.

Spin Mode Improvements

The architecture of the heritage Hornet's spin recovery mode was mapped directly into the new design. Spin mode enables when the airspeed is below approximately 120 KCAS and filtered yaw rate is greater than 15 deg/s. Spin mode disables when airspeed is greater than 245 KCAS, filtered yaw rate is below the 15-deg/s threshold, or when the product of filtered yaw rate times yaw rate is less than 225 deg^2/s^2. This last feature, new to E/F, was incorporated to speed the system's identification of spin recovery, a flaw in the earlier models.

Scope of Test

The flight-test effort represented the largest and most aggressive HiAOA program ever undertaken for the development of a production fighter.[3] Its scope included two distinctly different models (the two-place canopy is directionally destabilizing) and store loadings ranging from a clean wing to a full complement of external 480-gal fuel tanks and heavy bombs (symmetrically and asymmetrically loaded). Maneuvers spanned aggravated multiaxis departures, tail slides, and fully developed spins to 120 deg/s.

Philosophically, testing proceeded in four phases. The four phases systematically increased the team's knowledge of the airplane such that each increment in risk was led by an increase in the team's confidence in the airplane and supporting models.

The unacceptable cost of losing the test vehicle or its pilot necessitated an extensive risk reduction simulation effort as the preparatory phase. This comprised both off-line six-degree-of-freedom (6DOF) simulations and full hardware and pilot-in-the-loop [manned flight hardware simulation (MFHS)]. This effort, although costly (including over 50,000 computer trajectories), was invaluable to subsequent flight-test planning. Specifically, it identified the test points most important to understanding the airplane's characteristics as well as the points most prone to departure and requiring the most careful buildup.

The aerodynamic database was primarily developed using wind-tunnel data. Two sources of data played key roles. First, the primary static low-speed force and moment data were obtained using the 15% scale model in the NASA Langley Research Center 30 × 60 Foot Tunnel. Second, nonlinear rotary dynamic data were obtained from a 10% scale model in the NASA Langley Research Center 20-Foot Vertical Spin Tunnel over a wide range of AOA and sideslip. Overall, the wind-tunnel results proved extremely accurate, with a few noteworthy exceptions, when compared with flight-test results.

Phase 1 testing examined the departure susceptibility by the application of single-axis inputs at various flight conditions. Phase 1 also provided the updates to the aerodynamic model that proved crucial to the safe execution of later phases.

Phase 2 provided the first look at upright and inverted spins and sustained OOCF modes. Spins deliberately preceded aggressive maneuvering (Phase 3) so that any unpredicted departures would be expected to transition to sustained modes visited earlier.

Phase 3 opened the envelope for aggressive maneuvering and included the full spectrum of multiaxis sequenced maneuvers and zero-airspeed tail slides.

These phases were initially strictly followed with no wing stores on a specially equipped single-place (E-model) airplane, whose modifications included a spin recovery parachute and emergency power accommodations. The sequence was then repeated in each of the desired external store loadings, followed by limited scope tests of the two-place (F-model) airplane.

Over the course of three years, a total of 221 flights and 378 flight h were devoted to HiAOA maneuvering, departure, and spin testing.

Testing and Refinement

Little of the initial HiAOA flight testing could have been considered dull. What was good was very good, affirming the design improvements over the heritage Hornet. What was adverse was neither pretty, nor expected. Where surprises occurred, flaws were found in our methodology or in the simulation.

Inverted Hang-Up

The first of the adverse characteristics to be discovered was protracted recoveries from inverted, negative 1-*g* stalls. With a gravity-command longitudinal control system, the airplane was expected to return to 1-*g* flight promptly after release of the control stick. Instead, counter to the design intent, the airplane remained at large, slowly decaying negative AOA, with the pilot hanging upsidedown in his harness.

