Prevention of External Store Limit Cycle Oscillations on the F/A-18E/F Super Hornet and EA-18G Growler Aircraft

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ABSTRACT

The F/A-18E/F Super Hornet and EA-18G Growler can trace their lineage back to the F/A-18A-D Hornet, which exhibited Limit Cycle Oscillation (LCO) phenomena with the carriage of medium and heavy weight under-wing ordnance. Flight testing of the F/A-18A-D variants to verify LCO-free flight envelopes continued throughout the production life of the aircraft. The need to continually flight test new external store loadings to define LCO characteristics is common to other thin-wing fighters such as the F-16 Falcon, and is very costly and time-consuming. Thus, the elimination of under-wing store related LCO on the F/A-18E/F, and the EA-18G, was a high priority of the Boeing/Navy aeroelastic stability team. This paper will review the 5.6 Hz and 8.5 Hz LCO phenomena on the F/A-18A-D Hornet, and will discuss design changes in the development of the Super Hornet to successfully eliminate these oscillations, as well as the analysis, and the ground and flight testing conducted on both the F/A-18E/F and EA-18G to ensure that a robust solution was obtained.

1.0 BACKGROUND

The so-called "Lightweight Fighter Competition" of the early 1970's eventually spawned two of the most successful aircraft of the late 20th century, the General Dynamics (now Lockheed Martin) F-16 Falcon for the U.S. Air Force, and the McDonnell Douglas (now Boeing)/Northrop F/A-18 Hornet for the U.S. Navy/Marines. Given the fact that the origins of these aircraft stem from similar design goals, it is not surprising that there are several similar design features, such as a thin wing (on the order of 3% thickness-to-chord ratio, t/c), underwing pylons, and a wing tip missile station. The similarity of these aircraft extends also to a shared difficulty; specifically, wing/store limit cycle oscillations, or LCO. These oscillations are an operational factor on external store carriage speeds for several configurations, both with wing tip missiles on and off. The F/A-18A-D aircraft has been able to minimize the impact of LCO for tip missile on configurations through the use of Active Oscillation Control (AOC) [1], [2]. However, even with the AOC, the cost impact of flight test verification and safe carriage envelope determination was very high. LCO testing was conducted on the F/A-18A-D throughout its production life, which ended in 2000, and it continues on the F-16, some 30 years after first flight. Therefore, the elimination of under-wing store LCO and related flutter issues was a primary design consideration for the Boeing/Navy aeroelastic stability team when the design of the F/A-18E/F Super Hornet was begun in 1991.

1.1. F/A-18A-D Hornet LCO with Tip Missiles On

The legacy Hornet exhibits antisymmetric wing/store LCO at approximately 5.6 Hz, with wing tip missiles on. The oscillations occur with the carriage of heavy and/or high pitch inertia under-wing stores on the outboard pylon in the high subsonic speed regime, and generally at low altitude. The LCO stems from the fundamental wing/store flutter mechanism involving wing bending and outboard store pitch modes. The wing bending mode shape is coupled with fuselage lateral bending, and the node line is aft of the cockpit, such that the pilot directly experiences the motion. The oscillations are very sensitive to Mach number and exhibit non-classical flutter behavior in terms of angle of attack sensitivity. The character of this LCO is shown in Figure 1, where the oscillations self-initiated as the Mach number slowly increased, and in Figure 2 where the oscillations occurred at elevated load factor (representing increased angle of attack) following a lateral control stick rap. The crew comfort limits of Mil-Spec 8870 [3], are shown in Figure 3, and ultimately defined the amplitude limits of permissible oscillation magnitude. The AOC was designed [1] using existing flight control sensors because the 5.6 Hz LCO frequency was low enough to be identified at the nominal control system sampling rate, and because the fuselage modal participation during LCO generated a measurable signal at the flight control sensors. The AOC was successful in reducing or eliminating 5.6 Hz oscillations for all original specification weapons. The efficacy of the AOC can be seen in Figure 4, where the controller was manually engaged after intentionally attaining flight conditions that resulted in significant oscillation amplitude. Although not eliminated, the oscillations were reduced to below specification levels. Various other mechanical and flight control fixes were attempted, and many worked for a specific flight condition; however, only the AOC was successful over the required speed, altitude, and angle of attack envelope.

