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Fluid-Structure Interaction Evaluation of F-16 Limit Cycle Oscillations

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14. ABSTRACT
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Fluid-Structure Interaction Evaluation of F-16 Limit Cycle Oscillations

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Application of high-fidelity computational science and engineering (CSE) tools provide better data for decisions to enhance weapon systems acquisition, testing, and support. Fluid-structure interaction (FSI) simulation is being evaluated to quantify aero-structural dynamic mechanisms that bound F-16 limit cycle oscillations (LCO). The intent of the research objectives is to provide a better understanding of flight-test aero-structural observations through the utilization of CSE tools. Validation of results provided by CSE tools using experimental testing as the truth source, allows for development of methods and processes to accurately determine coupled-field physical characteristics of full fighter aircraft configurations. Specifically for F-16 LCO, the response frequency, coupled mode response, and flutter/LCO onset velocity are evaluated for comparison of CSE tool results against flight test results.

I. Introduction

FLUID-structure interaction (FSI) modeling and simulation (M&S) is being tested to verify the ability to model and augment future flight tests by providing better data for decisions. The primary objective of the research is to understand and quantify aero-structural dynamic mechanisms that bound limit cycle oscillations (LCO). The research addresses a failure of linear analysis to accurately predict the onset velocity of LCO.[1] Computational FSI M&S may provide the ability to identify the oscillation frequency and modal composition of the LCO mechanism.[1] This paper will present that FSI simulations results closely predict the onset velocity of LCO. The other failure of linear analysis, predicting the amplitude or severity of LCO, is not addressed. A full description of the relationship between the flutter and LCO phenomena is outlined by Bunton and Denegri.[2]

Limit cycle oscillations are low-amplitude oscillatory wing responses that tend to occur at high subsonic and transonic flight conditions caused by critical store loadings. The type of LCO, in this case typical LCO on the F-16, extracts energy from the airstream permitting a bounded structural response beyond the flutter/LCO onset velocity up to a predetermined maximum allowable limit.[3] Denegri[4] shows that flutter/LCO mechanism in the F-16 is not caused by high energy extracting classical 1st bending and 1st torsion modes, but by forward wing and aft wing bending modes. The forward wing and aft wing bending modes dominant in the coupled aero-structural LCO/flutter mechanism extract lower amounts of energy from the airstream[4] than 1st bending and 1st torsion modes. Because the LCO mechanisms extract less energy from the airstream, the aero-structural response tends to be less critical than classical flutter.

The need for extensive flight testing could be reduced if the fundamental mechanisms involved in LCO are quantified.[5] A nonlinear flutter analysis tool capable of accurately predicting LCO response characteristics could play a key role in providing understanding.[5] Comparing flight test data to linear modeling results has provided insight into vital new observations. It is known from flight test and linear analysis that the typical LCO instability is antisymmetric.[1] The linear flutter analysis indicates strong sensitivity to velocity changes.[1] The linear flutter analysis also shows good correlation to the flight test response data and the flight test frequency, but predicts a significantly

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higher instability speed.[1] Some research has focused on understanding possible structure nonlinearities but recent analysis has shown that non-linear mechanisms may occur within the fluid domain. Viscous flow features may interact with the structure, limiting the magnitude of LCO mechanisms and may contribute to bounding divergent flutter.[6] Shock-induced separation flow features may also play a role in LCO mechanisms.[7] Studies have shown that the wing-tip store aerodynamics contribute to the structural response in some, if not all configurations.[8]

Current research efforts take advantage of the information learned from previous efforts. In addition, subject authors were consulted to better understand findings and to ensure that the research and data are presented to address objectives. As a best practice, all FSI simulations are run with wing-tip stores. Due to the computational cost of viscous FSI simulations on F-16 full load-out configurations, research efforts are concentrated on quantifying inviscid mechanisms.

Build-up approaches provide a practical way to execute aero-structural simulation analysis. A build-up approach requires verification with high confidence test results from a single discipline system, subsystem, and capability testing. Computational Science and Engineering (CSE) tools verification must be compared with relevant testing results, and advanced to compliment T&E needs. Verification of Computational Fluid Dynamic (CFD) results must be evaluated against relevant test data such as wind tunnel results. The verification of Finite Element (FE) analysis results must be evaluated against relevant test data, i.e., Ground Vibration Test (GVT) results. Computational FSI results, which combine the verified CFD and FE models, must then be evaluated against previous flight-testing programs or previously flown configurations. A build-up approach will quantify the validity and build confidence in the data being produced. Only when the applicable physics are understood and applied correctly in each of the coupled disciplines should the capability be used as a predictive tool.