Two effects caused the stabilators to force the hang-up. (To visualize this properly, recall the airplane is inverted and the control and N_z values are body axis.) Classic integrator windup proved to be the first culprit. The airplane's AOA sensors saturate at −10 deg; with low airspeed, a negative AOA greater than 10, and the forward stick (commanding more negative N_z than the aerodynamics could deliver in an inverted stall), the N_z error drove the stabilator full trailing-edge down (TED), trying to cancel the error. Protracted recoveries to 1 *g* then resulted while the integrator unwound.

The integrator windup was cured by turning the integrator off whenever the AOA exceeded −8 deg for dynamic pressures of less than 200 lb/ft^2. This had the effect of reducing the maximum AOA capability in the negative direction from about −30 to −22 deg. Because the airplane is fully stalled at −22 deg, the pilots regarded this reduction as operationally insignificant.

Next, the pitch damping augmentation, which when upright helps 1-*g* maintenance, also fought against the recovery to 1 *g* from inverted stalls by driving the stabilators TED. This was corrected by a fourfold increase in the N_z feedback gain. This aggressive increase in the gain created undesirable spin-recovery side effects, which required further refinement.

Directional Instability at Negative AOA

We discovered inadequate directional stability at −20 deg AOA during one of our first F-model flights when an inverted departure resistance point turned into an inverted spin. (This was an important validation of deliberately spinning early in the program. Having seen the incipient inverted spin on numerous prior occasions, the pilot diagnosed the departure as it developed, resulting in a prompt recovery.) A slightly weaker instability existed in the E model, but had been missed due to minor variation in the flight condition at which the point had been performed.

The early aerodynamic model had revealed a reduction in stability in the vicinity of −20 deg AOA. Although beta and beta-dot feedback had been implemented at greater than 15 deg AOA, these feedbacks were not originally implemented at negative AOA. Implementation at negative AOA eliminated the problem.

This episode also revealed a lapse in the test methodology. During the E-model flights, points such as this had always been preceded by a half-deflection step as buildup before full deflection. For the sake of test efficiency, the team consciously decided to omit all buildups, considering the E-model results to have satisfied the requirement. Although this approach was valid for conditions at which no variation from the E model was expected, a new buildup would have been appropriate for points such as this where minor differences were probable. In this case, the result would probably have been the same, but without the same postflight chagrin.

Falling Leaf

The falling-leaf characteristics of the E/F models have to be among the design group's great triumphs. Like the heritage Hornet, the mode naturally exists in the bare, unaugmented airframe. Unlike those models, the E/F flight control laws inhibit any undesirable motion. Despite extensive testing, no sustained falling leaf has been observed in any loading, or at any c.g. location.

To perform falling-leaf testing, the pilot disabled all FCS feedbacks (CAS-off) via the manual spin recovery mode switch. With the augmentation disabled, the airplane was slowed to 40 deg AOA/120 KCAS at 35,000 ft. One to two cycles of 1-in. lateral stick inputs, in phase with the bank angle, excited the mode. The stick was then held full aft and laterally neutral. The roll/yaw oscillations then diverged until they established a limit-cycle oscillation with a nominal 4-s period. The oscillations were bounded by ±30 deg/s of yaw rate, ±60 deg/s of roll rate, ±40 deg of sideslip, and 90 deg of bank angle. The rate of descent was typically 14,000 ft/min.

Falling-leaf testing was performed in several loadings and c.g. locations, including at the full aft limit. The basic character remained unchanged from loading to loading, varying only in subtle details of the mode shape. For example, the aft c.g. loadings exhibited a noticeably higher pitch attitude than with the c.g. forward.

The falling leaf gave the pilots a wild ride, but it was the CAS performance that watered eyes. Once the CAS-off falling leaf was stabilized, the pilot turned the FCS feedbacks back on. If the control stick was simultaneously released, the roll and yaw rates immediately subsided, and the aircraft pitched nose down and recovered to a low AOA dive. If the stick was held in the full-aft/neutral-lateral position, all airplane body rates abruptly stopped, and the airplane stabilized at 50 deg AOA, with the nose near the horizon. It was rare in this case to see two overshoots as the body rates dampened. This was dramatic given the prolonged effort required to restore control from a heritage Hornet's falling leaf.

