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Operational Lessons Learned from the F/A-18E/F Total Flight Control Systems Integration Process

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ABSTRACT

The F/A-18E/F Super Hornet is a growth version of the F/A-18 A through D model "heritage" Hornet, first fielded in 1983. Some of the primary design goals for the Super Hornet included increasing the range, providing greater weapon loading flexibility, increasing carrier landing bring back weight, and improving survivability. Improving the survivability was addressed in various ways, including reductions in radar cross section, expanded self-protection systems, and enhanced maneuverability. The heritage Hornet was the first tactical aircraft in the world to fully exploit high Angle of Attack (AOA) maneuvering in the air combat environment. The heritage Hornet is widely known for its ability to attain and maintain high angles of attack, providing the pilot with a distinct advantage in the low airspeed, high AOA arena. Hornet pilots have achieved great success by simply "intimidating" threat aircrews. This intimidation can cause threat pilots to make grave tactical maneuvering errors in this flight regime. Despite these capabilities, the heritage Hornet has had a history of inadvertent departures from controlled flight, mostly in the low speed, high AOA flight regime. Heritage Hornet pilots must always maintain situational awareness of their aircraft state (aircraft store loading in combination with perceived yaw rate and sideslip, AOA and airspeed) to ensure they do

not inadvertently cause one of these departures. One of the primary goals for improving the Super Hornet's maneuverability included addressing the total systems design and integration of the Flight Control System (FCS), Operational Flight Program (OFP), and Mission Computers (MC) in order to optimize the control effectors in all phases of flight, including failure modes and battle damage. This integration would be key to approaching, if not achieving, an inherent ability within the Super Hornet to be maneuvered without concern for inadvertent departures, even with heavy and/or asymmetric store loadings, and to remain a safe and potentially lethal weapon system even with flight control failures or battle damage to some control surfaces. This paper addresses this total integrated design with the FCS, OFP, and MCs in the Super Hornet, including discussion on how the control effectors were integrated with feedback sensors to reduce the likelihood of departures, how the flight envelope was expanded to provide greater maneuverability, some surprise lessons learned on the control of asymmetric flow characteristics over the wing, and the positive and negative lessons learned from this design concept by the fleet operators.

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BACKGROUND

The heritage Hornet first entered service in 1983 and quickly became one of the most successful and lethal weapon systems ever deployed. The intent of the original design, to provide a fighter capability even when configured for an attack mission, was proven during the Persian Gulf war when a F/A-18C carrying a heavy air to ground load, engaged and shot down an Iraqi fighter aircraft and then went on to successfully complete its primary air to ground mission. In the fighter arena, the heritage Hornet has always been able to attain and maintain high angles of attack. Unfortunately, the heritage aircraft is prone to inadvertent departures when a pilot loses track of the state of the aircraft. A significant number of heritage Hornet aircraft have been lost following these departures due to Out of Control (OOC) events, most commonly, the "falling leaf". This problem still persists today with three F/A-18C/D aircraft lost in the past nine months due to OOC and during the lifetime of the heritage Hornet, approximately 20% of all aircraft lost have been a direct result of OOC flight. In addition to the requirement for Hornet pilots to maintain close watch of the aircraft state, the heritage Hornet also has little to no tactical roll performance in the high AOA arena, inhibiting the pilot's ability to achieve a "quick kill" over threat aircraft. As a result, this area was a prime focal point during the preliminary design process for the Super Hornet. The heritage Hornet FCS design architecture possessed a limited capability for expanding the high AOA utility of the Super Hornet. A shift in thinking would be required in order to exploit new flight control integration concepts developed jointly by the Naval Air Systems Command, NASA, and Virginia Polytechnic Institute and State University (Virginia Tech) and independently by General Dynamics (now Lockheed) and McDonnell-Douglas (now Boeing). These new concepts deviated from the primarily "single focus flight control surface design" used by most aircraft up to and including the heritage Hornet, in favor of fully integrated "control effectors" design. Significant advancements were made in this area during the 1990's which matured rapidly when the US Navy and NASA married their joint program with similar projects being funded by the US Air Force under the "Innovative Control Effectors" (ICE) program. The Joint Strike Fighter program is now making extensive use of this concept. For the Super Hornet, a redesign of some of the basic flight control system architecture was required in order to allow full integration of the FCS, OFP, and MCs. Additional real-time aircraft state feedback were needed and new control surfaces were added that could be used in a multi-axis environment. The control system was being optimized to provide the maximum control about each axis after providing basic aircraft stability. The result was a dramatic improvement in departure resistance and near ability to maneuver with "reckless abandon". However, as will be discussed within this paper, it was realized that a significant increase in inherent FCS derived departure resistance could result in a loss of tactical utility by the fleet pilot if not implemented properly.

FLIGHT CONTROL SYSTEM DESIGN

The F/A-18E/F is a growth version of the F/A-18C/D but with additional control effectors (leading edge extension (LEX) spoilers) and increased multi-axis integration of the existing flight control surfaces as well as a fully integrated speedbrake function (making it possible to delete the heritage Hornet "dedicated" speedbrake control surface). The F/A-18E/F Super Hornet is shown in figure 1.



US NAVY PHOTO

Figure 1
F/A-18E/F Super Hornet

The Super Hornet FCS is a digital, quad redundant, fly by wire, full authority Control Augmentation System (CAS). Improved integration of the FCS has provided a significant increase in flight safety following FCS failures and/or battle damage to flight control surfaces. This has allowed for the elimination of the heavy and redundant mechanical backup system found in the heritage Hornet. All control law computations are performed by four digital computers that work in parallel. Redundancy in the control system allows multiple like failures to occur before the pilot notes any degradation in stability or controllability. Unlike the heritage Hornet which can revert to an alternate mechanical system without a CAS function, the Super Hornet CAS function always provides closed loop control with available control effectors even after failures and always attempts to provide acceptable flying qualities.