II. Motivation and Goals

The benefits of a proven and accurate simulation capability that provides data for decisions are: 1) Early discovery of defects that are typically only discovered in flight testing, 2) Reduced risk of flight test though a better understanding of the physical phenomena, 3) Rapid clearance of aircraft envelopes with new store combinations, and 4) Improved value of each test point.

Computational science and engineering tools must be capable of replicating trends similar to trends found during flight testing. Due to uncertainty in the data and the complexity of multi-physics trends, an exact solution is neither required nor desired. Without acute understanding of the physics, exact solutions to single configuration/single flight condition simulations are not reliable. Typical LCO flight test results for straight-and-level flight at a test altitude of 5000 feet mean sea level (MSL) are plotted in Figure 1 with respect to Mach number. The data show that the LCO onset velocity for this configuration is Mach 0.70, and relatively low amplitude LCO was encountered at Mach 0.80 and 0.85. Higher amplitude LCO was encountered at velocities of Mach numbers 0.90 and 0.95.

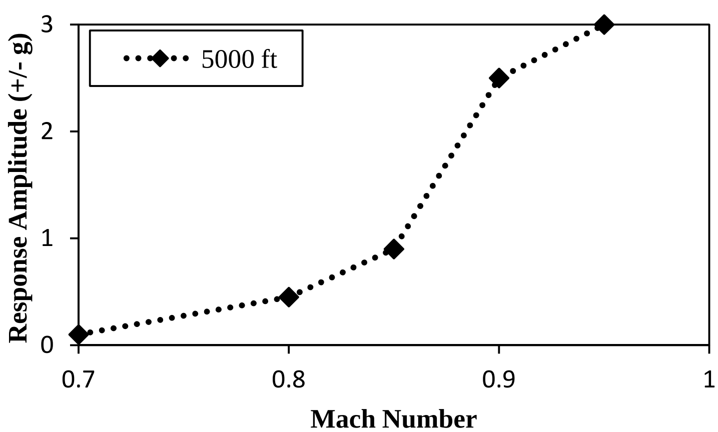

Figure 1. LCO Response Amplitude at 5000 Feet MSL Altitude.

An intended product of this research is the development of methods and processes to consistently and accurately determine aero-elastic characteristics of fighter aircraft. A challenge will be to use simulation and test data in conjunction to improve the physical understanding of LCO. Systematic analysis of the results will hopefully

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quantify multiple interacting mechanisms from fundamentally different disciplines. Predicting LCO in the transonic and low supersonic flight regime, Mach numbers 0.8 through 1.2, will establish a full model-to-test validation set for future work.

The following trends will be evaluated when comparing simulation data to flight test results. Simulation results should generate an anti-symmetric response, a response frequency near 7.9 – 8.2 Hz, a flutter onset velocity of Mach number 0.70, and a multiple level LCO response amplitude. The fundamental LCO test derived characteristics for this configuration are defined in Table 1.

Table 1. LCO Simulation Criteria.

Response Frequency (RF) 7.9-8.2 Hz	Anti-Symmetric Response (ASR)	LCO Onset Velocity (LCOOV) Mach 0.70	Multiple Level Response Amplitude (MLRA)

Simulation data provides managers and flight testers with decision data as well as a physical understanding of an aero-structural system. In practice, simulation output data are tailored to support imminent decisions to improve program requirements. Late cycle program efficiency can be increased by leveraging previous simulation results. Proper communication of testing results, system engineering processes results, and simulation results will further program effectiveness.

III. FSI Simulation Synopsis

Using M&S to provide better data for decisions will advance weapon systems acquisition, testing, and support. The AERO Suite of Codes[9] couples Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) solvers. The coupled framework of the code provides the capability of predicting non-linear FSI phenomena on complex full aircraft configurations. The CFD code, AERO-F, is an unstructured grid solver capable of both invicid and viscous simulations for compressible flows. The CSD code AERO-S is capable of both finite element modal and dynamic non-linear simulations. The code suite AERO-F utilizes robust mesh-motion solvers that handle large displacements. The mesh-motion solvers update the position of surface and near surface nodes in the fluid domain so that the fluid grid motion replicates the structural grid motion output from the AERO-S solver. Parallel processing and grid deformation algorithms, available in the AERO Suite of Codes, provide the capability to simulate long time histories and large displacements on full aircraft. A verified FSI capability will provide the ability to conduct virtual flight testing in order to support future flight-test project planning, support, and missions.