Falling-leaf entries were also performed with the INS off, thereby disabling the primary beta-dot feedback, validating the robustness of yaw rate feedback as a backup. This assessed the severity of an INS failure and provided data on the contribution of the beta-dot feedback to the stability of the airplane at these flight conditions. In the INS-off case, the restoration of CAS (minus primary beta-dot feedback) resulted in moderately damped cessation of the developed falling leaf.

We were, therefore, able to assess the relative contributions of the yaw rate feedback vs the INS beta-dot feedback. Because the heritage Hornet's falling leaf lacks both natural and augmented damping, we concluded that even a less-than-ideal damper is adequate to suppress the falling-leaf mode.

By independently disabling the beta feedback alone, we had already determined that it made no contribution to suppression of the falling leaf. This was not surprising given the limit-cycle behavior of the falling leaf. Strong stabilizing moments were clearly present. The bare airframe lacked a damping mechanism, which yaw rate and beta-dot feedback amply provided.

Falling-leaf entries were also attempted with the feedbacks fully engaged (CAS on). No sustained falling-leaf episodes were successfully developed directly with the CAS enabled.

Transient falling-leaf behavior CAS on was observed incidentally during other events. For example, during zero-airspeed tail slides, the airplane occasionally fell into very large sideslip angles (60–90 deg). The airplane responded with an abrupt roll/yaw away from the sideslip, identical to the falling leaf. After a single overshoot, all body rates were damped.

Historically, many development programs have regretted declaring their airplane to be spin-proof, having had some young lieutenant quickly prove them wrong. Some hesitation is, therefore, understandable before declaring the Super Hornet to be falling-leaf proof. The CAS-on behavior out of tail slides, the stark difference in the behavior of the airplane with CAS on and off, and the large number of loadings and conditions tested all provide tremendous confidence that no sustained falling-leaf mode exists in the airplane with the FCS operating properly.

Upright Coupled Departures

Preflight modeling of a step left-and-full-aft stick command at 200 KCAS predicted a sharp left roll and pitch up into stall, a benign outcome. The actual result provided the most significant surprise of the program. Within 3 s of the input, the airplane rolled left, pitched

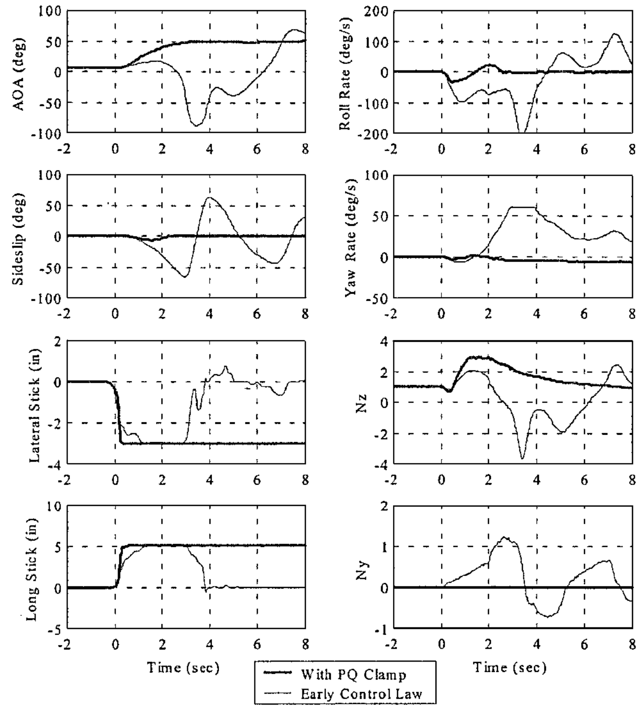

Fig. 2 Inertial coupling, before and after.

up, and then departed nose right, going flat plate to the airstream in the negative direction. The resulting -3.7-g N_z exceeded the structural design limit, and the pilot's helmet struck the canopy with sufficient force to leave an audible crack on the cockpit recorders. The event is depicted in the dotted traces of Fig. 2. The next point was to have been 300 KCAS, doubling the dynamic pressure.

