MCAIR NO. 84-009

F/A-18 FLYING QUALITIES DEVELOPMENT

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F/A-18 FLYING QUALITIES DEVELOPMENT

by Jack M. Abercrombie
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Since the F/A-18 fighter-attack aircraft (Figure 1) made its first flight in November 1978, some significant changes have been made to the control system to improve flying qualities characteristics. This paper covers some of the highlights of that flying qualities development, touching briefly on the initial design criteria and the evolution of the control system as we progressed through the flight test program. Particular emphasis is placed on some unique and very innovative features of the flight control laws.

Evolutionary Developments During Flight Test

Some of the evolutionary (in some cases: revolutionary) developments are indicated in Figure 2. Among the more interesting ones are:

- The improvements made to the takeoff rotation characteristics
- The problems encountered in achieving the required roll performance
- The control law philosophy changes which were required to reduce response sensitivity and PIO tendencies for high gain tasks
- A unique feature for reduction of pitch coupling during rolling maneuvers, and
- The improvements made to the departure and spin recovery characteristics.

In addition to improving flying qualities characteristics, we were also able to solve several structural problems with the flight control system -- empennage loads during rolls, wing bending moments at elevated load factors, wing store pylon loads during high speed rolls, and one of the more elusive problems -- a limit cycle structural oscillation with certain store loadings.

Aircraft Configuration

The F/A-18 configuration details shown in Figure 3 include a low-sweep, trapezoidal wing planform with 400 ft^2 area, short coupled twin vertical tails, two GE F404 turbojets each with 16,100 pounds sea level static, maximum power thrust, and a large leading edge extension (LEX). Here, in the air-to-air configuration are shown two AIM-7F Sparrow missiles on the fuselage and two wing-tip-mounted AIM-9L Sidewinders. Additional missiles as well as a variety of air-to-surface weapons can be carried on the four wing pylons and fuselage centerline pylon.

GP33-0248-1

- REQUIREMENTS AND GUIDELINES
- EVOLUTION DURING FLIGHT TEST
- INNOVATIVE/UNIQUE FEATURES

FIGURE 1. F/A-18 FLYING QUALITIES DEVELOPMENT

FLYING QUALITIES

- IMPROVED NOSEWHEEL LIFTOFF
- INCREASED ROLL PERFORMANCE
- BETTER CROSSWIND LANDING CHARACTERISTICS
- REDUCED SENSITIVITY AND TIME DELAY
- REDUCED PITCH COUPLING DURING ROLLS
- REDUCED SIDESLIP IN CONFIGURATION PA
- IMPROVED SUPERSONIC COORDINATION
- INCREASED DEPARTURE RESISTANCE AND SPIN RECOVERY
- REDUCED SPEEDBRAKE TRANSIENTS
- AIR DATA AND ANGLE-OF-ATTACK LOGIC

STRUCTURES

- REDUCED EMPENNAGE LOADS
- DECREASED WING BENDING MOMENTS
- REDUCED WING PYLON LOADS
- ACTIVE OSCILLATION SUPPRESSION

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FIGURE 2. EVOLUTIONARY DEVELOPMENTS DURING FLIGHT TEST

Figure 4 illustrates the control surfaces with which we had to work:

- A large span, single slotted trailing edge flap capable of 45° deflection in the landing configuration but doubling as a differential flaperon with ±8° deflection in the up-and-away maneuvering configuration. In addition, these flaps are scheduled with angle of attack and Mach number for optimization of drag and stability.
- Single slotted, drooped ailerons for takeoff and landing, with ±25° deflection for up-and-away conditions.
- Leading edge flaps which are scheduled with angle of attack and Mach number to a maximum of 34° L.E. down. In addition, they are used differentially ±3° for roll control augmentation.
- Twin rudders which are used for the normal purposes of directional control and roll coordination but which are used also for enhancement of longitudinal stability and control in the takeoff and landing configurations
- And last, an all-moveable stabilator with differential deflection for roll.