There are 12 primary flight control effectors on the F/A-18E/F. An example of the use of fully integrated controls in a multi-axis environment can be seen in the longitudinal axis where control is provided through a combination of stabilators, leading and trailing edge flaps, ailerons, LEX spoilers, and rudder toe-in. The FCS is a fully integrated system with cross dialogue/use of the hydraulic/electrical systems, cockpit controls and displays, MC, Stores Management Set (SMS), Air Data System (ADS), Inertial Navigation Set (INS), Data Link Receiver (DLR), landing gear control unit, Signal Data Computer (SDC), radar altimeter, AOA sensors, and pitot-static system. The aircraft is a "load factor (g)" command system above

corner speed and an AOA command system below corner speed. The SMS provides rate-limiting functionality when air-to-ground or external fuel stores are carried on wing stations. Sideslip and sideslip rates are fed back to the FCS to reduce sideslip buildup during dynamic maneuvers and to improve overall stability. To date, the Super Hornet FCS has met or exceeded all design expectations.

There are two flight phases configured in the control laws: Auto Flap UP (UA) for up and away flight and Power Approach (PA) for takeoff and landing. UA is activated if the cockpit FLAP switch is in the AUTO position or if the FLAP switch is in any position and the calibrated airspeed is greater than about 240 knots. The PA phase is activated if the cockpit FLAP switch is in the HALF or FULL position and the calibrated airspeed is less than about 240 knots. FULL flaps are used for ship based approach and for catapult takeoff. HALF flaps are used for field takeoffs.

There is one trailing edge flap, one aileron, and two leading edge flaps per wing, which can be deflected symmetrically or differentially. For longitudinal control the leading and trailing edge flaps, drooped ailerons, and toed-in rudders are scheduled to optimize lift, drag, pitching moment, and lateral-directional departure resistance. Laterally, roll damping is provided by the aileron, differential leading and trailing edge flaps, and differential stabilator.

There are two rudders, one per vertical tail, that can be toed-in or flared for additional control. In UA, the rudders are toed-in at high g's in the supersonic region to reduce hinge moments and are flared out at high AOA to improve nose-down pitch acceleration. In PA, the rudders are toed-in for takeoff and to smooth pitching moment variations with AOA. Rudders are only flared for nose-down pitch acceleration at higher AOAs. Above 25 degrees AOA the rudder signal is sent to the lateral axis and indirectly commands the rudder through the Rolling Surface to Rudder Interconnect (RSRI). The RSRI coordinates roll maneuvers by removing the yaw generated by the lateral surfaces using rudder commands. There is one LEX spoiler per side of the aircraft. In UA the LEX spoilers perform a speed brake function and augment nose down control power. The LEX spoilers are always retracted in PA.

The longitudinal stick commands load factor in UA and AOA in PA, through symmetric stabilator movement. In UA, AOA feedback is added to the control integrator above 22 degrees AOA. The primary feedbacks are load factor, pitch rate, and AOA. The AOA command system used in PA gives more precise airspeed control. The primary feedbacks for PA are AOA and pitch rate. Laterally, the stick position commands stability axis roll rate. Lateral-directional control uses deflection of differential stabilators, ailerons, differential leading and trailing edge flaps, and symmetric rudder deflection. Directional control is accomplished with a directional CAS that commands yaw rate via the rudders.

The control system contains an Automatic Spin Recovery Mode (ASRM) that provides the pilot with full control

authority in order to recover from a spin. Spin mode will automatically engage when a spin is detected. All of the following conditions must be met to automatically engage the spin mode: lagged yaw rate greater than 15 deg/sec, the product of lagged yaw rate and actual yaw rate greater than 225 deg²/sec², and the indicated dynamic pressure must be less than 50 pounds per square foot (approximately 120 knots). The spin mode logic will automatically disengage when the spin is arrested. Any of the following three conditions will disengage the spin mode: lagged yaw rate less than 15 deg/sec, the product of lagged yaw rate and actual yaw rate less than 225 deg²/sec², or indicated dynamic pressure greater than 200 pounds per square foot (approximately 250 knots).

There are specific features of the F/A-18E/F control laws that are designed for high AOA flight with enhanced departure resistance and roll performance. Sideslip rate feedback to the ailerons and the differential tail provides additional roll coordination and increased roll rates. Above 22 degrees AOA, a stall warning is implemented by adding angle of attack feedback to the integrator error signal. A steady state AOA command system is created above 34 degrees by increasing the integral AOA gain. Nose-down pitch acceleration from high AOA is augmented by the use of LEX spoilers, rudders flare, and a "pitch bucking" modification. The LEX spoilers are deflected if the aircraft is above 22 degrees AOA and the pilot is making a large nose-down stick command. Symmetrically deflected rudder flare is also used during high AOA and large nose-down stick commands. Immediate pitch response is obtained by a modification to the forward loop integrator that is intended to eliminate "pitch bucking" at maximum trim AOA. This control law modification unloads excess (the difference between the unlimited stabilator command and the actual surface command) nose-up command from the pitch integrator. As such, the response to nose-down control inputs is immediate since the pitch integrator does not have to unwind from an over commanded state.

DESIGN PHILOSOPHY

The basic design philosophy for the F/A-18E/F can best be summarized as follows:

1. Reduce or eliminate all operational maneuverability issues that were inherent in the heritage Hornet, such as, falling leaf mode, low AOA (near zero degrees) departure susceptibility, maneuvering limitations with large lateral weight asymmetries, reduce/eliminate potential to enter OOC flight, increase high AOA roll performance, eliminate two seat high subsonic Mach maneuvering restrictions, eliminate center of gravity maneuvering limitations and decrease roll coupling departure tendencies with forward longitudinal control stick inputs.
2. Focus on the "Total Control Power" required to conduct the mission and implement a "Multi-Axis Control Effector" FCS design integration scheme vice a "Single Axis-Single Control Surface" control system design.

3. Actively solicit feedback from the end user, the fleet, on what the priorities should be for improving the Super Hornet.

