Stability and Control Test and Evaluation Process Improvements through Judicious Use of HPC Simulations (3348)

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This paper documents progress made in developing a computational method for accurately determining aircraft response to pilot input while incorporating the flight control system (FLCS), engine model, control surface deflections (CSDs), and 6-DoF simulation. Rather than flying all possible configurations in a flight test matrix to clear or expand an aircraft/store envelope, the present approach is to identify configurations that are susceptible to undesirable flight control attributes/flying qualities such as lateral instabilities and spin using a high-fidelity Computational Fluid Dynamics (CFD) solver. Identifying adverse flying qualities early in a program's lifecycle will reduce cost and risk by reducing the test matrix and having a better understanding of the instabilities being tested. To date, time-accurate, steady simulations and dynamic, prescribed-motion simulations have shown CFD is capable of accurately predicting forces and moments and flow nonlinearities during high-performance maneuvering. Simulating moving control surfaces on the F-16 has been accomplished with all control surfaces modeled. External control of the boundary conditions during simulation is undergoing verification and is required to implement an engine model. The FLCS for the F-16 is programmed for use on HPC systems, and a 6-DoF calculator is incorporated into the simulation. Static, time-accurate A-10 CFD results and their impact on test programs are also presented. The main benefits of this effort are: 1) early discovery of complex aerodynamic phenomena that typically are present only in dynamic flight maneuvers, and are therefore not discovered until flight test; and 2) rapid generation of an accurate aerodynamic model to support aircraft and weapon certification by reducing required flight test hours and complementing current S&C testing.

$\mathbf{v}_B$	=	body-axis velocity vector
$\mathbf{F}_B$	=	body-axis force vector
m	=	mass
B_B	=	rotation matrix
$\boldsymbol{g}'_0$	=	gravity vector
$\boldsymbol{\omega}_B$	=	body-axis angular rate vector
J	=	inertia tensor
$\mathbf{T}_B$	=	body-axis moment vector
$\mathbf{\Phi}$	=	Euler angle vector
$\mathbf{p}_{\mathrm{NED}}$	=	inertial position vector

$$\mathcal{E}(\mathbf{\Phi}) = \begin{bmatrix} 1 & \tan\theta\sin\phi & \tan\theta\cos\phi \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix}$$

1. Introduction

The present paper discusses the development of a virtual flight test capability using high-fidelity Computational Fluid Dynamics (CFD) simulations that will bring together aerodynamics, propulsion, and flight mechanics into a time-accurate simulation capability. The benefits from such a capability to the areas of aircraft stability and control, flight simulation, and aircraft and weapon certification could potentially result in savings reaching into the billions of dollars [1]. A description of the methodology and flow solvers has been presented in a previous paper [2].

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Moving Control Surfaces

Cobalt provides the user a way to simulate moving control surfaces during a CFD simulation using its overset grid technology. This technique allows the user to independently move control surfaces while simultaneously simulating flow over the aircraft. This ability is critical to a virtual flight test capability since control surfaces are so instrumental in the flight of any aircraft. The aircraft and control surface movements are directed via transformation matrices that can be read from a time history, calculated from a formula, or provided by user-defined code via *Cobalt*'s external control interface.

Cobalt External Control

Cobalt has the ability to utilize user-provided code during the simulation via its external control interface. Using this interface, the user has the ability to manipulate boundary conditions, move single or overset grids within the flow environment, or both, all during the simulation. This flexibility allows the user to incorporate logic into the CFD simulation that previously could be achieved only through hardcoding into the CFD solver by the solver's developer. The interface utilized by *Cobalt* uses MATLAB as its external control computation engine. The user develops code either in MATLAB or code that can be made to run in MATLAB via MATLAB mex files, and *Cobalt* calls and uses this code via specially-named functions made available to *Cobalt* during the simulation. The modeling and simulation pieces that are conducted outside *Cobalt* in the current work include 6-DoF calculation, computing control surface deflections via an integrated FLCS, and adjusting engine flow via an engine model.

There are two methods used to initialize a complete simulation that incorporates 6-DoF, the FLCS, and an engine model. The first is to use Lockheed Martin's Aircraft Trim Linearization and Simulation (ATLAS) trim output to obtain initial values for the aircraft states and variables and to initialize the FLCS. This process will not be discussed here since the goal is to create a standalone simulation capability without prior knowledge of these initialization variables. The second method, called the trim, is used to calculate the aircraft states and variables needed to initialize the aircraft and FLCS to some desired initial condition, or trim, state. During the trim, the aircraft orientation, thrust, and CSDs are determined through an iterative approach to acquire the desired trim state. Once these values are found, initial FLCS variables for the trim state can be found through a similar iterative approach.

