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AFFORDABLE EVOLUTION: ENGINEERING CHANGE PROPOSAL (ECP) 6038 F/A-18E/F FORWARD FUSELAGE STRUCTURAL CERTIFICATION

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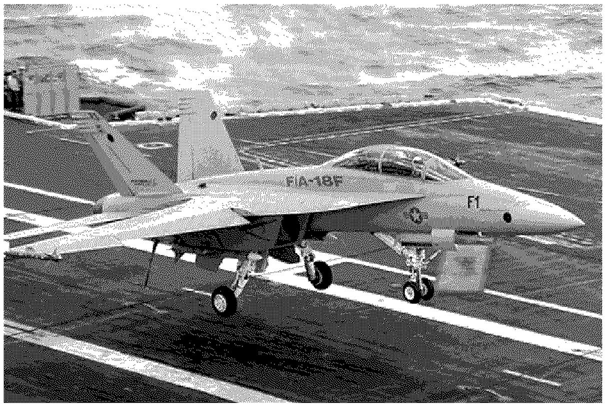

Abstract

The F/A-18E/F is getting an improved forward fuselage which can be built at a substantially lower cost while accommodating a new Active Electronically Scanned Array (AESA) radar. Structural design and certification costs have been mitigated by simulation and analysis. These efforts launched early in the program established confidence that some requirements, traditionally demonstrated by test, could instead be satisfied with high fidelity modeling and simulation.

Structural recertification costs have created a barrier to change in the past. At the same time, aircraft programs face pressure to improve performance, accommodate new avionics and equipment, expand payloads, correct defects and improve affordability. Engineering Change Proposal (ECP) 6038 authorizes a change to the F/A-18E/F Forward Fuselage. Early high fidelity analysis and simulations built upon the large foundation of data gathered during the Engineering and Manufacturing Demonstration (EMD) phase of the F/A-18E/F program provided the confidence that design goals could be met and that testing could be minimized.

The excellent matching of EMD test data was not only a major accomplishment of the ECP 6038 team. It also establishes a concept of modularization in that a relatively large component of the aircraft has undergone a significant design change without affecting the rest of the air vehicle. This has far reaching implications toward future change strategies.

Introduction

The F/A-18E/F Program has demonstrated excellent program performance over the last decade. Incorporating a larger wing plan form with thirty three percent more fuel and two more wing pylons results in twenty eight percent more payload. The E/F has been on schedule, on cost and performing to plan.

At its beginning an Active Electronically Scanned Array (AESA) radar was envisioned in the E/F's future. The airframe was designed to accommodate the weight of such a component. Engineers even tried to anticipate how they might integrate the future radar with its neighboring structure. As AESA has come to fruition its fiber optics, cooling lines, wire, and conduit could still just fit in the space provided some years back. However, future growth was very constrained. Figure 1 represents the forward fuselage systems with none of the structure represented.

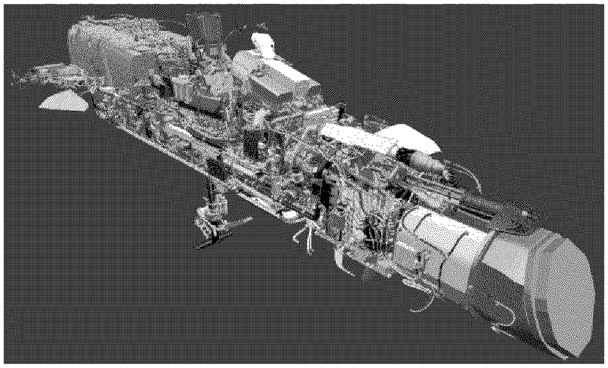

Figure 1. Forward Fuselage Systems With AESA

A critical eye was cast upon the existing forward fuselage structure. This component of the F/A-18E/F airframe retained much similarity to it's A/B/C/D ancestors. An integrated team of designers, structural analysts, dynamicists, manufacturing engineers, airframe mechanics,

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systems installers, test engineers and cost analysts studied the forward fuselage for ninety days in February to May of 1999. They concluded a different design could be built for less recurring cost and systems routing could be enhanced. ECP 6038 implements the conclusions of this study.