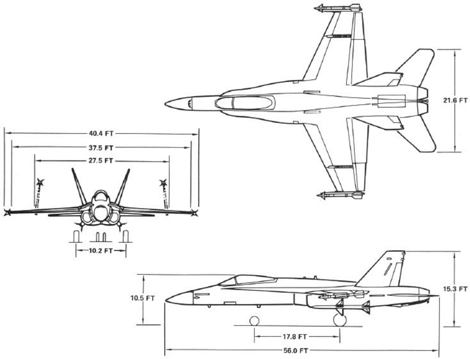


FIGURE 3. F/A-18 NAVY "HORNET" AIRCRAFT

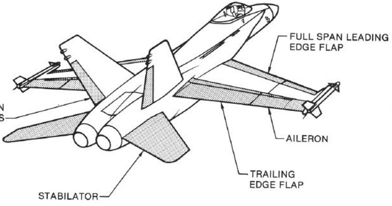
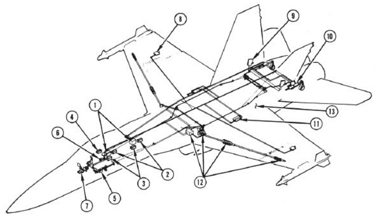


FIGURE 4. CONTROL SURFACES

In general, the various surfaces are scheduled as functions of angle of attack, Mach number, dynamic pressure, altitude, and aircraft configuration.

The various surfaces "talk to each other" -- that is, they are electronically interconnected in various ways, such as rolling-surface-to-rudder interconnect, rudder pedal-to-rolling surface interconnect, flaperon-to-differential tail interconnect, etc.

Of course, as shown by Figure 5, there are many items of interest inside the airplane. The primary flight control system is a fly-by-wire CAS with quadruply redundant channels. The wires, hydraulics, sensors, and cockpit controls are also shown. Not illustrated are the pick-ups for angle of attack and airspeed (vanes and probes on each side of the nose barrel) and a back-up mechanical system to the stabilator surfaces.



1. FLIGHT CONTROL COMPUTERS
2. RATE GYROS
3. ACCELEROMETERS
4. BACKUP AIR DATA SENSOR ASSEMBLY
5. PITCH STICK POSITION SENSOR/FEEL SPRING
6. ROLL STICK POSITION SENSOR/FEEL SPRING
7. RUDDER PEDAL FORCE SENSOR
8. AILERON ACTUATOR
9. RUDDER ACTUATOR
10. STABILATOR ACTUATOR
11. TRAILING EDGE FLAP ACTUATOR
12. LEADING EDGE FLAP ACTUATION SYSTEM
    - HYDRAULIC DRIVE UNIT
    - SERVOVALVE ASSEMBLY
    - ASYMMETRY SENSOR
13. THROTTLE CONTROL SERVO

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FIGURE 5. F/A-18 FLIGHT CONTROL SYSTEM

At the heart of the flight control system are the digital flight control computers with Programmable Read Only Memories (PROM's) with not only the sophisticated flight control laws, but also the required functions for Built-In-Test, fault detection and voting, autopilot functions, and data signal management. The computers have a memory of 40,960 words -- 9,235 of which are used for the flight control/autopilot laws.

Flying Qualities/Flight Controls Requirements and Guidelines

The flying qualities requirements and guidelines used for the initial design of the flight control system are outlined in Figure 6. Essentially, the 1969 version of the flying qualities specification and the 1955 flight controls specification, each with minor modifications, were used. Criteria which were used but not sufficiently applied were the tracking, PIO, and equivalent system criteria then in existence or development (more on this later). And we drew from our very successful F-15 high angle of attack experience for departure resistance criteria.

MIL-F-8785B (ASG) (1969) - MODIFIED FOR

- CARRIER SUITABILITY/PERFORMANCE
- ROLL PERFORMANCE REFINEMENTS
- SPECIFIC DEGRADED MODE CHARACTERISTICS
- ADDITIONAL HIGH ANGLE-OF-ATTACK REQUIREMENTS

MIL-F-18372 (AER) (1955)

- VULNERABILITY/SURVIVABILITY REQUIREMENTS
- AUTOMATIC CARRIER LANDING

- TRACKING CRITERION
- PILOT INDUCED OSCILLATION CRITERIA
- EQUIVALENT SYSTEM TIME DELAY CRITERIA
- DEPARTURE RESISTANCE CRITERIA
- PILOT OPINION (FLIGHT SIMULATION)