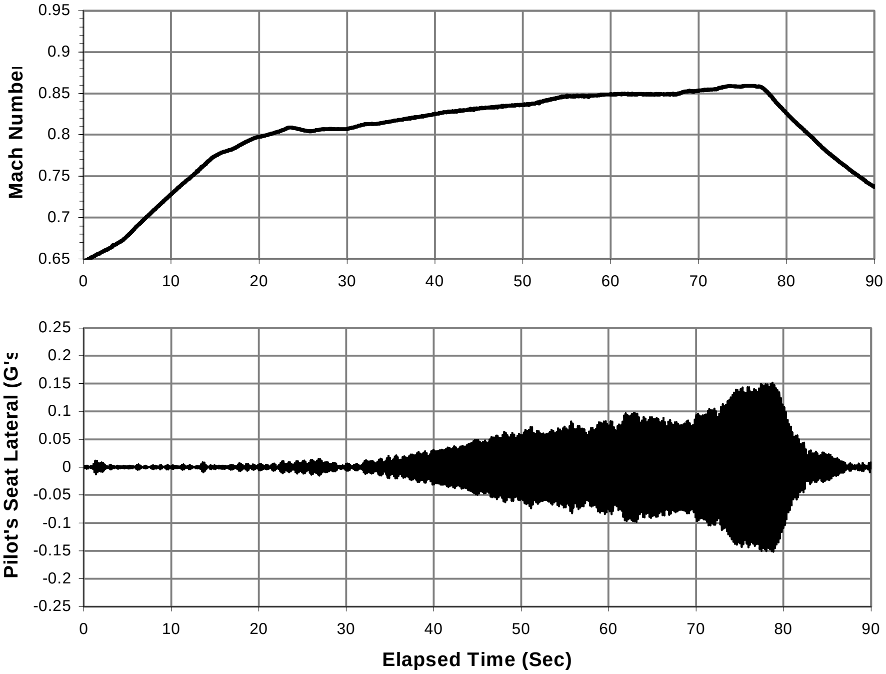


Figure 1: Typical 5.6 Hz LCO Mach Sensitivity with Legacy Hornet, Tip Missiles On

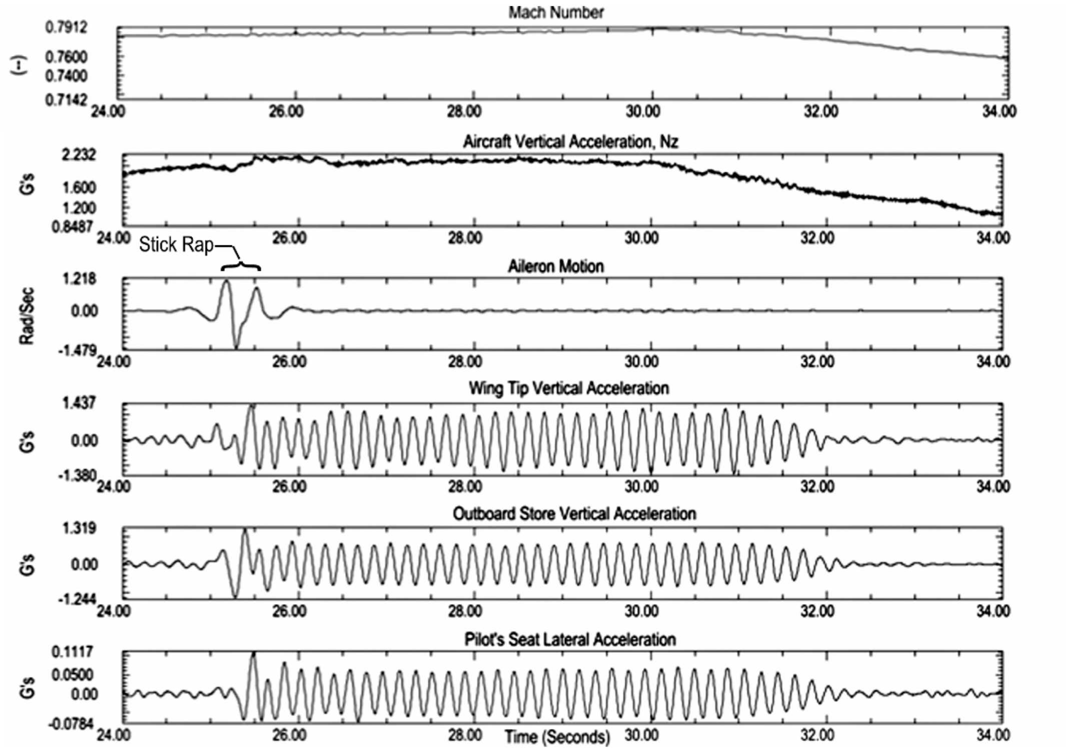


Figure 2: Typical 5.6 Hz LCO Angle of Attack Sensitivity with Legacy Hornet, Tip Missiles On