The ECP 6038 Configuration

The ECP 6038 configuration replaces the extensive use of sheet metal and smaller machinings with composite moldline skins, highly unitized machinings and a large aluminum sand casting in the in-flight refueling probe area. The part count reduction is evident by the comparison of Figures 2 and 3.

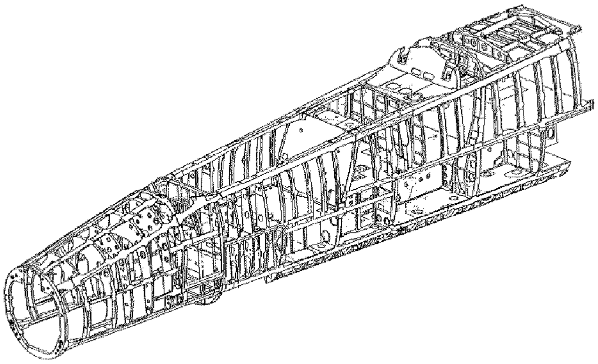

Figure 2. Original F/A-18E/F Forward Fuselage Substructure

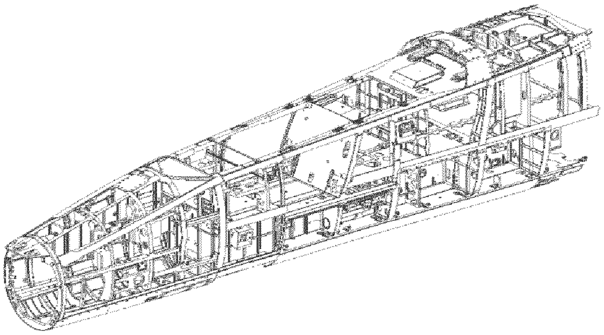

Figure 3. ECP 6038 Forward Fuselage Substructure

In addition to the obvious part count reduction, the assembly of these parts is further simplified by coordination of part features so that the need for assembly tooling has been dramatically reduced along with the part count. These structural modifications to the forward fuselage improve the affordability of the F/A-18E/F forward fuselage while integrating equipment and providing additional system routing paths for future growth.

The scope of ECP 6038 completely redesigns the forward fuselage from Y128.5 at the radome to Y383 at a manufacturing splice. Major forward and aft running members were retained from the original structure preserving the load paths of the previous design. Although extensively changed this configuration maintains commonality with the original configuration at the outer moldline, pilot's eye, inflight refueling receptacle, gun, nose landing gear, canopy, and the aft manufacturing splice. These areas are shown in Figure 4.

The new ECP 6038 configuration has achieved forty percent fewer parts, fifty one percent fewer fasteners, and twenty six percent fewer standard assembly hours. The first article to be built, designated FT76 and serving as the full scale structural test article, demonstrated eighty four percent fewer defects than airframes (E20 to E25) constructed of the original configuration. In full rate production the assembly cycle time is expected to shrink by thirty one percent.

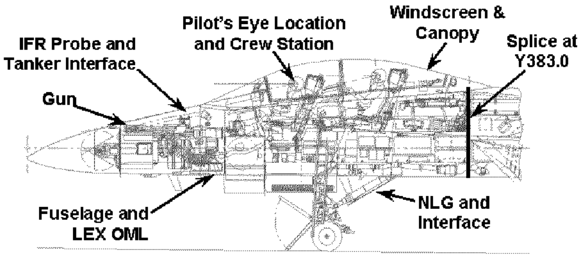

Figure 4. F/A-18F ECP 6038 Design Constraints

The Structural Certification Challenge

The F/A-18E/F ECP 6038 Forward Fuselage implements a redesign of the structure for maximum affordability and systems growth. It maintains the overall structural load paths of the existing E/F forward fuselage but minimizes part count through unitization. This strategy preserves the applicability of what has been learned in the Engineering and Manufacturing Development (EMD) phase of the program. The legacy static, dynamic and flight test data including the associated lessons learned have been comprehensively applied during the synthesis of the ECP 6038 configuration. Testing has been minimized and test assets are being reused where possible.

As previously mentioned, the new fuselage preserves the load paths of the original design. This was a critical strategy. To preserve the assumption that the external loads and some internal loads of the forward fuselage did not change, it was important to control the dynamic characteristics of the airframe and some local interface stiffness. These would be continuously monitored throughout the synthesis and maturation of the design.