FIGURE 6. F/A-18 FLYING QUALITIES/FLIGHT CONTROLS REQUIREMENTS AND GUIDELINES

Nosewheel Liftoff

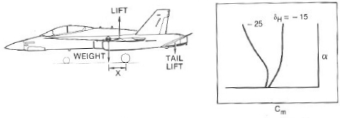
Figure 7 illustrates the first problem encountered in the flight test program which was experienced on the first flight: poor takeoff rotation characteristics -- high rotation speed and, as a result of a very brief time between nose gear liftoff and main gear liftoff (not much time for pilot reaction) a characteristic that was described as "explosive". The cause was two-fold. First, a main gear well aft of the center of gravity (to satisfy the unrealistic tip back requirement to be able to apply full brakes rolling backwards downhill on a 5° sloping deck without bumping the tail on the deck). Secondly, a horizontal tail that was virtually stalled at full airplane nose up deflection at takeoff attitudes. This problem was anticipated by us in the flying qualities business (as a matter of fact, our pre-first-flight simulations were virtually identical to actual flight experience) but it was decided to await flight verification before making any major changes.

FIRST FLIGHT CONFIGURATION PROBLEMS

- HIGH NOSEWHEEL LIFTOFF SPEED
- SHORT TIME BETWEEN NWLO AND MGLO
- ABRUPT ROTATION AFTER LIFTOFF
- CRITICAL PILOT ACTION REQUIRED

CAUSES

- UNREALISTIC TIP-BACK REQUIREMENTS
- MAINGEAR TOO FAR AFT
- HORIZONTAL STABILATOR STALLED



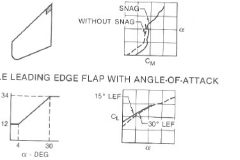
AT NWLO AERODYNAMIC MOMENTS = WEIGHT MOMENT = 36,000 • X

FIGURE 7. NOSEWHEEL LIFTOFF

This may have been, in the final analysis, fortunate. The problem forced us to become very innovative, as Figure 8 illustrates. Through the magic of aerodynamics and digital technology we were able after some months of testing to solve the nosewheel liftoff problems rather painlessly. First, we slightly increased the stabilator size by filling in a leading edge snag area which had originally been incorporated for improvements to the predicted flutter speed. Then, later on, after a great deal of missionary work to convince people that it would work, we incorporated (first on a trial basis) the capability of toeing the two rudders trailing edge inboard for a predicted sizeable increase in airplane nose up pitching moment. The unorthodox concept worked, and non-believers became believers. Still later, an additional improvement was realized through the incorporation of angle of attack scheduling of the L.E. flaps as opposed to the previous fixed 30° down position for takeoff and landing. As a result of all this, we realized a 25 to 35 kt improvement (18%) in nosewheel liftoff speed, depending on gross weight (more at the heavier weights).

Had it not been for the nosewheel liftoff problem and the partial solution by toeing in the rudders, we might have been longer in solving another problem. The control law development of the landing configuration presented a unique challenge. The basic configuration was statically unstable at approach angle of attack as shown in Figure 9. The precise task of angle of attack and speed control for this unstable platform was more than the control law concept and stabilator deflection rate could handle. The solution was to schedule the angle of toe-in/flare of the rudders with angle of attack -- providing about 7% $\bar{c}$ improvement in static margin, while retaining the airplane-nose-up moment at nosewheel liftoff conditions.

