Computational Fluid Dynamics Use, Application and Challenges in Support of Store/Aircraft Compatibility

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ABSTRACT

Store compatibility with the parent aircraft requires extremes amount of data to include structural, aerodynamic and electromagnetic data. The availability and use of data enables the assurance or caution on how a store will react to being cared and released on an aircraft and how the aircraft will perform carrying the store at a specified carriage location. Often the costs and time to acquire data causes program conflicts. Today's environment takes advantage in the use of modeling and simulation to acquire as much data as possible in the timeliest and most cost effective manner. Computational Fluid dynamics (CFD) provide the means to simulate flight testing and ground testing to gain aerodynamic and trajectory data. Often CFD supports the data gathered in wind tunnel testing by filling in the gaps and extending the data. Sometimes CFD provides all the aerodynamics data needed to understand the store compatibility conditions needed for flight test. For 25 years the Air Force SEEK EAGLE Office (AFSEO) has led in the use of CFD in support of store compatibility. This lecture note describes the standard practices for use of CFD in the AFSEO and the future challenges faced.

1.0 INTRODUCTION

Store compatibility has evolved in an attempt to use the best tools available. Safety being the foremost goal of course yet budget and schedule always pushes for more efficient and better methods. Both ground testing and flight testing will always be a major source for data and testing. Yet, both of these consume time and money at an ever increasing rate. Stores have evolved as well becoming lighter and more agile requiring greater attention to store/aircraft compatibility concerns. Physics based simulation methods have become common place requiring an initial investment of high performance computing (HPC) resources and skilled modelers. The HPC resources often can be shared across many organizations and cooperating stakeholders reducing the cost. Today, physics based simulation such as CFD still requires a moderate level of skilled workforce.

The Air Force SEEK EAGLE Office (AFSEO) located at Eglin Air Force Base in the United States (US) has inserted the application of CFD methods into its store certification process since 1993. It remains the premier user of CFD in a production mode throughout the US Department of Defense. Utilizing hundreds of thousands of computing hours and completing tens of thousands of CFD solutions each year. The use of CFD in AFSEO supports the engineering analysis for store separation, store/aircraft loads, aircraft flutter and aircraft stability & control (S&C).

This educational note is broken into three main sections, 1) the AFSEO, 2) current applications of CFD in support of store/aircraft compatibility and 3) the future challenges and anticipated use of CFD.

2.0 AIR FORCE SEEK EAGLE OFFICE

The Air Force SEEK EAGLE Office, a part of the 96th Test Wing at Eglin AFB, is the USAF center of excellence in the aircraft-store compatibility process.

AFSEO Mission: Deliver war-winning capability by efficiently evaluating the integration of state-of-the-art weapons on current and future generation aircraft, providing accurate combat weapon delivery software, while serving as responsible stewards of our nation's resources.

The SEEK EAGLE Program, detailed in AFI 63-104, is the United States Air Force certification process for determining safe/acceptable carriage and release (employment and jettison) limits, loading and unloading procedures, safe escape parameters, and ballistic accuracy, when applicable, for all stores in specified loading configurations on USAF and foreign military sales aircraft. Additionally, the process re-evaluates stores after modifications to hardware or software that alter the aerodynamic, structural, or electromagnetic characteristics of the aircraft or store, or the ejection characteristics of the suspension equipment. Examples of stores include weapons (conventional and nuclear), deployable countermeasures (chaff, flares, towed decoys, etc.), suspension equipment (including lanyards and umbilicals), tanks, and pods carried internally or externally.

The goal of the AFSEO is to be the most agile, trusted, and responsive provider of innovative and cost effective war-winning weapons integration and mission planning solutions in the Department of Defense. To accomplish this mission, the AFSEO employs digital modeling, simulation, and analysis, as well as ground and flight tests to obtain the data needed to verify safe and acceptable aircraft-store compatibility.

2.1 AFSEO Functions

The AFSEO provides a variety of products which enable system program offices to complete the SEEK EAGLE Program. Additionally, the AFSEO provides a range of engineering and analytical support to developmental store and aircraft system programs, as well as DoD contractors. The AFSEO's engineering core is comprised of technical teams with expertise in the areas listed below:

Store Fit
* Comprehensive database of 3-dimensional aircraft and store models
* Computerized fit checks
* Assessment of Store Fit through creation of models from engineering drawings or photogrammetry

Ballistics
* Database of aerodynamic and ballistic information for munitions
* Mathematical modeling for fuze arming and function
* Software verification/validation for weapon delivery portion of Operational Flight Programs

Store Carriage and Release
* Aircraft and store loads
* Aircraft flutter
* Vibration
* Aircraft stability and control
* Store Separation Analysis
* Ground and Flight Test Support
* Electro-Magnetic/Interference
* Electro-Magnetic/Compatibility

Combat Weapons Delivery Software
* Single Source for aircraft delivery planning for all fighter and bomber mission planning in the USAF
* Supports a wide-range of munitions
* Incorporates USAF-Certified safe escape and safe separation methodology

Safe Escape
* Minimum Release Altitudes
* Safe separation times for safe fuze arming
* Conduct test, chase plane, and aircraft deconfliction analysis

Information Based Tools
* Historical data on thousands of compatibility actions for use to clear new configurations by analogy
* Mass and physical measurement with computerized library of over 1,500 stores

2.2 AFSEO SEEK EAGLE Process

Figure 2.1 depicts this process within the AFSEO. Need statements come into AFSEO in the form of a SEEK EAGLE Request (SER) and this specifies the requirements. Not all disciplines are needed in every SER. CFD supports all disciplines needing aerodynamic data for their analysis. The System Program Office (SPO) holds the sole responsibility for store compatibility. AFSEO maintains the expertise and resources to provide the needed analysis for the process.