External Loads - Flight maneuver loads associated with multiple store releases were one type of loading which could affect the forward fuselage. However, the most important loads where associated with catapult and arrested landings. Global bending stiffness and local nose landing gear backup stiffness of the fuselage are important to these types of loading.

The shock loads at the terminal phase of a catapult were particular concern. This event induces high accelerations on the locally mounted equipment and the forward fuel tank. Increases in the severity of this phenomenon could affect equipment qualification loads. The tank would undergo extensive unitization and the design team needed to pay attention to this event in the tank design.

Aero-elastic Stability – Although flutter is not usually particularly sensitive to forward fuselage dynamics, the F/A-18 has a quite long and narrow forward fuselage configuration. In the early A/B/C/D models the wing Leading Edge Extension (LEX) had only a couple of discrete structural connections to the fuselage. In these models, forward fuselage lateral bending stiffness played an important role in some of the flutter mechanisms.

The E/F configuration has a much larger LEX which is continuously attached to the side of the fuselage. Therefore lateral fuselage bending is not as predominant in the flutter mechanisms as with the earlier models. Still the ECP 6038 team needed to assure that this characteristic was preserved.

Aeroservoelastic (ASE) Stability – The first vertical bending frequency of the fuselage affects the longitudinal stability of the flight control system. If this frequency changed by much, new software and new validation tests may be required.

Y383 Manufacturing Splice Loads – Containing the extent of the redesigned areas was a major concern of this program. The rest of the airframe was already certified. Change beyond the manufacturing splice would clearly begin increasing the nonrecurring implementation costs. Therefore it the splice had to remain the same both physically and with respect to loading distributions.

Other Components – The canopy, windscreen, nose landing gear system, and gun were not to change. The stiffness at the interfaces with these items had to be controlled so that interface loads to which these items were qualified would remain the same.

Weight Neutrality – The forward fuselage changes were to be weight neutral in there impact upon the airplane. As previously stated, the beginning of the E/F program the added weight of an AESA radar was included in the design. Performance and loads calculations included this affect and weight and balance was preserved in the existing aircraft thru ballast in the nose. The new fuselage was not to impact the combined structure/ballast weight.

Three Lifetimes – The only exception to weight neutrality was an allocation to design the new airframe to three lifetimes (Eighteen thousand hours of spectrum fatigue). The airframe is intended to have a six thousand hour life. Normally the fatigue test is intended to demonstrate twice the design life to account for normal variation in material properties and variations in the severity of fleet usage.

The rational behind the three lifetime requirement was the desire to make the airframe as robust as possible. The EMD fatigue test has already extended its required twelve thousand hour demonstration toward a goal of three lifetimes. If three lifetimes were used as a goal for the ECP 6038 design, it increases probability of achieving its required minimum the two lifetimes and holds the possibility of extending the life by analysis of the test results.

Simulation Addresses Early Risks

The F/A-18E/F is in production. If introduction of the new fuselage were delayed until all the risks could all be mitigated with testing, the benefits would be moot. So there was a practical reason for minimizing test requirements aside from their nonrecurring costs. A strategy of combining simulation, testing and reusing existing test assets was explored. What requirements could substantially be satisfied by analysis alone and what requirements absolutely required test verification?

An Underappreciated Asset - The biggest asset the ECP 6038 customer/contractor team had was the wealth of data that had been collected during EMD. There was static, fatigue and dynamic strain gage, deflection gage and accelerometer data for thousands of ground and flight test points. Plus there was the knowledge within the team composted of F-18 veterans combined with state of the art developers of what had worked and what did not.

The concerns over external loads, flutter, ASE and component interface loads all revolve around stiffness. Stiffness could be determined by finite element modeling. In the last decade, computing capability had increased by orders of magnitude. Therefore very comprehensive models could be built.

One major confidence building measure was to build a completely new finite element model (FEM) of the EMD forward fuselage as depicted in Figure 5. The new FEM was then rigorously correlated with the test data acquired during the static, fatigue and ground vibration testing. The FEM of the new ECP 6038 configuration would incorporate anything learned in this process. With these two models there was a consistent way to evaluate the relative differences between both configurations.