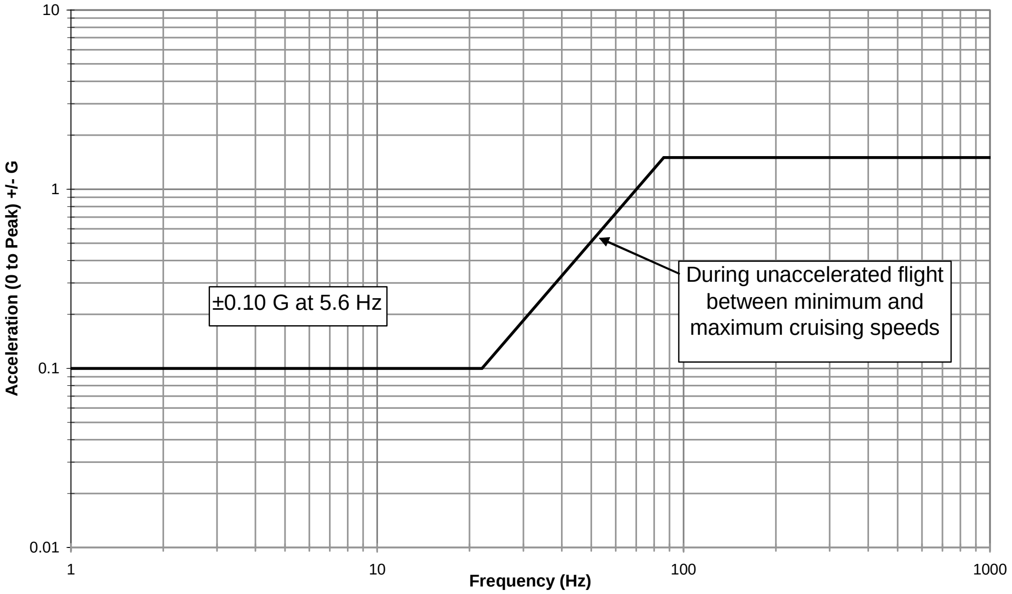


Figure 3: Mil-A-8870(ASG) Crew Comfort Specification

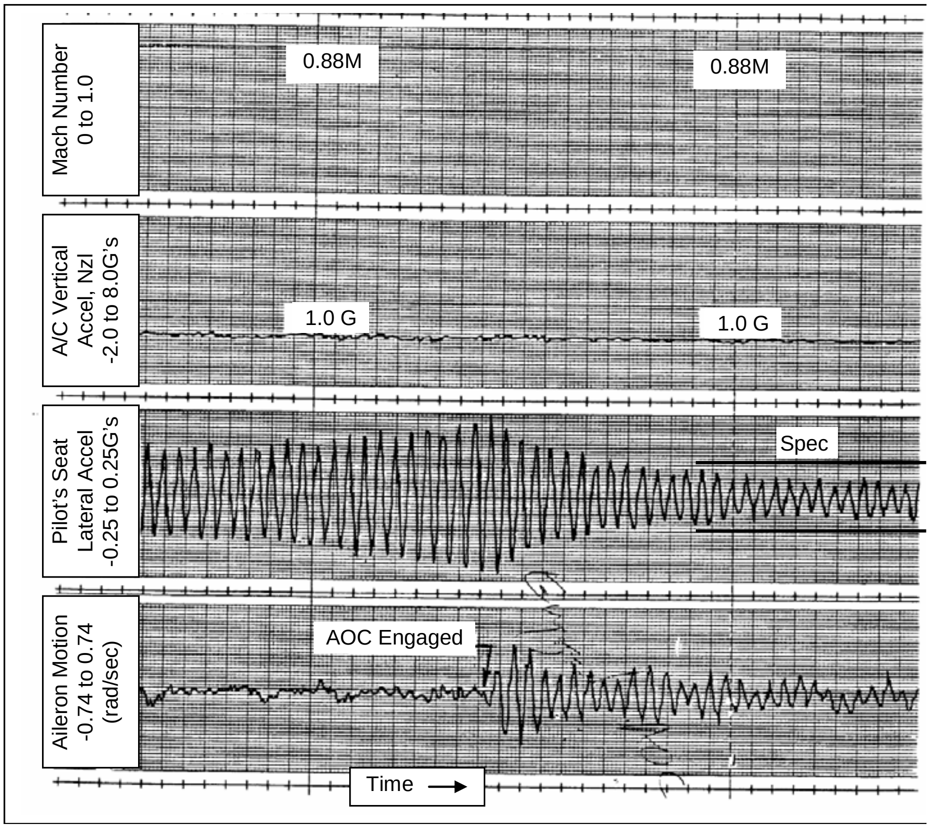


Figure 4: Example of AOC Suppression of 5.6 Hz LCO with Legacy Hornet, Tip Missiles On

Linear flutter analyses successfully identified the correct frequency of the 5.6 Hz LCO, but failed to correctly identify the onset speed, over-predicting by more than 100 KEAS. Analytical variations were performed for external store and wing tip missile aerodynamics. It was found that the wing tip missile aerodynamic modeling was very influential in controlling the predicted flutter speed; however, no analytical change was found that would successfully reconcile the analysis to the observed LCO phenomena for the broad range of stores in the Hornet inventory. This mandated flight testing for many new stores to ensure either the absence of LCO, or the efficacy of the AOC in controlling the oscillations. Several F/A-18 inventory weapons that were not part of the original contract, are not effectively controlled by the AOC, and require flight limitations

1.2. F/A-18A-D Hornet LCO with Tip Missiles Off

With the wing tip missiles removed, the legacy Hornet exhibits a second antisymmetric LCO at approximately 8.5 Hz. This oscillation occurs when mid-weight underwing stores are carried on the outboard pylon, in high dynamic pressure flight conditions, both subsonically and supersonically. The missile off LCO stems from the fundamental wing/store flutter mechanism involving wing/fuselage bending and outboard store pitch. The oscillations exhibit both classical and non-classical flutter behavior. For example, the LCO is sensitive to classical parameters such as mass distribution (internal fuel), and dynamic pressure. For example the onset dynamic pressure at a subsonic Mach would closely correspond to the onset dynamic pressure at a supersonic Mach number. In the non-classical sense, the 8.5 Hz LCO is sensitive to angle of attack. The character of the 8.5 Hz LCO is shown in Figure 5, where the oscillations were initiated by a 3-second dwell excitation from the flutter exciter system. In this example the LCO is low level, but it serves to illustrate the fact that, once initiated, the LCO will continue until flight conditions are altered.