The “how” for the implementation of this philosophy was drawn from on-going Joint Service/Agency efforts that were underway during the A-12 development. In the early planning days of the Advanced Tactical Aircraft (ATA), which became the A-12 (which was subsequently canceled), the US Navy, NASA, Virginia Tech (under a research grant) McDonnell-Douglas (now Boeing) and General Dynamics (now Lockheed/Fort Worth) worked closely to determine what the next generation fighter/attack aircraft should be. What is the principle design philosophy that should be the focus of these efforts? A quick look at the F-14A, F-16A and F/A-18A design progressions made it clear. It was no longer acceptable to hand an aircraft designer the Military Specification for Piloted Aircraft (MIL-F-8785C) and expect an aircraft that met the operational requirements would be delivered three years later. Rapid expansion in high AOA capability (due in part to advances in flight control system integration required for use with relaxed static or statically unstable longitudinal designs and in part to improved aerodynamic design) was first exploited by the F-14A Tomcat and exceeded the design areas covered by MIL-F-8785C. When this specification was first introduced, high AOA was considered to be about 16 degrees. The F-14 expanded that to over 50 degrees, although the Tomcat did not have the control power to exploit this region. The fact was that no clear design criteria were in place to govern this new generation of aircraft. In addition, the advances in flight control technology allowed the designer significant “wiggle” room in what design guidelines existed. In other words, the designer could “point design” the aircraft to meet vague design guidelines, sacrificing maneuvering about one axis that had no clear design goal in order to meet a requirement about another axis that did. This resulted in an aircraft with decidedly non-uniform maneuvering capability in the high AOA region. The F-14A can safely be maneuvered to 50 degrees AOA, but then requires the pilot to execute a “controlled departure” to maneuver tactically because it has very little excess roll/yaw control power above that needed for stability purposes in this area. The F-16A has an AOA limiter (incorporated because of an inherent deep stall problem in this design) which precludes maneuvering above approximately 27.5 degrees limiting its tactical maneuvering options when the pilot is flying on this limiter. The heritage Hornet has no AOA limiter, but does have aft center of gravity (cg) limitations to preclude AOA hang-up (defined by weak nose down control power with full forward control stick, which delays recovery to lower AOA and results in severe altitude loss) and has very little roll capability in the high AOA region.

Clearly, design guidelines to preclude longitudinal problems (deep stall and AOA hang-up) and to define lateral-directional requirements for stability and control were needed for higher AOA (AOAs not addressed in any existing specification). This need resulted in joint US

Navy-NASA programs to address longitudinal (the “HANG,” High AOA Nosedown Guidelines program) and lateral-directional (the “HAIRRY,” High AOA Investigation of Requirements for Roll and Yaw program) problems in cooperation with the US Air Force and sharing of information from the ICE program. These efforts included extensive piloted simulation. The resulting guidelines were verified by flight experiments conducted on US Navy F/A-18C aircraft at Patuxent River and on the F-18 HARV at NASA Dryden Flight Research Center. Additional information and data were derived from the X-31, F-15 S/MTD and F-16 MATV projects, all flown at Edwards Air Force Base.

Initially, the longitudinal requirement seemed obvious, ensure the high AOA hang-up problem was eliminated. This would enhance safety of flight and eliminate center of gravity restrictions. What was not clear was how much additional nose down control was required/desired to enhance tactical utility. Likewise, a look at all current and projected roll performance capabilities of next generation aircraft would provide the baseline roll performance capability desired for the Super Hornet. Again, it was not clear how much roll/yaw capability was required just for safety versus an increase in tactical utility. Since no previously fielded aircraft has had these capabilities, the operational community has not reported on how these increased capabilities truly factor into the multi-aircraft threat engagement arena with off boresight, all aspect weapons employed. The typical response from the operators when asked these questions is “we’ll take as much as you can give us!” A viable concept, but one that can have significant impact on cost and aircraft weight (and require much soul searching to determine the need for additional control effectors such as thrust vectoring). Consequently, a Program Manager must consider the cost to benefit ratio of exploiting a portion of the flight envelope that may have an exposure time of only about two minutes during a two-hour tactical mission.

Data from the HAIRRY program was reviewed with the following question in mind, “what is the tactical utility of increasing roll performance with increasing AOA?” since a roll about the stability axis (the inherent design for rolling these generation of aircraft) really becomes more of a yaw maneuver rather than a roll. Combine this question with that of “how much nose down control power is required to be tactically useful versus providing safety of flight?” and you get a complex tradeoff in design that still has no clear answer. These questions were much easier to answer for 50/60’s generation aircraft that were very statically stable. In these cases, the horizontal tail was the longitudinal control and was typically sized by nose wheel lift-off requirements. The aileron was sized typically by low airspeed (landing) requirements and the vertical tail/rudder by stability and turn coordination requirements (and in the case of multi-engine aircraft, minimum control airspeeds). HANG, HAIRRY and ICE provided a more in-depth look at the “control effector” problem. Prior to these efforts, control allocation issues were discussed behind closed doors for very specific designs. The results of these designs

may have flown, but they were never reported publicly. The answers that eventually came forward were significant. The primary focus for all future designs would be on total mission control power requirements. The challenge is to identify early in the design process the control power requirement for each axis, regardless of flight phase. If the challenge is met, the resulting design will have sufficient control power to do all mission tasks. Boeing and Virginia Tech have been leaders in the development of methods for assessing control power requirements and have developed "Control Allocation" routines independently but with similar results. These methods help to ensure an optimum FCS, using the maximum amount of control power available about each axis for stability and controllability. Results from these efforts have now been coordinated and compiled in the Joint Service Specification Guide (JSSG) currently under development by the US Navy and US Air Force, with drafts already released to industry. The F/A-18E/F unique specification requirements were the forerunner for many of the new additions in the JSSG.

This new design guidance fit ideally with the initial development plan given by the Super Hornet's Program Manager. The program design goals for the F/A-18E/F was simple, provide significant improvement to the following critical areas over the heritage Hornet: range, weapon loading flexibility, carrier landing bring back weight, and survivability. All other areas should be equivalent or better than the baseline (F/A-18C/D). Improving the maneuvering aspect of survivability would require a clear understanding of what the user (the fleet pilot, hereafter referred to as "the fleet") wanted. What would really improve survivability from the maneuvering vantage point? The initial answer was clear: increase lateral, directional, and longitudinal control power at all AOAs.