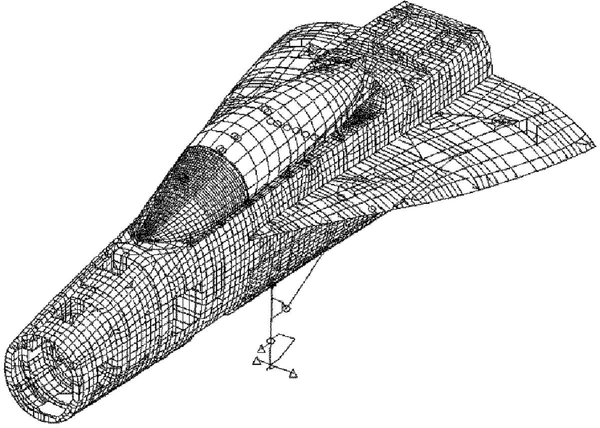

Figure 5. A New EMD Finite Element Model

What constitutes good correlation? That was not a straight forward question. In the static tests, ultimate load was only reached once. That really could not be considered a statically significant sample. The fatigue tests provided a better sample size with strain surveys being repeated throughout the test. This not only provided an average response. It also provided a standard deviation. Variation was something that had not really been considered until the team started asking how to implement the process. The standard deviation provided an estimate of systematic variation in the tests. Something for which the FEM could not be held responsible.

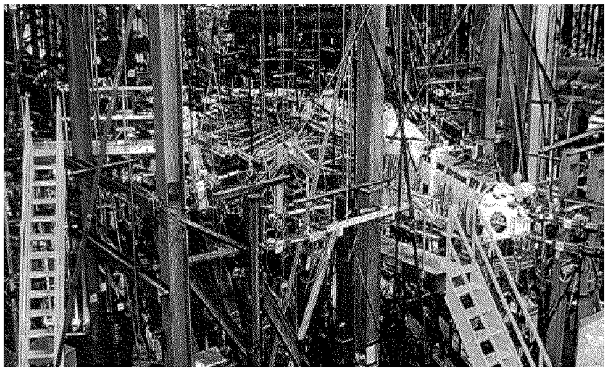

Figure 6. EMD Full-Scale Airframe Test

Although an individual hydraulic cylinder might have very little individual variation, when combined with the one hundred and eighty one other load controllers in the full-scale fatigue test as shown in Figure 6, greater variation is bound to occur.

This study of the fatigue test strain survey results for seventy five gages and thirteen conditions showed the strain gage standard deviation to be about 7.6% for measurands placed near the major members during the repeated strain surveys conducted every one thousand spectrum flight hours. For secondary members the variations were higher although stress levels were lower.

Manufacturing variation could introduce additional variation in a new test article which should be considered in predicting responses. Taking this variation into account, all the strain gages associated with the significant load paths in the EMD FEM matched the test data. The model deflections were indistinguishable from the test article as well. Similar to the terminology used in manufacturing to describe a design that accounts for manufacturing process variations, ECP 6038 refers to the FEM as being correlated within the process capability of the test data.

Although the forward fuselage had relatively few problems during the EMD test program, those anomolies that did occur were studied during the strain correlation work. These results suggest that every part of the vehicle that has a remote chance of picking up load by straining sympathetically with the structure should be represented in the FEM even though past practices tended to discount "nonstructural" parts.

Interface Loads at Y383- A detailed comparison of the validated EMD finite element model with the model of the new structure showed a good match of the interface loads for the critical design conditions. The major members matched within 5% with no attempt to tune the results. As the model matured, the differences between the models narrowed to about 2.5%, well within the scatter of the test data. For all intents and purposes the interface loads were deemed "no change" with respect to the rest of the vehicle.

Any risks could now really be considered to be contained within the redesigned area. Since the static test article, dubbed ST 50, was still available (Figure 6) with its complicated test set up in place, the costs of a fatigue and static test of the forward fuselage were relatively small considered the risk reduction it could provide. Although for new structure and the analysis capability available today one might argue foregoing a test was a legitimate possibility, in this case it was decided to test the new design using the old test set up to mitigate the cost. Fatigue first, after which the static ultimate tests would be conducted of a new forward fuselage on the reused aft section of static test article.

