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Applied Computational Fluid Dynamics in Support of Aircraft/Store Compatibility and Weapons Integration – 2004 Edition

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Abstract

The Air Force SEEK EAGLE Office (AFSEO), Eglin Air Force Base (AFB), FL, is the United States Air Force (USAF) authority for weapons certification efforts. AFSEO performs test and evaluation for aircraft/store compatibility certification and uses Computational Fluid Dynamics (CFD) to support this process. Determining the flow about an aircraft/store combination can be extremely difficult. Complicated geometry such as pylons, launchers, and internal weapons bays can create severe acoustic and aerothermodynamic environments, which are challenging to numerically simulate. The additional challenge of rapidly and accurately simulating the trajectory of a store separation in a high-volume simulation environment is beyond the capabilities of most CFD programs. The USAF requirement for numerous, simultaneous and quick-reaction solutions for a wide variety of stores and aircraft can only be accomplished through application of parallel high-performance computing resources that meet the significant computational and memory demands of the various cases.

This project increases combat capability for the current USAF fleet of tactical and strategic aircraft with associated weapon systems. Before operational use, all aircraft/ store configurations must be certified for safe loading, carriage and jettison/release. AFSEO provides flight certification recommendations, which are based on combinations of engineering analysis, ground, and flight testing. Engineering analyses come from disciplines in carriage loads, store separations, flutter, ballistics, stability and control, and electromagnetic compatibility and interference. The AFSEO CFD team provides time-critical support for engineering analyses—in the form of computed aircraft/store carriage aerodynamic loads, predicted store separation characteristics, and visualized flow field physics—used to optimize the application of ground and flight testing, reducing risk and lowering cost of fielding new weapons. This paper discusses four of the most recently applied AFSEO CFD tasks and code

development, related to specific aircraft/store certifications.

1. Introduction

The Air Force SEEK EAGLE Office (AFSEO) determines ground test requirements, performs engineering analyses, develops flight test profiles, and directs real-time flight tests to support the aircraft and store certification process. AFSEO maintains a core of engineering expertise in the areas of aircraft and store loads, store separations, vibration and flutter, stability and control, ballistics, and electro-magnetic compatibility and interference. As aircraft and weapon systems become more complex, certification cost will rise due to dependence on expensive, time-consuming ground and flight testing. Over the past few years, the USAF has significantly reduced the amount of funding available to acquire weapon systems, effectively limiting resources to perform store certification. Consequently, AFSEO has increased emphasis on modeling and simulation (M&S) tools to supplement current ground test methods and to optimize flight test requirements.

Because its engineering disciplines depend on aerodynamic data to drive simulation tools, AFSEO uses Computational Fluid Dynamics (CFD) to supplement wind tunnel data and provide high-fidelity aerodynamic solutions for inclusion in the engineering analyses. For numerous USAF tactical and strategic aircraft carrying sophisticated weapon systems, AFSEO CFD currently is capable of calculating carriage aerodynamic loads (point and/or distributed), predicting store separation trajectories, generating aerodynamic databases, determining the delta in stability and control handling characteristics, and providing an emerging design capability (validating stability and control systems and analyzing unsteady aerodynamic loading on components and control surfaces).

AFSEO uses a CFD code called Beggar. It has a unique, user-friendly grid assembly process that utilizes

the latest developments in overset grid technology. Beggar is tightly coupled with a multiple degree-of-freedom (6+DOF) algorithm that provides a time-accurate store separation prediction capability, including control surface deployment and deflections. This CFD capability has been extensively validated using wind tunnel and flight test data.

Quick-reaction projects typically do not budget sufficient time for wind tunnel or extensive flight testing, thus such projects often rely on CFD to provide rapid, accurate prediction and analyses. Beggar provides a parallel computing capability for rapid turn-around times in support of operational requirements and developmental test and evaluation requirements. Nonetheless, in its response to quick-reaction projects, the AFSEO CFD team is slowed by limited available computing resources; DoD Challenge Project status on HPC resources and/or dedicated HPC Distributed Center hardware are critical to the CFD team's successful responsiveness.

2. Problems and Methodology

The primary challenges for CFD in the AFSEO production environment include rapid turn-around to immediate warfighter needs and accurate aerodynamic data to mitigate risk in testing throughout the acquisition cycle. Hence, as HPC capabilities expand, warfighter expectations rise and, consequently, CFD problems grow in frequency and in complexity (e.g., smaller, precision-guided munitions that are more susceptible to aerodynamic perturbations and active autonomous weapons).