Unlike the 5.6 Hz LCO with tip missiles on, the fuselage node line for the 8.5 Hz tip missile off LCO is closer to the cockpit, so the pilot is less aware of the oscillation. This meant that the crew comfort limits applied to the 5.6 Hz LCO were not sufficient to protect the aircraft from excessive oscillations. Instead, the 3% structural damping criteria was applied as in traditional flutter testing [3].

An AOC system similar to the solution for the 5.6 Hz LCO was considered but not pursued due to concerns about controlling at the higher frequency, and the lack of a suitable production sensor to measure the oscillation. As was the case for the 5.6 Hz oscillations, various mechanical fixes were attempted such as: outer wing box tripper strips, structural stiffening of the fuselage to alter the modal coupling, and control surface rigging changes. Although each solution reduced the oscillations for some flight conditions, none was effective over the entire flight envelope. Consequently, the 8.5 Hz LCO required flight restrictions, or placards to prohibit flight into known LCO flight regimes.

Linear flutter analyses were used to successfully identify the correct frequency of the 8.5 Hz LCO, and correctly identified stores that would likely be susceptible to the LCO, but failed to correctly predict the onset speed by more than 50 KEAS. Analytical variations were performed for external store aerodynamics, and careful correlation of internal fuel quantity reduced the analytical error in specific cases to less than 10 KEAS. However, no analytical change was found that would successfully reconcile the analysis to the observed LCO phenomena for the broad range of stores in the Hornet inventory. This mandated flight testing for many stores to ensure either the absence of 8.5 Hz LCO, or to define safe flight envelopes to avoid LCO. Several weapons in the F/A-18A-D inventory have flight restrictions due to 8.5 Hz LCO.

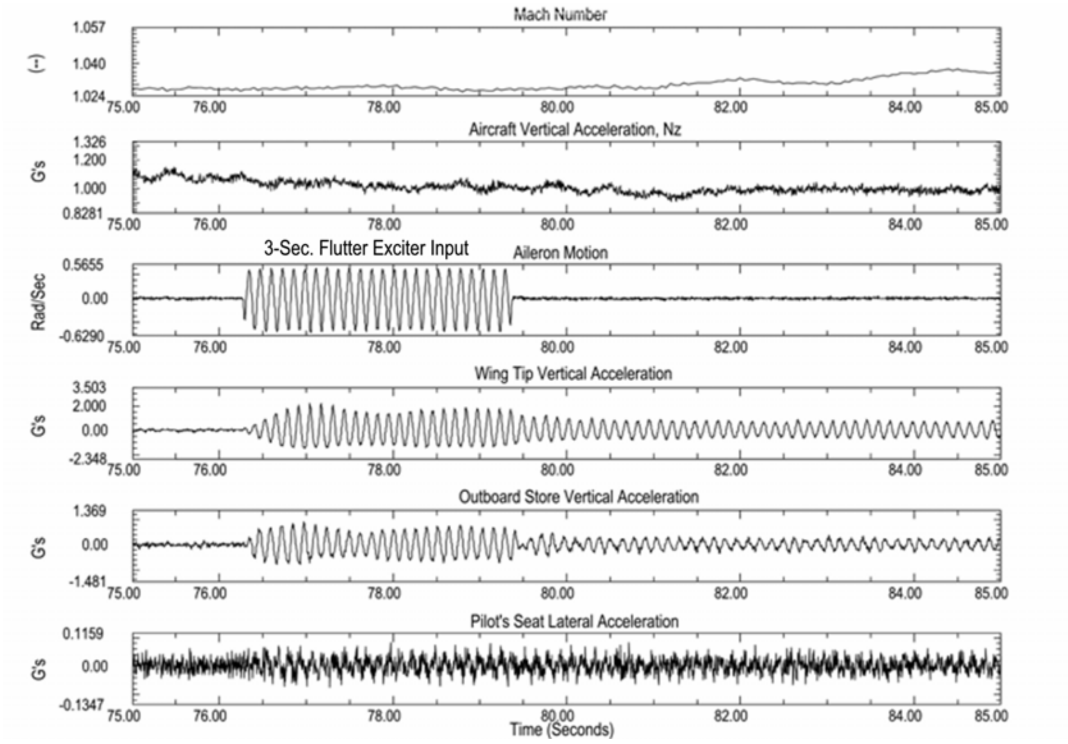


Figure 5: Typical 8.5 Hz LCO with Legacy Hornet, Tip Missiles Off

2.0 F/A-18E/F DESIGN AND DEVELOPMENT

The F/A-18E/F Super Hornet was designed as an upgrade to the existing U.S. Navy and Marine Corps F/A-18A-D Hornet. Many systems and design features of the F/A-18E/F retain commonality with the legacy Hornet; however, several structural and aerodynamic changes made the Super Hornet a completely new aircraft from an aeroelastic stability stand point. The wing and empennage physically increased in size by approximately 25%, a leading edge snag was introduced and the LEX was re-contoured, see Figure 6 and Figure 7. In addition, a third outboard under-wing pylon was added, shown in Figure 8, which provides both air-air and air-ground capability, and increases the total possible aircraft specification external store loading combinations to approximately 2 million. Therefore, a comprehensive aeroelastic stability analysis and test program was essential to define the flutter and divergence speed boundaries, and to obtain operational certification for the fleet. Due to the many external stores carriage flight limitations existing on the F/A-18A-D, one of the key design drivers for the Super Hornet was the goal to provide an unrestricted external store carriage airspeed envelope for the fleet.