Once the initial trim solution has been found, the aircraft and FLCS states and variables are used to begin the simulated maneuver. 6-DoF motion is calculated using the *Cobalt*-computed forces and moments to provide position, orientation, and velocity information to the various simulation components. A desired maneuver is input into the pilot model where stick forces, pedal forces, and throttle position are determined and delivered to the engine model and the FLCS. The engine model and FLCS use these values along with the aircraft and flow states to determine the engine inlet and exit flow parameters and the CSDs. Grid motion for the aircraft and the control surfaces and boundary condition information is then sent to *Cobalt*. A CFD solution is computed on the new aircraft state to determine a new set of forces and moments to be fed into the 6-DoF calculation, and the next iteration begins. This process is repeated until the maneuver is complete. The components used to create a flight test maneuver in CFD are discussed below.

Cobalt External Control: 6-DoF

Six-degree-of-freedom aircraft motion is computed during each iteration of the maneuver simulation. *Cobalt* provides to the 6-DoF module the forces and moments acting on the aircraft. The 6-DoF module takes these inputs and other flow information as well as the current aircraft state and computes the next aircraft state using the Flat Earth aircraft equations of motion in **Equation 1**. Comparison data from ATLAS and this method is presented in the Results section.

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\begin{aligned}
\dot{\mathbf{v}}_B &= \frac{\mathbf{F}_B}{m} + B_B \boldsymbol{g'}_0 - (\boldsymbol{\omega}_B \times \mathbf{v}_B) && \text{(force equation)} \\
\dot{\boldsymbol{\omega}}_B &= J^{-1}\left[\mathrm{T}_B - \left(\boldsymbol{\omega}_B \times (J\boldsymbol{\omega}_B)\right)\right] && \text{(moment equation)} \\
\dot{\boldsymbol{\Phi}} &= \mathcal{E}(\boldsymbol{\Phi})\boldsymbol{\omega}_B && \text{(attitude equation)} \\
\dot{\mathbf{p}}_{\mathrm{NED}} &= B_B^T \mathbf{v}_B && \text{(navigation equation)}
\end{aligned}
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Equation 1. Flat Earth aircraft equations of motion used in the 6-DoF module.

Cobalt External Control: Flight Control System (FLCS)

FLCS manipulation of the control surfaces is integrated into the simulation via MATLAB/Simulink models of the aircraft FLCS. The FLCS module is called at the same rate as the FLCS in the real aircraft, i.e., 32 or 64 Hz, etc., and uses inputs gathered from *Cobalt*, the 6-DoF module, and the Pilot module to determine control surface deflections. **Figure 1** shows the F-16 FLCS components as modeled in Simulink.

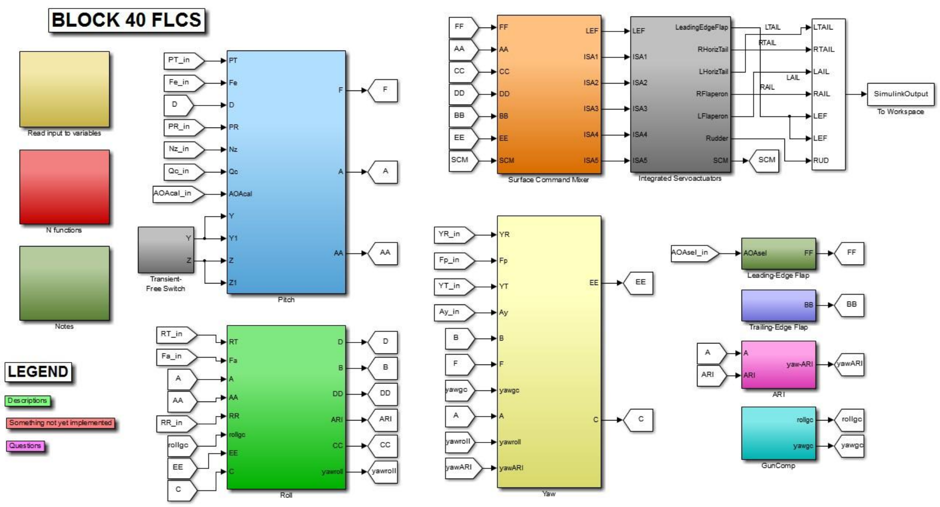

Figure 1. F-16 FLCS logic modeled in Simulink.

Cobalt External Control: Engine Model

Engine variation during the maneuver is simulated by manipulating the boundary conditions on the engine inlet and exit patches at each iteration. Throttle settings are determined in the Pilot model based on information from *Cobalt* and the 6-DoF module. Throttle settings and information from *Cobalt* and the 6-DoF module are sent to the Engine module where mass flow rate, pressure, and temperature are determined for the engine inlet and exit patches, and this information is passed to *Cobalt* for the next iteration.

2. Results

The discussion below focuses on studies of USAF fighter aircraft with and without stores that include the A-10C, F-16C, and F-22. Static, time-accurate results are presented of the A-10C with 600 gallon fuel tank for which limited validation data is available. A discussion on the development of virtual flight test capabilities is also presented. The capabilities being developed to virtually fly an aircraft include developing modular components such as the aircraft flight control system and engine model that can be "plugged in" when needed, and that work with CFD to provide a highly-accurate, realistic simulation of maneuvering aircraft. Results of a prescribed motion maneuver with deflecting control surfaces on an F-16 in the clean configuration are presented. *Cobalt*'s external control capability is utilized by allowing the aircraft to respond in 6-DoF to changes in the forces and moments due to prescribing CSDs and engine parameters. Wind tunnel data, flight test data, and

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Lockheed Martin-sourced aerodynamic data serve as validation data. All grids are full-span, 3D, viscous, and unstructured, and were built using SolidMesh and AFLR3 grid-generation software (Mississippi State) [3,4,5].