- INCREASE HORIZONTAL TAIL LIFT BY FILLING-IN SNAG AREA
- SCHEDULE LEADING EDGE FLAP WITH ANGLE-OF-ATTACK



- PROVIDE PILOT STICK STOP TO PREVENT STABILATOR SATURATION
  - SCHEDULE RUDDER TOE-IN/FLARE WITH ANGLE-OF-ATTACK

FIGURE 8. NOSEWHEEL LIFTOFF IMPROVEMENTS

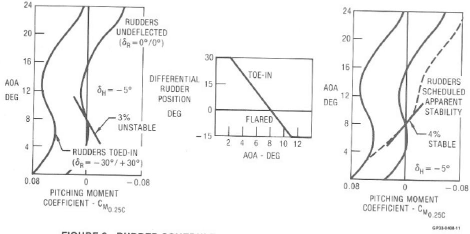


FIGURE 9. RUDDER SCHEDULE IMPROVES LONGITUDINAL STABILITY

Control Sensitivity for High Gain Tasks

It was mentioned previously that criteria addressing high gain piloting tasks should have been emphasized more in the initial development. The initial philosophy utilized for the early control laws (Figure 10) reflected the general industry's inexperience with digital control law development. Since the digital effects of fly-by-wire control systems were largely unknown, the closed-loop stability requirements were quite conservative with 10 db of gain and 60° phase margin considered the minimum acceptable. Only limited use was made of air data and angle of attack scheduling, partly because of concern with unknowns about signal selection, accuracy, and failure logic. The first control laws attempted to mask aerodynamic nonlinearities, but in so doing they also masked some of the natural aerodynamic characteristics so familiar to the pilot (such as damping variations with speed). Also, a roll integrator which attempted to obtain a constant roll rate with stick deflection was utilized (this created PIO tendencies when the CAS asked for and got more control deflection in regions where there just weren't enough aerodynamics left to change things). In addition, there were excessive time delays between pilot input and control surface motion for reasons which will be discussed later. The results of these characteristics are illustrated in this film clip of an in-flight refueling operation.

(Film clip shown here)

This problem is further discussed in Reference 1.

INITIAL DESIGN CRITERIA

- DAMPING RATIO 0.7
- STICK FORCE/g 3.5 LB/g
- CONSERVATIVE CLOSED LOOP STABILITY 10 dB GAIN AND 60° PHASE MARGIN
- MINIMUM USE OF AIR DATA/ANGLE-OF-ATTACK SCHEDULING
- ATTEMPT TO MASK AERODYNAMIC NONLINEARITIES
- CONSTANT ROLL RATE PER STICK DEFLECTION

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FIGURE 10. CONTROL SENSITIVITY FOR HIGH GAIN TASKS

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MIL-Spec Requirements Satisfied

Very briefly, here is a view of some of the classical flying qualities parameters of the first flight configuration. In Figure 11 it is shown that the requirements on short period frequency and damping were well satisfied. As a matter of fact, the initial configuration was described as having superb stability characteristics but extremely poor controllability. Figure 12 may illustrate why.

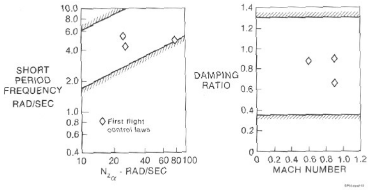


FIGURE 11. MIL-SPEC REQUIREMENTS SATISFIED
MIL-F-8785B CRITERIA
EQUIVALENT SYSTEM RESULTS

In Figure 12 is shown how the initial control laws stacked up with two recently developed criteria for evaluation of tracking characteristics. These correlations show the early control law characteristics to fall outside of the frequency criteria boundaries and in the Level 2 (mediocre) region of the Neal and Smith criteria.

So what was the reason for these bad characteristics? Time delays, as illustrated in Figure 13. Time delays were created by forward path filtering to preclude inadvertant pilot input commands through the stick force transducer (force transducers can be very sensitive), structural filters to preclude coupling of structural modes with the pilot (and resulting force command input), and low digital sampling rates. The last two items were very significant. The problems brought about by the use of integrators were mentioned previously. But in addition, most of the design team were used to thinking ANALOG, not DIGITAL. As a result, there were computational time delays resulting from the use of analog oriented calculation paths (e.g., transient free switches) greater than those resulting from digital techniques (gain faders). The whole subject is somewhat esoteric, but the message is: too much time was spent calculating things.

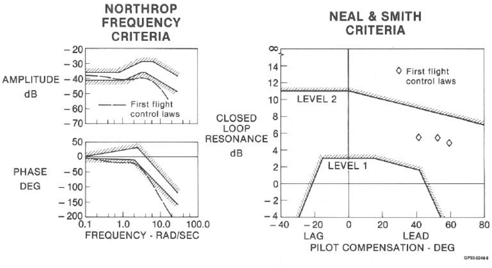


FIGURE 12. COMPARISON WITH TRACKING CRITERIA
INITIAL FLIGHT CONTROL LAWS

- FORWARD PATH FILTERING
- STRUCTURAL NOTCH FILTERS
- LOW SAMPLE RATES
- USE OF INTEGRATORS TO MASK BARE AIRFRAME CHARACTERISTICS
- USE OF ANALOG DESIGN TECHNIQUES FOR A DIGITAL SYSTEM