The AFSEO CFD code, Beggar, is equipped to hurdle these challenges, given its development process and sufficient, available HPC resources. After using an automated Chimera (overlapping) grid assembly, Beggar time-accurately solves the Navier-Stokes (for viscous flow) or Euler (for inviscid flow) equations of fluid motion, using an implicit, upwind Roe numerical scheme with limiters, coupled with a Newton relaxation method. Beggar's turbulence models include Baldwin-Lomax (preferred), Baldwin-Barth, $k-\epsilon$ with wall functions and Spalart-Allmaras. For each iteration in time, it performs three simultaneous tasks: grid blanking and interpolation between overlapping grids for block-to-block communication; computation of inviscid or viscous flow solution throughout computational domain; and integration and solution of 6+DOF equations of motion for the store, plus its fixed and moving control surfaces. References 1-4 give further details of the Beggar code. Recent and on-going development in Beggar includes accommodation of orphan grid points and enhancements to the 6+DOF model, namely closed-loop feedback control and spring-damping and friction for moving

components. These enhancements are addressed in the Results section.

3. Results

To be consistent with past User's Group Conference papers from AFSEO^[5,6,7], this paper presents results from project tasks completed in FY 2004, specifically NASA X-37 release from the B-52H, GBU-12B separation from a prototype unmanned air vehicle (UAV) designated YMQ-9A, CBU-104 release from the F-15E, and GBU-31, GBU-38 and CBU-104 separations from the A-10. While the AFSEO CFD team completed many other tasks, these are representative of the team's existing production, validation and development capabilities, as well as its emerging design capacity.

3.1. NASA X-37 Release from B-52H.

NASA plans on testing the X-37 Advanced Technology Launch Vehicle by releasing it from a B-52H. This plan requires mission, carriage loads, and separation analyses. NASA-Dryden requested that the USAF 412th Test Wing, Edwards AFB, California, contract the AFSEO CFD team to generate independent aerodynamic data. The AFSEO CFD team built a 15-million cell structured, inviscid numerical grid for the B-52H and a 10-million cell structured, viscous grid for the X-37. Computational runs required an average of 40 processors, such that the team needed to use remote HPC resources (Edwards AFB and MSRCs) with greater numbers of processors vice AFSEO internal resources. The team delivered more than 150 static CFD solutions and a dozen time-accurate trajectories for the X-37 carriage and release tests. The run matrix included solutions for the following: freestream X-37 (Mach 0.68 and 42,400 feet altitude), including the nose-boom geometry, at angles of attack ranging up to 40°; static carriage at various angles of attack and sideslip and at various departure distances for the combined B-52H/X-37; and freestream B-52H. CFD data show the details of the interference effects during the X-37 separation below the B-52 wing. Figure 1 shows surface contours of Mach, separation aft of the X-37, and temperature contours aft of the engines. To increase model accuracy, the team prescribed mass flow rates in and out of the engine, including a temperature initial condition at the engine outlet.

To investigate control surface sensitivities for the X-37, where these flight surfaces actuate autonomously for stability and control during separation, AFSEO CFD developers added a rate-control autopilot to the rigid-body solver portion of the Beggar code. NASA provided the AFSEO CFD team with an autopilot design, similar to the

one used for X-37. Dynamic trajectories, where the autopilot was active, demonstrated significantly greater control of the X-37 during release, as seen in Figure 2. This was the first time AFSEO applied closed-loop feedback control to existing dynamic CFD modeling. The CFD team continues to enhance fidelity of the autopilot system to simulate the actual X-37, which has commanded pitch authority and a porous drag chute, in addition to autonomous roll and yaw control.

Success with the X-37 has created additional work for the AFSEO CFD team to run CFD freestream and carriage solutions for the B-52H with the Mailbox (similar in design to X-37 but without wings and most of the control surfaces – it looks like a mailbox). Included in that numeric model is a dynamic drag parachute, which releases from and trails the Mailbox. Flight test data to validate the drag chute model will be available in August 2004.

3.2. GBU-12B Separation from YMQ-9A.

General John Jumper, USAF Chief of Staff, made it a priority to drop GBU-12B's from the YMQ-9A (a 7,000-pound version of the upcoming UAV, Predator-B), shown in Figure 3.

