AIAA

AD-A284 206

AIAA 94-2138
Flight Testing High Lateral Asymmetries on Highly Augmented Fighter/Attack Aircraft

G. D. Dungan and C. M. Clark
Strike Aircraft Test Directorate
Naval Air Warfare Center, Aircraft Division, NAS Patuxent River, MD

7th Biennial AIAA Flight Test Conference
June 20-23, 1994 / Colorado Springs, CO

FLIGHT TESTING LARGE LATERAL ASYMMETRIES ON HIGHLY AUGMENTED FIGHTER/ATTACK AIRCRAFT

G. D. Dungan† and C. M. Clark‡
Strike Aircraft Test Directorate
Naval Air Warfare Center - Aircraft Division
NAS Patuxent River, Maryland

Abstract

The F/A-18's flight control system (FCS) is highly augmented to tailor flying qualities, increase departure resistance, and help protect the airframe structure throughout the flight envelope. Since the F/A-18 flight control laws were designed primarily for the symmetrically loaded airplane, the effects of high lateral asymmetries represent a significant off-design condition where control margins may be substantially reduced. Adequately defining the flight envelope limits requires a flight test program that addresses the stability and control, structural, and mission suitability issues associated with these large lateral weight asymmetries. This paper will address the risk reduction techniques, test methodologies, and real-time analysis tools that have been used in the past or are planned to be used in an ongoing flight test program to expand the lateral asymmetry limits of the F/A-18.

Nomenclature

AOA or α	=	angle of attack, deg
I_{xx}, I_{yy}, I_{zz}	=	rolling, pitching, and yawing moments of inertia, slug-ft^2
I_{xy}, I_{xz}, I_{yz}	=	products of inertia, slug-ft^2
L, M, N	=	roll, pitch, and yaw moments, ft-lb
n_z	=	load factor, g
p, q, r	=	roll, pitch, and yaw rates, rad/sec
$\dot{p}$, $\dot{q}$, $\dot{r}$	=	roll, pitch, and yaw accelerations, rad/sec^2
W_{STO}	=	asymmetric store weight, lb
X_B, Y_B, Z_B	=	body reference axes
X_S, Y_S, Z_S	=	stability axes
Y_{STO}	=	store lateral distance from aircraft centerline

I. Background

Recent experience in Operation Desert Storm demonstrated the need for large, penetrating weapons against well defended, hardened targets. Many current or soon to be developed families of "smart" weapons are significantly larger and heavier than modern fighter/attack aircraft such as the F/A-18 aircraft were originally designed to carry. Normal employment of these weapons can result in very high lateral weight asymmetries while certain weapon delivery profiles may require significant maneuvering to establish proper release conditions to maximize the weapon's effectiveness. An example of the large lateral weight asymmetries that may be expected on the F/A-18 is the carriage of a store weighing 2,400 lb where the physical size of the store requires that it be carried on the outboard pylons. In this loading, the resulting lateral asymmetry exceeds the current flight manual limits.

The problem of asymmetric loadings can be illustrated by examination of the generalized equations of motion for roll, pitch, and yaw moments for a rigid body[1].

$$
\begin{aligned}
L &= +I_{xx}\dot{p} - \underline{I_{xy}}\dot{q} - I_{xz}\dot{r} - \underline{I_{yz}}(q^2 - r^2) - I_{xz}pq + \underline{I_{xy}}pr - (I_{yy} - I_{zz})qr \\
M &= -\underline{I_{xy}}\dot{p} + I_{yy}\dot{q} - \underline{I_{yz}}\dot{r} - I_{xz}(r^2 - p^2) - \underline{I_{xy}}qr + \underline{I_{yz}}pq + (I_{xx} - I_{zz})pr \\
N &= -I_{xz}\dot{p} - \underline{I_{yz}}\dot{q} + I_{zz}\dot{r} - \underline{I_{xy}}(p^2 - q^2) + I_{xz}qr - \underline{I_{yz}}pr - (I_{xx} - I_{yy})pq
\end{aligned}
\qquad (1)
$$

It is important to remember that these equations are defined at the center of gravity of the rigid body and the underlined terms in equation (1) are usually assumed to be zero as long as the body has a plane of symmetry. When asymmetric store loadings are carried, however, the center of gravity is offset from the aircraft centerline as shown in figure 1.

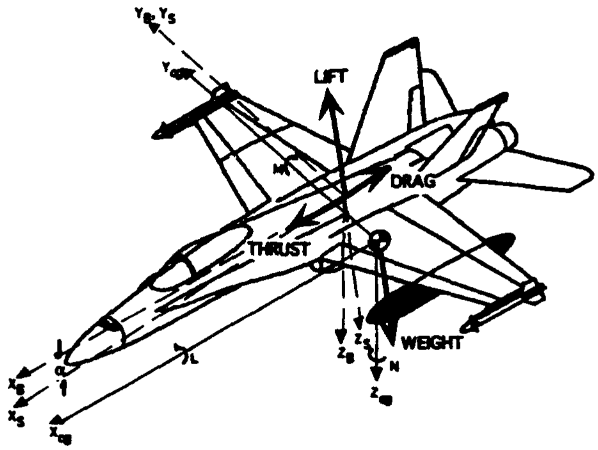


Figure 1
AXIS SYSTEM FOR AN AIRPLANE WITH AN ASYMMETRIC LOADING

From equation (1) and figure 1, we can see at least two of the flight mechanics issues associated with asymmetric loadings that should be considered: 1) cross-axis coupling resulting from the lateral shift in center of gravity position and the resulting non-zero products of inertia, I_{xy} and I_{yz}, and 2) the possible aerodynamic effects of the store asymmetry. With

---

† F/A-18 Flying Qualities Engineer, Flight Systems Department

‡ Flying Qualities and Flight Controls Technical Specialist, Flight Systems Department, member AIAA

small store asymmetries, the center of gravity shift and the associated products of inertia, I_{xy} and I_{yz}, are usually sufficiently small that the plane of symmetry assumption is still used for simplicity. However, these assumptions may be invalid with the addition of large store asymmetries.