FIGURE 13. TIME DELAYS IN FIRST FLIGHT CONTROL LAWS

The solution to the problem is outlined in Figure 14. We adapted a completely new control law philosophy and assembled a team of experts in aerodynamics, guidance and control, and avionics to put this control law philosophy into effect. The new philosophy encompassed a change in architecture with the goal of computation time reduction, increased use of air data and angle of attack scheduling tailored to the bare airframe aerodynamic characteristics, and, instead of the stick force transducer, we made a hardware change to a position transducer which resulted in less noise, reduced filter requirements, as well as a better blend between what the pilot thought he was commanding versus what the CAS computer thought.

- **NEW CONTROL LAW ARCHITECTURE TO REDUCE COMPUTATION TIME**
- **INCREASED USE OF AIR DATA/ANGLE-OF-ATTACK SCHEDULING**
- **INCORPORATION OF POSITION (vs FORCE) SENSING CONTROL STICK**
  - REDUCED NOISE
  - FEWER STRUCTURAL FILTER REQUIREMENTS
  - BETTER MATCH OF ELECTRICAL AND MECHANICAL BREAKOUT
  - ELIMINATION OF PREFILTERS
  - REDUCE FORCE COUPLING

FIGURE 14. REDUCED SENSITIVITY FOR HIGH GAIN TASKS
PRODUCTION CONFIGURATION PHILOSOPHY

As a result of this effort, the time delay between input and response was cut roughly in half from the original 150 to 200 milliseconds to well within the requirements of the newer spec, MIL-F-8785C, Figure 15.

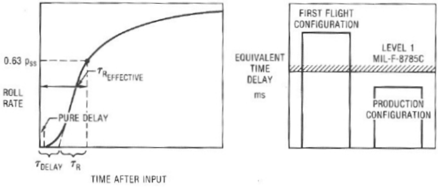


FIGURE 15. TIME DELAY

<u>Comparison of the New Control Laws With Specification Requirements</u>

Now, returning to the frequency and tracking criteria, Figure 16 shows that with the current production control laws, the criteria are satisfied. The same three points which had been rated as Level 2 are now within the Level 1 boundary. Recall the previous film clip showing the in-flight refueling. Here are the results with the production control laws.

(Film clip shown here)

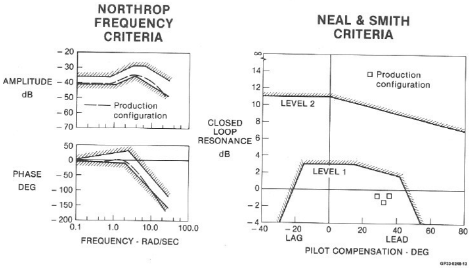


FIGURE 16. COMPARISON WITH TRACKING CRITERIA
PRODUCTION FLIGHT CONTROL LAWS

Roll Performance Requirements

The roll performance requirements were essentially as defined by MIL-F-8785B in terms of the bank angle change in one second. However, we had an additional requirement on roll rate -- 180 to 220°/sec throughout most of the flight envelope. These requirements are illustrated in Figure 17. As we expanded our testing envelope, it became apparent that we were not going to satisfy requirements in the low altitude high speed portions of the flight envelope. The problem was found to be caused primarily by an excessive amount of wing aeroelasticity resulting in an early aileron reversal speed and a large amount of aeroelastic roll damping.

The improvements in the roll rate characteristics as they were changed from the first flight configuration to the current production version are shown in Figure 18. Initially, only the ailerons and differential tails (with rudder for roll coordination) were used. An interim change to the control laws to modify the aileron Mach and dynamic pressure schedules combined with increased aileron span, and differential flaperons helped, but at the higher speeds, the roll response was still too low. Consequently, the leading edge flap hydraulic drive unit design was changed to enable the flaps to be driven differentially so that we could take advantage of the wing elastic properties by warping it as did a couple bicycle builders 80 years ago. The results were dramatic above about 0.9 Mach -- this for only ±3° deflection.