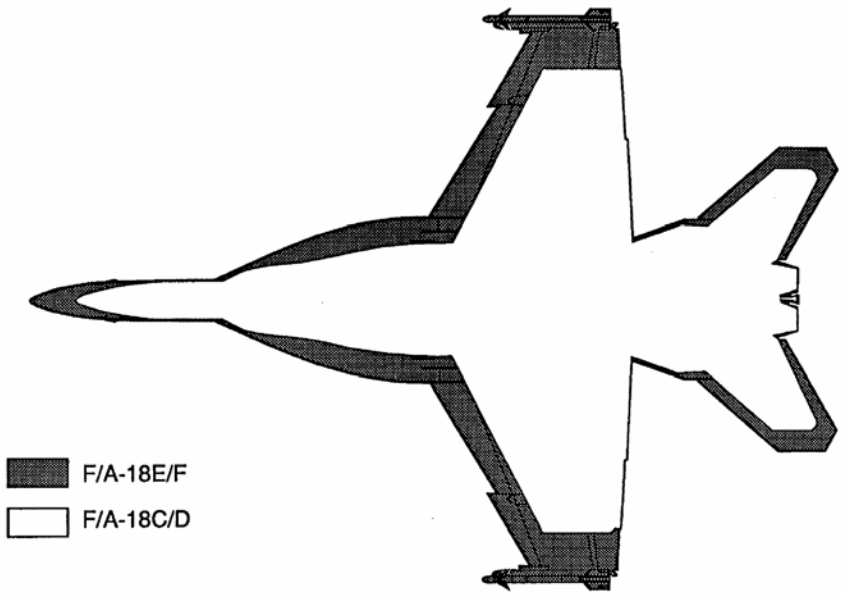


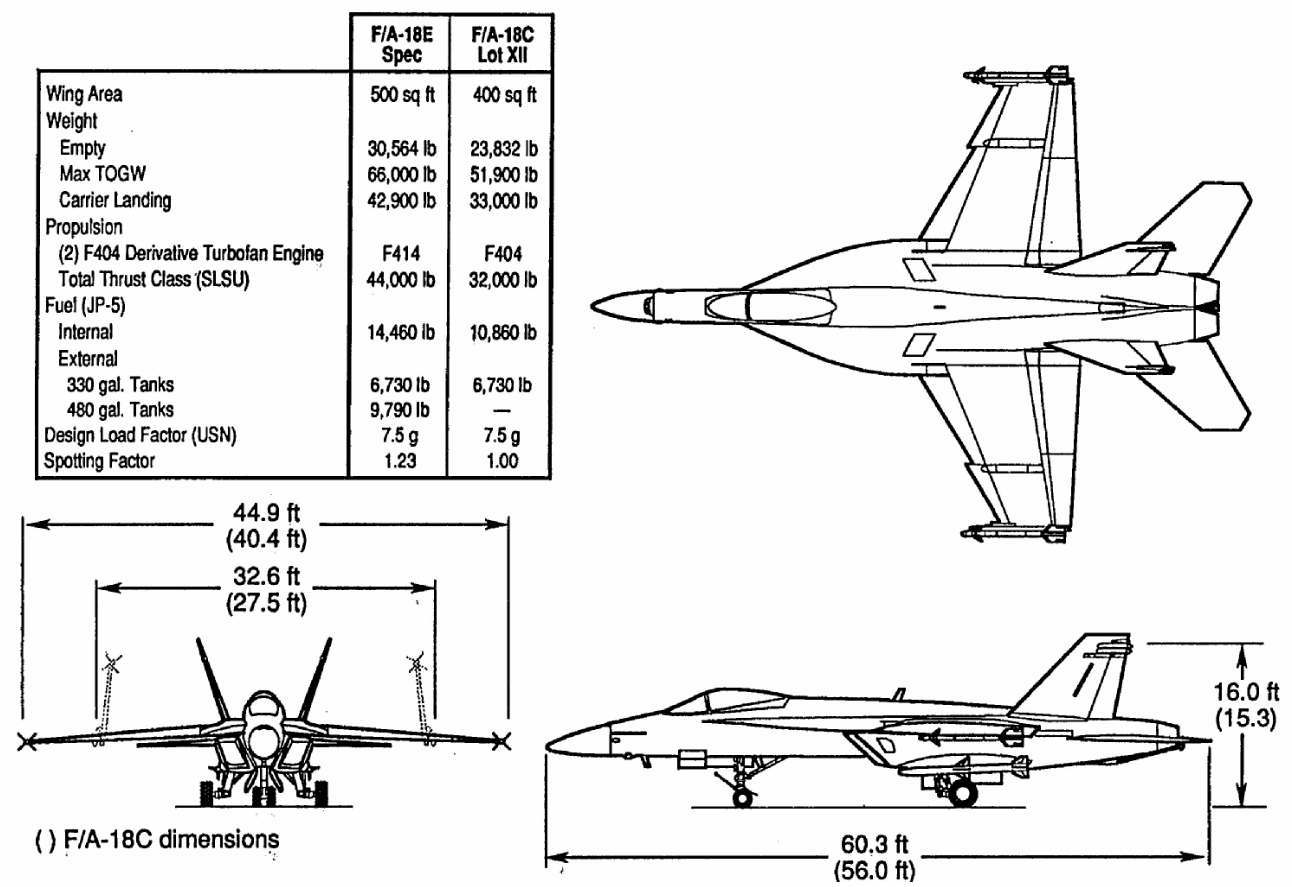
Figure 6: Planform Comparison of F/A-18C/D Hornet and F/A-18E/F Super Hornet

2.1. F/A-18E/F Aeroelastic Design

The successful aeroelastic design of the Super Hornet depended upon 3 key elements: 1) Analysis Capacity, 2) Criteria Assessment, and 3) Management Support. These elements worked in concert to permit an aeroelastic assessment to be made, and design changes proposed, prior to “freezing” the design and commencing fabrication.