A-10C Static Analysis: 600 Gallon Centerline Fuel Tank

Full-scale, static, time-accurate analysis of the A-10C configured with a 600 gallon centerline fuel tank was conducted to examine the possibility of envelope expansion. Shown in Figure **2** is a static, time-accurate simulation depicting iso-surfaces of vorticity colored by pressure at Mach 0.3. Lateral directional results at Mach 0.65 are shown in **Figure 3,** with angle-of-attack (AOA, α) equal to 5 degrees. Plots of C_Y, C_l, and C_n versus angle of sideslip (β) are shown left to right. The comparison data in **Figure 2** is from a wind tunnel test conducted in 1978 and includes a clean configuration (red curve) and a 3 tank configuration (teal curve). The current CFD data (blue curve) shows a similar trend, and was able to extend the available data to the necessary sideslip values being tested today. The CFD data presented here was used to estimate safe flight test limitations. Directional static stability degradation is predicted by CFD and confirmed safety limitations set during other A-10 flight test programs.

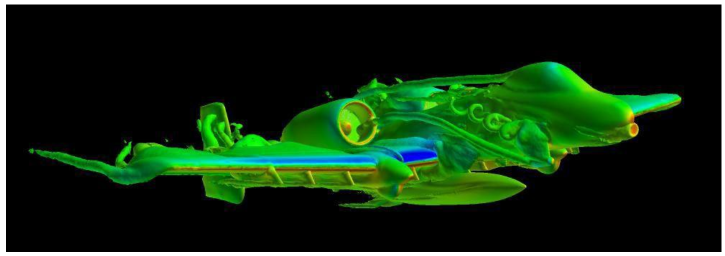

Figure 2. A-10C with 600 gallon fuel tank at Mach 0.3

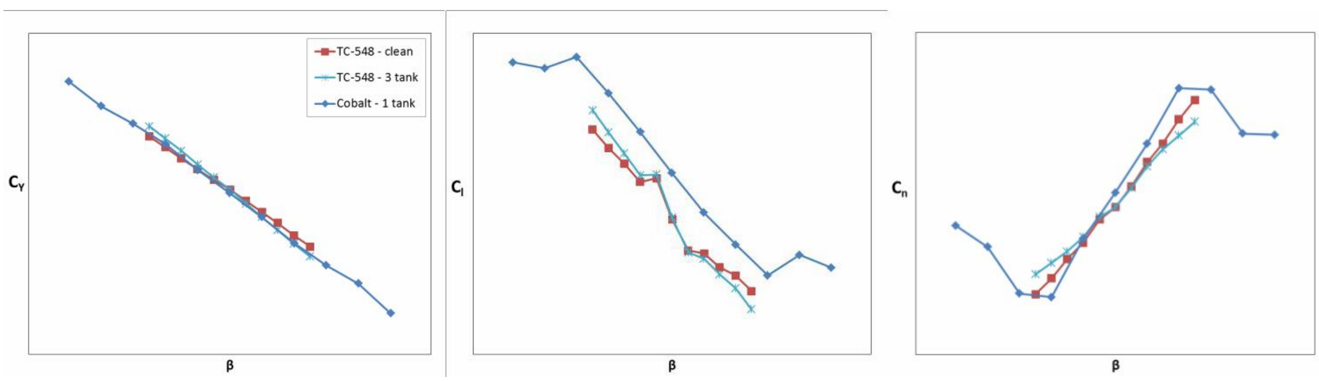

Figure 3. A-10 Static CFD data vs. wind tunnel data at Mach 0.65

F-16 Moving Control Surface Analysis: Pitch Doublet

Modeling moving control surfaces on a full-scale aircraft is a critical step in capability development. Full-scale, dynamic, time-accurate analysis of the F-16 in the clean aircraft configuration with moving horizontal tails and moving leading-edge flaps (LEF) is accomplished using *Cobalt* and the overset grid method. The aircraft and control surface motions are obtained by reading in time histories computed using ATLAS and forcing the aircraft and control surfaces through a prescribed motion. **Figure 4** depicts the F-16 horizontal tail and LEFs at different instances during simulation of a pitch doublet. The horizontal tail is shown at center, maximum leading-edge-down, and maximum leading-edge-up deflections and the LEF is shown at the starting in-flight condition and maximum leading-edge-down deflection. Color contours depict pressure variations over the surface during the maneuver.