Figure 19 illustrates the potent effect of the differential L.E. flaps in terms of rolling moment coefficient. The aeroelastic effects are very dramatic.

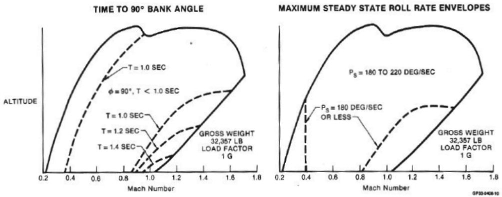
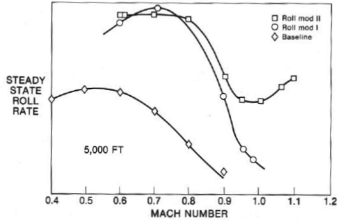


FIGURE 17. ROLL PERFORMANCE REQUIREMENTS



BASELINE - AILERONS/DIFFERENTIAL TAILS/RUDDERS

ROLL MOD I - ADDED DIFFERENTIAL FLAPERONS AND MODIFIED AILERON MACH/DYNAMIC PRESSURE SCHEDULES

ROLL MOD II - ADDED DIFFERENTIAL LEADING EDGE FLAPS FOR WING WARPING

FIGURE 18. ROLL PERFORMANCE IMPROVEMENTS

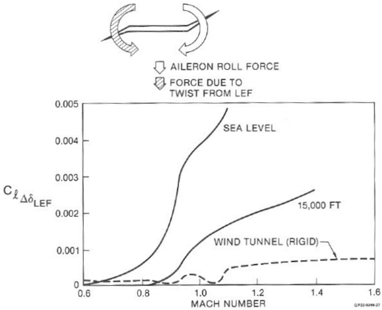


FIGURE 19. DIFFERENTIAL LEADING EDGE FLAPS ROLL POWER

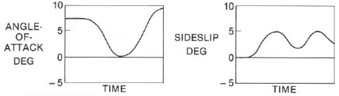
Pitch Coupling During Rolls

Because of soggy LAHS roll performance, the pilots became more aware of other roll associated problems, namely pitch coupling. Pitch coupling is nothing new -- it's always there to some degree due primarily to two factors: kinematic coupling for a body axis roll as angle of attack converts to sideslip and gyroscopic coupling through the inertia terms. Figure 20 shows an example of a 1 g roll with a 7 degree angle of attack change (slightly more than 1 g at this condition) and a not unreasonable level of adverse sideslip. This magnitude is not peculiar to the F-18, but with the flexibility afforded by the digital computer, we had the opportunity to compensate for the phenomenon by cross-coupling the pitch, roll, and yaw axes response to stabilator and rudder commands.

The results of this unique control law are illustrated in Figure 21. By allowing a small amount of proverse sideslip in this region and commanding stabilator and rudder through the inertia cross-coupling terms, the pitch coupling was very significantly reduced.

KINEMATIC COUPLING $\dot{\alpha} = -P \sin\beta$

INERTIA COUPLING $\dot{q} = \left(\frac{I_z - I_x}{I_y}\right) pr$



SOLUTION

- ALLOW SOME PROVERSE β DURING LOW ALTITUDE/ HIGH SPEED ROLLS
- INCORPORATE ACTIVE CONTROLS TO SEDATE THE INERTIA COUPLING

  $\Delta\delta_R = f(p \cdot q) \qquad \Delta\delta_H = f(p \cdot r)$

FIGURE 20. PITCH COUPLING DURING ROLLS

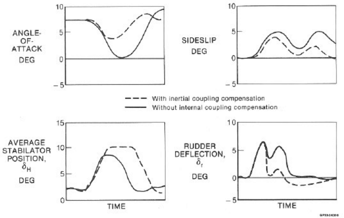


FIGURE 21. EFFECT OF INERTIAL COUPLING COMPENSATION
360° FULL STICK ROLL

Power Approach Configuration Steady Heading Sideslip

It was mentioned previously how the various surfaces "talk" to each other. An extreme example of this occurs in the takeoff and landing configurations. With the initial control laws, poor harmony existed between the aerodynamic characteristics and the available rudder surface commands. An excessive amount of sideslip resulted from only partial rudder pedal force during wings level steady sideslips. However, we could not reduce the pedal commanded authority without degrading the one-engine-out minimum control speed requirements. Thus, we had to invent another unique solution which interconnected the rudder pedals to the ailerons and differential tail. The interconnect shown in Figure 22 modifies the aileron and differential stabilator gains when rudder pedal inputs are applied. As the pedal input magnitude increases, proportionately less aileron and more differential stabilator is commanded by the lateral stick. The resulting aileron/stabilator ratio produces the required rolling moment while minimizing the aileron adverse yawing moment. Complicated, but it worked beautifully as shown in Figure 23, reducing the steady sideslip capabilities from who knows what (?) to a reasonable 11°.