2.1.1. Analysis Capacity

In order to evaluate the adequacy of the Super Hornet design, particularly with regard to external stores carriage, an accurate aeroelastic analysis was required. This analysis consisted of Nastran for the structural model [4], and Doublet Lattice [5] and Doublet Point [6] for the unsteady aerodynamics. A beam-rod structural representation was used based on legacy Hornet experience. The beam rod model was initially derived from the detailed strength finite element model (FEM) because ground vibration test (GVT) data were not yet available. The aerodynamic models were compared to preliminary wind tunnel steady aerodynamic and loads data. The flutter analysis was performed using a proprietary code to assess the entire stores inventory through a series of flutter speed contour plots as a function of store weight versus pitch inertia. Details of this process are presented in [7]. In this manner, the approximately 2 million store configurations could be represented by about 20,000 individual flutter runs in just a few week's time. Once critical external store weight and inertia regions were identified, the design cycle could be further expedited to address changes in desired parameters.



	F/A-18E Spec	F/A-18C Lot XII
Wing Area	500 sq ft	400 sq ft
Weight		
Empty	30,564 lb	23,832 lb
Max TOGW	66,000 lb	51,900 lb
Carrier Landing	42,900 lb	33,000 lb
Propulsion		
(2) F404 Derivative Turbofan Engine	F414	F404
Total Thrust Class (SLSU)	44,000 lb	32,000 lb
Fuel (JP-5)		
Internal	14,460 lb	10,860 lb
External		
330 gal. Tanks	6,730 lb	6,730 lb
480 gal. Tanks	9,790 lb	—
Design Load Factor (USN)	7.5 g	7.5 g
Spotting Factor	1.23	1.00

Figure 7: F/A-18E (Single Seat) Super Hornet Characteristics Compared to F/A-18C Legacy Hornet

2.1.2. Criteria Assessment

With the analysis capacity established, the target criteria with which to assess the results had to be established. Traditionally, the Mil-Spec 15% margin of safety [3] on the aircraft limit speed has been used as the minimum requirement for the flutter analysis. For reference, the relevant limit speeds for the Super Hornet are shown in Figure 9. However, legacy Hornet experience indicated the linear flutter analyses, though related to LCO, frequently over-predicted the aeroelastic stability relative the onset of LCO. It was determined that additional margin would be prudent. Therefore, a 25% analytical flutter margin was set as the design goal, a 10% increase over the 15% Mil-Spec requirement. This 10% value was based on statistical studies of legacy Hornet wind tunnel flutter data, GVT correlation experience, and correlation of flight test results to analysis predictions, all of which showed a typical 5% reduction in flutter speed due to unsteady aerodynamic effects not captured in the analysis, and another 5% reduction in flutter speed due to structural effects, such as fastener flexibility, so that the predicted wing stiffness did not fully materialize in the GVT. The 25% analytical margin requirement was applied to all flutter analyses during the initial design phase of the F/A-18E/F.