Additionally, the presence of an asymmetry causes pilot inputs in one axis to perturbate all three axes, thus complicating the performance of any precision handling qualities task such as weapons delivery. For example, a pure longitudinal stick input would result in roll moments which would require lateral stick to counter. For aircraft with augmented flight controls like the F/A-18, the task may be further complicated by the requirement for additional compensation to counter the effects of FCS interconnects.

To further illustrate the significant problems associated with carrying heavy weapons, consider an airplane loaded symmetrically with two heavy stores. After dropping one store, the lateral center of gravity shifts instantaneously resulting in an aircraft with flying qualities different from the instant before. The significance of this sudden change in aircraft flight characteristics should be thoroughly evaluated and understood before clearing the fleet to deliver these large weapons.

The flying qualities of the F/A-18 with asymmetric loadings up to 26,000 ft-lb were initially evaluated during flight tests conducted by the aircraft manufacturer and by the Navy during full-scale development (FSD)[2]. Flying qualities with asymmetric store loadings were again tested in 1988 after incorporation of fences on the upper surface of the leading edge extension (LEX) which were designed to relocate the vortices shed from the LEX away from the vertical tails[3]. Although only tested at lower asymmetries (below 12,000 ft-lb), an asymmetric loading of the YBQM-145A Reconnaissance Drone was flight tested at Patuxent River in December of 1992[4]. Finally, as part of the GBU-24B/B Low Level Laser Guided Bomb certification program, asymmetric loadings of this store were conducted in the spring of 1993 by the authors[5]. Naturally, after each test program, the understanding of the flight characteristics with large lateral asymmetries increased significantly and the results of GBU-24B/B testing, in particular, indicated the potential to increase the lateral asymmetry limit above 26,000 ft-lb. Although the F/A-18 can carry a considerable mix of weapons, a higher lateral asymmetry limit would increase the store carriage options available to fleet squadrons. Also, expanding the limit would provide the F/A-18 with an established flight envelope such that the flight test burden would be reduced to affordable levels for future store certification programs.

The objectives of the current lateral asymmetry limit expansion program on the F/A-18 are: 1) determine if the control input restrictions for lateral asymmetries between 22,000 to 26,000 ft-lb can be relaxed, 2) determine if the 26,000 ft-lb asymmetry limit can be raised (with a goal of approximately 30,000 to 32,000 ft-lb), 3) determine if vertical tail strains and pylon structural loads remain within acceptable limits throughout the required flight envelope, and 4) recommend suitable flight manual limits and wording for the flight characteristics section. However, before attempting flight tests to satisfy these objectives, the test team required improved methods and procedures for reducing the associated flight test risks.

II. Unique Flight Test Considerations

USN/USMC F/A-18 HORNET

The F/A-18 was the first operational U.S. Navy airplane designed with a flight control system that used full authority control augmentation. The very nature of such augmentation systems presents the flight test team with a significant challenge in designing safe flight test programs. When planning flight tests of severe off-design configurations, this challenge is significantly amplified and must be approached with greater caution.

Understanding the Augmented Flight Control System

The F/A-18 flight control system is an irreversible, full authority control augmentation system (CAS) consisting of two digital flight control computers (FCCs), each having two channels running in parallel to provide four channel redundancy for each control axis.[6] The control augmentation system uses gain scheduling, cross-axis interconnects (e.g., rolling surface to rudder) and closed-loop control of aircraft response to enhance flying qualities, protect the aircraft from overstress, actively control structural mode oscillations and augment basic airframe stability. The F/A-18 uses five left/right pairs of hydraulically actuated flight control surfaces: stabilators, rudders, ailerons, leading edge flaps, and trailing edge flaps. Additionally, a hydraulically actuated speed brake is located on the upper-aft center section of the fuselage between the vertical tails.

With the landing gear up, longitudinal control is provided by symmetric deflection of the stabilators, and leading edge and trailing edge flaps. Lateral-directional control is provided through ailerons, differential deflection of the stabilators, and differential deflection of leading and trailing edge flaps, as well as rudder deflections through cross axis interconnects.

In the landing configuration longitudinal control is similar to that for the gear-up configuration with the addition of symmetric aileron droop and a rudder toe-in/flare-out feature. Lateral-directional control in the landing configuration is also similar to the gear-up configuration except that differential leading and trailing edge flaps are not used. The maximum surface deflections are shown in Table I; however, the control system mode logic and gain schedules can limit the surface deflections to less than maximum depending on flight condition.

Table I

Control Surface	Maximum Surface Deflections
Stabilator	24 deg TEU to 10.5 deg TED
Aileron	25 deg TEU to 45 deg TED
Rudder	30 deg TEL to 30 deg TER
Trailing Edge Flap	8 deg TEU to 45 deg TED
Leading Edge Flap	3 deg LEU to 34 deg LED

Note: TEU = Trailing Edge Up TED = Trailing Edge Down
TEL = Trailing Edge Left TER = Trailing Edge Right
LEU = Leading Edge Up LED = Leading Edge Down

Control Authority Limiting: The cross-axis coupling resulting from asymmetric loadings must be controlled by aerodynamic restoring moments. Since flight control systems are usually designed with the symmetric airplane assumption, there is a limit to the amount of asymmetry that can be accommodated. Determining the maximum control surface deflection schedules can provide significant insight into the available control power.