As noted above, the design philosophy was not to ensure that you could fly the F/A-18E/F with reckless abandon or with "carefree" maneuvering as some would think. Since the Super Hornet was a growth version of an existing design, it was obvious that carefree maneuverability could only be a "goal" since a "derivative" aircraft has additional limitations in its design space over a totally new design. The primary goal was to improve the safety of flight issues first and then work on expanding operational utility to the maximum extent possible within the design constraints this aircraft derivative brought forward from the heritage design. The falling leaf was a significant safety of flight design concern, having claimed many heritage Hornet aircraft in OOC flight. This mode is a sustained in-phase roll and yaw event which produces a nose-up inertial coupling moment in excess of the generally weak (depending on cg location) nose down moment generating capability of the aircraft. The character of the motion is highly oscillatory in both AOA and sideslip and even though the AOA frequently oscillates down to low AOA (a typically "flyable" AOA) the accompanying sideslip (usually well beyond 10 degrees) helps to reinforce the falling leaf motion. Elimination of this problem was a primary design goal for the Super Hornet. The design goals were:

1. Enhanced departure resistance and post departure (should it still occur) elimination of "falling leaf" or unrecoverable spin modes.
2. Requiring the aircraft to meet all flying quality requirements with a centerline fuel tank since this is a common operational configuration in all services, foreign and domestic.
3. Elimination of high AOA hang up and the accompanying AOA/cg restrictions.
4. The aircraft must be able to land on an aircraft carrier following most flight control failures.
5. Improved roll performance at elevated AOAs in the gear up/flaps Auto configuration.
6. Expanded tactical utility with large lateral store weight asymmetries (since high value stores are frequently deployed one at a time and can result in significant lateral weight asymmetries and aircraft maneuvering limitations after release of one store).
7. Reduction of likelihood of encountering pilot induced oscillation/aircraft-pilot coupling tendencies.
8. Adequate control following a dynamic and/or static loss of one engine (which sized the F/A-18E/F vertical tail).
9. No reduction in flight envelope for the two seat F-model over the single seat E-model, since both aircraft would be mission capable aircraft.

ACHIEVEMENT OF DESIGN GOALS

How was it possible to achieve the design philosophy and associated goals? By changing the approach to integrating the systems on the aircraft. The goals could only be achieved if the team focused on the end result desired vice the "typical" method for achieving it in the past. Historically, ailerons were considered the primary, if not only, roll control surface. New generation aircraft, including the Super Hornet, have adopted the "control effector" philosophy. Adoption of this philosophy provides new freedoms to the designer. As noted earlier, the F/A-18E/F uses virtually all of its control surfaces, "effectors," to provide longitudinal control. This is the same for all three axes. In the roll axis, the team focused on what was needed to attain increased roll performance as a function of AOA as opposed to assuming that when you ran out of aileron control power you were basically finished. In fact, the F/A-18E/F does not even use ailerons for roll control in some portions of the flight envelope. Pitch, roll, and yaw generating capabilities were "book kept" for all control effectors and then blended as needed to achieve desired rate and/or angular change in the airplane. Certainly, this is not a new concept and definitely not invented here, but the Super Hornet has become the first operational aircraft in production to exploit this capability to an unlimited angle of attack range.

In order to achieve these goals, the team decided not to "photographically" enlarge the aircraft, as is often done in larger derivative aircraft. Instead, each part of the aircraft was looked at separately and enlarged, as needed, to meet the new design goals. In this way, better control of

unnecessary weight growth was maintained by not “over-designing” the aircraft. Figure 2 depicts the physical differences between the Super Hornet and the heritage Hornet.

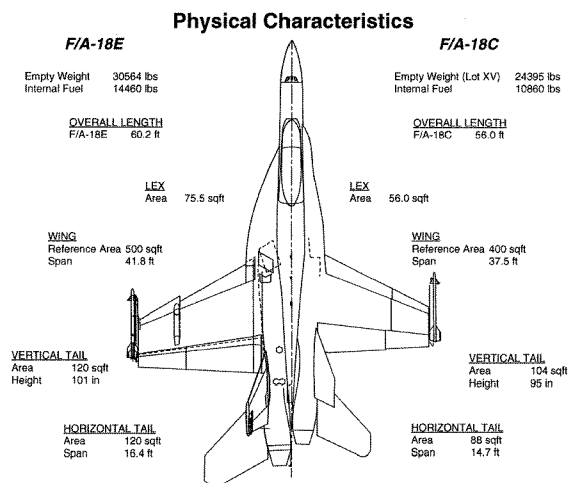


Figure 2
Planform Comparison - E/F to Earlier Models

As noted earlier, the vertical tail was sized by single engine minimum control airspeed in the approach/landing configuration. The vertical tail was grown 15% over the heritage aircraft, although initially, it was to remain the same size as the F/A-18C/D. The growth was added after stability and control assessments proved the baseline was inadequate. The wing was grown 25% to meet performance requirements. The horizontal tail was enlarged 36% to meet the demands of high AOA flight and eliminate AOA hang up and falling leaf. This nose down control is augmented by the addition of new LEX spoilers, which also function as part of a fully integrated speed brake. This was all part of the new systems approach to the aircraft design.

Nose down control power, a major deficiency in the heritage Hornet (resulting in complex cg/AOA restrictions as a function of store loading) was addressed by blending three control effectors, the horizontal stabilators, the new LEX spoilers and flared rudders.

The control effector allocation scheme was significantly improved at elevated AOA over the heritage aircraft, which suffers from limited turn coordination and control blending flexibility as well as the lack of feedbacks for sideslip or sideslip rate. The heritage Hornet uses ailerons and differential stabilator working together to roll the aircraft, approximating a stability axis roll (since no sideslip feedback is available to help control sideslip buildup during the roll). Unfortunately, this differential stabilator produces significant adverse yaw which cannot be countered by the rudders, requiring reduced roll gains and hence, performance, in the heritage Hornet. The Super Hornet, in contrast, uses the ailerons and rudders to roll and

coordinates the roll with differential stabilator (a very strong yaw generating effector). Sideslip and sideslip rate feedback were added to the ailerons and differential tails. These feedbacks are used to improve the Dutch Roll mode damping and essentially has eliminated the falling leaf. This would not have been possible without the targeted horizontal tail size increase noted earlier providing the necessary control power to accomplish the task.

The control stick and rudder pedal blending was also improved in the Super Hornet. Above 25 degrees AOA, a lateral stick and/or rudder pedal input should provide the same output to the control effectors in the heritage Hornet. No matter which combination (rudder pedal and lateral stick) or single input (rudder pedal or lateral stick) the pilot elected to use to roll the aircraft, theoretically, the same control effector deflection would occur. Unfortunately, this was not the case in reality for the heritage Hornet. It was discovered that this design could be defeated by clever pilots phasing rudder pedal and lateral stick in such a way as to induce a larger control effector deflection than the designers thought possible (because of the way the SAS and CAS interpret these inputs and act to provide stability and control). These larger inputs produced larger aircraft rates that were not accounted for in the SAS and could (and periodically do) result in unintentional departures from controlled flight. In the Super Hornet, cross-controlled inputs are canceled and combined inputs are limited to that which could be commanded by a full lateral stick. The desire here is for the pilot to always roll with lateral stick, letting the control blending functions within the FCS decide which control effectors to use to achieve the desired output. This significantly reduces pilot workload and improves safety compared to F-4 Phantom vintage aircraft which rolled with ailerons at low AOA, but were only rolled with rudders at high AOA (unless you wanted to depart from controlled flight) because the ailerons generated significant adverse yaw with increasing AOA that would easily lead to OOC flight. An F/A-18E/F pilot can fly “feet on the floor.” Lastly, roll/pitch limiting was added to the Super Hornet to preclude inertial coupling into the yaw axis when large roll and pitch commands are present. This feature significantly reduces departure susceptibility.