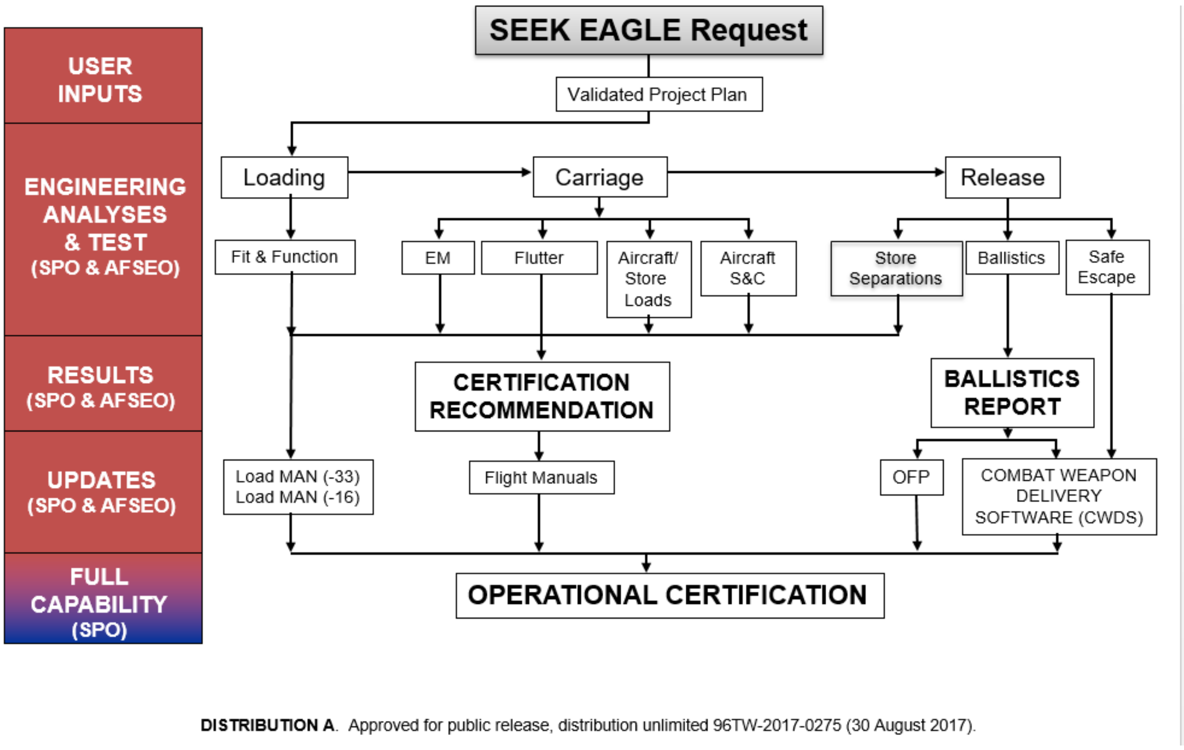

Figure 2.1 US Air Force SEEK EAGLE Request Process and disciplines

3.0 CURRENT USE OF CFD

Within each discipline for store/aircraft compatibility aerodynamic data is used to produce further discipline centric data. Figure 3.1 below depicts the inputs to the CFD methods and possible outputs from CFD back to the disciplines. From the top the basic inputs to CFD are the geometry provided most often by the Computerized Physical Fit (CPF) team and the inertial properties provide by Mass Property Measurement Facility (MPMF) and documented on the Store Technical and Mass Property (STAMP) sheet. The geometry can be either provided by the manufacturer or laser scanned by the CPF team. Either source requires time and skill to clean the computational geometry into a form that can be utilized in a CFD simulation. Inertial properties aid in time-accurate multibody dynamic simulations using CFD methods to support separation, loads and flutter calculations.

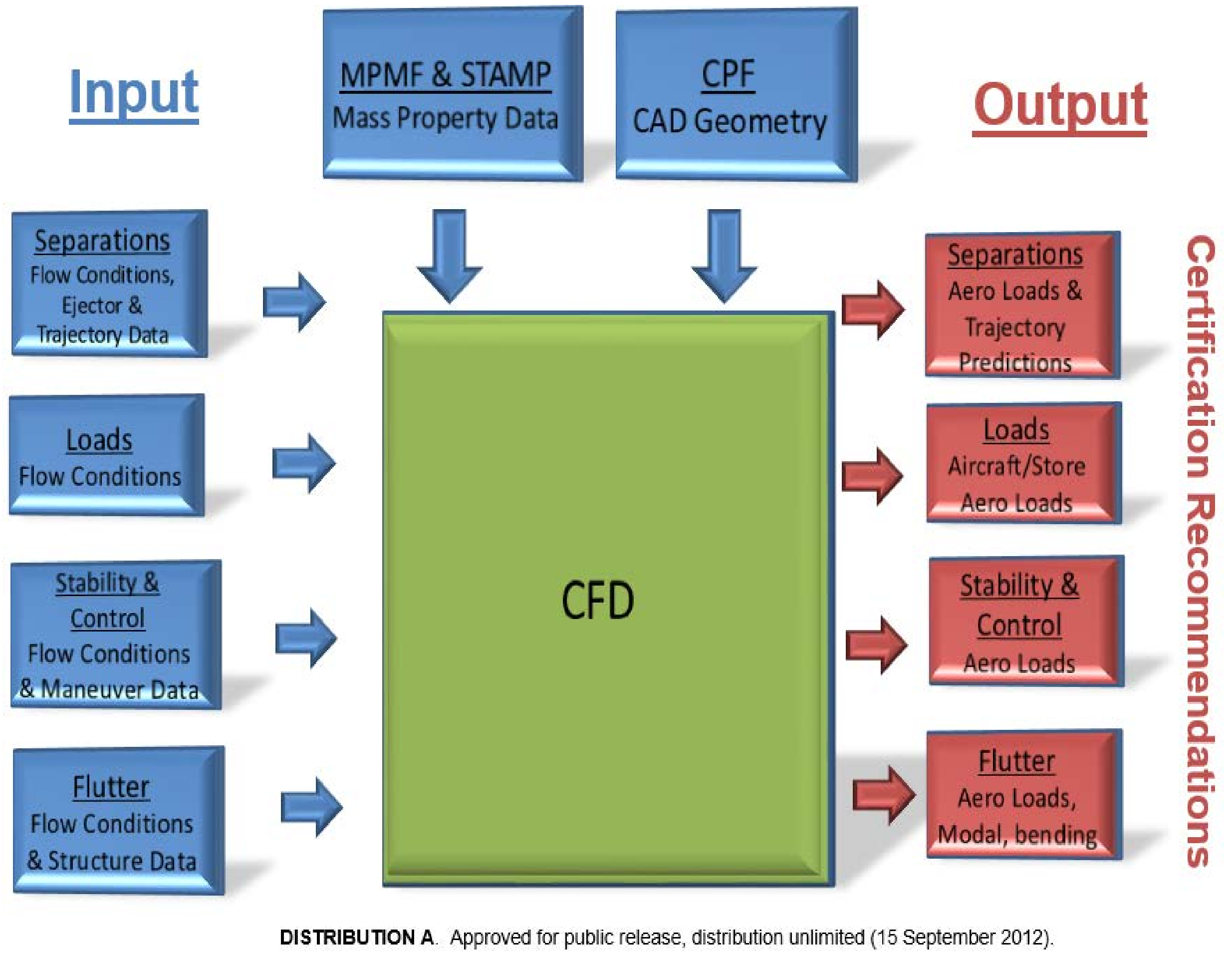

Figure 3.1 Disciplines in AFSEO that supply inputs to CFD and gain support from CFD

