A DESCRIPTION OF THE F/A-18E/F DESIGN AND DESIGN PROCESS

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Abstract

This paper describes the design and the design process used to develop the F/A-18E/F aircraft. It is presented here to document the state-of-the art of the design process for development of a modern high performance fighter aircraft. It is intended that this information will provide a background for researchers developing Multidisciplinary Design Optimization (MDO) processes for aircraft design. The design process itself was an advance for the F/A-18E/F in that it marked the first application of the Integrated Product Development (IPD) design process to an Engineering Manufacturing Development (EMD) program at the McDonnell Douglas Corporation. Since the F/A-18E/F's flight test program is well under way, results are available by which to judge the success of this design and the design process. Finally, some conclusions and recommendations for additional work to improve the design process are made.

Introduction

In 1990 the MDO Technical Committee (TC) was formed as a technical committee of the AIAA. One of the tasks that this committee undertook was to define the state-of-the-art as it existed at that time and the results of this study were published as Reference 1. Since 1990 other documents have also presented state-of-the-art approaches with Reference 2 being an excellent example. The references have done an excellent job of documenting theoretical developments. However, the AIAA MDO TC felt that more was required to transfer the MDO message from the theoreticians to the aircraft designer and for the theoreticians to have a better perspective on what is required to design a new aircraft. It was determined that a series of papers by industry documenting the current design process as used on current design programs would be an appropriate step in making this happen. This paper, which addresses the F/A-18E/F, is one of a series of papers in response to that action item.

The F/A-18E/F, shown in Figure 1, represents the next step in the evolution of the F/A-18 aircraft. In addition, its development represents a next step in the evolution of the aircraft design process. The E/F was designed using the Integrated Product Team (IPT) approach and this represents a significant advance from the design process used in the development of the original aircraft. This paper presents a description of the aircraft design as well as a description of the design process.

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

In MDO an objective function subject to a set of constraints is defined and a mathematical process is used to minimize this objective function without violating the constraints. Sensitivity derivatives are usually computed as part of the optimization process. Reference 3 provides a good description of the mathematical process.

If the above definition of MDO is applied in a strict sense, then MDO was not used to design the F/A-18E/F. However, the F/A-18E/F was designed using a Multidisciplinary Design Process. Based on results obtained from the flight test program, the aircraft is a very successful one. Thus, the current design process must also be regarded as successful.

The F/A-18E/F was designed to meet a specific set of requirements rather than by optimizing a specific objective function. From the perspective of MDO, these requirements can be viewed as constraints which implies that the F/A-18E/F is a feasible design.

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Description of the Aircraft

Aircraft Missions - The F/A-18E/F is a multi-mission aircraft designed for the US Navy. The concept of a multi-mission aircraft is significant for the MDO process in that there are multiple requirements that the aircraft must meet, and this complicates the definition of an objective function. For a single mission aircraft, the formulation of the objective function is a simpler task. The F/A-18E/F was designed to perform both air-to-ground and air-to-air missions. These missions were defined as requirements and the goal was to develop a design that satisfied them. A description of the MDO process as it applies to a multi-mission aircraft was initially presented in Reference 4.

Figure 2 illustrates the multi-mission concept starting with maritime air superiority on the left and proceeding to all weather attack on the right. These mission extremes are significant in that historically they have been performed by dedicated aircraft. The F-14D performs the air superiority mission and the A-6F performs the all weather attack mission. While the F/A-18C/D has some capability to perform these missions, it has not been optimized for them. For fleet defense the F-14 with its Phoenix missile system is superior to the F/A-18C/D. However, as a multi-mission aircraft, the F/A-18C/D still has significant capability in this area. Similar arguments can be made for the ground attack missions.

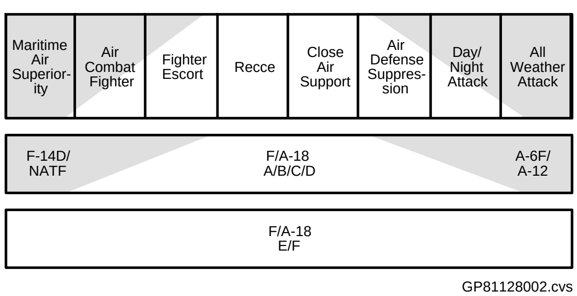

Figure 2. Hornet Spans the Mission Spec

As the F-14D's and the A-6F's are retired form the fleet, they will be replaced by F/A-18E/F's. Thus, the original mission spectrum of the F/A-18C/D has been expanded even further for the F/A-18E/F as shown in Figure 2.

Each of these missions has a specific set of requirements that the aircraft must meet. An MDO approach to meeting these requirements was not taken because MDO design techniques were not available at the time the F/A-18E/F was designed. However, for future aircraft design this approach may offer significant improvements if appropriate tools can be developed.

History of the Configuration - The F/A-18E/F is a derivative of the F/A-18C/D aircraft, which was originally derived from the Air Force lightweight fighter competition. Consequently, there is a great deal of history behind this configuration with the general shape of the aircraft being defined by the original YF-17. Figure 3 shows the planform view of these three aircraft and the heritage of the E/F aircraft is obvious. Table 1 summarizes some of the basic geometry data. The original YF-17 had a wingspan of 35 ft and a wing area of 350 sq. ft. For the F/A-18A the corresponding numbers are 37.5 ft and 400 sq. ft. While the basic aerodynamic concept of the YF-17 and the F/A-18A were essentially the same, the interior of the F/A-18A was completely redesigned. Most of the required changes were a result of transforming what was a light-weight fighter for the Air Force to a ship-board multi-role aircraft for the US Navy.