Departure resistance was a primary focal point throughout the design. Many aircraft since the F/A-18A/B was introduced in 1983 have attempted, with varying degrees of success, to implement Departure Resistance (DepRes) systems either implicitly (through Aileron-Rudder Interconnects and/or Rolling Surface to Rudder Interconnects) or explicitly (through the addition of a so-called DepRes system, Automatic Spin Recovery Mode or other FCS design concept) into their designs. No matter what they are called, they all attempt to do the same thing, control sideslip buildup and eliminate or reduce inertial and kinematic coupling. In order to be truly successful, DepRes type systems must have feedback paths for sideslip, sideslip rate, pitch rate, roll rate and yaw rate. These feedbacks are then integrated into a FCS to produce stability axis rolls (to eliminate kinematic coupling), to limit combined rate build-ups (to eliminate inertial coupling) and to control the Dutch

Roll mode and keep the aircraft in the stable region of directional stability. All of this is predicated on having sufficient control power and a control allocation scheme to make maximum use of the control power available about each axis after accounting for and maintaining stability. It also assumes that control effector actuator rates are fast enough to input the desired control effector command and achieve the desired deflection before the aircraft goes unstable. Figure 3 provides a summary of the control surface actuator rates and deflection limits for the F/A-18E/F.

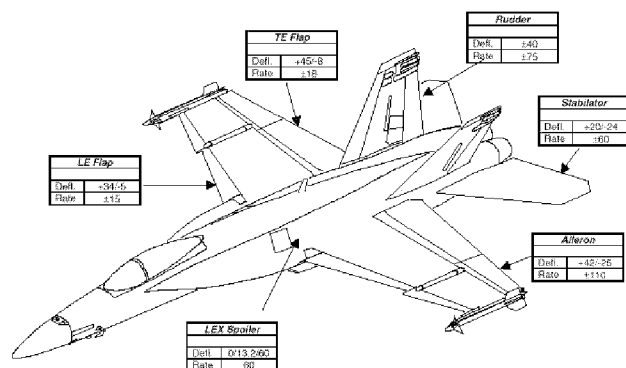


Figure 3
Actuator Rates & Surface Deflection Limits

As with all other DepRes systems, the F/A-18E/F relies on controlling the sideslip and rates to mitigate departure tendencies. Since this was an up-front requirement, adequate control power was ensured through design and redesign in the early phases of wind tunnel testing, validation in simulation and verification during both Developmental and Operational Testing. The Super Hornet generates direct control of sideslip and sideslip rate by feeding those signals to the ailerons and differential stabilator. The use of sideslip and sideslip rate feedback proved to be a significant improvement over the heritage Hornet DepRes system. Sideslip feedback is used to maintain directional stability and ensure stability axis rolls are achieved. The sideslip rate feedback works to dampen the Dutch roll mode, which in turn, helps eliminate the falling leaf mode (the falling leaf is considered an exaggerated Dutch roll). A roll/pitch (pq) product limiter and a pq “clamp” are included to reduce inertial coupling tendencies. The roll/pitch limiting was originally a feedback loop but the dynamic nature of some of the Super Hornet tactical maneuvers made it clear this was too slow to be effective at eliminating departures so it was subsequently supplemented by a feed forward path (pq “clamp”). By adding command limiting to the feed forward path, you risk losing some roll performance. After a closely

examining this potential impact, it was found that departure tendencies were directly related to the rate of aft stick input. Using this information, a “clamp” was added to the feed forward path which made the pq limiting a function of aft stick input rate. This significantly reduced departure tendencies through continuous rolls of up to about 540 degrees of bank angle change, (well beyond the operational need of 360 degrees) but maintained the high level of roll performance.

The “DepRes” system on the Super Hornet works continuously to preclude inadvertent departures. The CAS does this by attempting to keep the aircraft from achieving certain thresholds (airspeed <121 knots, lagged yaw rate >15 deg/sec, and product of lagged yaw rate and yaw rate > 225 deg²/sec²) that could lead to departure. If these conditions are met, the ASRM will engage to provide additional control authority to the pilot to effect recovery.

The highly integrated FCS of the Super Hornet is the primary reason it has achieved great success. Success that is a direct result of priorities set in the wind tunnel to ensure the control power was inherent in the design to achieve the objectives. The F/A-18E/F has accumulated well over 14,000 tunnel occupancy hours of wind tunnel test to date. The hard lessons learned by many previous aircraft development programs; not ensuring adequate control power was provided up front, was not repeated here. While many people believe that a sophisticated FCS can solve all aerodynamic design flaws, it has been proven time and time again that a FCS cannot *create* control power that does not exist. Once a control surface is fully deflected, the limit of that control effector’s control power contribution is reached. If sufficient control power is inherent to the design, you can do great things, which the Super Hornet has done. The integrated process of the Super Hornet is best seen through the following summary of each control axis:

Longitudinal: Control is provided by symmetric stabilators, rudder toe-in and flare, symmetric leading and trailing edge flaps, symmetric ailerons and symmetric LEX spoilers.

Lateral: Control is provided by asymmetric use of aileron, differential stabilator, differential trailing edge flaps and differential leading edge flaps.

Directional: Control is provided by twin tail rudders deflected symmetrically and asymmetrically (toe in/out). The rudder is commanded by a combination of rudder pedal, RSRI, yaw rate feedback, lateral acceleration feedback, high AOA sideslip and sideslip rate crossfeed to the ailerons and differential stabilator, roll rate feedback, and directional coupling compensation.