Figure 8: F/A-18E Super Hornet Illustrating 3rd Wing Pylon Store Loading

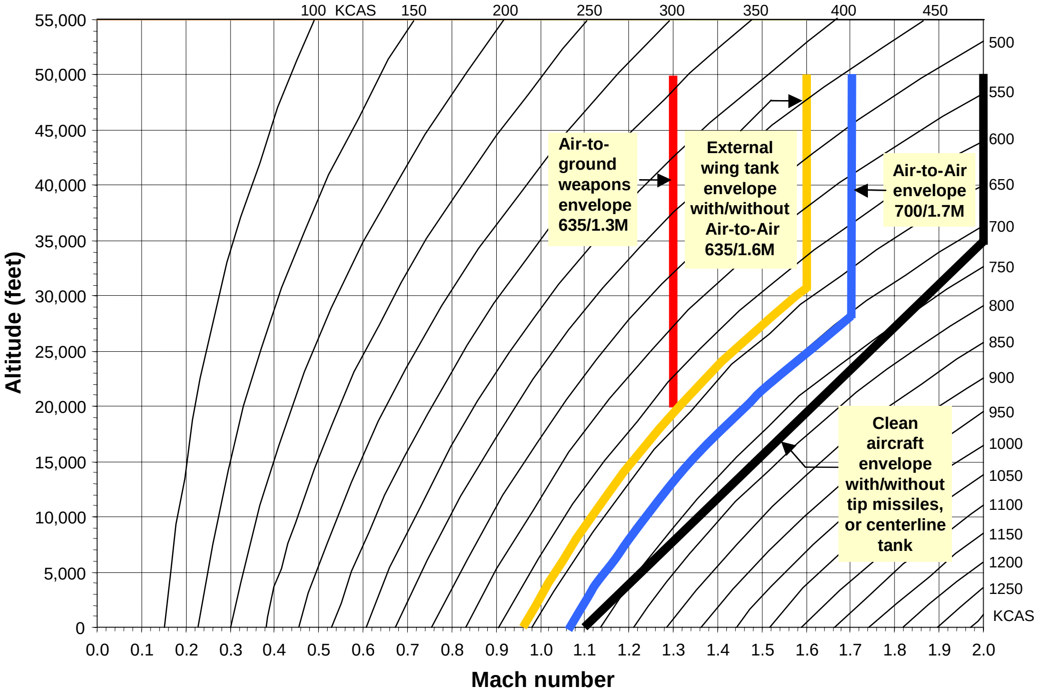


Figure 9: F/A-18E/F Super Hornet Carriage Airspeed Envelopes With and Without External Stores

2.1.3. Management Support

The establishment of a new analysis criterion is well and good until it requires a design change, at that point the understanding and support of program management becomes essential. The Super Hornet program management (both Boeing and Navy) was well acquainted with the LCO difficulties of the legacy Hornet, and were committed to a flutter and LCO-free E/F. The aeroelastic analysis assessment determined that the inner wing torsional stiffness was not adequate to pass the 25% margin requirement for the more critical store loadings. An increase of 34% in GJ was needed to clear the majority of the inventory. This was a substantial stiffness increase, and it was arrived at through extensive trade studies involving strength, design, aerodynamics and mass properties communities to determine the best overall solution for the aircraft/weapons system.

Two main proposals were evaluated by the design teams to achieve this stiffness increase: 1) Additional composite wing skin plies, and 2) Additional wing thickness. It was determined that increasing the inner wing thickness to chord ratio, t/c, by 0.6% was the best solution. It provided the needed torsional stiffness, reduced the inner wing structural weight, and increased available wing fuel volume. The down-side was some reduction in supersonic acceleration performance, but that parameter remained within the specification requirements. Management approval of a substantial wing stiffness change without hard test data, based only on analysis and the experience of the aeroelasticians, was unprecedented. It would not have been possible without an organizational structure that fostered open communication and trust between management and the technical community.

2.2. Aeroelastic Development

The F/A-18E/F aeroelastic stability development program consisted of wind tunnel, GVT, and flight test activities, all integrated with a unified analysis process. This process is described briefly below, and in more detail in a previous work by Hayes and Goodman [7].

2.3. Wind Tunnel Testing

Both low and high speed flutter model tests were performed. Three series of low speed tests on a 17% beam-rod model were conducted in the Boeing tunnel to validate the analysis process, including flutter speed contours for a broad range of weapons, the predicted flutter mechanisms, and to perform parametric variations on mass, stiffness, and aerodynamics in order to assess the impact on flutter speed. Four series of high speed tests were conducted on an 18% stressed-skin model in the NASA-Langley Transonic Dynamics Tunnel (TDT), using Freon for the test medium. These tests employed the NASA 2-cable mounting system during external stores testing to permit flexibility of all important LCO-related degrees of freedom. During the legacy Hornet flutter model testing only half-span wall mounted models were utilized. It had been theorized that the wall mount effectively eliminated the fuselage lateral degree of freedom, which was later seen to be a key participant in both the 5.6 Hz and 8.5 Hz LCO phenomena. The TDT testing showed the Super Hornet to be free of LCO, having tested up to 1.2M and to an equivalent -20,000 feet altitude.

2.4. GVT

It has long been a policy of the Boeing-St. Louis aeroelastic stability team that almost any NASTRAN model can be made to match a single set of GVT data, and therefore, model accuracy is only obtained by forcing the structural stiffness model to match multiple variations in boundary conditions and mass loadings. This is achieved by using a building block approach beginning with components such as control surfaces, stabilators, vertical tails, pylons, etc, and testing them using free-free, cantilevered, and fully assembled boundary conditions. Finally, the full aircraft is tested with variations in fuel quantity, external store loadings, and wing tip missiles on and off. The end result is a single stiffness representation of the aircraft that matches all the available GVT data to within a +/-5% frequency criterion for flutter related modes. In addition to numerous component GVTs, 3 clean wing configurations and some 25 external store loadings were tested for model correlation purposes.

2.5. Flight Testing

It has been said that, "The airplane did not read the flutter report", and "The airplane does do these things", indicating that sometimes unexpected things occur during flight testing. The flight flutter test program is where the analytical predictions are confirmed or refuted. Because the 5.6 Hz and 8.5 Hz LCO found on the legacy Hornet were first discovered during flight testing and not predicted in advance, the Super Hornet flight flutter test program for external stores proceeded with some natural apprehension. A total of 15 critical external store loadings were identified for testing, and a rigorous test matrix was developed, based on legacy Hornet experience, to thoroughly search for LCO. In addition to covering the entire Mach-dynamic pressure range of the flight envelope, particular attention was paid to investigating the range of AOA through a dedicated series of wind-up turns (WUT) and reduced Nz pushover (PO) maneuvers conducted with flutter excitation at critical frequencies. No wing/store LCO, nor low damping, was observed during any of the Super Hornet testing, confirming the analysis and wind tunnel predictions, and permitting the full goal carriage speed envelope for all weapons.