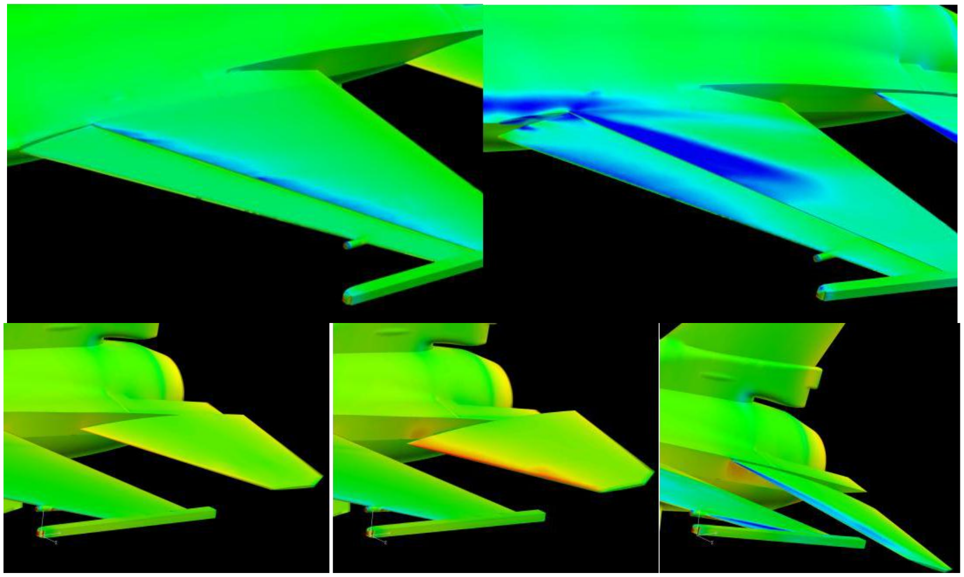

Figure 4. Overset Grid of Clean F-16 during a pitch doublet with moving horizontal tails and LEFs at Mach 0.6 and 10,000 feet.

A pitch doublet maneuver was simulated both with moving Horizontal Tails (HTs) only and with moving HTs and LEFs. Longitudinal results for C_L, C_D and C_m are shown left to right in **Figure 5**. ATLAS aerodynamic data serves as validation data. Overall, forces and moments match well for both cases in that the trend and magnitude are similar throughout the entire maneuver. It can be seen in the plot of C_L that the grid with moving LEFs (blue curve) does not predict validation data (red curve) as well as the grid with only HTs (black curve) modeled. This reduced lift may be an artifact of how the LEFs were modeled. Because the grid with moving LEFs has a gap where the control surface hinge line is modeled, there is an expected loss of high-pressure flow bleeding up to the low-pressure side of the wing. This gap is not present on actual aircraft. The HT&LEF curve for the pitching moment coefficient shows a better fit to the validation data than the curve with just HTs modeled. This may be due to the large influence LEFs have on pitching moment. In this and previous papers, moments are often not predicted as well as the forces. The current results are promising, and similar improvements are expected in the other moment predictions as more control surfaces are incorporated into the simulation.

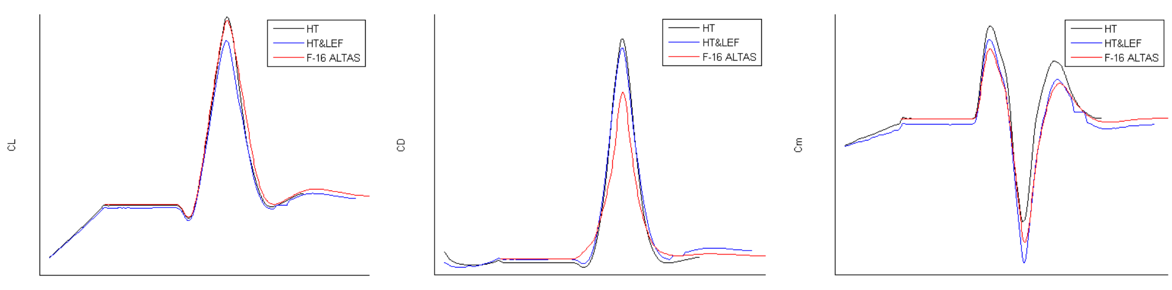

Figure 5. F-16 Pitch Doublet CFD simulation with moving HTs and LEFs at Mach 0.6 and 10,000 feet.

The overset grid generated to model the horizontal tail control surfaces increased the number of grid cells by 11.68 million over the rigid-body grid. To model all control surfaces, the clean grid is increased by approximately 31.10 million cells. The amount of time per iteration utilizing 512 processors and the DoD HPC machine Garnet was approximately six minutes per iteration for the grid with all moving control surfaces modeled. The approximate time per iteration for a dynamic, time-accurate simulation without moving control surfaces using 512 processors is approximately 10-15 seconds per iteration on Garnet. This increase in required time will need to be addressed in the future if CFD is to be used as a Modeling and Simulation (M&S) tool for aircraft-store certification activities.