The results from the Engineering and Manufacturing Development (EMD) flight test program demonstrated that the design goals had been achieved and the Super Hornet was ready for Operational Evaluation (OPEVAL). EMD flight testing in this high AOA regime was accomplished during approximately 221 flights, totaling some 378 flight

hours for both single and two-seat aircraft¹. The flight test program was broken into five phases, with the first three phases covering simulation aerodynamic data base validation, verification of spin and spin recovery control power and recovery techniques and aggravated control input attempts to depart the aircraft from controlled flight. Phases 4 and 5 evaluated asymmetric store loadings. The improved departure resistance of the aircraft and integrated control effector blending enabled unrestricted clearances for both single and two-seat models in all external loadings with less than 8000 ft-lb asymmetry. Loadings between 8000 and 12,000 ft-lb permit unrestricted maneuvering at AOA's less than maximum lift, with less restrictive limits overall up to and including the maximum allowable asymmetry of 26,000 ft-lb. This provides the fleet user greater tactical utility and flexibility in weapon loadings and deployment.

THE UNKNOWN/UNKNOWN'S

Every flight test program encounters some "unknown-unknown," things that were not planned, thought of, or considered possible to occur in flight-testing. The Super Hornet was no exception. Early in the flight test EMD program, the aircraft experienced uncommanded "wing drop" during wind up turns and straight and level accelerations. As the program matured and the envelope expanded, it became clear that this was a serious problem that would impact aircraft performance if not corrected. Over an eight-month period from August 1997 through March 1998, maximum resources were brought to bear to solve this problem. In all, over 10,000 wind up turns were executed on over 100 wing configurations before a solution was found. This effort required use of up to 4 of the 7 flight test aircraft to solve, causing significant rework to an already tight EMD schedule. The "wing drop" phenomenon was a rapid, uncommanded bank angle change of up to 180 degrees (if left unchecked by the pilot) that would cause a pilot to lose a guns-tracking solution on a threat aircraft. Wing drop occurred at all altitudes and from about 0.55 Mach to approximately 0.95 Mach. Extensive wind tunnel, simulation and CFD testing and analysis was conducted coincident with the flight-testing. In general, it was concluded that wing drop occurred due to a sudden, asymmetric wing stall event that was focused around the wing fold fairing (which is new and unique to the Super Hornet from the heritage Hornet). Some of the flight test "fixes" assessed included modified snag locations, vortex generators, grit, stall strips, modified flap scheduling, control surface biasing, fences and porous wing fold fairing covers. Eventually, the porous wing fold cover proved to be the most effective solution to the "wing drop" phenomenon, by dissipating adverse pressure gradients fore and aft of the shock forming on the wing and reducing the effect of the asymmetric stall. Throughout history, many aircraft have experienced "wing drop" or "roll off" tendencies, for various reasons, but none have proven to be as elusive to solve as the Super Hornet's. Expert panels were convened with some of the best high-speed wing design engineers in the country participating from Academia,

Industry, and Government. The conclusion was that this phenomenon was not well understood and required immediate attention for future aircraft program designs to ensure they too do not suffer the same setback the Super Hornet did. In 1998, a three-year National Abrupt Wing Stall (AWS) effort was funded by the Office of Naval Research in conjunction with NASA and Academia to investigate this phenomenon.

PREPARING FOR OPEVAL

Since OPEVAL pilots flew coincident with the Development Test (DT) pilots, they were able to monitor the progress of EMD testing and get a preview of what to expect during the formal OPEVAL period. The most notable concerns with the Super Hornet included the inability to perform a "pirouette" maneuver (a maneuver commonly employed by the heritage Hornet, described as a nose high to nose low 180 degree heading transition), sluggish roll performance at 20 to 25 degrees AOA, two seat aircraft directional instability at minus 20 degrees AOA, uncommanded roll reversal at full aft stick, "yaw-off" due to decreased directional stability with wing pylons and lateral stick plus full aft stick departures.

The pirouette maneuver was an interesting problem. The airplane was doing exactly what it was designed to do, preclude large yaw rate and sideslip buildup, thereby reducing departure tendencies. But, as expected, everything is a trade-off and this was no exception. By increasing departure resistance to the initial levels used on the Super Hornet, some "controlled" type tactical maneuvers/departures were no longer possible. In the heritage Hornet, you can execute a pirouette maneuver, but you are effectively executing a controlled departure by allowing yaw rate and sideslip to exceed that desired to maintain control of the aircraft. Since the aircraft ends up nose low, airspeed increases rapidly through the regions of directional instability and departures do not occur. Unfortunately, the Super Hornet FCS/CAS fights the pilot on this same maneuver and does not allow it to be executed in the same manner. To provide this capability to the Super Hornet pilot, fundamental stability and control techniques were employed which made use of proverse sideslip and dihedral effect to increase roll and yaw rates at high AOA. Since it was intended to provide basically a point design capability for executing a pirouette maneuver, it is only possible to command proverse sideslip when lateral stick and rudder pedal are combined at high AOA and low airspeed, exactly where and how the Super Hornet pilot wants to perform this maneuver. This was done since the generation of proverse sideslip does not produce linear or predictable responses with time, potentially allowing sideslip and yaw rate to build to unacceptable levels. The CAS was re-tuned to deviate from trying to produce a pure stability axis roll and allowing some proverse yaw to build. A control shaping filter was added to reduce this new sideslip command function with time so that the CAS function would return to normal at approximately the time it takes to complete the pirouette.

Sluggish and unpredictable/non-linear roll performance occurred in the 20 to 25 degree AOA region creating significant roll predictability issues during reversals, horizontal and rolling scissors maneuvers. Increasing aileron deflection and modifying the coordination with the rudders and differential tail solved this deficiency².

Two-seat directional instability at negative 20 degrees AOA resulted in a dramatic departure and entry into an inverted spin. This problem resulted from weak inherent directional stability, a fact that was known from early rotary balance wind tunnel testing, but thought to be insignificant in this region since the tactical need for maneuvering the airplane aggressively at negative angles of attack was not clear. However, when expanded capabilities are given to pilots, they will find a way to make it tactically useful, and this was no exception. This problem was solved by increasing sideslip and sideslip rate feedback which augmented the directional stability. Again, it was fortunate that the aircraft focused on control power early on in the wind tunnel design phase. This focus helped ensure that this control power was available to address issues just like this one².