Global Dynamic Response - With a correlated static representation of the structure, the dynamic response was contemplated next. Although the thicker composite outer moldline skins make the forward fuselage slightly stiffer than the EMD configuration, it was important to assure the global mode shapes are essentially the same to prevent gross changes in the flutter mechanisms of the vehicle. A slight frequency increase was expected.

Should the stiffness increase pose a problem, ways of stiffening the skins were contemplated that would lessen the fuselage impact. But these approaches would cost more. Continuing with the stiffer fuselage and evaluating the ramifications in pursuit of cost savings was the course followed. The detailed finite element models were used to support the analytical estimation of global air vehicle natural frequencies. Compatible with the detail included in the FEMs for structural analysis, the mass properties were distributed to these models in a very detailed fashion. The detailed models were excercised dynamically along with less detailed beam-rod dynamic FEMs to evaluate the responses of the new configuration.

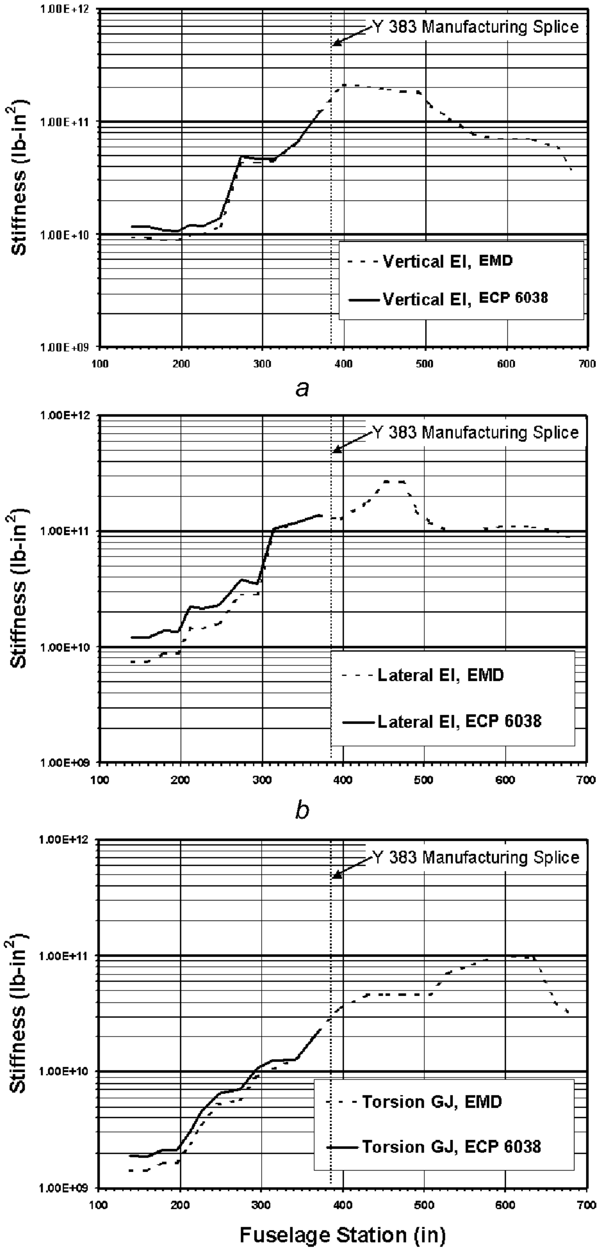

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Figure 7. Half Fuselage Vertical, Lateral and Torsional Stiffness Comparisons

Within two months of the program kickoff the first estimates of frequency differences between the

EMD and ECP 6038 configurations were being determined and preliminary impacts on flutter, ASE and store release loads were being assessed. Even with stiffness differences well in excess of these initial estimates, run as hypothetical worst case scenarios, the affect was benign. Figure 7 compares the vertical, lateral and torsional stiffness differences the EMD and ECP 6038 configurations.

	Min.	Max.	Avg.
F1VB	2.5	6.6	3.4
F2VB	2.1	5.4	2.4
F1LB	1.3	10.4	6.4
F2LB	3.7	11.8	7.8
F1T	1.4	13.4	5.6

Table 1. Percent Change In Air Vehicle Frequencies

With the stiffness increases determined they were subsequently used to determine natural frequency changes and finally the impact of these changes on flutter mechanisms and speeds. Table 1. shows the change in frequencies over a variety of internal fuel and store configurations. The first vertical bending frequency increase ranges between a 2.5% to 6.6% increase.