The flight control computers in the F/A-18 schedule commanded surface deflections as functions of Mach number (M), static pressure (Ps), impact pressure (qc), angle of attack (AOA), and normal acceleration (n_Z), as well as control system mode logic discretes (e.g., gear and flap position, spin recovery mode enabled, etc.). In addition to the schedule limited control surface deflections, a roll rate limiter is activated in the feedback and command paths when wing stores are present to keep the wing pylon loads within acceptable limits. This is accomplished by increasing the roll rate feedback gain and modifiying the control stick command gain in order to limit the maximum roll rate to approximately 150 deg/sec.

To better understand the implications of these scheduled command authority limits, test planners required information on the maximum control authority available across the flight envelope. Using a software model of the lateral control laws, the maximum lateral control surface deflections for a full lateral stick input were obtained as a function of altitude, Mach number, and load factor. The output for 20,000 ft is shown in figure 2.

The aileron command authority is scheduled with AOA and air data to improve coordination at high AOA and low dynamic pressure, as well as, minimize the effects of hinge moment limiting, wing flexibility, and roll reversal at high dynamic pressure. Differential stabilator command authority is limited by pitch command and load factor, in addition to AOA and air data schedules, to place priority on pitch commands, improve coordination, minimize the effects of hinge moments, and alleviate bending moments during accelerated flight. Differential trailing edge flaps are scheduled with air data and AOA to prevent hinge moment limiting or excessive vertical tail loads. Differential leading edge flaps are scheduled with air data and load factor to counter the effects of wing flexibility and provide improved roll rate in the low to mid altitude transonic region. In the directional axis, a Rolling Surface to Rudder Interconnect (RSRI) provides aileron and differential stabilator commands to the rudders to improve roll coordination. These commands are also scheduled with air data and AOA.

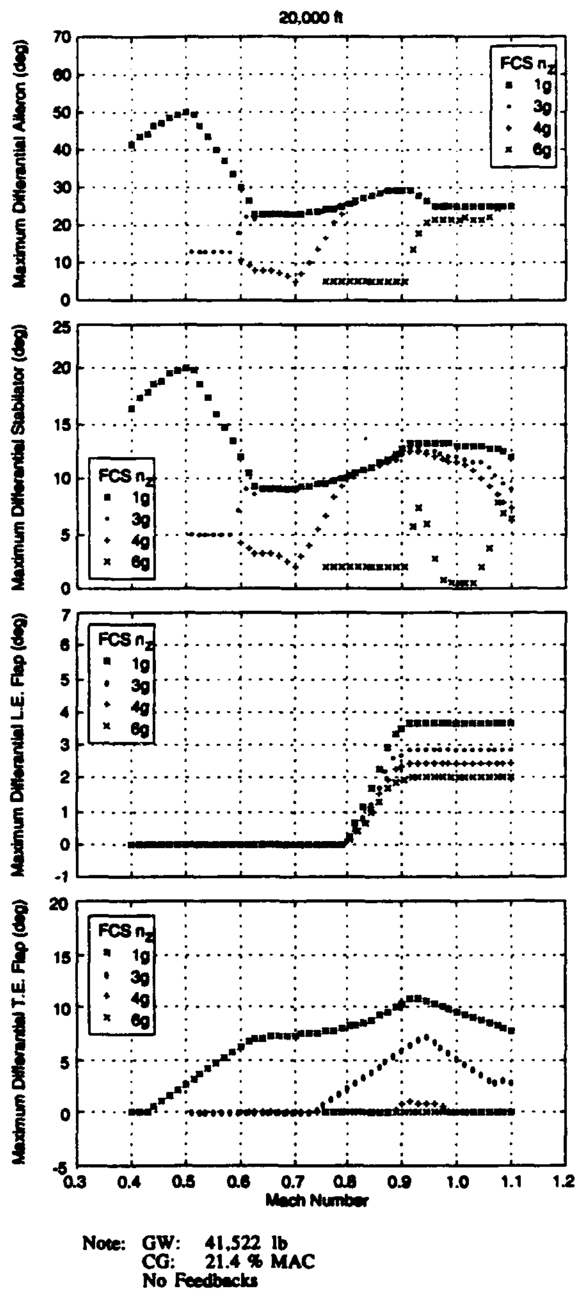


Figure 2
MAXIMUM LATERAL CONTROL
SURFACE DEFLECTION MAPS

Control Power Assessment: Once the maximum authority limits were defined accross the flight envelope, the associated rolling moment capability was estimated using the aerodynamic database for a symmetrically loaded airplane. The effects of rolling moment due to rudder deflection, sideslip, and roll damping were neglected.

The rationale behind this approach was based on experience gained from previous simulation and flight tests with high lateral asymmetries. These tests highlighted the impact of weight asymmetry on the intended design goal of the RSRI: coordination of rolling maneuvers. However, during accelerated flight, the RSRI also responded to the rolling surface deflections required to counter the moment due to the weight asymmetry and maintain bank angle. These rudder deflections introduced significant levels of sideslip (>10 degrees) and required the pilot to use rudder pedal inputs to counter the RSRI and maintain coordinated flight. The result was near-zero rudder deflection, sideslip, and roll rate. The influence of the RSRI in test maneuver development is discussed later.