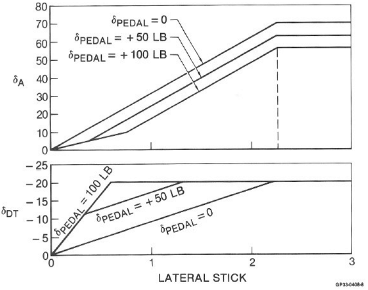


FIGURE 22. RUDDER PEDAL TO ROLLING SURFACE INTERCONNECT

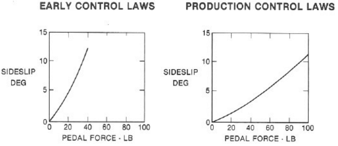


FIGURE 23. P.A. CONFIGURATION STEADY HEADING SIDESLIP

Basic Airframe Departure Resistance

The F/A-18 relies very much on the maneuvering flap schedule with angle of attack to provide departure resistance. Figure 24 illustrates the effect of the leading edge flap schedule on the static sideslip stability parameter, $C_{n_{\beta_{DYN}}}$. Note that with zero LE flap deflection, the aircraft would be susceptible to departure above about 21° angle of attack, even with no control input.

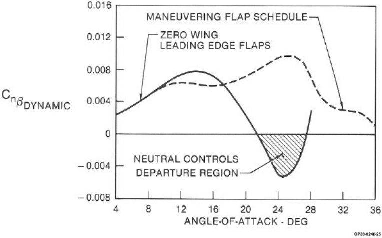


FIGURE 24. F/A-18 BASIC AIRFRAME DEPARTURE RESISTANCE

Figure 25 illustrates a parameter similar to $C_{n_{\beta_{DYN}}}$ but also including the yawing and rolling moments created by full lateral control. Here is an example where our wind tunnel data base did not agree with the characteristics of the actual full-scale aircraft. So the first flight control law configuration was actually departure susceptible above 17° angle of attack. As a result, changes to the relationships of aileron, differential tail, and rudder deflection resulting from full lateral stick input were made to arrive at a statically stable configuration with the production control laws.

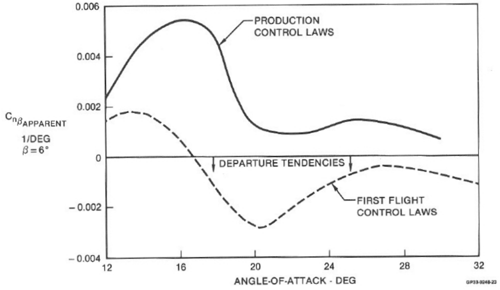


FIGURE 25. DEPARTURE RESISTANCE WITH FULL LATERAL STICK
MACH 0.8 @ 40,000 FT

Effect of Inertia Coupling Feedback on Departure Resistance

The effect of the inertia coupling feedback on roll characteristics was discussed earlier. Figure 26 shows the improvement that the concept provided for aggravated control input. The effect of full cross-control application (i.e., right stick, left rudder) on yaw rate illustrates a tremendous improvement in response -- from a spin-prone 55°/sec to a reasonable 30°/sec.

Spin Modes

As with any aircraft, however, spins can occur. In the case of the F/A-18, it is difficult to generate a spin except with large lateral weight asymmetries, certain control system failure modes, or asymmetric engine thrust. A film will show the spin characteristics. You'll see three spin modes -- a low yaw rate, mildly oscillatory spin at about 35°/sec yaw rate, a very oscillatory spin with various yaw rates, and a steady, flat spin with yaw rates in excess of 120°/sec as depicted in Figure 27. In all cases, however, application of recovery controls stops the spin in about 2 turns or less.