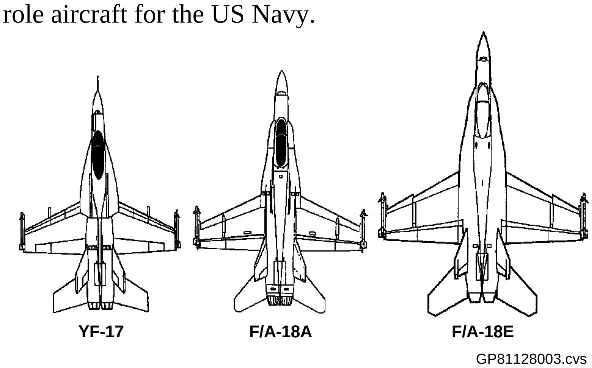

Figure 3. Comparison of Aircraft Planforms

Dimensions	YF-17	F/A-18A	F/A-18 E
Span (without missiles)	35.0ft	37.6ft	42.9ft
Length	56.0ft	56.0ft	60.2ft
Height	14.5ft	15.3ft	15.8ft
Tail span	22.2ft	21.6ft	23.3ft
Wheel track	06.9ft	10.2ft	10.45ft
Wing area	350sq ft	400sq ft	500sq ft
Weights			
Empty	17,000lb approx.	21,830lb	30,600lb
Fighter configuration	23,000lb	34,700lb	47,900lb
Maximum		51,900lb	66,000lb

Table 1. Comparison of Specifications

At the time that the F/A-18A was under going preliminary design, the lightweight fighter competition was still ongoing. This provided a constraint on the original F/A-18A that resulted in the F/A-18A still having essentially the same size and shape as the YF-17. For the MDO process, this is significant because it implies a constraint that would not be present if the F/A-18A were a totally new aircraft.

Similar observations can be made for the F/A-18E relative to the F/A-18A. The F/A-18E configuration grew relative to the F/A-18A configuration. The span of the F/A-18E is 44.7 ft and the wing area is 500 sq. ft. However, the general shape of the aircraft has been maintained. A comparison of the F/A-18E Super Hornet to the original Hornet is shown in Figure 4. In addition to the Super Hornet being a larger aircraft with a new inlet, changes in the Leading Edge Extension (LEX) and the addition of a wing leading-edge snag are apparent.


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Figure 4. Super Hornet Compared to Original Hornet in Flight

Hornet 2000 Study - The evolution of this new configuration had its origins in the Hornet 2000 study, Reference 5, which was conducted in 1988 by a joint team composed of the US Navy and McDonnell Douglas. Over the life of the F/A-18A/B and F/A-18C/D aircraft many changes were incorporated that resulted in an increase in weight and the internal space being used for new and additional avionics equipment. Because of this growth, reductions in range and other performance metrics occurred. In addition, changes to meet the increased threat that the aircraft was to face were required. It was anticipated that the capabilities of the threat would continue to increase. Quoting from the Hornet 2000 study;

"Major advances in threat capability have occurred since the F/A-18 was designed in the mid 70s. The original design goal for the Hornet was to have superiority over FISHBED and FLOGGER class air threats and to penetrate battlefields with SA-2, SA-3, SA-6, and SA-7 class surface-to-air threats. That threat has changed rapidly in character and capability, primarily as a result of successful Soviet efforts in technology transfer. The Soviets have demonstrated an ability to implement rapidly technologies developed domestically and acquired through legal and covert means. Through this aggressive program of modernization, the ability of the threat to confront the Carrier Battle Group has increased significantly."

Since 1988, a great deal has happened to change the nature of the threat. However, while the need to deal with the Soviet threat may have diminished, new threats have emerged. The need to deal with these threats formed a significant requirement for an advanced Hornet.

In addition to recognizing the need for a new aircraft, the Hornet 2000 Study identified planned improvements for the F/A-18C/D aircraft through 1995. These improvements were in three major areas: avionics, propulsion, and equipment. The avionics upgrades were to improve the F/A-18 weapon system capabilities in the areas of situational awareness, air superiority, air-to-surface attack and survivability. The propulsion upgrade consisted of replacing the baseline engines with the Enhanced Performance Engine (EPE). This engine offered significant performance improvements at higher speeds and could be incorporated without airframe changes. The equipment growth consisted of installing an On-Board Oxygen Generating System (OBOGS) increasing the aircraft cooling capacity by an ECS upgrade, and adding a bay in the left hand LEX to allow installation of additional avionics.

In summary, because of the changing nature of the threat and because the basic aircraft, even with the EPE, had just about reached the limits of its capabilities, a new aircraft was required. The Hornet 2000 Study produced a set of requirements and an aircraft configuration that addressed them. This study looked beyond the 1990s to determine the requirements for the aircraft such that it could continue to meet the threat. The goal of the study was to identify high value upgrades and develop a phased incorporation plan to ensure continued F/A-18 survivability and effectiveness.