Whereas the aircraft had tracked the simulation predictions earlier, this departure was completely unexpected (5 min earlier, the team had told the pilot that this would be a benign event). Departure testing was suspended for four months to allow for analysis, redesign, testing, and fielding of new FCS software.

Model extraction of the flight-test data revealed that the aircraft's aileron power had been significantly underestimated. Two wind-tunnel entries had provided the bulk of the stability and control derivatives for the HiAOA models. The two measured aileron control powers varied by approximately 20%. The lower value had been adjudged to be more reasonable and was inserted into the aerodynamic database servicing the simulation and design studies. After the departure, the database was revised to use the higher of the two values and simulated recreations of the test point matched the flight-time history. More alarming, the simulation now indicated that had we attempted the same maneuver at 300 KCAS, we would have far exceeded the ultimate strength of the airplane.

Diagnosis

The corrected simulation now permitted a full understanding of the dynamics of the departure. Inertial coupling between the left roll rate and the nose-up pitch rate generated a significant nose-right yawing moment, resulting in significant negative sideslip.

Equation (1) describes the AOA rate (alpha-dot):

$$\dot{\alpha} = (q - p \sin \beta) + (g/u)(\cos \phi \cos \theta - N_z) \tag{1}$$

The first term $(q - p \sin \beta)$ is the kinematic coupling. The second term is the resolution of the weight and normal lift vectors. At the departure flight condition, the kinematic coupling term can easily swamp the second term. The departure, specifically the reversal in AOA, coincided with the kinematic coupling term changing sign.

This can be seen clearly in Fig. 2. Peak pitch and roll rates were 50 and 100 deg/s, with a peak sideslip of 65 deg; the kinematic coupling contribution to alpha dot was consequently a -57 deg/s. Thus, contrary to AOA increasing monotonically with full-aft stick, as one would expect, AOA reversed and dove negative, the sideslip built through 50 deg, and the AOA reached −90 deg.

pq Limiter and *pq* Clamp

Limiting the pq product was the obvious path to defeating this departure mode. The challenge was defeating the mode without unduly restricting the maneuverability of the airplane at HiAOA.

Originally, pq limiting was performed in the feedback loop. When the pq product was observed to exceed the threshold value, the roll command was reduced to maintain the desired maximum. This was effective at lower Mach numbers, but too slow and ineffective at the end-point condition (0.9 Mach, 35,000 ft, and 300 KCAS). The simulation indicated that departure would occur before the feedback loop could rein in the pq product.

Restricting the pq product in a feedforward path raised the issue of cutting into the roll performance. Because the departure appeared to be related to the abruptness of the aft-stick input, the design team decided to perform pq limiting as a function of stick rate. This was called the pq clamp, and the simulation indicated it would have minimal impact on the nominal HiAOA roll performance.

Testing resumed once the pq limiter and pq clamp were incorporated in the FCS software.

Testing Resumed

The resumption of testing this maneuver strained our confidence in the simulation's modeling. The abrupt nature of these departures precluded the idea that any monitored parameter could provide timely warning of danger. Whereas the points had to be flown—the maneuver was too basic to a fighter pilot's repertoire—the risks of losing the test airplane and pilot had to be faced.

Buildup was performed both in Mach number and in the amount of lateral roll command to permit a slow, methodical approach to the endpoint. Interleaving these approaches and point-to-point monitoring of the departure susceptibility provided confidence that the next data point could be attempted without substantial risk.