The rolling moment generated by a store carried at a distance, Y_{STO}, from the aircraft centerline is:

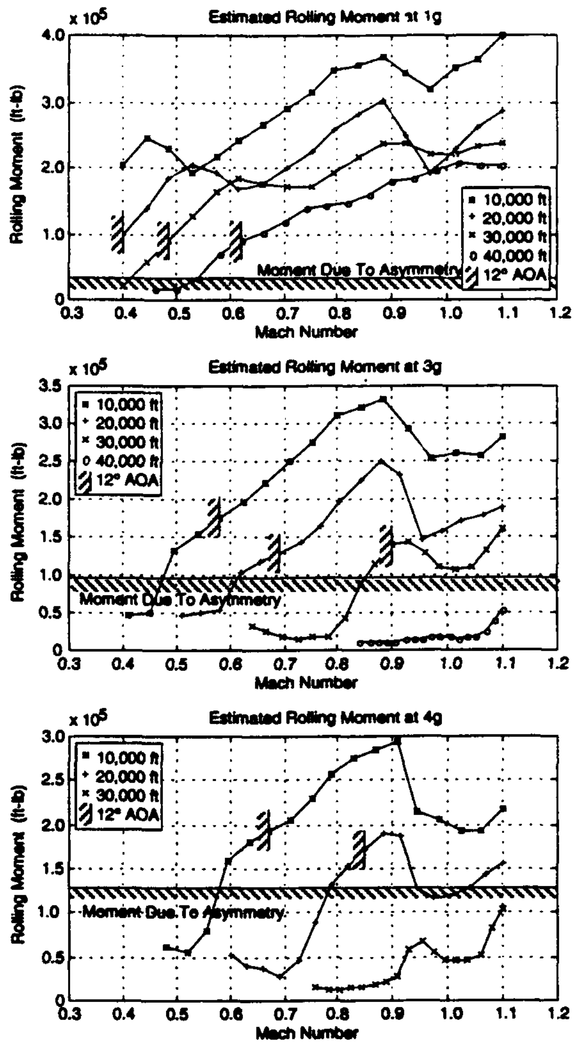
$$L_{STO} = n_z \cdot W_{STO} \cdot Y_{STO} \qquad (2)$$

To maintain a given bank angle, this rolling moment must be countered with aerodynamic moments generated by deflecting the flight control surfaces. Figure 3 presents an estimate of the total rolling moment available as a function of Mach number for 1, 3, and 4g load factors for an interdiction loading at 41,522 lb gross weight and 21.4% MAC center of gravity. The hashed horizontal line represents the result of equation (2) for a 32,000 ft-lb store asymmetry at each load factor. This data provides trend information regarding the effects of FCS authority limiting on lateral control power across the maneuvering envelope as well as the roll control margins within the existing flight manual AOA limits.

It must be emphasized that the rolling moment data is presented for a static case (i.e., zero roll rate) and is not equivalent to the rolling moment available from a step lateral input. In the case of a step lateral input the effects of control surface rate limiting combined with roll rate feedback would yield a different rolling moment and roll acceleration. It is also important to realize that the curves shown in figure 3 are valid only for the particular gross weight and center of gravity shown. A different weight would result in a different AOA and/or n_z, both of which are inputs to the roll control surface limit schedules. This highlights the need for real-time analysis tools to monitor available roll control power as weight varies considerably during a flight. These tools will be discussed later.

The Departure Risk

The most obvious hazard to flight with large lateral weight asymmetries is encountering a departure from controlled flight. In the F/A-18, as in many other aircraft with augmented flight controls, departure boundaries are not easily determined and one must question whether the aircraft will be recoverable or even survive the departure without catastrophic structural failure. The symmetrically loaded F/A-18 has generally shown relatively good recovery characteristics after a departure as long as recovery controls are correctly applied and sufficient altitude remains to effect recovery. During full-scale development in the early 1980's, testing with up to 26,000 ft-lb lateral asymmetry indicated adequate departure resistance. However the results of spin testing with lateral asymmetries up to 18,000 ft-lb indicated that there may be a recovery problem if a spin were to develop (see reference 2).



Note: GW: 41,522 lb
CG: 21.4 % MAC
No Feedbacks

Figure 3
ESTIMATED ROLLING MOMENT WITH MAXIMUM CONTROL SURFACE DEFLECTION

Figure 4 presents results from early F/A-18 FSD spin testing which shows the number of turns to recover from a spin as a function of lateral asymmetry. Also shown are the simulation predictions for the number of turns to recover from spins at 26,000 ft-lb[7] and 32,000 ft-lb asymmetries.