Unfortunately, hardly any aerodynamic data were available for the YMQ-9A. When asked to provide a risk assessment and since the AFSEO Separations Group had minimal data for conducting this engineering analysis, they asked the CFD team to simulate the separation event. Within a 4-week period, the CFD team worked intensively to generate and assemble CFD grids of the YMQ-9A and the GBU-12B, complete with deploying fins and deflecting canards. Both grids were structured and inviscid, where the YMQ-9A consisted of 4.8 million cells, and the GBU-12B had 10 million cells. The team also completed CFD solutions to provide the needed aerodynamic data for carriage, separation, fins deployment and canards deflection. Specifically, the GBU-12B releases included one port-side at 0.5 g with $\beta = 0^\circ$ from the pylon and a dual ripple at $\beta = 5^\circ$ from the inboard pylons. The team computed a total of five time-accurate trajectories, each at 0.34 Mach and $30,000\text{ feet}$ altitude, and 10 carriage solutions with canards fixed or free-floating^[8].

In addition to the standard carriage and separations data, the CFD team quickly responded to a request for analysis of unsteady aerodynamic behavior around the non-uniform navigation/sensor pod on the forward underside of the YMQ-9A. As a result of the CFD unsteady analysis, seen in Figure 4, engineers and technicians agreed to recess the pod several inches into the airframe – a design change implemented as a result of CFD analysis and a change which significantly improved air vehicle stability and control during flight.

All computations were performed on in-house AFSEO resources because the task was time critical. Resolving data transfer challenges, moving toward pseudo-instantaneous transfer, will enable the team to use MSRC resources in the future on similar quick-reaction tasks.

3.3. CBU-104 Separation from F-15E.

To support an AFSEO separations analysis prior to ground and flight tests for the F-15E, the CFD team completed inviscid analysis of Mach and configuration effects for the CBU-104^[9], which is a CBU-89 with the Wind-Corrected Munitions Dispenser (WCMD). The team investigated three load configurations at three different flight conditions for a total of nine carriage solutions and nine separation trajectories. Flight conditions were Mach 0.85, 0.90 and 0.95 at 7,100, 5,100 and 3,000 feet altitude, respectively; configurations included mixtures of store location and interference effects from one, two or three 610-gallon fuel drop tanks. Cell counts for the inviscid, structured computational grids are 9.4 million for the CBU-104 and 3.5 million for the F-15E. Figure 5 shows Mach surface contours on the F-15E and CBU-104 shortly after the fins deployed.

One prediction gives a near hit (within 3 inches) when the CBU-104 is on LC-3 (a forward location) at Mach 0.95; the CFD team performed an additional viscous analysis for this location. Flight test data for comparison are not yet available, so plotted results are not shown here.

Noteworthy contributions of these computations include successful demonstration of the 6+DOF solver, where the WCMD fins deployed from the combined effect of spring force and aerodynamic loads from the flow field. Additional follow-on work in FY 2004 and 2005 will involve adding an extended range kit, where wings deploy (WCMD-ER).

3.4. GBU-31, GBU-38, CBU-104 Release from A-10.

To support flight testing of CBU-104 separation from the A-10, the AFSEO CFD team accomplished within six weeks the task of completing assembly of an inviscid, structured numerical grid of the A-10, including all external pods and pylons. In the absence of updated and accurate CAD files of the A-10, team members spent time at the Air Armament Museum, Eglin AFB, studying and measuring the details of this revered aircraft then implementing them into the numerical model, which consisted of 9.4 million cells.

Modeled stores include the CBU-104 (WCMD), GBU-31 and GBU-38; these numerical grids were

inviscid structured, with cell counts of 9.4, 0.9, and 1.9 million, respectively. These cell counts indicate nearly an order of magnitude increase for models with moving components, such as the CBU-104's deploying fins. Figure 6 shows an overlaid history of the CBU-104 separating from an inboard pylon on the A-10's starboard wing. Close inspection of the image reveals deployment of the four fins early in the time history.

CFD simulations included a total of 18 carriage solutions and 18 trajectory predictions, where all but two cases computed with 0.75 Mach (two cases at 0.65 to evaluate Mach effect), at 6,000 feet altitude, high dive angle and a load factor of 0.5 g^[10]. Figure 7 shows surface pressure contours for one of the A-10 carriage solutions with two GBU-38s. Since all cases predicted benign results (i.e., aerodynamically stable stores and minimal interference effects), test engineers were able to minimize flight test cases, scheduled for the summer of 2004.