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F-16 Moving Control Surface Analysis: Loaded Roll

Full-scale, dynamic, time-accurate analysis of the F-16 in the clean aircraft configuration, with all control surfaces prescribed is accomplished using *Cobalt* and the overset grid method. The aircraft and control surface motions are obtained by reading in time histories computed using ATLAS and forcing the aircraft and control surfaces through a prescribed motion. **Figure 6** depicts the F-16 at different instances during a 6.0 G loaded roll simulated at Mach 0.6 and 10,000 feet altitude. Color contours depict pressure variations over the surface during the maneuver.

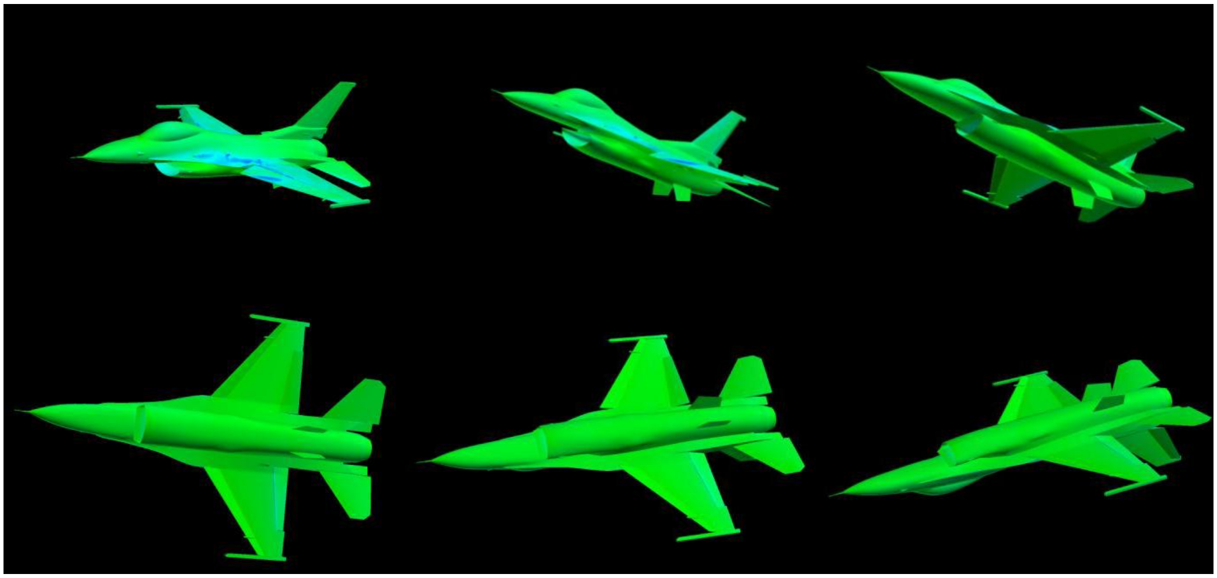

Figure 6. F-16 Loaded Roll CFD simulation at Mach 0.6 and 10,000 feet.

Results for the CFD-computed forces and moments are shown in **Figure 7** and are compared to the same maneuver simulated in F-16 ATLAS. The red curves are sourced from ATLAS. The curves in black are CFD's time-accurate solution for the prescribed motion. Previous papers illustrated the need for more accurate moment predictions, mainly C_m. The plots in **Figure 7** show a good match between CFD's and ATLAS's moment predictions. The discrepancy between CFD and ATLAS for C_D highlight the need to include engine models in CFD simulations. The lack of an engine model is suspected to account for some of the discrepancies between ATLAS and CFD drag predictions.

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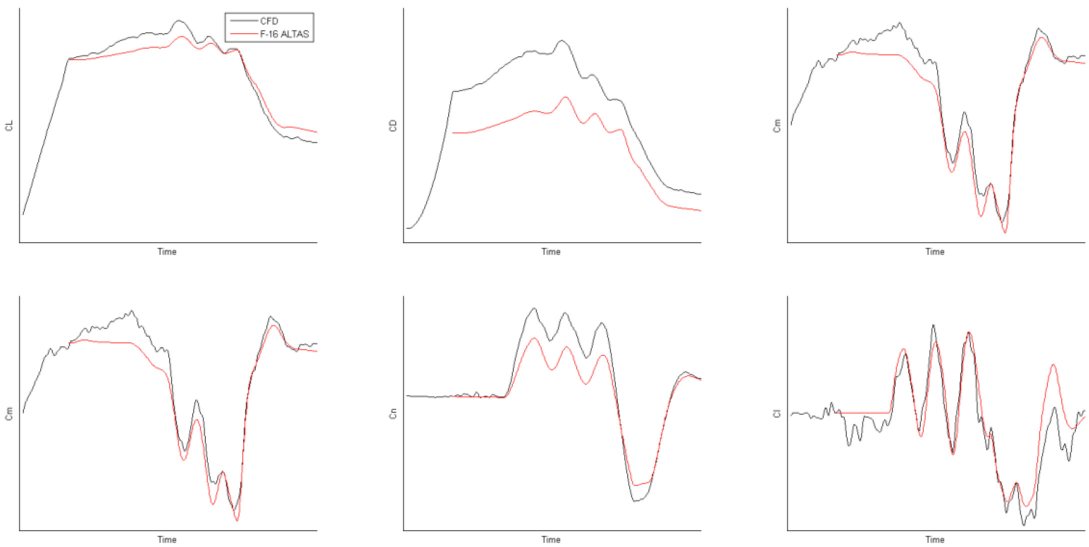

Figure 7. F-16 Loaded Roll CFD simulation with moving control surfaces at Mach 0.6 and 10,000 feet.