3.1 The CFD Method

The extent of CFD support greatly depends on both the capabilities of the CFD method and the throughput of the HPC resources. Most compressible, time-accurate CFD methods will provide store/aircraft carriage loads. In order to simulate a weapons bay the turbulence model and experience of the modeler will play an important role. A coupled multiple body solver or 6 degree-of-freedom (6DOF) will be required to simulate a time-accurate trajectory. The latter is less common but today many CFD methods offer this capability. Production CFD requires proven accurate methods. Most often the use of a one-equation or two-equation turbulence model, such as Spalart-Almaras or K-omega with Delayed Detached Eddy Simulation (DDES) will run robustly and capture the vast majority of unsteady behavior in the flow whether external or internal carriage. The modeler needs to take great care in the computational grid when using these models to insure adequate resolution of the dominant, turbulent structures. It has been proven that the acoustic frequencies in the cavity directly correlate to the force and moment frequencies on the store. This requires greater care in capturing the Rossiter tones to at least the first three modes in order to capture the most influential unsteady force and moment frequencies. The higher modes are easy but unnecessary. It is the lower modes that require long run times just to “set-up” the cavity flow behavior.

3.2 The CFD Overset Method

When simulating bodies in relative motion such as a store separation event an overset CFD method is required. No matter if using a structured CFD method or an unstructured method current production CFD methods require overset or overlapping grids (sometimes called Chimera Grids). The reason for this stems from the need to move rigid bodies in reletive motion with each other while maintaining adequite near body grid resolution. Figure 3.2 depicts the standard process for using overset methods. As mentioned above, the grid starts with a smooth, water-tight surface geometry to produce a surface grid. Using the appropiate means a volume or near-body grid is developed. The aircraft grid can extend out to the far-field boundary condition (BC) but for structured CFD methods that ususally results in a large amount of unnesseccary grid points. Making the aircraft a near-body grid set inside a larger “flow-aligned”, orthogonal grid has many advantages. The main extra step needed in using overset methods is the grid integration or assembly. In this step, solid boundaries “cut holes” in non-conforming grids and interpolation “fringe” cells are set to communicate the point-to-point flow conditions in conservative variables. These are density, the product of density to each directional velocity vector and energy. From these varibles every thermodynamics state variable can be calculated. After one or more time-steps of the flow solver the bodies move relative to each other either by prescribed motion to collect loads data or by solving the equations of motion. When solving the 6-DOF equations-of-motion all forces couple to predict the next location in time. These will include ejector forces, gravity forces, aerodynamics forces and any other forces such as thrust or motion contraints. Using a fully multibody dynamics solver allows for fin deflections and even auto-pilot controls during the separation event. When using fin deflects the fins will need to be overset grid(s) into the store body, which in turn will be overset grid(s) into the aircraft and far fields grids.

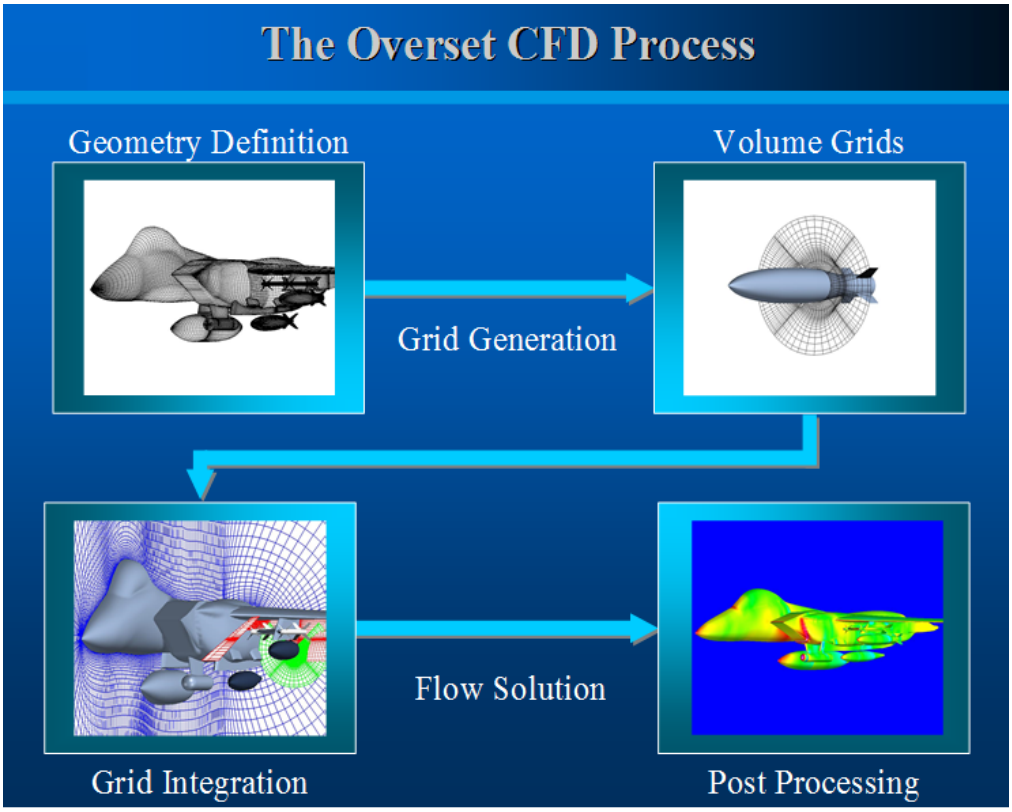

Figure 3.2 The CFD overset method and solution process for support to store separation

3.3 Sample Application

The follow are just a brief example of applications for CFD and are intended to provide insight into strategic capabilites that CFD can provide. In viewing these applications the reader must assume that to accomplish these functions a well extablished CFD method, engineers and HPC resource are available.