Roll command power was varied with the FCS software, which provided the capacity for software gain changes in flight. A software stop was programmed so that full lateral stick deflection commanded only increments of the available roll rate. This provided for a buildup in roll command (full aft and 38% roll, full aft and 56% roll, full aft and 75% roll, and, finally, full aft and 100% roll). The software roll command limit provided a precision the pilots could not have achieved manually (and a stick-mounted switch provided instantaneous reversion, if required). At a given Mach number, the team could thereby perform an incremental buildup in pq product. Once 100% roll power was achieved, the Mach number was increased in 0.1 Mach increments to buildup the dynamic pressure.

Knowing the departure mechanism permitted point-to-point assessment of the departure susceptibility. Specifically, a departure could be expected whenever the peak $(p \sin \beta)$ product exceeded the peak pitch rate. There throughout the buildup sequence, the test team could project the margin for the following point.

Practically, these risk mitigation measures worked together as follows: When started at 0.5 Mach and 35,000 ft (180 KCAS), the step left-and-full-aft stick input was performed with the reduced roll authority settings and then full authority. The peak $(p \sin \beta)$ product and pitch rate were then plotted vs Mach number for each roll authority value in Mach increments of 0.1. As depicted in Fig. 3, the trend lines at 0.9 Mach indicated that the $(p \sin \beta)$ product and the peak pitch rate did not cross at full lateral stick, and testing was performed to the limit flight condition with benign results. The solid trace of Fig. 2 depicts the results after the incorporation of the pq limiter and the pq clamp.

More Coupled Departures

Having cured the step-lateral-and-aft departure mode, testing proceeded to phased inputs. The point of the phased inputs was to generate the highest possible body rates in one axis before inserting a step command in a second axis. These inputs were considered to represent the worst possible inertial coupling load on the flight controls. For the lateral-and-full-aft maneuver, building on the step directly to the left and aft corner, the sequence was a step lateral input, allowing the roll rate to build to its peak, followed by a step full-aft input.

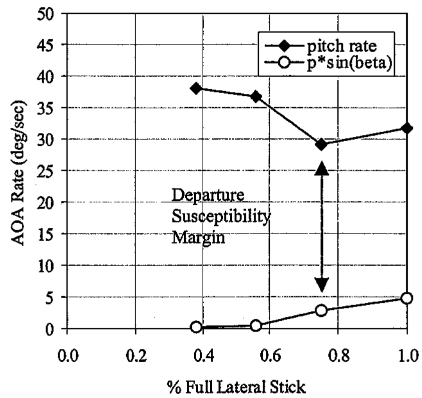

Fig. 3 Departure susceptibility margin, 0.9 Mach, 35,000 ft, step left and aft input.

The simulation predicted that the pq limiter and pq clamp would easily control the phased inputs. Flight tests confirmed this positive result. The team now had great confidence that, given a symmetric loading, there was little likelihood of a fleet pilot encountering a departure through any combination of lateral and aft stick movements.

At this point, simulation work discovered a kink in the armor. Engineers at play found a way to beat the pq clamp. To avoid unnecessarily limiting roll rate, only a rapid aft-stick input in the presence of roll rate activated the clamp. Slower aft inputs were regarded as nonthreatening because of reduced susceptibility to inertial coupling. This assumption proved to be inaccurate. The simulator indicated that, in the presence of a full lateral stick roll, if the stick was brought to the aft limit in 3–5 s, an abrupt departure would occur. This prediction was passed to the test team to validate.

The simulation was correct, with the most disorienting departures yet seen. Our pilot laughed aloud at the sight of his own exhaust through the front windscreen. The departure mechanism was similar to the departures observed earlier, with a much slower growth in sideslip, the departure occurring after about 360 deg of roll. The departure was highly sensitive to stick rate, too slow with the aft stick, and the 720 deg roll-testing limit was reached before sideslip built too far. If the stick came aft quickly, the clamp worked perfectly.