Cobalt External Control: 6-DoF

The Flat Earth aircraft equations of motion have been programmed in MATLAB and are incorporated into the CFD solution. 6-DoF integration allows the aircraft to respond during the simulation to the forces and moments acting upon it. Comparisons have been made to 6-DoF simulations from ATLAS for verification of the 6-DoF module. **Figure 8** shows a comparison of the ATLAS and MATLAB 6-DoF predictions for a Max G Pull-up maneuver at Mach 0.6 and 10,000 ft. It is seen that the MATLAB-computed 6-DoF motion (Red line) matches very well with ATLAS (Blue line) over the course of the maneuver.

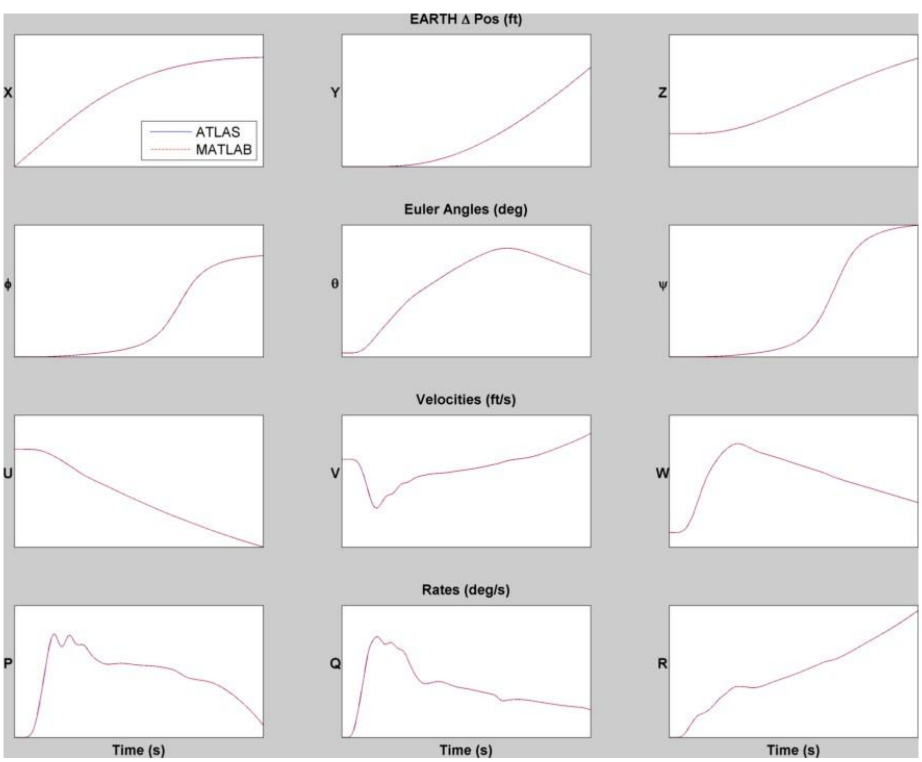

Figure 8. 6-DoF comparison, MATLAB vs. ATLAS, Max G Pull-up, Mach 0.6 at 10,000 ft.

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Cobalt External Control: Flight Control System (FLCS)

The F-16 Block 40 inner loop control laws have been programmed in MATLAB/Simulink and are being incorporated into the CFD solution. Integrating the FLCS into the simulation allows pilot commands to be input into the simulation rather than prescribing the motion of the control surfaces. An updated example of a 360 degree right roll at Mach 0.6 and 10,000 feet is presented in **Figure 9**. Notice that the Simulink model (Blue dotted curve) closely follows the ATLAS deflection prediction (Black solid line) except for a couple peaks in the flaperon deflections. Previous discrepancies reported in Reference [6] were corrected by determining initial integrator values within the control laws. These initial values were the source of the offset previously reported.