3.3.1 F-22 / GBU-39 Separation

As an example using CFD in both an unstructure and structured approach look at Figure 3.3. In this example the small GBU-39 store is to be carried and release from the F-22 weapons bay. The CFD and flight test that followed show no safety issues. The two techniques differ in many respects but most notibly in the number of imbedded grids. For the structure method using 1043 grid blocks and several imbedded grids not only between the store and aircraft but many components on the aircraft need to be separate imbedded grids as well, i.e. the bay doors. The ability to compute rapidly on a HPC system using the structure method is limied to balancing the grids across the computing cores. The hard limit will usually be the number of grid blocks but the realistic limit is much less as the size of the blocks vary greatly from 50,000 points to 250,000+ points. Using the unstructure method only one embedded grid system is needed here and that would be the store to the aircraft. That is the norm unless moving fins or wings are to be modeled, then each would need to be a separate embedded grid. Note that both CFD methods result in about the same number of grid points. This is not uncommon since most of the points are near the body and in or near the boundary layer. Yet the ability to adapt grids or even modify the grid system to be optimized to the solution is easier using an unstructured method. Structured grids still have the advantage of computational speed and solution time can be important if thousands of solutions are needed for a certification.

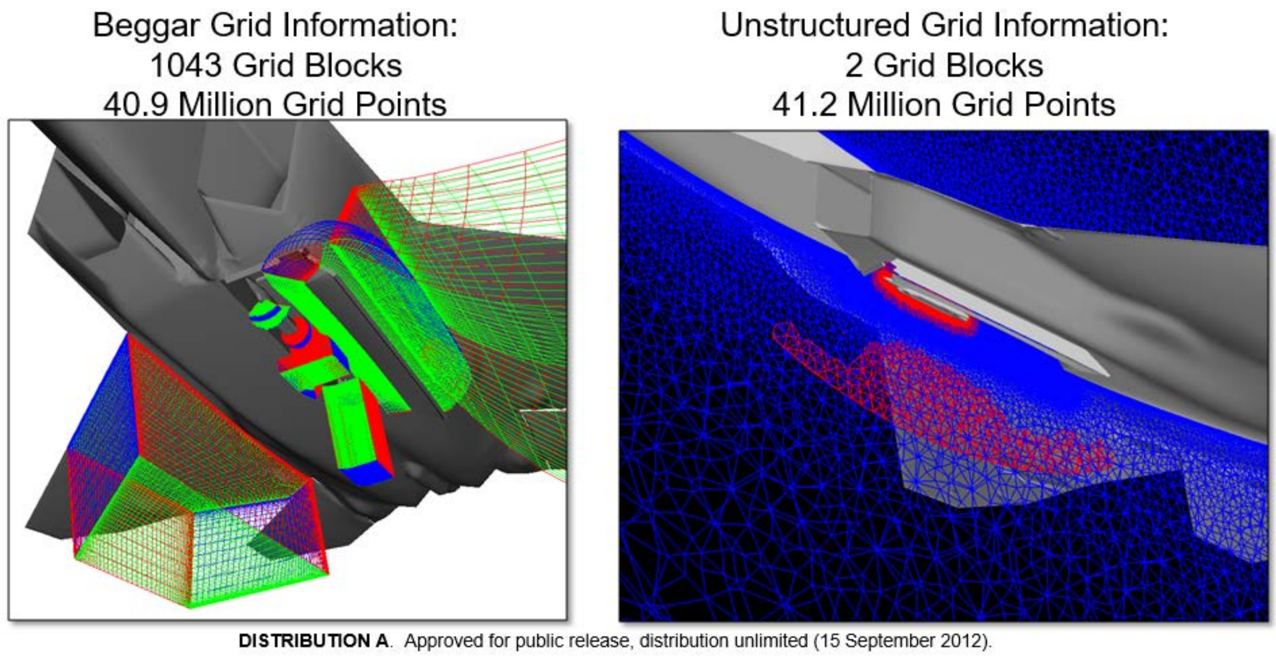

Figure 3.3. GBU-39 in the F-22 weapons bay. Structured overset grid blocks examples on the left with unstructured overset example on the right.

Figure 3.4 Shows the results compared to flight test telematry data. As one can see within the first half second the results compare to FT quite well and vary only a little between the two CFD methods during the whole simulated trajectory. This suggests that any "error" is not with either the grid or CFD solver method but with unmodeled details of the geometry and input conditions such as inertia values of weight and moments of inertia and initial conditions such as ejector stroke force and duration, etc. These later inputs make reproducing test results very challenging if not just lucky. The important part suggests that the simulation models perfect conditions and can be repeated in such as way that off conditions can be properly controled and documented. The best advantage of simulation is the ability to repeat an event in multiple ways to safely test a sufficient number of possibilities to consider going ahead with flight test or moving flight test to the next point or even canceling flight test. Rarely are flight tests completely canceled. Testing safer and smarter through simulation first is generally the goal.