A. Description and Validation of the CFD Grid

The practice of excluding under-wing store aerodynamics is sufficient for a large set of flutter analysis.[5] In doublet-lattice aero-structural methods, no aerodynamic modeling of under-wing stores is included.[5] The research presented is conducted using inviscid CFD fluid models that do not include the under-wing stores. Nevertheless, the method is expected to be a significant enhancement over the simulation capabilities offered by linear analysis. Increased simulation fidelity could demonstrate improved methods and results that can be applied to other configurations.

The F-16 Outer-Mold-Line (OML) geometry used for the CFD is a representative model of the actual fighter. This geometry is used to simulate the dynamic fluid flow around the aircraft producing representative force distributions. The grid used for the flow solution is a full span complete aircraft containing 247,967 points and 1,255,962 elements. A picture of the fluid grid is presented in Figure 2.

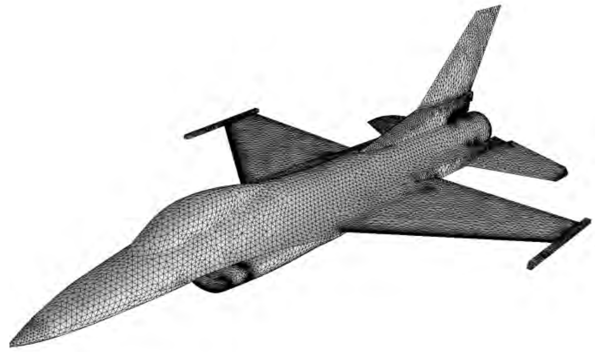

Figure 2. Euler Fluid Grid.

To validate the CFD model, correlating and representative flight data are compared to simulation results. Steady state simulation results are compared to known lift data at flight representative trim angle-of-attack (AoA) for Mach numbers 0.65 through 0.95, in increments of 0.05, at 5000ft MSL standard day conditions. The fluid model provides representative lift characteristics of the actual aircraft. Ideally more validation would be conducted to ensure the integrity of the F-16 fluid model used.

B. Description and Validation of the Finite Element Structural Model

The typical LCO configuration structural model is a modal representation of a full-span F-16 aircraft with stores. The model has been used for store clearance analysis in NASTRAN at the Air Force SEEK EAGLE Office at Eglin AFB, FL.[1] The full-span aircraft model has a symmetric store loading at stations 2 through 4, and stations 6 through 8.

Various configurations of the underlying structural model are established by Denegri.[1,4,5,10,11,12] A complete description of this typical LCO structural model is provided by Denegri.[5] Structural modes 1 through 26 are used, and include all wing, store, and empennage modes. Modes of the full aircraft model contain both symmetric and anti-symmetric characteristics. The structural model is converted and verified in the AERO-S solver format. All 26 mode shapes and frequencies in both NASTRAN and AERO-S models are compared for verification. Mode shape examples are presented in figures 3 and 4. Due to the extensive validation already performed on the structural model no further validation was completed.[5]

The use of this F-16 structural model is ideal due to its extensive validation in support of flight test. The structural F-16 model correctness is unparalleled compared to any known structural model of the F-16. The complete F-16 finite element model geometry described is used along with the first 26 flexible modes for all of the aero-structural simulation data presented herein.

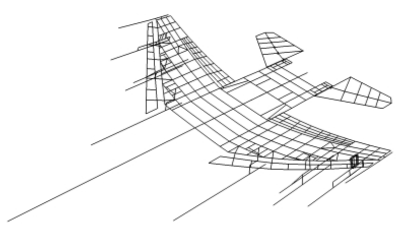

Figure 3. 1st Mode Shape.

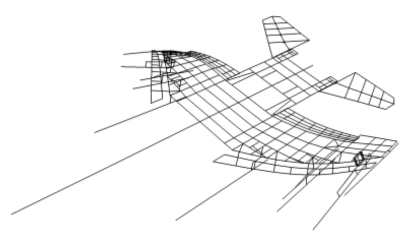

Figure 4. 2nd Mode Shape.

