STORE SEPARATION TRAJECTORY SIMULATION FOR THE HIGH SPEED ANTI-RADIATION DEMONSTRATOR (HSAD) FROM THE F-4 AIRCRAFT

Eric N. Hallberg
United States Naval Academy

A. Cenko and S. Dodbelle
Naval Air Systems Command, Patuxent River, MD

Abstract

The High Speed Anti-radiation Demonstrator is a follow-on replacement for the HARM missile and is planned for carriage on the F/A-18C aircraft. A wind tunnel test was conducted to generate the data necessary to clear HSAD for a launch from the F/A-18C parent aircraft at a Mach number of 0.8 and a pressure altitude of 30,000 feet. It was subsequently decided that the first HSAD launch would occur from the QF-4 aircraft. Due to cost and time limitations, it was not possible to conduct a wind tunnel test for the HSAD missile in the QF-4 flowfield. CFD tools were used to generate the QF-4 flowfield data necessary to conduct HSAD trajectory simulations.

1 Introduction

THE High Speed Anti-radiation Demonstration Program (HSAD) addresses the Navy's requirement to strike swiftly and decisively control time critical mobile forces. It intends to accomplish this by providing the capability to defeat short dwell mobile targets at range. The approach taken in developing the HSAD was to combine the proven capability of the AGM-88E HARM missile with advancements in propulsion technology, specifically advanced integral nozzleless rockets and variable flow ducted rocket ramjets. The program expects to demonstrate a substantial increase over current tactical capabilities including an increase of over the baseline HARM missile through a series of two flight tests from an F/A-18 C/D aircraft.

Originally, the HSAD flights were to be conducted from a modified LAU-118, on station 3 of the F/A-18C test aircraft. Figure 1 shows a mockup HSAD on a baseline LAU-118. The first free flight test of the HSAD missile was planned for release condition will be a Mach number of 0.8 and an altitude of 30,000 feet. Prior to the store receiving an airworthiness certification for release, a detailed simulation was conducted to estimate the HSAD trajectory immediately after launch. The simulation was based on wind tunnel testing at the Arnold Engineering Development Center (AEDC) and the running of two store separation codes.[1]

AEDC uses a Six-Degree Of Freedom (6-DOF) code known as the Multi-Dimensional Interpolation Trajectory Generation Program. The U.S. Navy generalized store separation code is known as NAVSEP, and is based on an early version of the AEDC TGP code. Both

Figure 1. HSAD Missile on F/A-18C (baseline launcher).

codes have undergone numerous improvements and modifications during the past 15 years. It is the practice of the U.S. Navy to independently verify store separation simulations, and as a result multiple codes were used to verify the safe release of the HSAD missile. This paper describes the original HSAD trajectory simulation in the F-18C/D aircraft flowfield, and the subsequent analysis that was performed to determine the separation characteristics for the QF-4 aircraft.

2 Wind Tunnel Tests

The U.S. Navy relies on wind tunnel testing using the Captive Trajectory System (CTS) to obtain store freestream and aircraft flowfield aerodynamics.[2] Ejector force characteristics, mass properties, and rocket motor thrust profiles are obtained through separate testing prior to flight test. The carriage loads and aerodynamic effects on the store after release are computed using data from three types of wind tunnel tests. The first type of test captures the flowfield effects of the interaction of the store with the aircraft. Aerodynamic data for various store orientations and positions is taken in a grid in proximity to the aircraft. The results of these tests are naturally referred to as the grid data. Freestream data captures the aerodynamic loads on the store away from the influence of the aircraft. Finally, CTS trajectory data are obtained by using the store mass, thrust, and aerodynamic loads in a quasi-steady trajectory simulation.

The Freestream data to be implemented into any 6-DOF code is often a much larger scale than that of separation testing. To this end, a 40% scale HSAD vehicle manufactured by Trimodels (shown in Fig. 2) underwent freestream testing in the Allied Tunnels 7-FT Trisonic Tunnel prior to the separation loads testing.