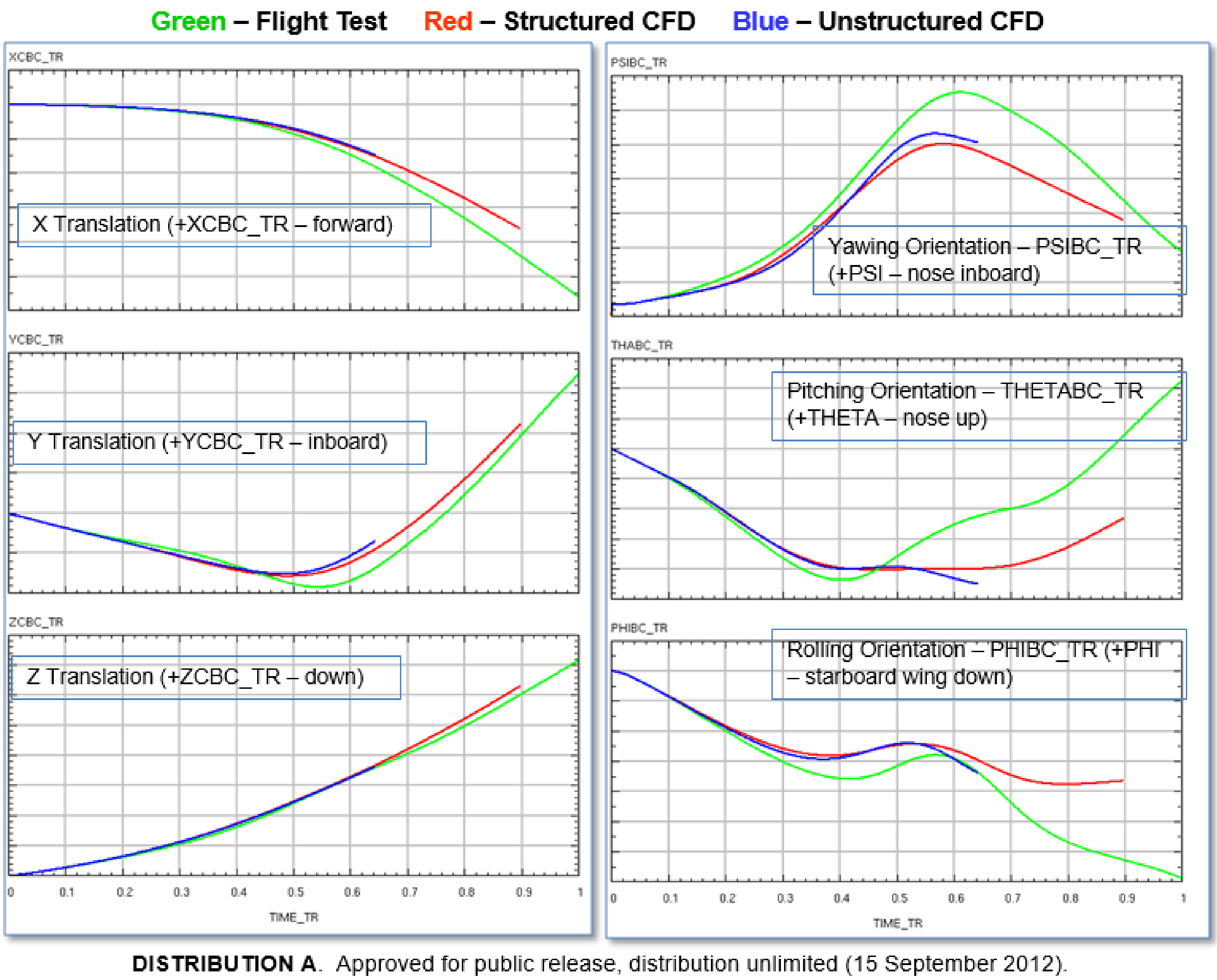

Figure 3.4 GBU-39 release trajectories from flight test telemetry and both structure and unstructured CFD methods.

4.0 FUTURE CHALLENGES IN CFD

Future challenges in using CFD in support of store-aircraft compatibility falls primarily into the two areas: non-repeatable trajectories and multidisciplinary simulation. Several computational techniques are being used and researched to achieve not just a capability but a production capability. The challenges for a production CFD method are the skills required and the feasibility of the solution process. Generally speaking a CFD capable engineer in the AFSEO will have at least a graduate degree in CFD or computational science. If no experience outside of school, they usually can be trained to be productive within six to eight months and considered independently functional within two years. Unfortunately this investment often makes others desire AFSEO CFD engineers and they are hard to keep. The feasibility of the solution process involves several aspects of the simulation: the availability of required modeling data, the robustness of the modeling process and finally the speed of the simulation to produce results. For example, a FSI simulation with moving control surfaces driven by an autopilot is technically achievable with the tools today in production. Yet, getting the required structures data and autopilot, control surface hinge constraints along with the aerodynamic mold-line would be challenging. The skills to model the structures and the aerodynamics and tune the auto-pilot can be above the average CFD engineer and require a team approach. This team approach needs a seamless and effective process to work in a production environment.

4.1 CFD Process for "non-repeatable" trajectories

During the store separation certification process assuming a store will take the same trajectory from the aircraft if released under the same conditions has always been the baseline assumption. The assumption allows one to study changes due to single variations such as CG or Mach Number or ejectors, etc. However, if for various reasons the store trajectory becomes a function of the time-of-release (TOR) then the certification process becomes an even more complicated statistical process. CFD is the only truly unsteady aerodynamics method for simulating non-repeatable trajectories do to TOR. Though rare to date, there have been a few examples of TOR sensitivity. Unless specifically tested for it will not be seen in flight test, though if present it may eventually be seen in operation. Figure 4.1 shows a sample CFD simulated release of a GBU-12 from the weapons bay of a B-52H. During a night training mission a released GBU-12 hit the B-52 horizontal tail. Using CFD in the investigation that followed demonstrated that the GBU-12 was a non-repeatable trajectory as release from the B-52 weapons bay. See Ref [AIAA-2003-0456]. That is the concern for the future as stores become lighter and less stable in their release configuration.

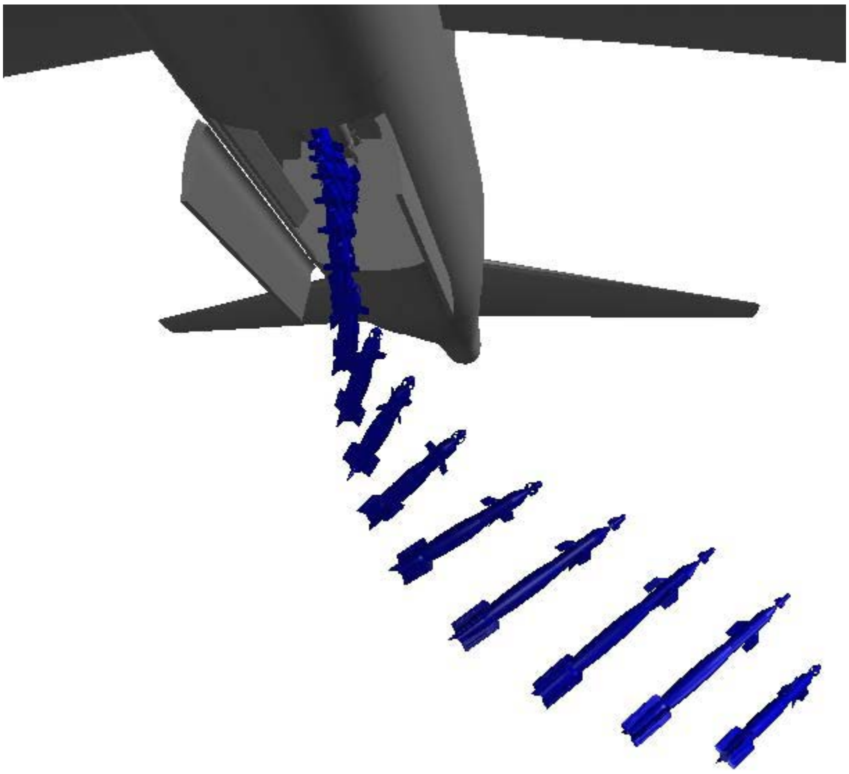

Figure 4.1 GBU-12 CFD simulated separation from a B-52 weapons bay. Exert from AIAA-2003-0456 by Jacob Freeman.