Tightening down the clamp delayed departures to after 540 deg of roll, but the team was now faced with a quandary. Any further improvement would have had a clearly adverse effect on roll performance. The alternative was to live with it. Because slow-aft departures were all occurring well after 360 deg of roll, and a fairly precise stick trajectory was required, the pilots decided that the conditions required to provoke this departure were sufficiently isolated such that degrading the roll performance would be unwarranted. A flight manual limit was imposed, identical to that on the heritage Hornet, restricting full stick rolls to 360 deg.

Spin Recovery

The spin program's scope included upright and inverted spins to 120 deg/s; clean, symmetric, and asymmetric external store loadings; FCS failure states; the full c.g. range; misapplied recovery controls; and both models.

As with the falling-leaf testing, spins were initiated with the feedbacks disabled (CAS-off). Upright and inverted modes were identified. Whereas the upright modes were more stable and repeatable, inadvertent entries from CAS-on departures favored inverted modes.

As predicted, recoveries in auto spin recovery mode were generally prompt with the application of full lateral stick with the yaw rate for upright spins and against the yaw rate for inverted. Releasing the controls completed the recovery as the airplane restored CAS-on operation with the yaw rate unwinding through 15 deg/s. (To speed identification of the recovery, the spin mode disabled with (yaw rate) × (filtered yaw rate) < 225 deg^2/s^2.)

Several exceptions are discussed hereafter.

Flip-Flops

A significant minority of spins experienced a change in polarity during the recovery, an upright spin flipped inverted, or an inverted spin popped upright. From a bird's-eye view the direction of spin was unchanged; from the pilot's perspective what had been an upright spin to the right was now an inverted spin to the left. The N_z accelerometer signaled whether the spin was upright or inverted to the FCS.

The challenge was getting the FCS to diagnose properly the reversal. Because filtered body-axis yaw rate (which changed slowly), and N_z accelerometer polarity (which changed quickly) drove the spin arrow, the arrow could flip erroneously while the filtered yaw rate signal caught up with the new spin direction. The result was spurious flips of the arrow, confusing the pilot and commanding a prospin input. This problem was eliminated by reinitializing the filtered yaw rate to zero with every change in N_z polarity, thereby requiring a sustained yaw rate in the newly developed direction before display of the arrow.

Low Rate Spins

Midway through the program, a low-rate, CAS-on spin mode was identified that required attention. The CAS-on spin was characterized by 30 deg/s of yaw rate and 40 deg AOA with the FCS in CAS mode. The entry criteria were 1) recovering from a high yaw rate spin with large yaw acceleration (i.e., body rates greater than could be generated directly in CAS), 2) the yaw rate briefly near zero to turn off the spin mode, and 3) the airspeed high enough to prevent re- entry into spin mode. With these conditions, the stabilators would be fully deflected TED to break the AOA, but they could not overcome the nose-up moment from roll/yaw inertial coupling. Furthermore, with the stabilators saturated by their pitch priority, no yaw power could be extracted from them to brake the yaw rate. Furthermore, the FCS deflected the ailerons to counter the roll, providing a prospin, adverse yaw moment. Imposing a yaw rate limit on the aileron command path in the presence of the low-rate spin parameters eliminated the mode.

Asymmetric Stores

In general, both the automatic spin logic and antispin controls were proven to be very effective in flight test. However, spins with various lateral weight asymmetries revealed that recoveries were particularly oscillatory and unpredictable (Fig. 4). These recoveries were adequate given that smooth or quick spin recoveries with lateral weight asymmetries were never a design requirement, and a number of these spins recovered promptly without undesirable oscillatory motion. Although adequate, the lack of correlation between spin rate and recovery altitude disturbed the team.