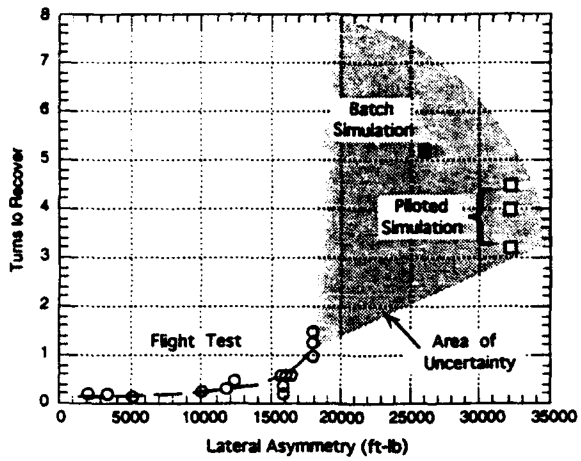


Figure 4
TURNS TO RECOVER FROM A SPIN

As lateral weight asymmetry was increased, the airplane exhibited a stronger tendency to enter a spin with the heavy wing to the outside of the rotation. At 18,000 ft-lb lateral asymmetry, the number of turns to recover increased at such a non-linear rate that the test team elected not to continue attempting spins with any higher lateral asymmetry. Also, spins tended to develop more rapidly at higher lateral asymmetries. The average altitude loss per turn decreased from 4,000 ft/turn at 2,000 ft-lb lateral asymmetry to 1,000 ft/turn at 18,000 ft-lb lateral asymmetry due to a higher spin rate, but the altitude required to effect recovery increased from just under 1,000 ft to over 3,500 ft. Although spins performed in both batch mode and piloted simulation tests indicated that recovery with higher lateral asymmetries may be possible, there is obviously some level of uncertainty in this extrapolation of predicted aircraft response. The flight manual requires the pilot to eject if out of control below 10,000 ft above ground level (AGL). Clearly, any out-of-control situation and the resulting potential for entering a spin must be avoided, especially at low altitude where a timely decision to eject is critical.

Structural Loads

Large lateral weight asymmetries can impose additional structural loads over what would normally be experienced with symmetric loadings. For example, high lateral asymmetries may impose loads on landing gear that were not anticipated when the aircraft was designed. In the case of the F/A-18, the higher loads on the landing gear limit the pilot to performing flared landings only. Additionally, there are at least two other structural concerns that must be thoroughly understood.

First, the asymmetric drag requires increased rudder displacements to maintain minimum sideslip which imparts higher than normal loads on the vertical tails. In a recent flight test program, the vertical tail loads approached the flight test limit at the high dynamic pressure conditions that would be experienced during typical weapons delivery profiles. Fortunately, the production aircraft is equipped to monitor various structural loads parameters through strain gauges installed during manufacture. This capability negated the requirement for an extended instrumentation lay-up period and allowed engineers to monitor and record vertical tail loads throughout each flight.

The second concern involves structural loads applied to the outboard pylon resulting from higher roll rates that may be experienced when rolling toward the heavy wing. As mentioned previously, the FCS incorporates a roll rate limiting feature, that is activated when the presence of wing stores is detected by the SMS. With high lateral weight asymmetries, rolls into the heavy wing can result in roll rates in excess of the 150 deg/sec design rate limit. If the pilot then applies a full opposite stick command to stop the roll, the structural loads on the pylon can be significantly higher than normal, especially at elevated load factors. During previous testing with a lateral weight asymmetry of approximately 10,000 ft-lb, the structural limits for the pylon were approached during loaded rolling maneuvers countered with abrupt stick checks. Therefore, the pylon loads should be monitored real-time to ensure loads remain within acceptable levels throughout the flight envelope. The good fortune of having production strain gauges available, as in the case of the vertical tails, is not enjoyed with wing pylons. However, several pylons specially instrumented for loads measurements are available and one must be mounted on the station which will be loaded with the heavy store.

III. Test Plan Development

Use of Piloted Simulation

Fixed-base piloted simulation was used extensively to support the flight test plan development, familiarize test pilots and engineers with the asymmetric loading flight and out of control recovery characteristics, assess knock-it-off criteria and departure susceptibility, estimate maneuvering requirements to perform typical mission tasks, and for test mission rehearsal to train the pilot/engineer team. All of these uses require an acceptable level of confidence in the simulation models used.

Simulation Model: Throughout the history of the F/A-18, little emphasis was placed on obtaining wind tunnel data for the aerodynamic effects of asymmetric store loadings. However, wind tunnel data for the asymmetric carriage of the BQM-145A was available from tests conducted by McDonnell Douglas Aerospace (MDA) using a 6% F/A-18 model.[8] Figure 5 shows the effects of three store loadings on rolling moment, yawing moment, and sideforce coefficients at 0.6 Mach and 10 degrees AOA. This data was generated with the flaps on schedule for a weight and CG position corresponding to an asymmetry of approximately

25,000 ft-lb; hence, the rolling moment data exhibit a large offset at zero sideslip due to the lateral CG offset. Figure 5 illustrates that the aerodynamic effects of the store, at least for this configuration, are small compared to the total coefficient levels.