Another example is the LAU-131 jettison from the A-10. This has no effect on the certification process but is unique in that it occurs in an external carriage configuration. Figure 4.2 shows the carriage side force of the LAU-131 and the different TOR chosen to sample using CFD trajectory simulation. Figure 4.3 shows the general computational separation. It also shows a few of the possible trajectories just due to TOR. Note since the variation is not until after a third of second this did not have any influence on the certification of the store. It did represent additional evidence that the possibility of non-repeatable trajectories due to the presence of unsteady aerodynamics could be a concern in the future, even in external carriage configurations.

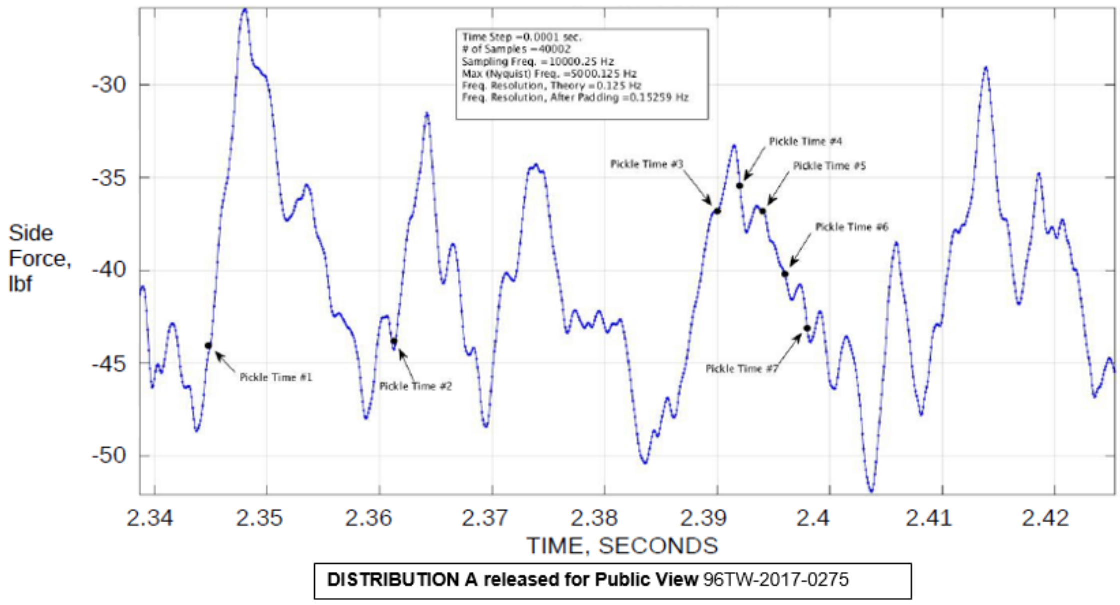

Figure 4.2 Side force versus time on the LAU-131 on the A-10 showing "Pickle" times for trajectory simulated using CFD.

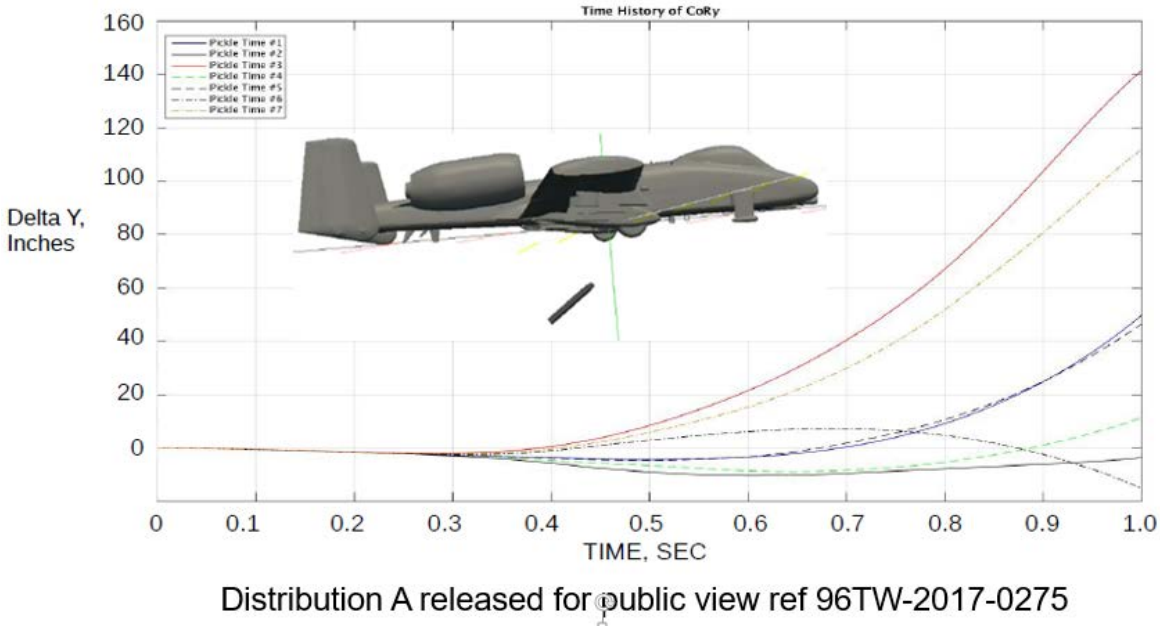

Figure 4.3 Side distance traveled by the LAU-131 when separated from the A-10 at random "Pickle" times, trajectory simulated using CFD

How is this a CFD future concern? The use of time-accurate CFD to capture either the unsteady flow data for use off-line or simulate the full trajectories to get a statistical model would be daunting. Today, in AFSEO the number of CFD produced trajectories remain on the order of 10 to 100 for a certification study. Those are just to examine the sensitivity to standard variations. Given a possible non-repeatable trajectory the number of CFD produced trajectories would increase by two orders of magnitude. The future will require CFD to produce more much faster.