This new aircraft configuration, however, had a constraint that required as much commonality as possible with the original aircraft. Even with this constraint, early in the design process, several alternative configurations were investigated and a sample of these configurations is shown in Figure 5. While this study was specifically directed to upgrading the F/A-18, it is believed that it is representative of the type of trade study that would be conducted by industry and therefore should be relevant to the development of MDO to the design process. Seven potential configurations to meet the US Navy missions needs in 1995 and beyond were investigated. These configurations spanned the range from minimum changes through Block Upgrades to major concept changes that reflected canard-wing arrangements popular at the time. The configurations were built from the same baseline and took advantage of planned upgrades. They also shared common requirements for an updated weapon system, survivability improvements and increased thrust.

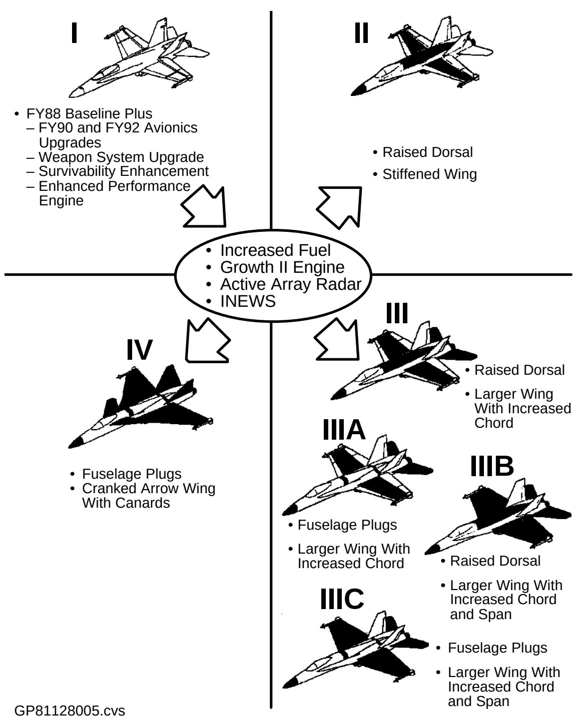

Figure 5. Configuration Options

Configuration I minimized the impact to the airframe. Weapon system updates were achieved within the existing space/volume. Pilot situational awareness was improved and workload decreased by upgrading the cockpit to display integrated weapon system information. Advanced air-to-air missile capability was provided along with the capability to carry air-to-air missiles on the out-board pylons.

The remaining configurations incorporated changes to the airframe. Common elements include increased fuel, new Growth II engines, and an electronically scanned active array radar.

Configuration II expanded mission flexibility with additional internal fuel in a raised dorsal. A configuration of this type was successfully used on the A-4M. Performance improvements were achieved with the higher thrust engines that required enlarged inlets. External stores carriage speeds were increased with a stiffened wing. Target detection range was more than doubled by adding the active array radar. Adding new electronic warfare equipment for passive missile detection and laser warning enhanced survivability.

Configuration III incorporated the upgrades of Configuration II while replacing the stiffened wing with an enlarged wing for enhanced carrier suitability, maneuverability, and mission performance. Additional growth space was also provided. Configuration IIIA enhanced the transonic/supersonic flight regime by utilizing a fuselage plug rather than the raised dorsal for increased fuel. Configuration IIIB optimized the wing area growth of Configuration III with an increased wing span for improvements in mission radius and carrier suitability performance. Configuration IIIC combined the fuselage of Configuration IIIA and the wing of Configuration IIIB for enhanced transonic/supersonic flight and improved mission and carrier suitability performance.

Configuration IV added fuselage plugs similar to Configurations IIIA and IIIC. However, the aerodynamic configuration was completely new and was targeted at potential co-development by the USN and an international customer. The wing was a cranked arrow wing and the stabilator was replaced by a canard. The vertical tails were also of a new design. This configuration shared the fuselage and all of the internal components of Configurations IIIA and IIIC including one of the major cost contributors, its avionics suite.

A detailed discussion of the features and benefits of each of these configurations is beyond the scope of this paper. Each presents new operational benefits and, in general, as additional benefits are added so is additional cost. For the future, MDO could be used to determine which configuration best meets the new requirements for an improved strike fighter. At the time the study was conducted, MDO techniques to aid in this decision did not exist.

The new engine, which was assumed for Configurations II through IV, fostered a significant multidisciplinary design integration activity. At the time of the Hornet 2000 study, this new engine was designated the F404 Growth II engine. The Growth II engine was to be an upgraded version of the F404-GE-400 engine that would have significant performance improvements throughout the flight envelope. It was to provide approximately a 25 percent increase in sea level, static installed thrust. At up-and-away conditions the installed thrust increase was estimated to be up to 40 percent over the current engine. The improved performance was to be achieved through incorporation of engine components that featured advanced aerodynamics and materials. The engine also featured increased engine airflow and higher operating temperature capabilities without a reduction in the current hot section life. While a growth inlet was required for optimization of the Growth II performance, the engines fit within the current F/A-18 engine bay. The engine that is installed in the F/A-18E/F has been designated as the F414-GE-400 engine and is an advanced derivative of the Hornet's current F404 engine family.