3.5. Code Development.

The AFSEO CFD team continues to increase accuracy, fidelity and credibility of its modeling and simulation capabilities by validating and enhancing its 6+DOF rigid-body solver. This paper has shown production-level validation of this capability, given the cases of X-37, GBU-12B, and CBU-104, which stores include deploying fins, and deflecting canards and other control surfaces. Efforts are or will soon be underway to model a dynamic drag parachute and deploying wings. Modeling enhancements include internal resistance for moving components (applied spring force, viscous damping torque, and friction), closed-loop feedback control (autopilot—demonstrated with the X-37 model discussed above), computation of aerodynamic grid-run data (such as a dynamic sweep through a range of angles of attack), and rail release for propelled munitions. Other development efforts include coupling a structural solver with Beggar to model fluid-structure interaction for flexible wings, adding unstructured solver capability to Beggar, and validating Beggar's ability to interpolate computed values to orphan points in the numerical domain.

4. Significance to DoD

This project increases combat capability for the current fleet of tactical and strategic aircraft with associated weapon systems. Before operational use, all aircraft/store configurations must be certified for safe loading, carriage and jettison/release. AFSEO provides flight certification recommendations, which are based on combinations of engineering analysis, ground and flight

testing. The AFSEO CFD team provides time-critical support for engineering analyses used to optimize the application of ground and flight testing, reducing risk and lowering cost of fielding new weapons.

The AFSEO CFD team enhances combat capability for the DoD by reducing cost and schedule associated with wind tunnel and flight tests, by eliminating inherent limitations associated with current ground test techniques, by reducing risk associated with flight testing in developmental weapon programs, and by cultivating development and validation of the next generation of weapon systems. Furthermore, improved CFD capabilities are promoting quicker reaction to immediate warfighter needs, as demonstrated by the YMQ-9A task discussed in this paper.

Currently, the AFSEO library of numeric models includes 11 fixed-wing aircraft and more than 25 weapon systems, sensors and smart store interfaces. Plans to model other aircraft include the B-1B (in progress), B-2, F-117, F/A-22, F-35 (JSF) and Predator-B. This is important because more aircraft and weapon platforms in the library means greater capacity for the CFD team to respond to quick-reaction tasks, which in turn allows weapons to be fielded in less time for operational use.

5. Systems Used

HPC resources are crucial to successful execution of AFSEO CFD responsibilities. The CFD team has relied on internal AFSEO computing resources, on non-Challenge status at Space and Missile Defense Center, Alabama, and Army Research Laboratory, plus HPC resources at Edwards AFB, California, for the X-37 work. AFSEO's resources consist of the following: 28-processor, IBM NetFinity Blade with 2 GB RAM per processor; 64-processor, IBM Linux Cluster; and networked SGI Octane2's and Linux dual-processor desktop machines. Challenge status would certainly alleviate much of the strain on AFSEO's in-house resources.

For increasingly larger computing tasks, AFSEO front-end processing now requires 4 GB RAM per processor, as demonstrated with the X-37 tasks, while back-end processing generally requires 1 GB per processor. Table 1 summarizes some statistics on the tasks described in this paper, and Table 2 shows progressively increasing trends in number of solutions completed each year and in memory and data storage requirements.

Table 1. AFSEO CFD Task Statistics

Task	Avg. No. CPUs	Max RAM (GB)	Max File (GB)
B-52H/X-37	40	25	10
YMQ-9A/GBU-12	25	25	10
F-15E/CBU-104	15	25	8
A-10/GBU-31,38, CBU-104	15	6	5

6. Concluding Remarks

Different from past years, the project tasks presented in this paper have no validation against flight test data, where most of the flight tests are scheduled later this year. This is not a weakness, rather an encouraging indication that the testing community has greater confidence in CFD as a predictive tool vice a post-test analytical tool. The AFSEO CFD team hopes to channel that growing community confidence toward inserting CFD earlier in the design process. These capabilities were demonstrated by use of X-37's autopilot in Beggar's 6+DOF solver and by the unsteady CFD flow analysis on the YMQ-9A. CFD could be used to assist in designing an aircraft or store stability and control system and in evaluating effects of unsteady aerodynamic loading on aircraft components and control surfaces – an invaluable resource in a world of so many cracked fins.

Table 2. AFSEO CFD Computer Usage

	No. Solution	Avg. No. CPUs	Total CPU-Hours	Avg. Points (millions)	Avg. RAM (GB)
FY01	112	20	215,000	3.9	5.0
FY02	226	24	511,000	5.4	6.1
FY03	450	24	741,000	7.5	8
FY04*	650	30	980,000	15.0	12.0

* FY04 Projected

High-performance computing resources play a vital role in the AFSEO process of granting flight test clearances and aircraft/store certification recommendations. As applications become more complex and accurate and as predictive tools for these

complex systems need to approach real-time computing capability to address warfighter needs, HPC resources must have sufficient number of processors, computing speed, memory, data transfer rates, and availability. As the HPC community meets these continually expanding needs, the CFD community in general and the AFSEO CFD team specifically will be able to continue providing maximum combat capability for the warfighter now and for years to come.