This cannot be realized by computing increases only. A big part of through put is the human element of assembling and managing the multitude of CFD runs. AFSEO developed and uses a program called Tower. It is named after an air-traffic control tower and follows that paradigm in its development. In current use it allows a single CFD engineer to assemble, run, monitor, mine data and clean disk almost hands free for hundreds of CFD runs at a time. Future development targets multiple computing platforms and increased functionality to create an environment where by a single CFD engineer could run thousands of runs across multiple HPC resources.

4.2 Multi-discipline CFD

The ultimate goal of computational flight testing requires a multi-discipline approach to physics based simulation. Truth is there exist no event during carriage and release of a store that does not affect the aircraft structure. In turn the aircraft structure effects both the reactions of the store and the aircraft as well as its aerodynamics. Control surface effect the flow aerodynamics greatly and will need to be time-accurately functional during a simulation if simulating a maneuver or in some cases even steady flight given fly-by-wire control systems.

Today, the AFSEO can simulate actual flight maneuvers with control surface deflections and a modeled pilot at the controls. It has been demonstrated many times and is close to production use. Figure 4.4 shows some of the control deflections and pressure changes while simulating an F-16 in flight.

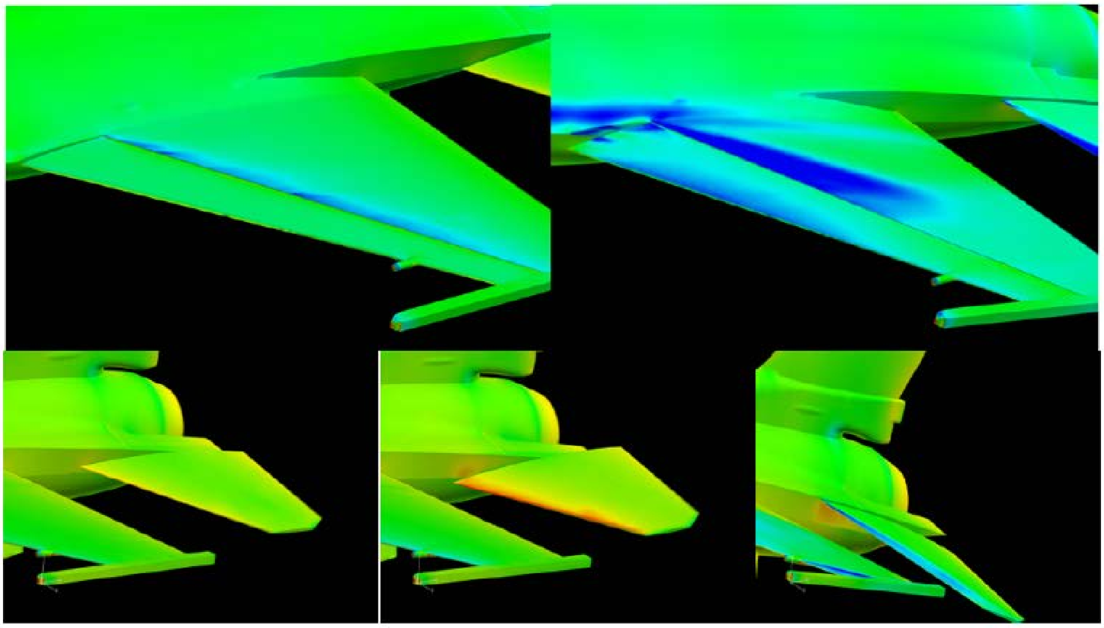

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Figure 4.4 F-16 control deflections and resulting pressure mapping during simulated flight maneuver using CFD, AFSEO Eglin AFB

Fluid-structure interaction with aerodynamic loads remains one-off simulations. The technology does exist and it can be done on clean aircraft or simple carriage configurations. It remains a challenging multi-disciplinary simulation for several technical reasons to include difference in structure versus aerodynamic time-scales, grid resolution and interpolation between structured and CFD grids. The engineer also has the difficulty of mastering both a computational structures dynamics (CSD) method and a CFD solution process to the point of effectively using them in a production environment. Currently, iterating between a structures code to get the mode shapes and solving the aerodynamics using CFD produces great results in a "near" production ready environment. Figure 4.5 shows such a case for the F-16, each mode being run through a CFD solver to populate the aerodynamic database for flutter analysis.