Configurations I through IV were evaluated against the following set of criteria: carrier suitability, strike mission, fighter mission, maneuverability, fire control system, survivability, growth potential, weapon system effectiveness and cost, both recurring and non-recurring. This evaluation was summarized in a stop-light format as shown in Figure 6 where G-green-indicates good, Y-yellow indicates marginal, and R-red indicated serious concern. It should be noted that if cost is considered, the conclusion as to which configuration is optimum is difficult to formulate. Clearly, all of the configurations represent some degree of improvement, but at some cost. All of the new configurations cost more than the baseline and all require some investment. The cheapest solution is to do nothing. On the other hand, as described earlier in the discussion of today's threat, to do nothing would put the aircraft in a situation where it would not be able to compete.

The Hornet 2000 Study identified four major study paths, with seven configurations for the Hornet Upgrade. The first path, Configuration I, was attractive from a cost standpoint but had degraded aerodynamic performance and little remaining growth potential. The second path, Configuration II had impressive weapon system improvement but suffered from carrier suitability shortcomings. The third path made up of Configurations III, IIIA, IIIB, and IIIC, had significant performance, carrier suitability and weapon system

Capability	Configuration							
	FY88	I	II	III	IIIA	IIIB	IIIC	IV
Carrier Suitability	G	Y	Y	Y	Y	G	G	Y
Strike Mission	Y	Y	G	G	G	G	G	G
Fighter Mission	Y	Y	G	G	G	G	G	G
Maneuverability	R	R	R	R	R	R	Y	Y
Fire Control System	R	G	G	G	G	G	G	G
Survivability	Y	G	G	G	G	G	G	G
Growth Potential	Y	R	R	Y	Y	G	G	G
Weapon System Effectiveness	R	Y	Y	G	G	G	G	G
Non-Dimensional Cost Range REC	1.00	1.14	1.30	1.37	1.36	1.40	1.39	1.46
NR	–	1.00	2.22	2.88	2.77	2.89	2.78	3.44

G Good Y Marginal R Serious Concern

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Figure 6. Hornet "2000" Configuration Evaluation vs. 2000 Threat

improvements. The fourth path, Configuration IV, had Control Configured Vehicle (CCV) potential with the canard-cranked arrow wing arrangement.

The Hornet Upgrade Configurations IIIB and IIIC offered the greatest increase in weapon system capability, carrier suitability and performance. They included a larger wing, more fuel, growth engine, 10 percent growth inlet, active antenna, upgraded crew station, integrated CNI avionics and an integrated electronic warfare system.

The final conclusion was that Configuration IIIC was the best path for upgrade since it was considered to have the best carrier suitability performance.

This discussion of the process that led to what was determined to be the best configuration provides valuable insight into the design process for MDO code developers. As stated elsewhere, an objective function that could be used to determine the optimum configuration would prove very difficult to formulate in this case. In fact, typical parameters that have been suggested as objective functions such as minimum weight or minimum cost were not the final discriminators of the selected configuration. In the final analysis, the configuration that was selected was the one that best satisfied the requirements within the constraint of retaining major F/A-18A configuration characteristics.

The F/A-18E/F Program - The F/A-18E/F program, which has its origins in the Hornet 2000 program, was awarded to McDonnell Douglas on May 12, 1992. The cost of this program for the development phase was $5.803 billion in 1992 dollars. This cost number can be regarded as another constraint on the design.

The F/A-18E/F rolled out on September 19, 1995 and its first flight was November 29, 1995. The aircraft as it appeared at roll-out is shown in Figure 7. Ten aircraft were built to support the flight and ground test programs, seven flight test articles and three ground test articles. The flight test program began at Naval Air Warfare Center Patuxent River, Maryland on February 14, 1996 and is ongoing. However, it is estimated that the EMD portion of the program is now 90 percent complete. As of January 31, 1998 1,463 flights representing 2,239.4 flight hours, had been flown.

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Figure 7. F/A-18 Super Hornet as it Appeared at the Roll-out Ceremony

While the Hornet 2000 study defined the basic shape and size of the E/F, the details of the design still were to be worked out.

Basic Changes - The primary changes developed during the study and the subsequent refinements are summarized here:

1) The area of the wing was increased by 25% to 500 square feet. This change was made to increase the range and payload of the aircraft.

2) A snag in the leading edge of the wing was incorporated. This design feature was part of the original F/A-18A design but was removed due to excessive loads on the leading edge flaps. It was reintroduced here to improve carrier landing handling qualities.

3) The LEX was enlarged and reshaped for better high angle of attack performance. Initially the LEX was basically an enlargement of the LEX used on the C/D aircraft. However, during wind tunnel testing the high-angle-of-attack characteristics of the E/F aircraft with that LEX were not as good as those of the C/D aircraft. The new LEX shape restored the excellent high-angle-of-attack characteristics that were pioneered on the F/A-18A aircraft.

4) The wing thickness-to-chord (t/c) ratio was increased. The C/D aircraft has a t/c of 5 percent at the wing root and a linear reduction from there to 3.5 percent at the wing fold. It is constant, 3.5 percent, from the fold to the tip. The E/F has a t/c at the wing root of 6.2 percent, tapering to 5.5 percent at the wing fold and further tapering to 4.3 percent at the wing tip. The increased t/c provides an increase in torsional stiffness with no increase in structural weight. It also allowed increased fuel carriage in the wing. However, the penalty is an increase in supersonic drag. The increase in torsional stiffness completely eliminates limit cycle oscillations when the aircraft is carrying external stores as has been verified by the flight test program.