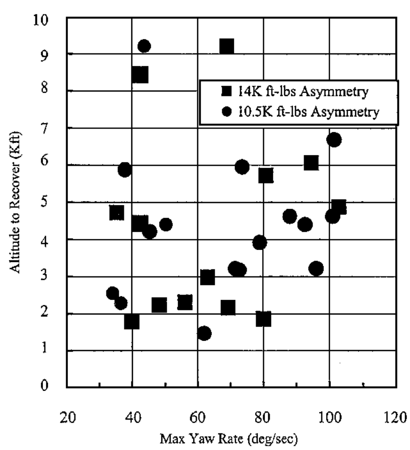

Fig. 4 Upright spin recovery performance, moderate lateral weight asymmetries.

The pilots suggested that the final moments before the yaw rate stopped seemed critical to the character of the recovery. Recoveries for low-rate spins were occasionally significantly delayed. Antispin controls that were neutralized too early would delay the recovery, and anti-spin controls held too long would likewise complicate and prolong the recovery. The challenge was to find a recovery technique to minimize the oscillatory nature of these errant recoveries without degrading recoveries with symmetric loadings. Hopefully, the spin recovery altitude loss could thereby be reduced for all loadings.

The delayed spin recovery of the low-rate spins gave cause to reconsider the fundamentals of the antispin control philosophy. It was puzzling that all of the preconceived aspects of the recovery were in order, the logic detected the spin and the full correct spin recovery control was inserted with the spin arrow, yet the aircraft tended to redevelop yaw rate.

The first inclination was to blame the asymmetry, which propagates a sideslip bias at higher AOA. Although playing a part, the magnitude of the bias did not seem sufficient to sustain the spin. Attention then turned to the antispin control surfaces in relation to the spin history.

Coupling can also prevail during spin recovery. As yaw and roll rates slow (considering the upright case), the nose-up inertial coupling reduces. The loss of nose-up roll/yaw inertial coupling brings the AOA down as the nose-down aerodynamic moment takes over, generating a nose-down pitch rate. If roll rate is on the aircraft during the recovery, then the combination of roll rate and nose-down pitch rate cause a prospin increase in yaw rate through pitch/roll inertial coupling.

In our case, as AOA decreased, antispin controls aggravated the spin through this coupling. The antispin benefits of the aileron and differential stabilator deflection assumed AOA would be at the extremes, where mostly yaw is generated. However, at low AOA, these surfaces perform their familiar roll-generating function, an adverse effect with pitch rate present. The antispin controls, especially with full deflection, were becoming prospin at low AOA in the presence of the nose-down pitch rate.

An example of a delayed recovery from a low-rate inverted spin is depicted in Fig. 5. After an inverted entry, the pilot applied the initial recovery controls (lateral stick against the spin) at a yaw rate of near 60 deg/s. Two instances of a respin were observed with the anti- spin controls, as denoted in the shaded regions. Increases in yaw rate coincided with AOA returning near zero, producing roll rate from the roll surfaces during a time with nose-up (body axis)

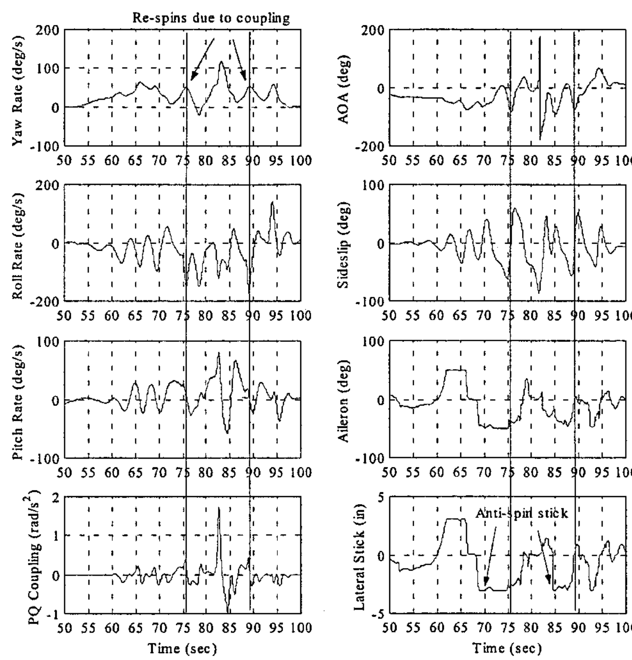

Fig. 5 Protracted recovery from an inverted spin.

pitch rate. As depicted by the yaw acceleration trace, the consequent inertial coupling provided an overwhelming prospin yawing moment.