The structural model contains complex modes where the store load-out contributes significantly to the frequency and shape. Structural shell and bar elements are used to transmit pressure loads and displacement data between the fluid domain and the structural domain, respectively.

C. FSI Simulation Setup

Preparation of the structure model for FSI simulations is similar to that which was used by Alyanak and Brooks.[13] The fluid-structure interaction methodology that is used in this paper is very similar to that which was used by Melville.[14] A notable difference between the methodologies is that two unstructured Euler fluid grids are used for the computation in this work instead of one structured grid. One fine Euler grid is used for the fluid computation, and one course Euler grid is used for improved mesh motion. In addition, the single discipline fluid and structure models were built and validated independently in unique reference frames. The CFD domain is converted to match the same reference frame as the structural model. Conversion of the structural model into a new reference frame is not considered as it is costly to convert and can be prone to errors. The F-16 finite-element model is not conformal to the fluid grid. The fluid-structural interface between the models ensures smooth consistent movement of both domains.[15]

Steady State solutions are run to a residual of 10^{-8} for each Mach number simulated. Each FSI simulation is started using the corresponding Mach number and altitude steady state solution. Computational FSI simulations are run at a time step of 0.00025 seconds for a total of 30 seconds. As a best practice procedure, a small time step is used to reduce the possibility of numerical time stepping sensitivities. Simulations with several similar aero-structural configurations show the affect of numerical time stepping on the onset velocity prediction is very small. Numerical time stepping effects are not investigated further on this configuration.

An advantage of a CFD-CSD aero-structure simulation capability over other techniques is that the fluid dynamic physical features are captured more precisely. A significant difficulty arises at the initial condition due to the modeling of both the desired dynamic response dominant at each simulated Mach number and the aerodynamic wing loading on the aircraft. For the simulations presented, the structural response to the flight representative aerodynamic loading is used as an initial perturbation. Unfortunately the initial structural response is symmetric, which for this configuration is not the desired physical response; however, for most of the simulations presented, the anti-symmetric dynamic structural response is dominant. This perturbation method is used mainly to avoid a series of tedious restarts, and provide consistency. The data derived from this work will be used as a baseline comparison for future work.

Three stages occur in each simulation. The time history in each simulation show a symmetric response (damped at 14-16 Hz), a response transition from symmetric to anti-symmetric, and anti-symmetric response (7.9-8.2 Hz). A sample time history is presented in Figure 5.

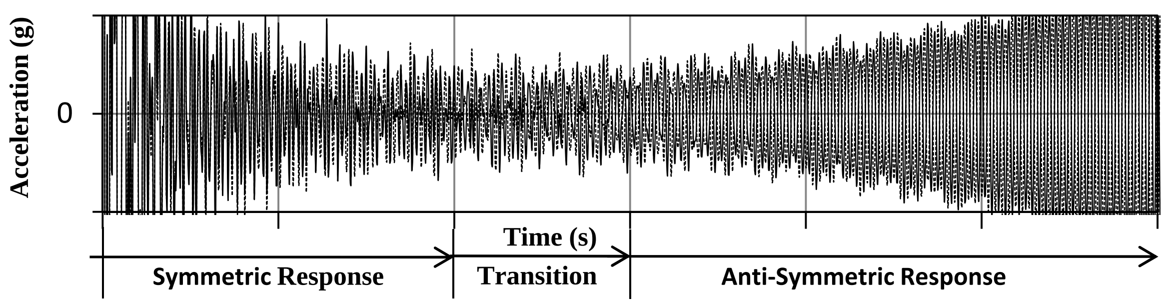

Figure 5. Sample Time History.

The process that is used for exciting the simulated aero-structural system is not used in actual testing. The general flutter mode frequency and response characteristic (symmetric vs. anti-symmetric) is known from linear analysis before testing begins.

IV. FSI Prediction of the Flutter Onset Velocity

The fluid-structure physics of the F-16 Typical LCO configuration are numerically simulated and compared to known results for Mach numbers 0.65 through 0.85 at 5000 feet MSL altitude. Trends of the simulation results demonstrate the correct response frequency, the correct participating coupled mode response, and the correct flutter/LCO onset velocity. In order to obtain the correct participating coupled mode response, modes 2 and 4 must interact at a combined single frequency around 8 Hz. Mode 2 is described as an aft wing bending mode and mode 4 is described as a forward wing bending mode[4]. The correct flutter/LCO onset velocity is a low amplitude response at Mach number 0.70.