(Film clip shown here)

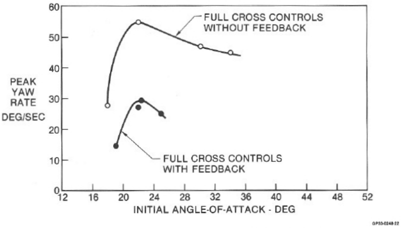


FIGURE 26. EFFECT OF INERTIA COUPLING FEEDBACK ON DEPARTURE RESISTANCE
FULL CROSS CONTROLS
40,000 FT MACH 0.6 FIGHTER ESCORT

Spin Recovery Mode Logic

Some innovative control law schemes were incorporated to provide for positive spin recovery control. We put a display in the cockpit that tells the pilot that he's in a spin and which way to move the stick to recover. Further, the control logic is such that if he should ignore the instructions and put the stick in the wrong direction, the surfaces won't respond enough to make the spin worse. See Figure 28. The next step is fully automatic recovery.

Active Oscillation Suppression

A late development in the flight control system was an active stores-oscillation suppression system. Late in the flutter test program, it was found that with certain combinations of wing stores/tip missile loadings, a limit cycle, low amplitude oscillation could be excited at low altitude, high speed conditions. The oscillation, at about 5.6 Hz, was driven by the asymmetric wing torsion mode. Although not a catastrophic oscillation as in flutter, it was disturbing, and it detracted from mission accomplishment. The solution: activation of an active oscillation suppression system driving the ailerons as a function of lateral acceleration in the cockpit when certain stores are installed, Figure 29.

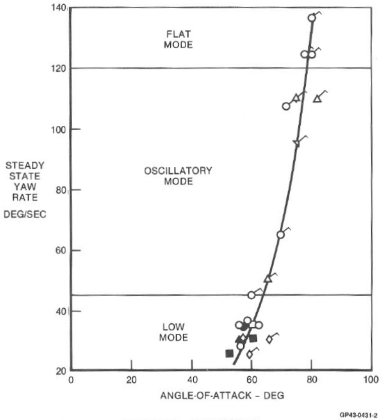


FIGURE 27. SPIN MODES

Summary

To summarize, as highlighted in Figure 30, our experience with the F/A-18 development shows that superior flying qualities characteristics can be achieved with today's digital fly-by-wire technology in an operational environment.

The flexibility and capabilities of digital computation enabled unique solutions to both flying quality and structural problems.

And last, experience has shown that with the proper redundancy and failure mode logic, back-up analog and mechanical control modes are not required.

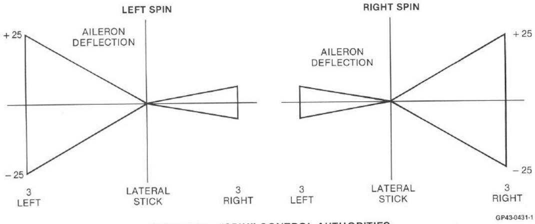


FIGURE 28. "SPIN" CONTROL AUTHORITIES
UPRIGHT SPIN
$\alpha \geq 30°$

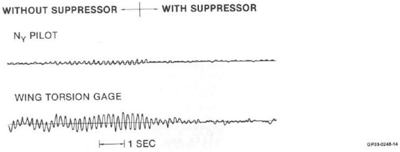


FIGURE 29. ACTIVE OSCILLATION SUPPRESSION

- SUPERIOR FLYING QUALITIES CAN BE ATTAINED WITH DIGITAL FLY-BY-WIRE TECHNOLOGY
- FLEXIBILITY/CAPABILITY OF DIGITAL COMPUTER ENABLED UNIQUE SOLUTIONS TO BOTH FLYING QUALITY AND STRUCTURAL PROBLEMS
- WITH PROPER REDUNDANCY, ANALOG AND MECHANICAL CONTROL MODES ARE NOT REQUIRED

FIGURE 30. SUMMARY

References

(1) MCAIR 82-026, Development of the F/A-18 Handling Qualities Using Digital Flight Control Technology, Lawrence A. Walker and William J. LaManna, presented at the 26th Annual Symposium, Society of Engineering Test Pilots, 22-25 September 1982.