5) A third wing station was added. This significantly enhanced self escort capability and gave the aircraft additional load carrying capability of 2,300 pounds. These new wing stations can be used for either air-to-air or air-to-ground weapons.

6) The inlets were enlarged for the increased airflow required by the F-414 engines and reshaped for improved radar signature. This reshaped inlet is clearly visible in Figure 8.

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Figure 8. F/A-18E/F Super Hornet Reshaped Engine Inlet

There are additional changes below the skin. These include substantially new structure, new mechanical systems, and modified cockpit displays. The avionics, however, are ninety percent common between the two aircraft. The reasons behind these design changes can be related to the design requirements described in the next section.

Description of the Design Process

Integrated Product Development (IPD) - During the 1980s McDonnell Douglas ran several pilot programs to test what was then an innovative concept for aircraft design called Integrated Product Development and this process played a significant role in the design of the F/A-18E/F. IPD is the process of defining, designing, developing, producing, and supporting a product, using a multidiscipline team approach. Note that the individuals on the team need not be multidiscipline but rather that the team has the required disciplines to perform its job. IPD, also known as concurrent engineering, pertains to the concept, analysis, and design stages of a product and provides the basis for bringing the optimum new product or product version to production in the shortest time. The word optimum as used here may not imply the same thing as one would obtain from a formal mathematical process. IPD encompasses the product life-cycle from initial concept through production and support. IPD also includes Integrated Product Definition plus product upgrades and process improvement for the life of the product. Integrated Product Definition is a subset of Integrated Product Development.

IPD requires a shift from serial to concurrent process structures. Traditionally, each discipline completed its tasks and passed the results on to the next discipline resulting in a sequential, or serialized, development process which generated rework because the delivered item did not fulfill the down stream customer's requirements, was incomplete, or was changed after release. Several iterations may be required to get the product delivered, corrected, and completed. The processes involved in the definition of a product have serial tasks. The IPD process strives to take the serial processes and perform as many of them concurrently as possible. Concurrent performance of sequential tasks requires redesign of those tasks to accommodate the new processes.

The IPD approach to product development has six definition phases that are shown in Figure 9. The first four phases are referred to as configuration synthesis and the last two are referred to as product/process

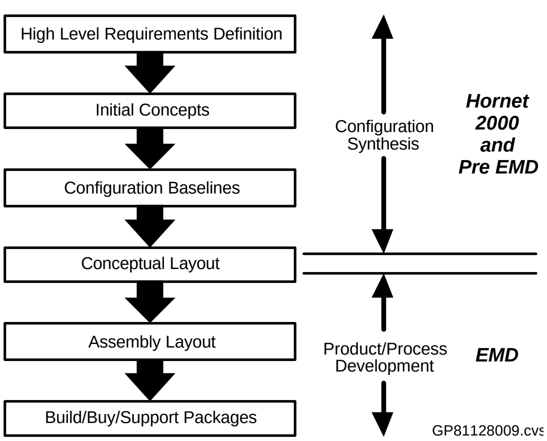

Figure 9. The Six Phases of Integrated Product Development

development. At the end of configuration synthesis a conceptual layout of the aircraft is available and at the end of the product development phase, the build to / buy to packages are defined. For the F/A-18E/F, the Hornet 2000 study corresponds to the configuration synthesis portion of the IPD process.

The six phases of product definition are executed during the DoD Acquisition Phases as shown in Figure 10. Each acquisition phase will satisfy certain milestone requirements before contracts are let for subsequent phases. Configuration synthesis, consisting of high level requirements, initial concepts, and configuration baseline definition phases, is executed during the concept exploration and development acquisition phase. The conceptual layout definition phase of configuration synthesis will occur during the Demonstration and Validation (DEM/VAL) acquisition phase. The assembly layout and build-to and support-to-package definition phases, for product and process development, are accomplished during the EMD acquisition phase.

<table>
<tr><th colspan="10">Program Phases</th></tr>
<tr><td colspan="3">Phase 0
Concept Exploration</td><td>Phase 0
Dem/Val</td><td colspan="4">Phase 2
Engineering and Manufacturing Development Phase</td><td colspan="2">Phase 3
Production</td></tr>
<tr><td colspan="6">IPD Phases</td><td colspan="4">Build Evaluation/
Production Phases</td></tr>
<tr><td>High Level Reqs</td><td>Initial Concepts</td><td>Configuration Baseline</td><td>Conceptual Layouts</td><td>Assembly Layout</td><td>Build-To, Buy-To, Support-To</td><td>Pre-Production Build</td><td>Initial Flight</td><td>Design Mods</td><td>Low Rate</td></tr>
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Figure 10. IPD Phases Related to the Major DoD Acquisition Phases

The F/A-18E/F program hierarchical team structure followed the Work Breakdown Structure (WBS), segmenting the work into discrete elements for estimating and budget allocation, tracking, and performance as shown in Figure 11. Budgets were allocated to each product center and team, making it easier for the team leader to manage the assigned work and maintain control of budget and schedule. Each level could then be assigned the responsibility, authority, and accountability for their product.