Uncommanded roll reversals at full aft stick occurred around 45 to 50 degrees AOA and generated a fairly mild 5 to 10 deg/sec roll rate opposite to the commanded stick position. This was eliminated by decreasing aileron deflection for the same lateral stick deflection and increasing the rudder deflection in this region to decrease the adverse yaw, resulting in rolls in the expected direction².

Yaw-off with wing pylons mounted occurred in the 30 to 50 degrees AOA region at airspeeds near 300 knots. In this case, it was found that the aerodynamic simulation model predicted higher directional stability than was realized in flight. Consequently, the CAS provided too little augmentation. Increasing sideslip feedback to the ailerons and differential stabilator in this region solved this problem².

The lateral plus aft stick departures were eye-watering and resulted in a few events which exceeded the negative "g" limits of the aircraft and greatly exceeded the pilot "comfort" levels. These occurred at approximately 0.6 Mach and 1-g initial conditions. The result was a rapid sideslip and yaw rate build-up opposite the direction of the lateral stick followed abruptly by a nose tuck that, on the worst test point, hit negative 3.7 g's. The solution to this problem was accomplished by iterating (tweaking) the inertial de-coupling *pq* limiter and adding the *pq* clamp discussed earlier³.

With these problems fixed, the aircraft was now ready to be turned over to the end user for evaluation of the airplane performance in an operational environment - under real world scenarios.

OPERATIONAL EVALUATION (OPEVAL)

The US Navy announced on 15 February 2000 that the F/A-18E/F Super Hornet was awarded the best possible grade by the OPEVAL team calling the aircraft "operationally effective and operationally suitable." In addition, the OPEVAL team recommended that the aircraft be introduced into the fleet. The Chief of Naval Operations stated that "The F/A-18E/F Super Hornet is the cornerstone of the future of Naval Aviation. The superb performance demonstrated throughout its comprehensive operational evaluation was just what we expected and confirms why we can't wait to get it to the fleet."

Air Test and Evaluation Squadron Nine (VX-9) at China Lake, California flew 1233 hours in over 850 sorties and expended more than 400,000 pounds of ordnance in the Super Hornet during nearly six months of evaluation. The 23 member team tested the aircraft in a wide range and complex variety of mission scenarios. The purpose of the OPEVAL was to test the aircraft in a realistic setting to determine its operational effectiveness as a weapon system and its suitability to be maintained and operated by the US Navy. The OPEVAL report specifically cited the aircraft's key enhancing features, including, survivability, growth capability, bring-back weight, range and payload.

OPEVAL concluded that there are three fundamental maneuvering characteristics provided by the F/A-18E/F Super Hornet's flight control law architecture that have proven to provide a significant advantage in the tactical employment environment. The three characteristics include aggressive and unconstrained pitch axis control to unlimited angles of attack (AOA) with all external loads up to 8000 ft-lb asymmetry, exceptional departure resistance, and the ability generate high yaw rates at high AOA. These three characteristics provide a combined, synergistic affect that allows even inexperienced F/A-18E/F aircrew to exploit the full capability of the aircraft and enjoy exceptional tactical maneuvering success. In spite of the fact that the Super Hornet did not incorporate expensive, high risk aeromechanical technologies associated with extreme agility such as a canard or vectored thrust, the three maneuvering characteristics achieved through ingenious flight control design provide an impressive agility and maneuverability. When the exceptional maneuverability is combined with the increased range, increased weapons capacity, improved survivability, mature weapons system and growth systems such as AIM-9X, Joint Helmet Mounted Cueing System (JHMCS) and Advanced Electronic Sensor Apparatus (AESA) the Super Hornet is and will continue to be a dominant force in any threat environment.

Unconstrained pitch pointing of the Super Hornet is exceptional. The peak instantaneous turn performance is similar to that of the heritage Hornet. However, the operational advantage provided by the Super Hornet is found in its ability to maintain that high instantaneous turn rate for a greater amount of time and to a higher AOA equating to increased total turn. For the fighter mission, the

increased total turn provides the Super Hornet the routine ability to achieve an angular advantage or a nose on position first. From an operational perspective, the pilot is able to commit to a full aft stick pull to maximum AOA before any other current fighter is able or willing to commit to the same maneuver. In many cases, the Super Hornet pilot is able to perform a maximum performance turn to a “nose on” position immediately if not within 180 degrees of turn from engagement initiation. At a minimum, this threatening maneuver forces the adversary to respond defensively. As a rule, the F/A-18E/F is able to employ the first weapon. In addition to impressive positive pitch pointing, the Super Hornet also has impressive negative pitch pointing. During initial operational test assessments, the negative pitch rates of the aircraft were deemed too slow for optimum operational employment. A simple flight control modification was incorporated to increase the pitch rates to a level just below the pilot’s physical pain tolerance threshold. Although the pitch pointing is most useful in the fighter mission, it also has impressive applications in the air to ground mission. The unlimited angle of attack and high pitch rates allow the Super Hornet to perform highly effective evasive maneuvers and rapidly designate targets with full air to ground weapons loads. Pilots can maneuver as aggressively as they desire without regard for AOA limits and can achieve a valid designation and release solution very rapidly.

The incorporation of sideslip and sideslip rate feedback in DepRes system virtually eliminates departures. Throughout the course of OPEVAL, 15 pilots, utilizing seven airplanes and flying over 1200 flight hours had only one departure from controlled flight. The single departure occurred in the only known area of relaxed directional stability and was well outside the normal maneuvering envelope. Recovery was virtually immediate. More importantly is the fact that pilots with less than 10 hours in the Super Hornet are able to maneuver using full stick and full rudder inputs at any airspeed and AOA without fear of departure. Instead of spending many hours learning the prohibited maneuvers, maneuvering limits or complicated control inputs, Super Hornet pilots are simply able to use logical inputs up to and including full stick and rudder to achieve their desired maneuver. One of the training missions provided to OPEVAL pilots was a high AOA demonstration. This demonstration included full aft stick stalls, full forward stick stalls, aggravated control inputs at all AOA and zero airspeed tail slides. Once the departure resistance of the airplane was demonstrated to aircrews, they were confidently able to maneuver to limits that were outside the frame of reference of adversary pilots. Comments from adversary pilots include amazement over the Super Hornet’s ability to hold its nose up to a virtually zero airspeed with good nose pointing control, the rapid pitch pointing, and the ability of the airplane to continue rapid nose pointing at very high angles of attack.