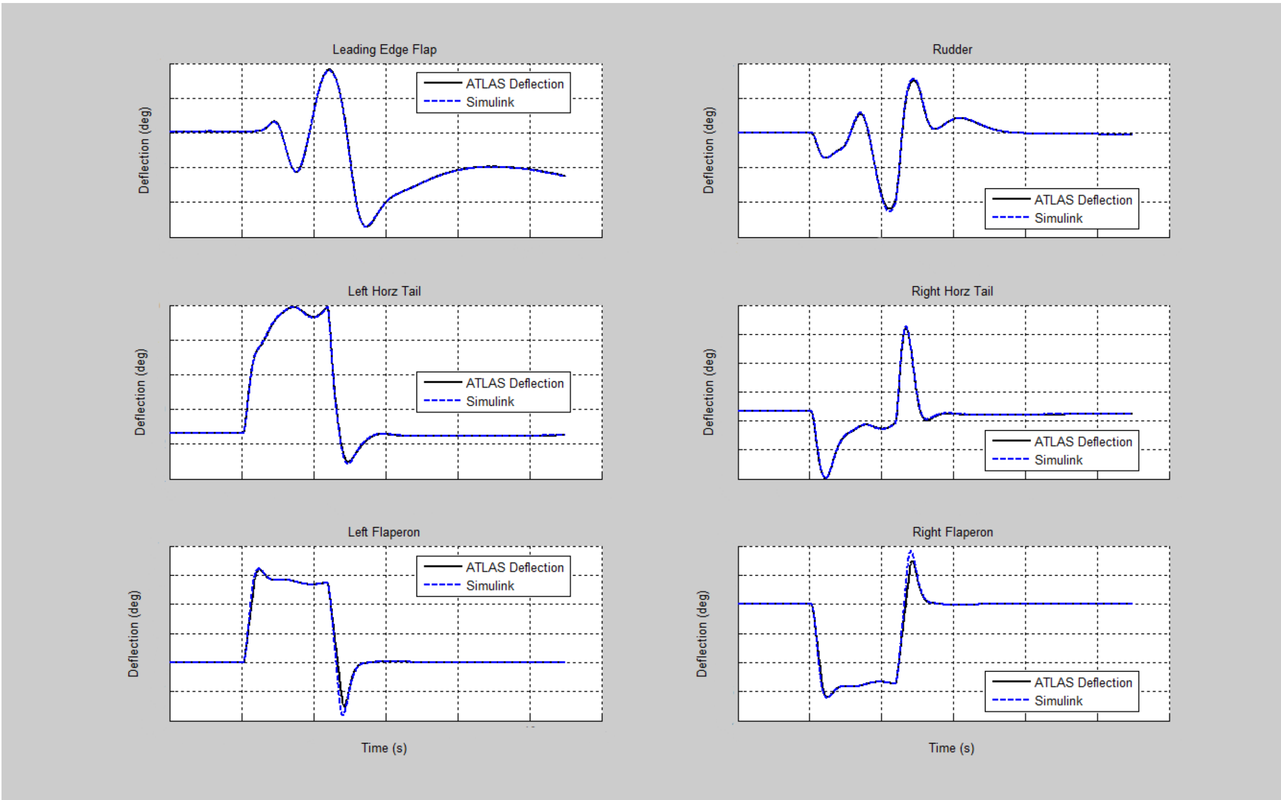

Figure 9. Right Roll 360 degree at 0.6 Mach and 10,000 Feet

Cobalt External Control: Engine Model

An engine model has been programmed in MATLAB and is incorporated into the CFD solution. Engine model integration allows for proper aircraft motion and induced flow calculations due to engine thrust, rather than forcing the aircraft along a prescribed path. **Figure 10** shows the first several iterations of "ramping-in" the engine inlet and exit boundary conditions with a stationary aircraft. An iso-surface of vorticity is shown via velocity vectors colored by velocity magnitude. Tests are currently underway verifying and validating the results of the forces and moments calculated in *Cobalt* for the Engine module.

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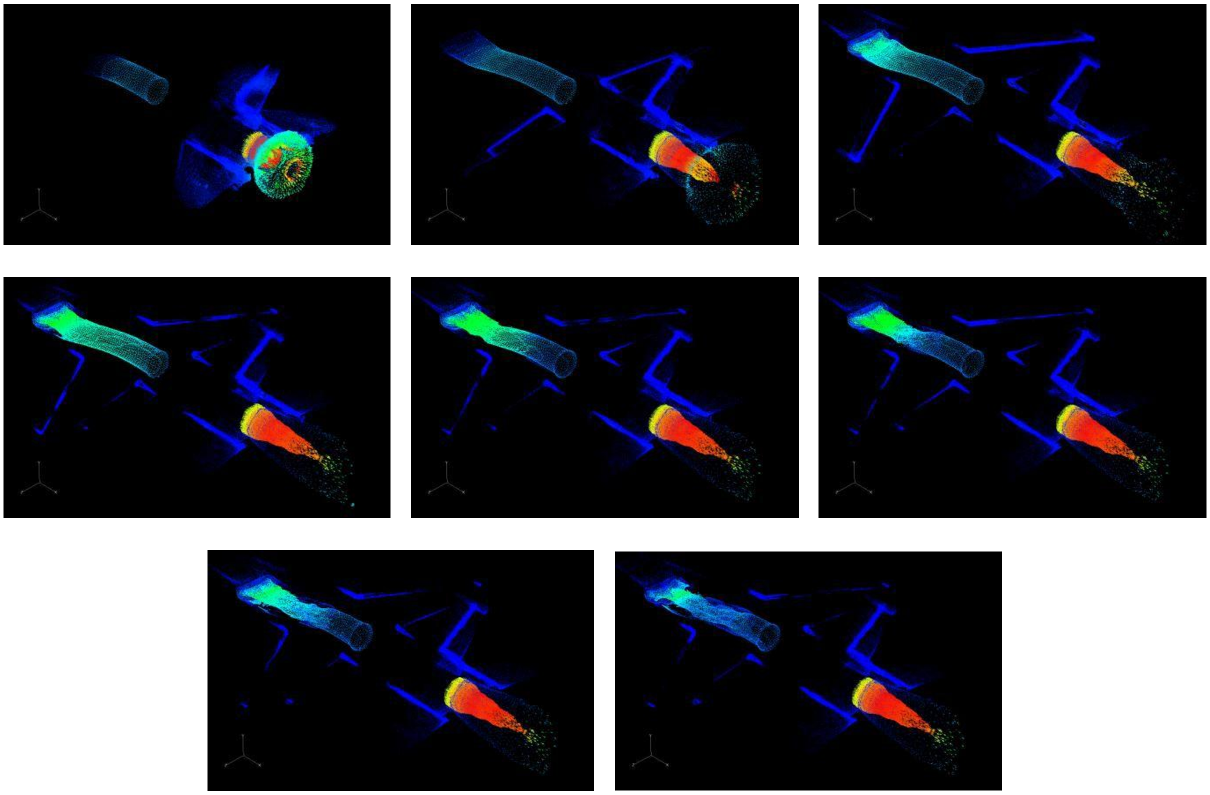