The team assessed methods to reduce the control-induced pitch/roll inertial coupling that was interfering with smooth spin recovery. Reducing either the pitch or roll rate during the final stages of recovery appeared critical. Roll rate was preferred because implementation would be more consistent with the simple lateral stick input used for spin recovery. The pursued solution was to reduce the amount of antispin aileron and differential stabilator deflection at low yaw rates. If our theory was correct, low yaw rates would yield low AOA, and reducing roll power would reduce prospin yawing moment from pitch/roll inertial coupling.

To test this theory, spin recoveries were attempted with half-lateral stick deflection for the antispin control when the yaw rate slowed below 40 deg/s. Spin recoveries improved dramatically with this trial technique. The lateral stick authority was consequently reduced by 50% when yaw rate fell below 40 deg/s while in the spin mode. This represented a significant departure in the structure of the spin mode because, up to this point, spin mode meant full surface throw with no feedbacks.

Spin recoveries with 14,000 ft·lb of asymmetry improved dramatically with the new control law (Fig. 6). Furthermore, recovery altitude now demonstrated strong correlation with yaw rate, consistent with intuition.

The ability to recover routinely from a spin of this magnitude of asymmetry was an important milestone. A fleet clearance for unrestricted maneuvering at any given AOA and asymmetry would require strong departure resistance coupled with predictable, consistent out-of-control recoveries. Strong departure resistance with 14,000 ft·lb of asymmetry and the ability to recover safely from any inadvertent spins fulfilled a major objective, allowing unrestricted AOA for moderate asymmetries. This represents a dramatic increase in operational capability over the heritage Hornet, which is restricted to 20 deg AOA for these moderate asymmetries.

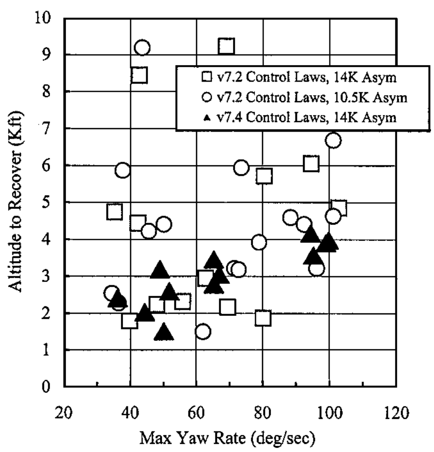

Fig. 6 Upright spin recovery improvement, moderate lateral weight asymmetry.

Conclusions

The F/A-18 E/F Super Hornet entered operational evaluation (OpEval) on 27 May 1999, with unrestricted clearances for both models in all external loadings with less than 8000 ft·lb asymmetry. Loadings between 8000 and 12,000 ft·lb permit unrestricted maneuvering at less than maximum lift AOA, whereas higher asymmetries are limited to 15-deg AOA. The airplane completed OpEval that fall with glowing reports of its safety at HiAOA.

Embracing many lessons from the older airplane, these capabilities represented substantial improvements over the heritage Hornet on which the E/F models were based. This paper serves to document several of the more interesting challenges faced during the development.

Representing the work of scores of people over several years' time, this paper has necessarily covered only the highlights of the effort required to achieve the design goals. The topics treated were selected based our perceptions of their interest to the flight dynamics and control communities. In particular, the paper focused on issues where results caught the team by surprise, where design decisions had unanticipated side effects, or where the most dialog was generated between designers, testers, and pilots as we decided how we really wanted the airplane to behave.

Two topics, roll performance enhancement and departure susceptibility with weight asymmetry, were too substantial to include and will warrant separate treatment in the future.

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