In addition to the impressive pitch pointing and departure resistance of the Super Hornet, there are several performance characteristics at high AOA that will allow the Super Hornet to dominate the engaged maneuvering

environment. During early operational tests, the inability to generate yaw rates at angles of attack above 25 degrees was identified as a major limitation to air to air combat. At that time, the use of sideslip and sideslip rate feedback to prevent departures had also limited the maneuverability of the airplane to an unacceptable level. Through an aggressive process of design and close interface with the operational community, the flight control logic was modified to allow proverse sideslip within a specific AOA and airspeed range. This change did not decrease departure resistance but significantly improved the ability of the Super Hornet to rapidly reposition the nose from a nose high to a nose low position. In addition to impressive pitch pointing, the Super Hornet has the combined roll/yaw axis to use in quickening the transition from nose high to nose low conditions. This maneuver is akin to the pirouette maneuver performed by the heritage Hornet with the notable exception of precise control. In the case of the heritage Hornet, the pirouette is essentially a controlled departure that quickly transitions the aircraft from nose high to nose low. Once the maneuver is initiated, the pilot is essentially along for the ride. By contrast, in the Super Hornet, the maneuver can be performed with good control throughout. In fact, the F/A-18E/F is easily transitioned from a pirouette to a precise guns tracking solution at virtually any point in the maneuver. A precipitous byproduct of the Super Hornet pirouette maneuver is an impressive horizontal plane maneuver that generates turn rates similar to maximum instantaneous turn rates but at airspeeds less than 150 knots. The maneuver is performed at full aft stick stall by invoking the pirouette maneuver for 2-3 seconds from a turn or level flight. Once initiated, the aircraft roll/yaws through 40-60 degrees of turn at which point the pirouette control inputs are removed and the aircraft is recovered back to level flight. This maneuver can be repeated in sequence to create an impressive “effective” instantaneous turn rate. This maneuver is frequently used as a secondary threatening maneuver after the pilot has used the impressive pitch pointing for a first shot advantage.

In summary, there is no single maneuvering characteristic that makes the F/A-18E/F an effective maneuvering platform. It is the synergy enjoyed by combining the effective pitch rate, pilot confidence that comes from departure resistance, high AOA maneuverability, pirouette, and deck transition. Although Air Combat Maneuvering (ACM) is usually avoided as much as possible and only used as a last resort, it is an excellent benchmark of maneuverability. The Super Hornet has proven to be an impressive ACM platform. Pilots have found that the Super Hornet is most effective when using an aggressive position fight. The pitch pointing provides the first shot capability, the departure resistance and high AOA maneuvering allows the Super Hornet to maintain the threatening position and lastly, the pirouette/deck transition allow the Super Hornet to achieve quick follow up shots. For a conventionally designed aircraft with relatively low thrust to weight ratio, the Super Hornet is one of the premier ACM aircraft available today.

END GAME

In contrast to the F/A-18A/B development in the early 1980's, the Super Hornet has delivered a fully capable weapon system to the users up front. The F/A-18A/B, an advertised strike-fighter, was delivered with virtually no air to ground capability in 1983. The Super Hornet has an extensive repertoire of weapons and is ready to go to war now.

LESSONS LEARNED

Some important lessons learned from the Super Hornet development include:

1. Make the end user a part of the development process, in this case, the Operational Community. Their inputs are critical to a successful program and delivering a weapon system that does its intended mission up front.
2. Unknown-Unknowns will occur. Fortunately, the F/A-18E/F Program Manager budgeted for these in management reserve, most of which was used solving "wing drop."
3. A fully integrated flight control system with control allocation algorithms making maximum use of all available control effectors is the present and the future of all piloted and unpiloted vehicles.
4. Ensure the preliminary design and subsequent engineering development has adequate wind tunnel testing included to determine if sufficient control power is inherent in the design. This should account for relaxed stability design concepts and completion of all critical mission tasks. It should also address what will be considered probable FCS failures for each individual design to make the FCS as robust as possible.
5. Wing design is still an art. Prediction of "wing drop" like phenomenon is still a "black art". Hopefully, the National AWS program will shed new light on this topic.
6. As more aircraft are able to exploit the high AOA region, new tactics will have to be developed. These tactics must be analyzed to determine exactly what kind of rates are necessary to be lethal in this environment without undue penalty to the airplane design in other areas (again, everything is a trade). To date, even with HANG and HAIRRY, it has been difficult to pin down critical design guidelines for high AOA tactical utility.
7. Regardless of how sophisticated, a FCS can do nothing without control power.
8. Designer engineers must realize that what they think is important is not always what a pilot thinks is important. Case in point, if the engineers think it is a great idea to design an airplane to be flown with "reckless" abandon by providing superior departure resistance in the flight control system automatically, they may actually (and probably will be) taking away some of the tactical utility of the aircraft. There was (and is) a lot of truth to the fighter pilots view of the world that you have to fly "to the edge of the

envelope", the point just prior to a departure, in order to maximize the effectiveness of your aircraft in combat. As shown in the F/A-18E/F and the initial inability to perform a pirouette maneuver, too much artificial departure resistance inhibits the pilot from tapping into the maximum capability of the aircraft. There comes a point where you have to let the pilot judge where and how to use the edge of the envelope vice the engineer and the DepRes type system.

9. And lastly, the team wanted to eliminate the time consuming process of modifying flight control laws, which plagued the F/A-18A/B development. This was done by incorporating a "dial-a-gain" function in the test aircraft that would allow for limited changes to control laws in order to optimize the existing OFP more efficiently rather than having to produce a new OFP every time a small gain change had to be made. The F/A-18A/B had over 110 OFP changes, over 70 of which flew on the test aircraft. In contrast, the F/A-18E/F had less than 10 OFP changes.

¹ Heller, Niewoehner and Lawson, "High Angle of Attack Control Law Development and Testing for the F/A-18E/F Super Hornet." *AIAA-99-4051*, August 1999.

² Madenwald, Niewoehner and Hoy, "F/A-18 E/F High AOA Flight Test Development Program," *SETP 1998 Report to the Aerospace Profession: Proceedings*, September 1998, pg. 128-142.

³ Hoffman and Heller, "Development of Improved High Angle of Attack Controllability in the F/A-18E/F." *SFTE European Chapter, 10th Annual Symposium Proceedings*, Linköping, Sweden, June 1998.

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