Figure 10. External control of the F-16 engine.

3. Conclusions and Outlook

Development updates of a computational approach for accurately determining aircraft response to pilot input while incorporating the FLCS, engine model, CSDs, and 6-DoF simulation have been given. The approach is being developed utilizing data and tools already on hand for the F-16, and will be easily applied to future aircraft systems. Simulations show extremely promising results and greatly enhance the ability to identify stability and control instabilities over the traditional wind-tunnel-generated database approach, as well as flexibility when encountering new configurations in the design phase. Comparisons of the results with flight test and F-16 ATLAS data verifies and validates the outlined approach, and will continue to be the subject of ongoing work. Methods for prescribed motion flight test maneuver simulation have been developed and shown to be robust for a range of maneuvers, from wind-up turns to high-angle-of-attack, post-stall maneuvers. Integration of moving control surfaces in the flow solver is complete and has been tested. External control of the engine boundary conditions, 6-DoF and moving control surfaces is complete and running with *Cobalt's* CFD solver. 6-DoF simulations with prescribed control surface movements and with the engine modeled are underway. Aircraft FLCSs have been modeled in Linux and Simulink for incorporating into CFD simulations, and will be the focus of future work.

Millions of CPU-hours have been utilized to reach the current level of Computational Stability and Control (COMSAC) capability. The above work was conducted utilizing 256-1592 processors and all of the above simulations required *Cobalt* solver licenses and *Cobalt* overset licenses. Trends show the time required per iteration is increasing with the simulation complexity, and is currently over 4 minutes per iteration. The testing and development would not have occurred as quickly as it did if the 1600 core dedicated server partition (DSP) on the Army Research Lab's (ARL) machine Harold was not available. In the next 1-2 years the number of processors required per job will increase from 1K to 4K-8K to reduce the computation time per iteration. To be a viable M&S option for the Test and Evaluation (T&E) community, jobs must be submitted and results analyzed in days or weeks rather than months.

Acknowledgements

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References

[1] F. T. Johnson, E. N. Tinoco, N. J. Yu, "Thirty Years of Development and Application of CFD at Boeing Commercial Airplanes, Seattle," AIAA Paper 2003-3439, 16th AIAA Computational Fluid Dynamics Conference, Orlando, Florida, June 2003.

[2] J.P. Dean, J.D. Clifton, D.J. Bodkin, C.J. Ratcliff, "High Resolution CFD Simulations of Maneuvering Aircraft Using the CREATE-AV/Kestrel Solver", *AIAA Paper 2011-1109*, AIAA Aerospace Sciences Meeting, January 2011, Orlando, Florida.

[3] Gaither, J.A., Marcum, D.L., and Mitchell, B., "SolidMesh: A Solid Modeling Approach to Unstructured Grid Generation," 7th International Conference on Numerical Grid Generation in Computational Field Simulations, September.

[4] Marcum, D.L. and Weatherill, N.P., "Unstructured Grid Generation Using Iterative Point Insertion and Local Reconnection," AIAA Journal, Vol. 33, No. 9, pp. 1619-1625, September 1995.

[5] Marcum, D.L., "Unstructured Grid Generation Using Automatic Point Insertion and Local Reconnection," The Handbook of Grid Generation, edited by J.F. Thompson, B. Soni, and N.P. Weatherill, CRC Press, p. 18-1, 1998.

[6] J.P. Dean, S.A. Morton, D.R. McDaniel, J.D. Clifton, and D.J. Bodkin, "Aircraft Stability and Control Characteristics Determined by System Identification of CFD Simulations", AIAA Paper 2008-6378, AIAA Atmospheric Flight Mechanics Conference, August 2008, Honolulu, HI.

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