The E/F program was managed under the Cost Schedule Control System or C/SCS. This system works with the WBS defined above along with a detailed schedule and cost for each task. Metrics in the form of a Cost Performance Index (CPI) and a Schedule Performance Index (SPI) are two of the tools that were

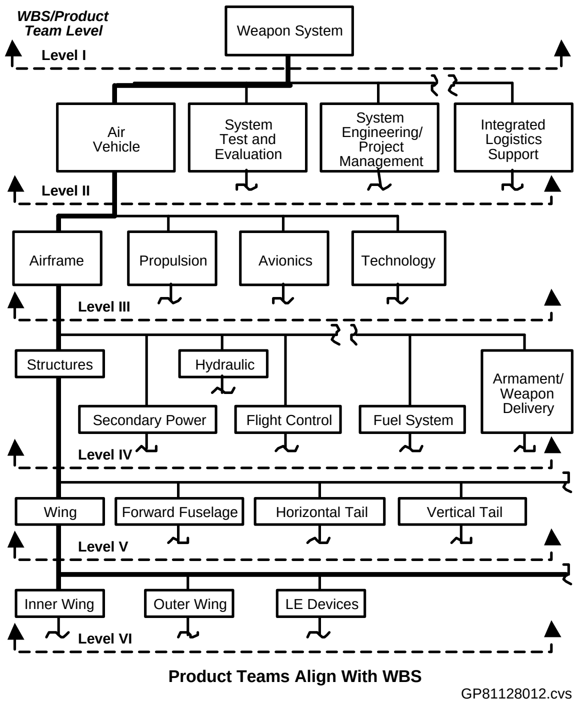

Figure 11. Work Breakdown Structure as Implemented on the F/A-18E/F

used to ensure that the E/F Program remained on schedule and within budget. These two indices provide the following information. The CPI is a measure of the work accomplished versus what it cost to accomplish it. This is an indication of the cost efficiency with which work has been accomplished. The SPI is a measure of the work accomplished versus what was scheduled to be accomplished. This is a measure of the schedule efficiency with which the work has been accomplished. These indices, along, with others were applied to the tasks defined through the WBS. Results were reported to the program managers so that they always knew where they stood relative to cost and schedule. It should be noted that the E/F program has basically remained on cost and on schedule since contract award in 1992.

Design Requirements - While the F/A-18C/D has performed well and demonstrated that the concept of a multi-mission aircraft is valid, usage also showed several areas where the aircraft could be improved. During the advanced design process, a number of requirements were investigated using standard trade studies and a final set of requirements was formulated and an enlarged aircraft that met these requirements was defined. These requirements were formulated relative to the C/D aircraft. In addition to the requirements defined below, if a requirement were not specifically identified, it was implicitly assumed that the E/F would be as good as or better than the C/D aircraft.

These requirements covered five areas where increased capability was desired. These were:

1) Increased Bring Back - The maximum weight of ordnance and fuel with which the aircraft can land on the carrier has been increased from 5,500 lb to 9,000 lb.

2) Increased Payload - The aircraft store stations have been increased from 9 to 11 and can be used for either air-to-air or air-to-ground weapons.

3) Increased Range - The maximum range of the aircraft has been extended up to 40 percent depending on the mission.

4) Increased Survivability - The ability to avoid damage from hostile forces was improved by up to 8 times depending on the threat.

5) Growth - Space for new hardware as well as electrical power and cooling capability have been increased by up to 65 percent.

These requirements were quantified and in effect became constraints that the design had to satisfy. In addition to the requirements described above a set of Technical Performance Measurements (TPMs) were defined which were allocated as appropriate to the IPD teams and were tracked for the aircraft. These TPMs were: weight empty, reliability, maintainability, survivability, signature, average unit airframe cost, growth in terms of internal volume, electrical power, and cooling, and built-in test which was tracked as false alarm rate and fault detection and fault isolation. In addition each team had requirements for cost, schedule, and risk.

Each of the TPMs was tracked in terms of its current value relative to a design-to value and a specification value. Figure 12 shows this tracking process as a function of time for empty weight. The chart shows that as of May 98 the actual weight was 666 lbs. above the design-to weight. However, this weight was over 384 lbs. below the spec value. Thus, while weight was not being minimized as an objective function, its value was being closely tracked to ensure that its upper limit was not exceeded. In addition the weight was being kept below the spec value in anticipation that changes might be required as a result of EMD testing. Similar tracking was carried out for all of the TPMs.

If the strict definition of MDO is used, MDO was not used to design the F/A-18E/F. However a multidiscipline process that produced a design that satisfies all of the constraints was used. As an example, the technology disciplines of aerodynamics, flight control flying qualities, structural loads and dynamics, and materials and structural development were linked

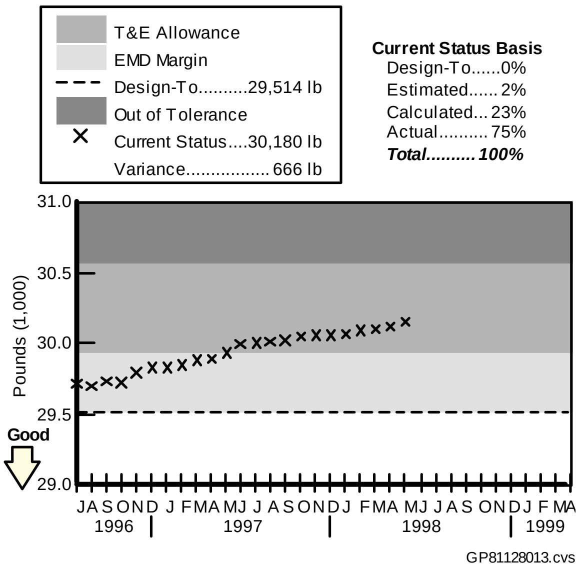

Figure 12. F/A-18E/F Empty Weight

through a common database and analysis tools as shown in Figure 13. Each of these disciplines is driven by a specific set of requirements and each is responsible for a given set of products that taken together define the airplane.