The aero-structural simulations are run in the time domain with a target of 30 seconds total simulation time. Dynamic aero-structural simulations with long time histories provide confidence that no new physics are being introduced after the initial transient, and that the simulation is numerically stable. For the purposes of this paper, time history response data of 18 seconds is presented in Figures 6 through 10.

A. Mach Number 0.65 Structural Response

The simulated wing-tip acceleration data in Figure 6 shows that the structural response for the Mach number 0.65 flight condition is damped. The initial aero-structural response is symmetric at an approximate frequency of 16 Hz, and the frequency remains at the same 16 Hz frequency throughout the duration of the simulation. The results are characteristic of the expected damped simulation response.

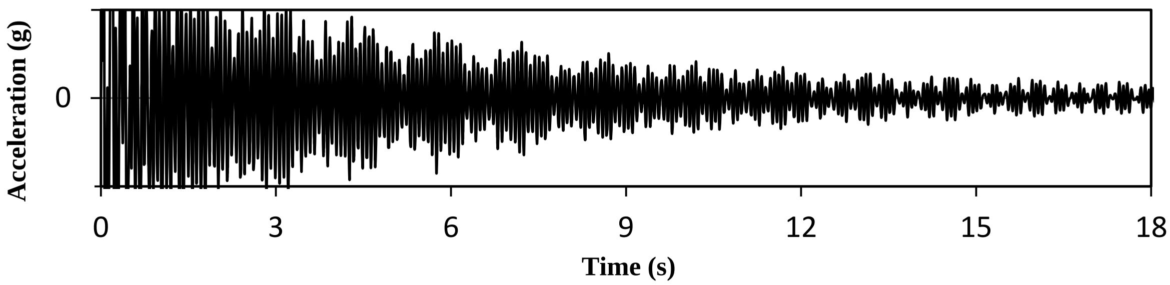

Figure 6. Mach Number 0.65 Structural Response Time History.

B. Mach Number 0.70 Structural Response

The simulated wing-tip acceleration data in Figure 7 shows that the initial aero-structural response is approximately 16 Hz for the Mach number 0.70 condition. The initial symmetric response of 16 Hz is damped and the response transitions into a constant amplitude neutral condition response at an approximate frequency of 8.5 Hz. Results indicate that the anti-symmetric response is dominant, and the transition into a constant amplitude neutral condition suggests that the onset velocity is being simulated at this flight condition. The results are characteristic of the expected response.

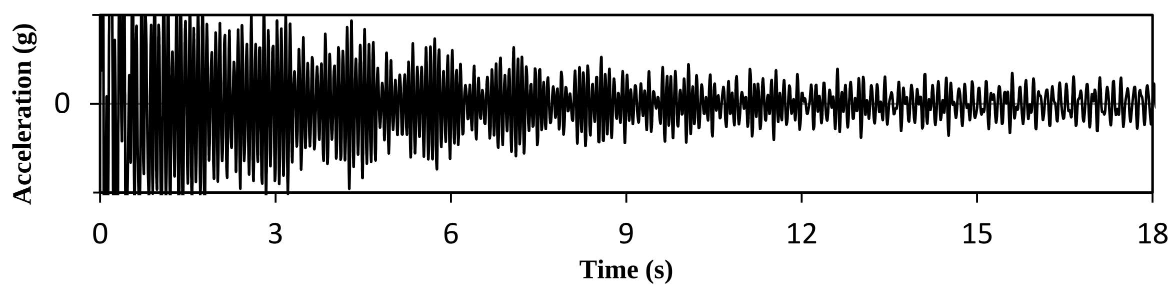

Figure 7. Mach Number 0.70 Structural Response Time History.

C. Mach Number 0.75 Through Mach Number 0.85 Structural Response

The simulated wing-tip acceleration data are presented for Mach numbers 0.75 through 0.85 in Figures 8 through 10. The data show that the initial symmetric response of approximately 16 Hz is damped and that the response transitions into an anti-symmetric response of approximately 8.5 Hz. Results show that none of the structural responses at conditions above Mach number 0.70 are bounded and the LCO is not being simulated. The aero-structural simulations show that the anti-symmetric response is dominant for the simulated flight conditions above Mach 0.70. The structural response of all of these simulations do not diverge rapidly as relatively large Mach number increases are simulated above the flutter onset velocity.