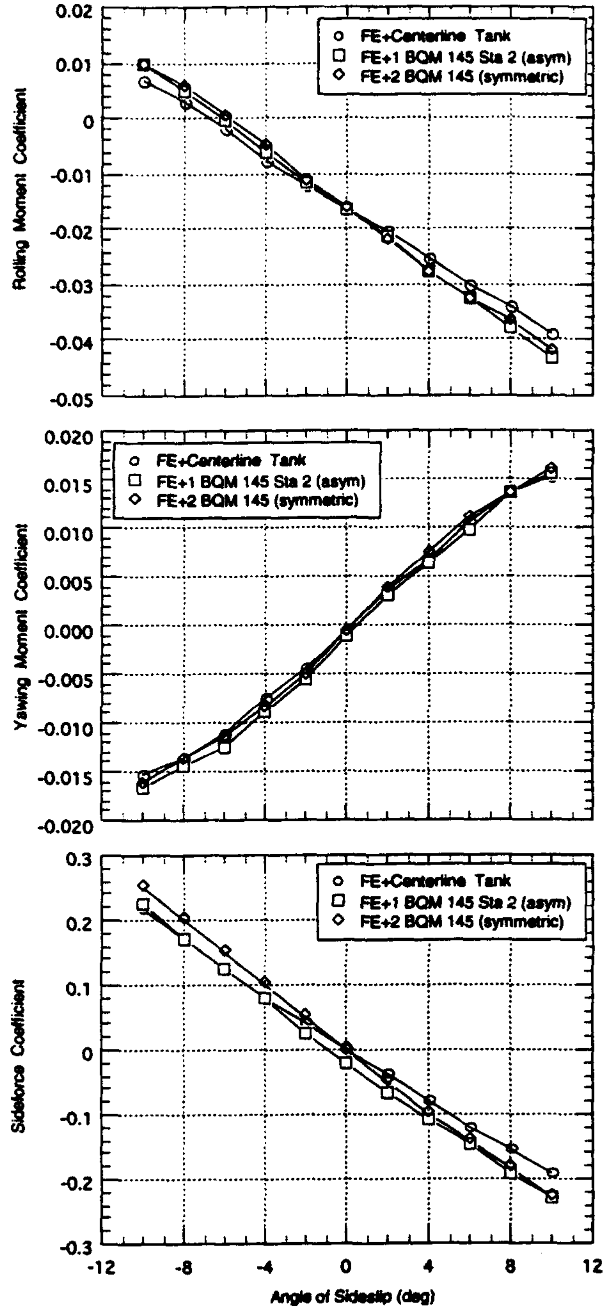


Figure 5
EFFECTS OF STORE AERODYNAMICS ON AIRCRAFT AERODYNAMIC MOMENTS

Flight tests of the YBQM-145A on the F/A-18 at 11,000 ft-lb (see reference 4) agreed with these results and indicated that if only trend information is desired from simulation and no wind tunnel data exists, the flying qualities with asymmetric store carriage could be reasonably estimated by only accounting for the lateral center of gravity shift and inertial effects of the asymmetry.

This approximation was also subjected to a qualitative assessment across the envelope with data available from the flight test program to certify the GBU-24B/B, a 2380 lb store, for carriage on the F/A-18 out to an asymmetry of 26,000 ft-lbs. Pilot qualitative comments indicated that for low AOA's the flying qualities of the simulator were representative up to 26,000 ft-lb, even though the absence of motion cues contributed to difficulties maintaining coordinated flight during mild maneuvering. This tended to support the opinion that a simulation which only modeled the inertial effects could be used reliably as a safety of flight and maneuver design tool. Care must taken, however, to not grossly generalize the effects of these two examples to all other stores and, whenever possible, stability and control wind tunnel tests should include an evaluation of the asymmetric store effects.

Test Maneuver Development: Once the test team was convinced that the simulation could be used, candidate test maneuvers including bank-to-bank rolls, wind-up turns (WUTs), and high angle dive-bombing profiles were performed to evaluate their suitability for evaluating the effects of lateral asymmetry on flying qualities.

During WUTs without coordinating rudder pedal inputs at 26,000 ft-lb lateral asymmetry (right wing heavy), significant sideslip angles (>10 deg, nose left) were observed which were accompanied by rudder deflections that tended to increase the sideslip. This prompted the test engineers to monitor each FCC command path individually to attempt to determine the source of the "unexpected" rudder deflections. The RSRI was designed to schedule rudder deflection when rolling surfaces are deflected in order to coordinate rolling maneuvers. However, during accelerated flight with high lateral asymmetries, rolling surfaces were deflected to maintain a constant bank angle instead of commanding a roll rate. All WUTs, regardless of direction, required left lateral stick as load factor increased to counter the natural tendency to roll toward the heavy (right) wing. During WUTs without rudder pedal inputs, rudder deflections correlated directly to the RSRI command which in turn, was responding to the deflected rolling surfaces commanded by left lateral stick. Regardless of RSRI commands, the pilot was able to override the RSRI with rudder pedal inputs and maintain near zero sideslip. The large lateral stick requirements observed during WUTs indicated a need for methods to define acceptable test limits to provide adequate lateral control margin. In previous test programs, a 2/3 lateral stick limit was imposed for all accelerated flight maneuvers. However, in a test program to expand the lateral weight asymmetry limits, 75% of available roll control surface authority was proposed as an additional criteria to ensure adequate lateral control margin.

The simulation was also used to determine lateral stick requirements while performing representative mission tasks such as high angle dive-bombing profiles. Various stick displacements and input rates were investigated out to the target asymmetry limit of 32,000 ft-lb. These tests indicated that smaller lateral stick displacements (≤1/2 deflection) kept the commanded roll rate and corresponding yaw rate and sideslip excursions to a minimum, allowing the pilot to more easily coordinate the maneuver. Roll rates with approximately 1/2 lateral stick displacements were slightly lower than desired but still sufficient to perform mission tasks.

Departure resistance with asymmetric store loadings between 22,000 to 32,000 ft-lb was also assessed. To better understand the problem and reduce the risk of encountering an actual departure, the simulator was intentionally departed to familiarize the pilots and test engineers with departure boundaries and thresholds, out-of-control flight characteristics, and methods of recovery. Departures at 30,000 ft were highly oscillatory and random in nature but the simulation was recoverable prior to reaching 10,000 ft using the flight manual recovery procedures. The results of this simulation testing increased the test team's confidence that maneuvering with large asymmetries up to 32,000 ft-lb could be performed safely during flight test.

Flight Test Build-up

In defining the build-up steps when testing high lateral asymmetries, particular attention should be focused on critical mission tasks such as, airborne refueling, formation flight, weapons employment, and landings. Additionally, high gain closed-loop tasks tailored for specific aircraft requirements should be used to expose any tendency for pilot induced oscillations (PIO) or other potential problem areas that could otherwise go undetected. The importance of the landing task can not be over emphasized. Even if there is not an operational requirement for the fleet to land with high lateral asymmetries, the luxury of expending ordnance before every landing may present unacceptable logistics or costs to the test program.