For example, the structural loads and dynamics group is responsible for design loads, the dynamic environment, and aeroelastic stability. In order to accomplish this each discipline must communicate with the other disciplines. One tool used to accomplish this was the use of a common database.

Taken as a whole the interactions among these disciplines produce a balanced set of requirements.

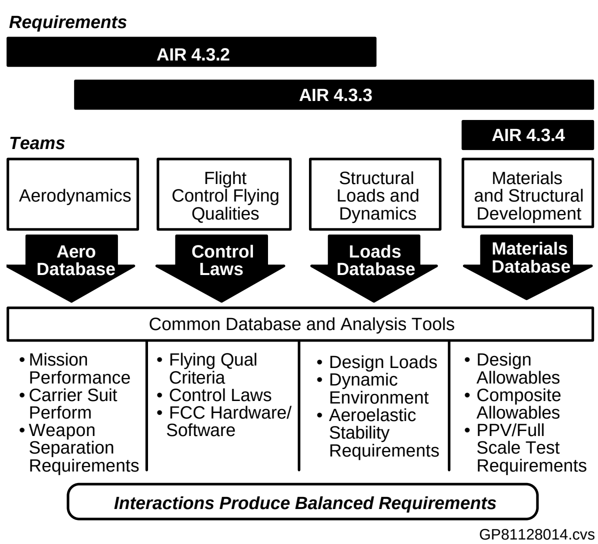

Figure 13. Airframe Technology Key Products and Requirements

The interactions among the disciplines can be viewed from the standpoint of common tools as well as common data. An example of this is shown in Figure 14. In this case a tool referred to as MODSDF which is a six degree-of-freedom simulation code is being used to determine critical design loads. For this tool to work, input is required from several sources. These inputs can be in the form of criteria, such as Mil Specs or data such as mass properties. One of the ingredients is past experience.

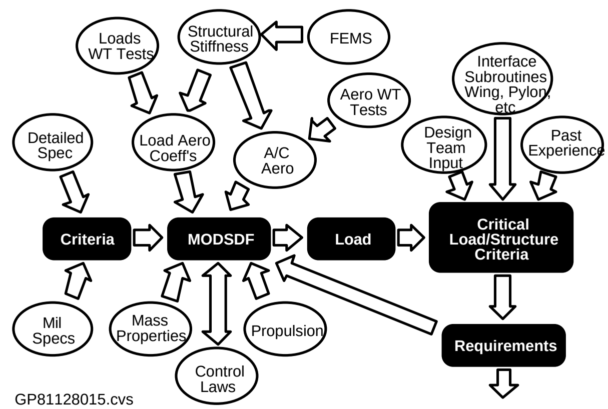

Figure 14. Flight Technology Requirements Development

An example of how this process can be used to improve the design is shown in Figure 15. In this case the trailing edge flap was used as a maneuver load alleviation device and its effectiveness was determined using the MODSDF code. As the aircraft pulls load factor the trailing edge flap is scheduled down by the flight control system as a function of load factor. The result is a modification of the lift distribution with less lift on the outer panel of the wing and more on the inner panel. This reduces wing bending moment, which results in a reduction in wing weight. This process is an example of a multidisciplinary approach to design that produces a better aircraft than would be possible if each discipline simply worked alone.

One final point about the design process needs to be made and that is the importance of the aerodynamic database. Figure 14 shows that two of the drivers for the MODSDF code are the aerodynamic wind tunnel tests and the loads wind tunnel tests. The generation of this data is one of the key ingredients in the design process. During the period from the start of EMD in 1992 to first flight in 1996, approximately 18,000 hours of wind tunnel occupancy time was accumulated with more than half of this being used by aerodynamics. In addition to the MODSDF simulation tool, pilot in the loop simulation is also extremely important and over

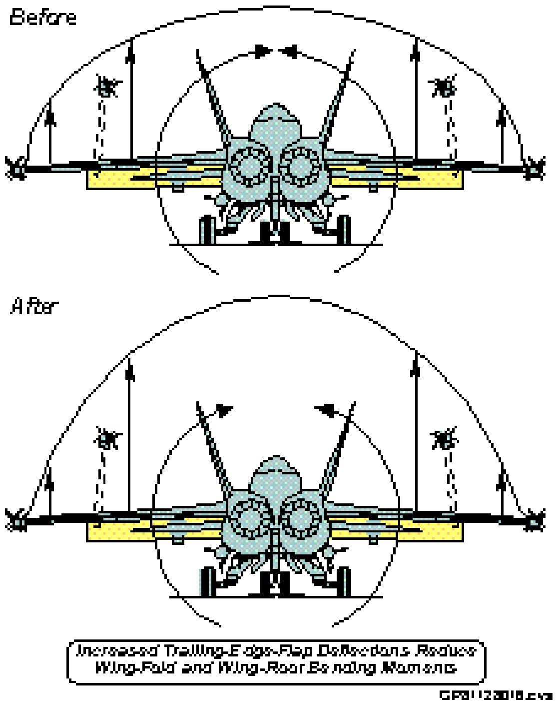

Figure 15. Load Alleviation of Wing-Fold and Wing-Root

1000 hours of pilot in the loop simulation were accumulated by first flight. Both of these simulation tools require a detailed aerodynamic database.