Based on flight flutter test results, the final minimum predicted flutter speed margins for the most critical external store loadings satisfied the specification criteria [3]. The only noteworthy aeroelastic stability activity found and eliminated during the Super Hornet flight flutter test program was low amplitude aileron and rudder buzz [8].

3.0 EA-18G DESIGN AND DEVELOPMENT

The EA-18G Growler is a tactical jamming system variant of the Super Hornet product line that modifies a basic F/A-18F (two-seat) aircraft with the incorporation of airborne electronic attack subsystems. The forward fuselage was redesigned to better accommodate the electronic attack mission. The new fuselage became common with all subsequent Block-II E/F aircraft. The external stores inventory was increased through the addition of electronic attack pods not previously carried on the Super Hornet. No changes were made to the basic wing and empennage structure. A key feature of the Growler mission is the wing tip sensor pod that replaces the launcher and wing tip missile on the Super Hornet. The new pod is similar in weight to the LAU-127 launcher/AIM-9 missile combination it replaces, but with a 6-inch aft shift in center of gravity, and at 13 inches in diameter, it is physically much larger than the 5-inch diameter missile, Figure 10. In addition, because the legacy Hornet 5.6 Hz LCO was shown to be sensitive to the wing tip missile aerodynamic configuration, the size of the Growler wing tip pod raised concerns about the potential for LCO. Uncertainties associated with the aeroelastic stability impact of these modifications required the aeroelastic re-certification of the Growler wing.

3.1. EA-18G Aeroelastic Design

Because the Growler was based on an existing airframe, the primary focus of the aeroelastic stability design phase was to analytically assess the flutter stability with the above described modifications. The flutter speed contour analysis process, described above for the Super Hornet, was repeated. The only significant change being the incorporation of ZAERO [9] aerodynamics in an effort to allow near-replica modeling of the wing tip pod, both subsonically and supersonically. The analytical results indicated that although the wing torsion modal frequency changed significantly (moving from 20Hz with tip missile off and 12 Hz with tip missile on for the Super Hornet, to 15Hz with the Growler wing tip pod), flutter speed predictions remained within a few percent of similar store loadings carried on the Super Hornet.), and no new flutter mechanisms were identified.

Figure 10: E/A-18G Growler with New Wing Tip Pod

3.2. EA-18G Aeroelastic Development

Aeroelastic stability similarities between the Growler and the Super Hornet were sufficient to permit a streamlined aeroelastic stability development program. Flutter wind tunnel testing was not performed, the number of GVT configurations was reduced from 25 to 15, and the number of flight test store loadings was reduced from 15 to 6. Throughout the flight flutter test program particular attention was given to test maneuvers designed to check for LCO. Specifically, more than 400 WUT and PO events were performed to perturb the AOA and to look for LCO. Generally, these events were performed using inputs from the flutter excitation system to give further opportunity for LCO to be seen if it were present. Boeing software called IDSINE [10], not available during the Super Hornet program, was used to efficiently assess the damping from each event in this large test matrix in a timely fashion. No wing/store LCO was found during this flight test program, and full carriage speed envelope was obtained for the entire Growler external stores inventory.

4.0 CONCLUSIONS

The presence of 5.6 Hz and 8.5 Hz LCO and limitations on external store carriage speeds for the legacy Hornet, and the absence of LCO and aeroelastically unrestricted store carriage speeds for the Super Hornet and Growler aircraft, offers several lessons applicable to the tactical fighter community.

- The 5.6 Hz and 8.5 Hz wing/store LCO found on the legacy Hornet were not (and are not) accurately predicted by flutter analyses, and were not identified until flight testing began. The aeroelastic stability team had limited impact on the Hornet wing stiffness in the design phase. The wing stiffness was basically a fall-out from the strength requirements, and it was very difficult to significantly increase the wing stiffness during the flight test phase of development. Therefore, the aeroelasticians must be involved early in the design phase, and empowered by management to make necessary changes if any are required.

- Active control of wing/store LCO is feasible, and may ultimately be the most desirable solution. However, active control requires significant aircraft capabilities in terms of on-board computer resources, actuator response rates, flight control loop speeds, and ideally, dedicated sensors in order to achieve a robust solution. In addition, significant resource investments are required in terms of control algorithm development and extensive flight testing of multiple store loadings to validate the solution.

- The LCO observed on the legacy Hornet occurred because of the presence of low-damped flutter mechanisms involving the wing and external stores. Increasing the basic wing flutter speed on the Super Hornet, by increasing the inner wing torsional stiffness 34%, eliminated the LCO as demonstrated by flight testing.

- It is possible to use linear flutter analyses to design for flutter and significantly reduce the risk of LCO if proper criteria are applied. The standard 15% margin of safety was not an adequate criterion for the Super Hornet. A 25% analytical flutter margin design requirement was successfully used to achieve adequate, but not excessive, flutter margins of safety with the most critical external store loading during the design phase. This approach proved robust enough so that the basic Super Hornet design remained adequate for flutter even though a completely different (inertially and aerodynamically) wing tip pod was installed on the Growler. Neither the F/A-18E/F nor EA-18G aircraft exhibited transonic store LCO during flight testing, and both fully satisfied the specification [3] flutter stability requirements.

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