To establish the required lateral asymmetries, one could obtain several different stores of various weights and load them in such a manner that allows a safe build-up. This method, however, would impose a significant logistics burden and introduce the undesirable effects of varying asymmetric drag characteristics. It would be preferable to isolate the inertia and aerodynamic effects individually to more easily determine the significance of each. The solution arrived at for this program involved maintaining a constant aerodynamic configuration and using fuel in an external fuel tank to control lateral asymmetry. An example of the test loading is shown in figure 6.

In the case of the F/A-18, there is no capability to transfer fuel from only one external wing tank; the pilot can only control transfer of fuel from both tanks at the same time. To overcome this limitation in the production fuel system, the external wing tank adjacent to the store loaded on the right wing was isolated from the aircraft's fuel system by blocking off the pressure and fuel feed lines at the pylon interface. The isolated tank can then be fueled with the exact amount required to establish each test lateral asymmetry. Transfer of fuel from the other external wing tank was retained to allow the pilot to takeoff with a lateral asymmetry that will remain well within the normal flight manual limits until reaching a safe test altitude.

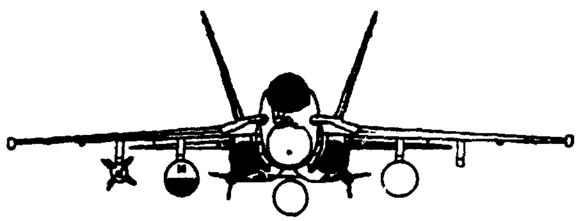


Figure 6
F/A-18 ASYMMETRIC TEST LOADING

After completing tests with a constant aerodynamic configuration and varying lateral asymmetry, then tests will be repeated with a known high drag store to evaluate the asymmetric drag effects. Of course, the lateral weight asymmetry should be adjusted to equal that of the previous tests.

IV. Real-time Tools for Flight Test

Additional tools were required to supplement the monitoring of traditional critical parameters used for avoiding departures or exceeding structural load limits. These new tools, desribed below, reley on the availability of high fidelity simulations and computational power.

Predicting the maximum available control power can be very difficult in aircraft with highly augmented flight controls. In aircraft with a full authority CAS, lateral stick deflection alone may not be an accurate indication of control margin. For instance, it was shown earlier that the rolling moment capability changes significantly over the flight envelope due, in part, to the tailoring of flight control surface deflections provided by the control augmentation system. All control surface commands and surface positions are available on the MIL-STD-1553 multiplex databus such that they can be telemetered in real-time to the ground station. Although the scheduled surface authority limits are not available on the databus, all flight control computer sensor inputs are and therefore, an alternate method was devised to calculate the authority limit schedules at any given flight condition.

Control Authority Available

Real-time indication of roll control authority available could provide the test team a rudimentary indication of lateral control margin. This indication could be used to supplement the 2/3 lateral stick test limit used in past programs, primarily during accelerated flight maneuvers such as wind-up turns or steady pulls where the pilot is controlling bank angle. The required sensor inputs provided via telemetry to an equivalent flight control computer in the ground station would allow the maximum control surface deflections available to be monitored real-time. Alternatively, a software model of the flight control laws, similar to that used to produce figure 2, can be driven with the telemetered data. Of course, steps must be taken to ensure the validity of such an implementation.

With control authority data now available, it may be displayed to the test team in any manner that would provide the easiest interpretation in a real-time situation. The pertinent parameter is the difference between the amount of control surface deflection commanded by the pilot and the maximum available from the flight control system. However, these parameters change significantly throughout the flight envelope, so a ratio of control surface commanded to maximum available would be more useful. To illustrate, figure 7 shows one potential format for such a display.

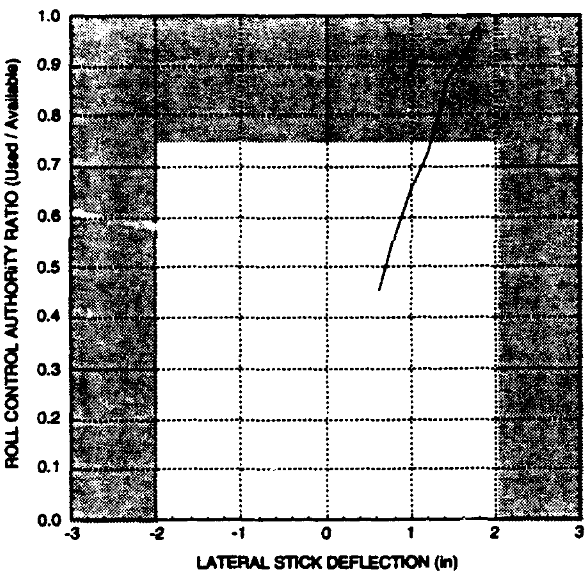


Figure 7
PROPOSED REAL-TIME DISPLAY FOR LATERAL CONTROL MARGIN BASED ON MAXIMUM POSSIBLE CONTROL SURFACE DEFLECTIONS

Presenting the data in this way allows the test team to set some limits on just how much of this margin can be used and still provide an acceptable safety margin. For example, in figure 7 above, the gray area represents the regions where the criteria of 0.75 has been set for Roll Control Authority Ratio along with the 2/3 lateral stick deflection criteria used in past F/A-18 programs. The "+" would represent the current state while the line (or "tail") would represent the last several seconds of data to allow the test team to observe data trends. It should be noted that the hypothetical case shown above illustrates a hypothetical condition where the 2/3 lateral stick criteria does not ensure adequate margin.