Results

The F/A-18E/F has completed the majority (90%) of its flight test program and the results to date have been outstanding. The program is on schedule, on cost, and the aircraft is below the specification weight. The aircraft has met all of its requirements and will provide the Navy with an aircraft that will meet its needs well into the 21st century. While these results validate the design process that was used for the F/A-18E/F aircraft, it is always possible to improve. What follows is a discussion of a series of questions from the session organizers concerning what is needed in the MDO process. This discussion is based on the experience from F/A-18E/F program and other experience of the authors.

Barriers, Obstacles, etc. - The major obstacle to MDO is the inability to analytically determine the design variables and their sensitivities. Meaningful design does not occur until the wind tunnel data base has been determined. While Computational Fluid Dynamics (CFD) may ultimately replace the wind tunnel, until this happens the aerodynamic model cannot be coupled with the other disciplines. Organizational barriers can exist. However, the F/A-18E/F program showed that the transition to an IPD organization is possible. Surely, the transition to an MDO based organization is possible once the benefits are demonstrated.

Design Problem and Design Goal - The goal is to design an aircraft that satisfies the requirements. An MDO code should aid in making the design feasible as rapidly as possible. Once a feasible design has been found, the next most important thing is to determine the robustness of the design.

State of Software Integration Tools - Tools such as database management, simulation, distributed computing, etc. have all contributed to the integration of the design process. The F/A-18E/F uses a common database for aerodynamics, control dynamics, loads, and structures.

MDO Simulation for non-linear Loads - The significant challenge here is the generation of the non-linear aerodynamic database. Once this data base is generated, the simulation and the control law design can proceed. Once these elements are in place, loads calculations can proceed.

Barriers to the Use of Disciplinary Analysis in MDO - While several issues were identified, fidelity of the models is the most significant. It makes no sense to optimize a design based on low fidelity data.

Loosely Coupled versus Tightly Coupled Approach - There is no inherent reason why a tightly coupled approach could not be used. However, it is difficult to see how a tightly coupled approach could contain all of the constraints that are present in the loosely coupled one that makes use of all current detailed design tools. A tightly coupled code run by an expert could serve as a check on the more detailed loosely coupled approach. However, this could also create conflict if the two methods don't agree.

Use of Sensitivity Derivatives - The use of sensitivity derivatives will become wide spread only after the design community becomes familiar with them. At present the concept of dollars-per-pound is well under stood by all designers but it is not clear that all sensitivity derivatives in general are in this category. On the other hand, a trade study where two variables are compared directly can usually be understood by anyone.

Automatic Differentiation - The trend in industry is toward off-the-shelf software when possible. Extending this to automatic differentiation might imply that the software vendors should assume the lead here.

Single Most Important Obstacle to MDO - The aerodynamic model matures first and the other models depend on this one. An accurate aerodynamic model is based on wind tunnel data that may not produce the sensitivity derivatives needed for MDO.

Use of MDO Based on Decomposition - Since MDO tools as such did not play a major role in the F/A-18E/F design, there is no reason to single out any particular method. However, before any method will be used in a production aircraft design environment, it will have to prove itself.

Top MD Development - Rapid CFD for air loads.

Summary/Conclusions

The design process for a modern high performance aircraft is a complex process that involves the integration of analyses, tests, databases, and finally the people who make the process happen. For the F/A-18E/F aircraft these ingredients have come together to produce a superior product. While the process did not make use of mathematical optimization in a formal sense, the final product does indeed satisfy all of the design requirements that would be represented in the form of constraints in the MDO process. In fact, since the F/A-18E/F is a multi-role aircraft, the formulation of a single objective function would be difficult if not impossible. The following observations can be made:

1. Formal MDO was not used as part of the F/A-18E/F design process.

2. For a multi-mission aircraft, the formulation of an objective function is difficult if not impossible to define.

3. The aircraft is designed by its requirements. This is another way of saying that the aircraft is designed to meet a set of constraints.

4. The design process involves more than a coupling of mathematical tools. The people who operate these tools are an essential ingredient.

5. The IPD design process contributed to the success of the F/A-18E/F program.

6. The design process is serial in that an aerodynamic database is required to design the flight control system. Both the aerodynamic database and the flight control system are required to define loads. Loads are required to define structure. Flex-to-rigid ratios are defined after the structure is sized. These ratios are used to correct the aerodynamic database. And the whole process is iterated. All of this can be done once the moldline of the aircraft is defined.

7. The aerodynamic database is the key. This database is very non-linear. For the F/A-18E/F, the aerodynamic database was established by wind tunnel testing. In the future CFD may have the capability to generate this database.

8. For a multi-mission aircraft, MDO tools that rapidly generate a feasible design, one that satisfies the requirements, would be valuable. Once the design is feasible, these tools should allow for rapid "what if" studies. The manufacturer and his customer should make the ultimate decision for what is best to meet the requirements.

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