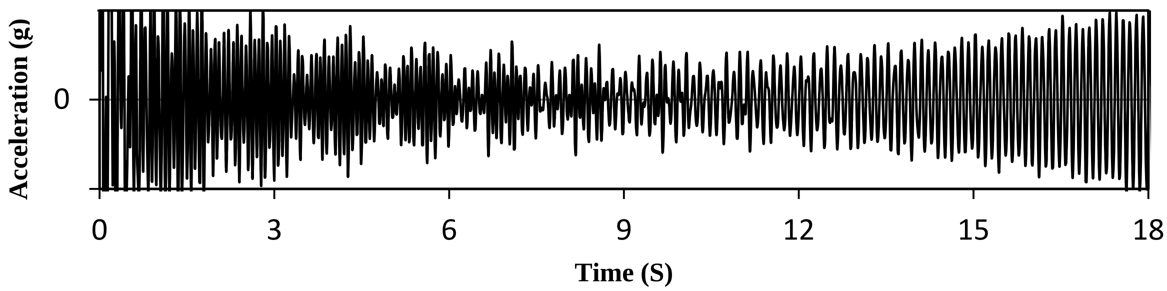

Figure 8. Mach Number 0.75 Structural Response Time History.

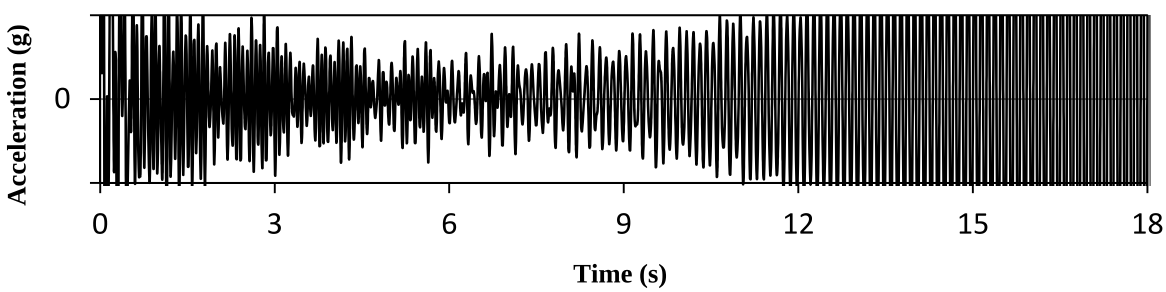

Figure 9. Mach Number 0.80 Structural Response Time History.

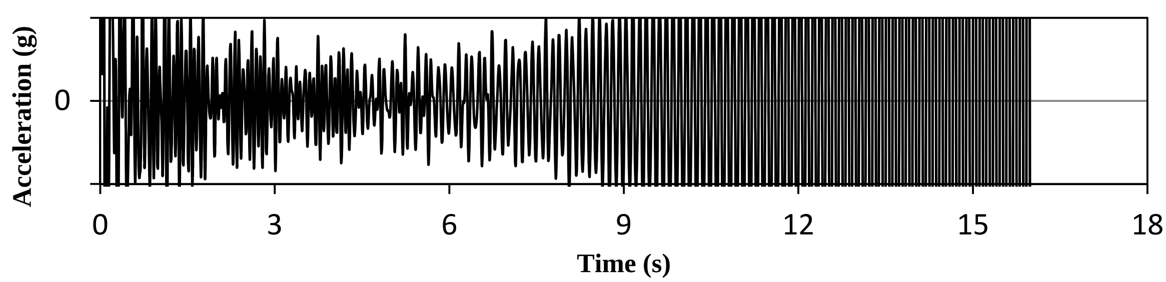

Figure 10. Mach Number 0.85 Structural Response Time History.

Simulated wing-tip acceleration data for Mach numbers 0.90 and 0.95 are not presented. Numerical instabilities of the aero-structural system prevented simulations at Mach numbers of 0.90 and 0.95.

Aero-structural simulations show that methods and processes are capable to accurately determine aero-elastic characteristics of fighter aircraft.