For most the flutter mechanisms these stiffness changes increased the flutter speeds. One clean wing mechanism dropped by 0.1% and one of eighteen critical stores carriage configurations lost 2%. These were considered acceptable. Structural modal Interaction (SMI) with the flight control system was not considered a barrier to proceeding either.

To confirm the performance of the new design an E-model aircraft with be ground vibration tested on three clean wing fuel states and two store configurations. An F-model clean wing will also be tested. An SMI test will be performed on an E-model aircraft. Far short of a comprehensive flight test program

<u>Catapult Shock Response</u> – The structure and the systems contained in the forward fuselage undergo large short duration accelerations during catapults and arrested landings. As illustrated by the load versus time history curve of catapult tow force in Figure 8, the force undergoes a moderately rapid rise to about 250,000 pounds at the beginning. It sustains this loading for a period of time. Then it abruptly drops to nothing when the shuttle of the catapult hits the water break, launching the aircraft.

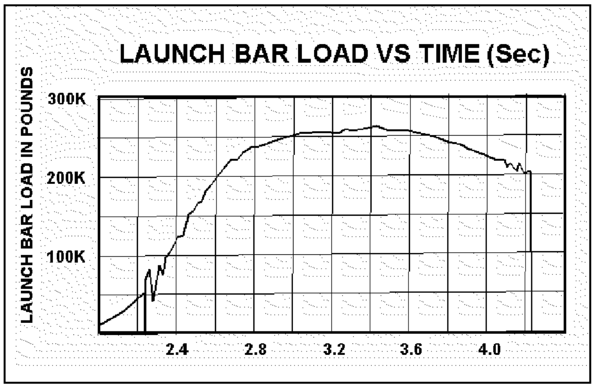

Figure 8. Catapult Force Versus Time

The abrupt event at the end of the stroke causes locally measured vertical accelerations of as high as 40g in local portions of the forward fuselage. The new design could not be permitted to increase the severe environment associated with this event. Much of the equipment in fuselage was qualified to this specific environment and a fuel tank is located in the area most subjected to the large vertical acceleration.

The structural response during the beginning of the catapult stroke is a direct result of the load applied with a small dynamic oscillation superposed. During the relatively flat plateau, the airframe stabilizes with a deflected shape similar to that pictured in Figure 9, an exaggerated representation of the finite element model under catapult loads.

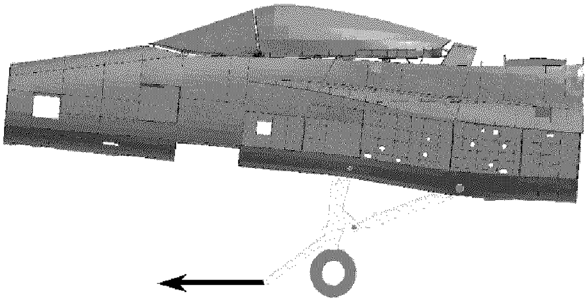

Figure 8. Catapult Distorted Forward Fuselage

The deflected shape of the structure clearly shows how the drag brace of the nose landing gear pulls forward and downward on the local structure. This strain energy is abruptly released at the end of the event. The high local distortion near the back of the drag brace results in a large vertical acceleration of the equipment bay and fuel tank directly above the drag brace.

The fuel tank was one of the areas of particular concern because of the configuration change to the floor of the tank turning it from a ninety piece combination of sheet metal and machinings into two highly integrated machinings buried in the heart of the assembly. The design team had to confident that they understood the fuel to structure interaction during this highly dynamic event to avoid future problems.

To fully understand the response a nonlinear transient simulation of the tank during the vertical acceleration was performed with fuel to structure interaction. This model is depicted in Figure 9.