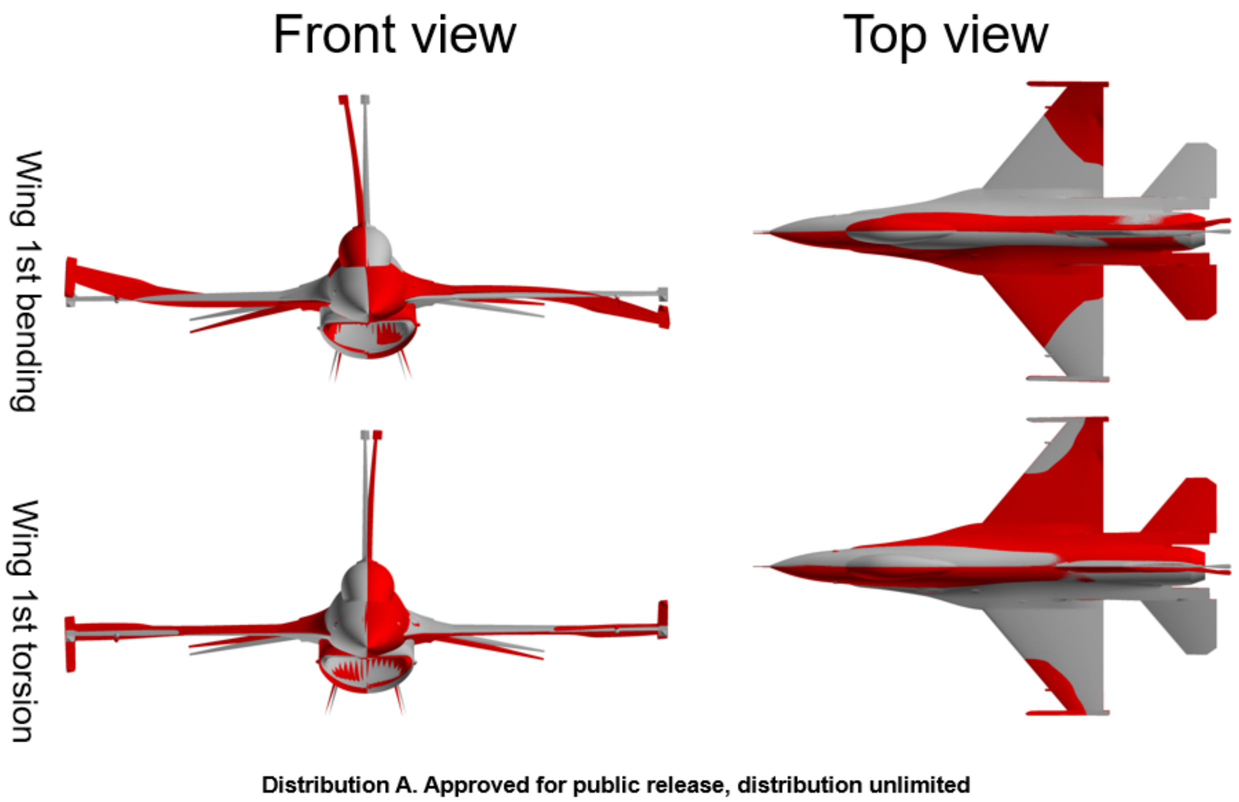

Figure 4.5 F-16 mode deflections using fluid structure interaction with CFD, AFSEO Eglin AFB

One approach to solve the issue of needing an engineer highly skilled in multiple disciplines would be to form a team. Given the CFD solution process and aerodynamic time-scales driving the overall simulation it would fit that the CFD engineer manage the solution, for example submit on the HPC resources. Yet, the computational grids, multiple discipline inputs and validating the results could be coordinated through a team approach in a highly effective production environment using the proper simulation software. This software would interface at the organization level rather than the engineer level only. Such an approach is being developed at the AFSEO called AFSEO Common Tool for Simulations (ACTS). ACTS starts as the program manager inputs the basic SER request specifying the aircraft, store at carriage location(s) and the flight conditions for the certification. Using the same interface with common data each engineer discipline involved in the simulation inputs their respective data, validates it and makes requests for simulation output. ACTS will be capable to not only interface with physics based simulation tools like CFD but also specific engineering level simulation tools used specifically within each discipline such as a loads code, flutter code and a separations 6-DoF code. This aids in the overall store compatibility process and ensures the CFD method uses accurate inputs to complete its computational intensive solutions. Figure 4.6 shows a screen shot of the ACTS being developed.

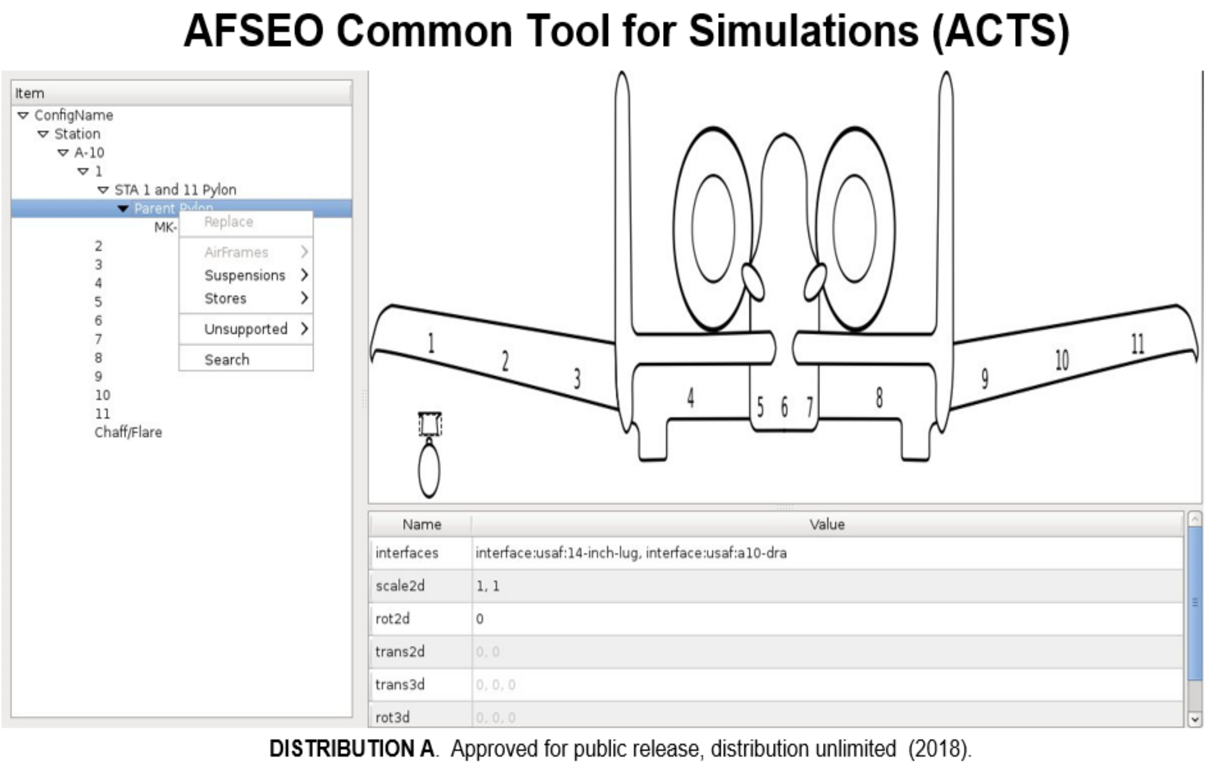

Figure 4.6 Sample screen for AFSEO Common Tool for Simulations (ACTS), AFSEO Eglin AFB

5.0 CONCLUSIONS

CFD produces accurate and cost effective aerodynamics data in support of store compatibility for every discipline. It requires both skilled engineers to operate in an effective production environment and adequate HPC resources to provide the data needed. Currently, CFD fills in the gaps left by more expensive wing tunnel testing and flight testing providing better information to test smarter and more efficiently than before. At times, it provides the primary aerodynamics data for a certification analysis. It also is the only method for gathering unsteady aerodynamics data and time-accurate, non-repeatable trajectories that may be needed in store compatibility. Tools such as Tower and ACTS enhance the engineer's productivity by orders of magnitude resulting in timely and effective data production. The future seems possible in achieving a fully coupled multiple discipline CFD method capable of virtual computational flight testing.