V. Forced Structural Displacement FSI Simulations

Computational FSI simulations are also performed using prescribed structural motion. The structural motion prescribed is a linear combination of mode 2 (aft wing bending) and mode 4 (forward wing bending) at a frequency of 8.42 Hz. The purpose of these simulations is to explore an alternative technique for identifying LCO mechanisms.

The simulated aircraft motion demonstrates some LCO characteristics, but not all. Aircraft structural motion models the correct anti-symmetric behavior. Wing-tip forward accelerometer point and trailing accelerometer point motion derived from modes 2 and 4 are out-of-phase.[5] The simulated amplitude of the wing-tip displacements and accelerations are not consistent with flight test. In simulation, the motion of the wing-tip leading accelerometer point is smaller than the wing-tip trailing accelerometer point, reverse of flight test observations. This result confirms that LCO motion is not purely a combination of structural modes.

To quantify fluid physics during LCO-like aircraft motion, pressure fluid values are monitored at selected locations behind the aircraft wing. A FFT plot of the pressure behind the wing-tip is shown in Figure 11, and shows frequencies at 8.5 Hz, 17 Hz, and possibly 25 Hz, even though the structure is only oscillating at 8.42 Hz. This result shows that fluid physics in the Euler flow field respond at several frequencies not driven by the structural domain. Further studies are necessary to characterize the fluid physics being observed.

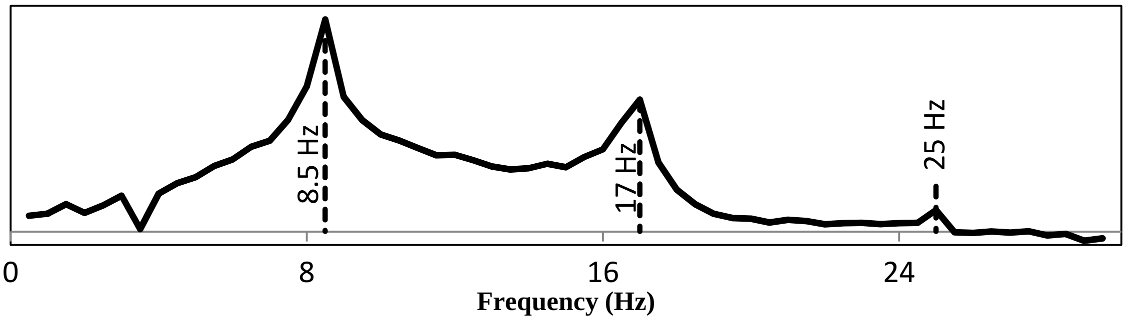

Figure 11. FFT of Pressure Data from Prescribed Structural Motion Simulation at a Point Behind Wing-Tip Launcher Rail.

VI. Conclusion

F-16 typical LCO simulation data and experimental data are evaluated. The simulation time history signals provide responses similar to flight test data. Aero-structure simulation results demonstrate LCO onset velocity but do not specifically characterize any mechanisms. Results show that correct response frequency and correct participating coupled mode response are always observed to occur together. Simulated flight conditions above the onset velocity produce data that indicate wing oscillations diverge. The simulated oscillations do not diverge abruptly, potentially modeling a physical characteristic of aerodynamic damping in the aero-structural system. Additional resolution provided by the CFD produce improved aero-structural results and demonstrate the possibility that the inviscid fluid physics contain LCO bounding mechanisms. An advantage of Euler CFD over doublet-lattice (or similar) methods is that the shock pressure and mach distributions are resolved more accurately. Increased resolution of these dynamic distributions on the wings is a possible physical bounding mechanism absent from other modeling techniques.[16]

Results from the simulations produce data that compare well with test results. Aero-structural simulations have matched three of the four required characteristics of LCO. The results of the LCO characteristics are summarized in Table 2.

Table 2. Summarized LCO Characteristics Obtained in Simulation.

Response Frequency (RF) 7.9-8.2 Hz	Anti-Symmetric Response (ASR)	LCO Onset Velocity (LCOOV) Mach 0.70	Multiple Level Response Amplitude (MLRA)
✓	✓	✓	

Although these results are promising, further validation is required. The first objective for future work is to quantify the mechanism(s) bounding LCO. It is expected that stepping up levels of fidelity in the fluid model will characterize individual physical mechanisms and mitigate non-physical numerical artifacts. The second objective for future work is to complete similar simulations on other LCO producing F-16 store configurations.

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