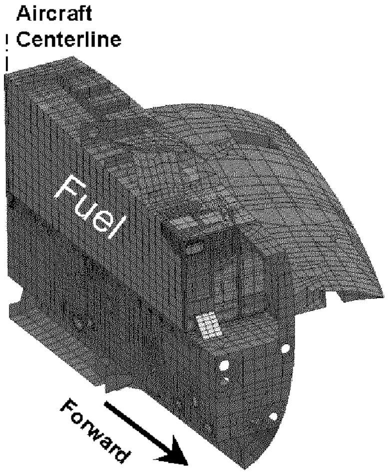

Figure 9. Fuel-Structure Interaction Model

The previously measured time histories from EMD flight test similar to the one shown in Figure 10. were applied to the model of the fuel tank. It was important capture the response time history as well as the peak stress levels to determine the allowable fatigue stresses for this part of the structure. This transient response was combined with the other flight and ground loads to create a composite loading spectrum representing a comprehensive set of loading events on the floor for design and also to assure repairability.

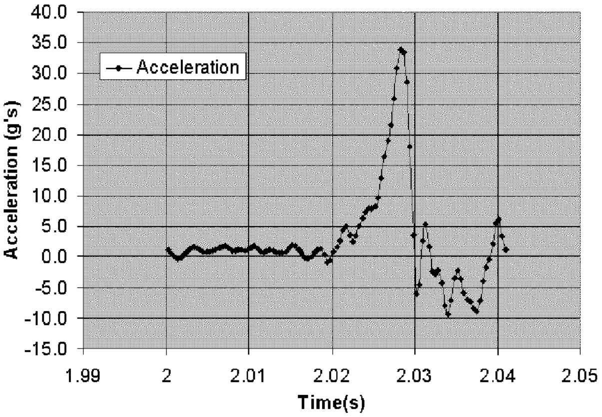

Figure 10. Structure Acceleration Time History

With the successful characterization of the this loading event it was not felt necessary to provide additional testing of the structure through some sort of component testing. Instead, the first airframe would be measured with a small number of accelerometers and strain gages during a full scale series of catapults to confirm the conclusions of the simulations.

Test Requirements Summary

Considering the scope of the ECP 6038 forward fuselage change, early analysis and simulations have built confidence in the understanding if the new design to keep the magnitude of the required physical test demonstrations austere. A fatigue test to two lifetimes and static test will be run on the same airframe reusing the aft section of the EMD static test article.

Because of the large panel sizes of the composite skins, an acoustic demonstration panel will be tested. Acoustic measurements will also be conducted on the ground during a gunfire test and for about four flights with about forty measurands.

Full scale ground vibration and structural mode interaction tests will be conducted to validate the flutter and control systems evaluations performed to date.

Finally the structural response of the forward fuselage will be measured during catapults and arrested landings to assure the responses match the detailed simulations run on the full cell and on other pieces of equipment.

Conclusions

Today's computing environment has provided the ECP 6038 program with alternatives to physical tests with modeling practices validated with previous similar experience. The vast test data available from the F/A-18E/F EMD Program provided a basis to validate modeling practices providing these analysis alternatives. The customer/design team could then contemplate what alternatives could satisfy some requirements traditionally done by physical demonstrations.

The EMD model validation effort built confidence that the scope of the change was limited to the forward fuselage requiring no effort beyond the manufacturing splice.

The global stiffness changes were determined to be benign with respect to flutter and the flight control system. This avoided the requirement for an extensively outfitted aircraft to perform flutter clearance and control law validation flying.

Finally the local simulations of transient response provided confidence that the structure would behave like its predecessor on a smaller scale avoiding equipment and systems re-qualification.

The ECP 6038 forward fuselage effort is proving that large changes to existing systems can be made affordably and that modularity concepts in new systems are viable.

Paper #24
Discussor's Name: Jacub Kacekowski
Author's Name: Mark K. Holly

Q: How do you perform static tests, especially with mixed structures?

A: Mixed composite/metallic structure present a certification challenge. It is uneconomical to perform tests at temperature plus it requires an extremely long time to saturate a structure with moisture to represent the environment properly. Therefore, even in the most test intensive of programs, it is usually necessary to rely on analysis to combine and evaluate the full-scale results, correcting for thermal and environmental factors. The environmental effects should be determined by coupons and thermal stresses would be determined by finite element modeling.

The full-scale article, if taken to failure, would help to determine the magnitude and mode of failure, then analytical corrections would be applied. If the mode of failure was precipitated by buckling, the analysis becomes nonlinear and complex.

In the end it is nearly impossible to certify a structure solely by testing.