Estimated Rolling Moment Available

Although roll control authority would provide a useful indication of control margin, a real-time display was desired to provide a better indication of rolling moment capability. The simulation aerodynamic database may be used similarly to the control model above to estimate the rolling moment as a function of the telemetered flight control surface positions and flight condition. The display of this information would be very similar to figure 5 except the ratio of commanded to available rolling moment would be plotted on the vertical axis.

Another real-time display that could prove useful would be one that compares equation (2) with estimated rolling moment available as a function of flight condition similar to the format of the plots shown in figure 3. An example of this display is illustrated in figure 8.

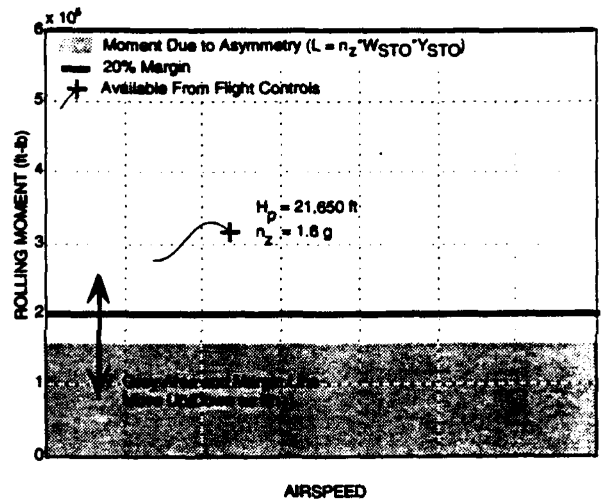


Figure 8
PROPOSED REAL-TIME DISPLAY FOR LATERAL CONTROL MARGIN BASED ON ESTIMATED ROLLING MOMENT AVAILABLE AND REQUIRED

The gray area and margin line would move up and down as a function of load factor and the "+" represents the calculated rolling moment available from the simulation datalink for the current flight condition. The tail presents a time history of the "+" position for last few seconds. The "margin line" would be defined by the test team as some percentage of the moment resulting from the asymmetry.

An effort is currently underway to link telemetered aircraft sensor and control inputs to the simulation database to perform a real-time calculation of the predicted rolling moment available. A proof of concept test of a two-way datalink between the Manned Flight Simulator and the ground station has been performed and after further development and validation, the utility of the datalink will be evaluated during the F/A-18 Lateral Asymmetry Limit Expansion flight test program.

Summary

This paper discusses the problems associated with the carriage of large lateral weight asymmetries on aircraft with highly augmented flight control systems. In preparation for a flight test program to expand the F/A-18 flight manual limit, the effects of these high asymmetries on the full authority control augmentation system were analyzed. Unique flight test considerations and the development of a test plan for evaluating these effects were also discussed. Finally, special tools for real-time analysis and data presentation to the flight test team in the ground station were proposed.

Since flight control systems are usually designed with a symmetric airplane in mind, large asymmetries represent a significant "off-design" situation that may have unexpected effects on aircraft stability and control. Therefore, the peculiarities of the aircraft flight control system in question must be thoroughly researched. For the specific program that motivated this study, the analysis shows that the primary effect of a high lateral asymmetry is the shift of the center of gravity away from the aircraft centerline whereas the non-zero product of inertia terms and store aerodynamic effects are of secondary importance. However, with different circumstances, the effects of store aerodynamics on the overall aircraft may be significant. Therefore, aerodynamic data should be collected, in a wind tunnel for instance, and accounted for whenever possible.

References

1 Etkin, B, *Dynamics of Atmospheric Flight*, John Wiley and Sons, Inc, New York, 1972

2 Behel, I. M., MAJ, USMC, and Kapinos, S. A., et al., *Limited Flight Systems Navy Technical Evaluation of the F/TF/A-18A Airplane*, Naval Air Test Center Report SA-126R-82, Patuxent River, MD, 17 March 1983

3 Magnusson, F., and Wilcutt, T., MAJ, USMC, *Handling Qualities and Performance Evaluation of the F/A-18A/B With Leading Edge Extension Fenses Installed*, Naval Air Test Center Report SA97R-88, Patuxent River, MD, 2 November 1990

4 Trost, C., Dungan, G. D., and Nielsen, W., LT, USN, *YBQM-145A Limited Carrier Suitability Evaluation*, Naval Air Warfare Center-Aircraft Division Report SA26R-93, Patuxent River, MD, 3 March 1993

5 Dungan, G. D., Clark, C., and Sternberg, C. A., LT, USN, *Flying Qualities Evalaution of the F/A-18 Airplane with High Asymmetric Loadings of the GBU-24B/B Low Level Laser Guided Bomb*, Naval Air Warfare Center-Aircraft Division Report SA-52R-93, Patuxent River, MD, 13 May 1993

6 Krone, S. K., Arnold, L. D., and Hess, R. K., *F/A-18A/B/C/D Flight Control System Design Report, Volume I*, MDC 7813, Vol. I (Rev C), McDonnell Douglas Aerospace Company, St. Louis, 23 December 1992

7 Ralston, J., Birhle Applied Research, Memorandum on F/A-18 Spin Recovery with a 26,000 ft-lb Asymmetry, February 1993

8 Haudrich, J. P. and McAtee, T. M., *F/A-18/BQM-145A Store Separation, Carriage Loads, and Stability Wind Tunnel Test Report, Volume II*, MDC 91B0375, McDonnell Douglas Aerospace, St Louis, MO, 1 November 1991.