7. CTA

Computational Fluid Dynamics (CFD)

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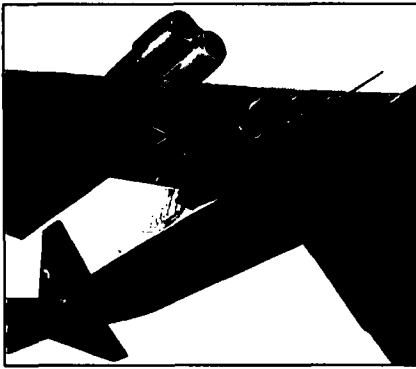


Figure 1. NASA X-37 Carriage on B-52H, Mach 0.68

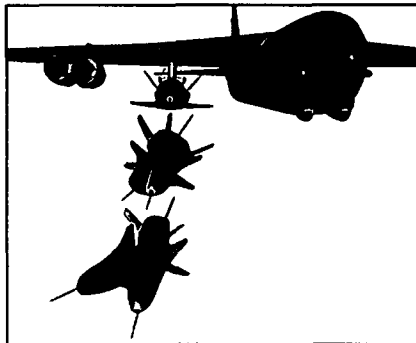


Figure 2. NASA X-37 Separation from B-52H: Unstable Without Autopilot (blue); Stable With Autonomous Control (gold)

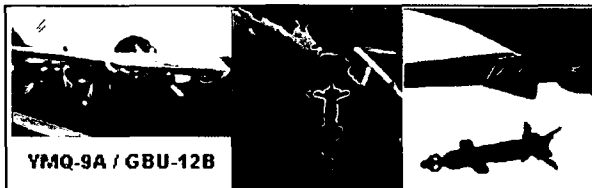


Figure 3. (left to right) YMQ-9A Loaded with Two GBU-12Bs; Flight Test Release (after CFD); CFD Prediction of Release, Mach 0.34

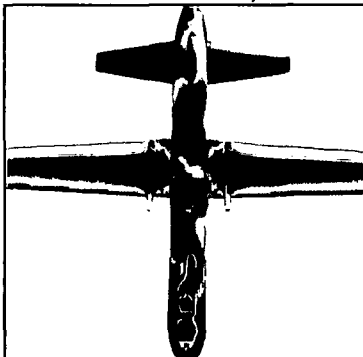


Figure 4. Unsteady Analysis of Flow Field Created by Non-Uniform Turret on Underside of YMQ-9A, Mach 0.34

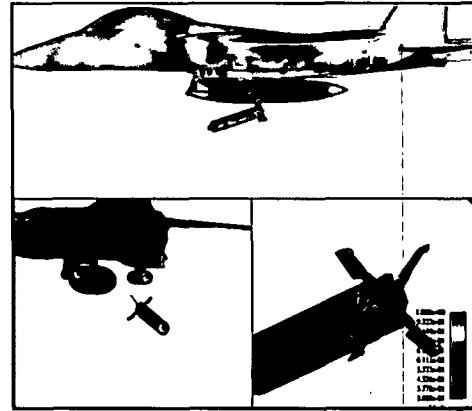


Figure 5. F-15E/CBU-104 Release with Deploying Fins, Mach 0.85

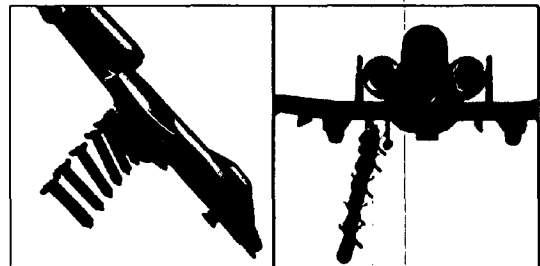


Figure 6. CBU-104 Release from A-10, Mach 0.75, High Dive Angle

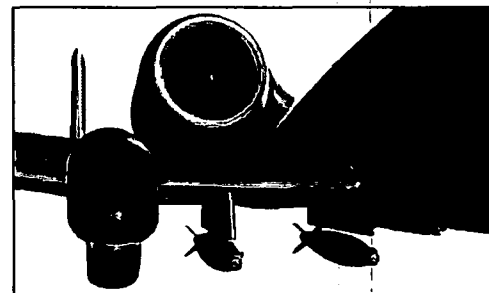


Figure 7. A-10/GBU-38 CFD Carriage Solution, Mach 0.75