Next, the 6% scale HSAD and F/A-18C aircraft models manufactured by Boeing underwent separation/loads testing in the AEDC 4T facility.[3] Following the principle of independent verification, the freestream and grid data, ejector and rocket motor characteristics, and mass properties of the store

Figure 2. HSAD 40% Freestream Model.

were used in conjunction with the U.S. Navy NAVSEP and STEME 6-DOF programs for comparison to the CTS trajectories in order to certify the store safe for release.

Run number 1210 from the CTS trajectories obtained at the AEDC 4T tunnel serves as a good test case because of the similarity to the planned first free flight test. The test conditions are summarized below

Configuration:

- HSAD on IB Station 3
- 330 gallon external fuel tank on CL Station 5
- ATFLIR on MW Station 4
- OB Station empty

Flight Condition

- Mach number of 0.80
- Pressure altitude of 30,000 ft
- Aircraft dive angle of 0 degree
- Aircraft angle of attack of 3.5 degree
- Store initial carriage pitch of -3.0 degree
- Store initial geometric angle of attack of 0.5 degree

Initially, the simulated trajectory from the NAVSEP code matched the CTS run extremely well. The two trajectories are virtually indistinguishable as shown in Fig. 3, where the axis refers to the Absolute Aircraft Axis System (FS, BL, WL System).

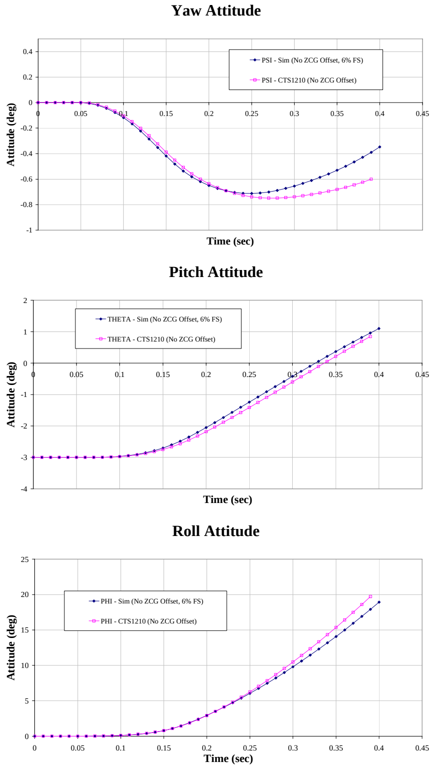

Figure 3. Trajectory Comparison of NAVSEP Simulation and CTS Run 1210

Incremental changes were then made to the simulation to better reflect the planned free flight test. The changes performed were to incorporate the 40% scale Freestream data, updating mass and rocket booster profiles to include a booster transient at the beginning of the launch, including varying mass properties of the store as the propellant is expended, and the thrust offset from the store CG which was not originally accounted for in the NAVSEP code.[7] The original and resulting trajectories are shown in Fig. 5. It was felt that difference between the modified NAVSEP trajectory and the CTS trajectory was significant enough to warrant further investigation.

Since the NAVSEP and AEDC Multi-Dimensional Interpolation Trajectory Generation Program shared a common development thread some 15 years back, it was postulated that the thrust offset defect discovered in the NAVSEP code might also be present in the AEDC TGP code. A thorough investigation of the AEDC TGP code showed this to be the case.

Appropriate corrections were implemented in the code and the CTS trajectory run was post-processed to reflect the changes. The resulting processed CTS trajectory showed excellent agreement with the modified NAVSEP and STEME trajectories. The resulting close correlation among the trajectories provided the confidence necessary to issue air worthiness certification for the HSAD at the flight condition investigated. Since the grid data were now validated, incremental changes were made to the simulation to better reflect reality. Grid data are generally implemented into a 6-DOF code as “delta” coefficients; that is, they are added to baseline store freestream values to account for the influence of the aircraft. To reduce systematic errors from the Wind Tunnel (sting aft end model distortion, scale effects, etc.), the freestream values subtracted from the “total” grid coefficients are from the same model as used for grid measurement (6% scale, in this case). However, NAVSEP has the ability to then use a better resolution freestream database to improve the quality of the simulation. The Navy took advantage of the 40% scale HSAD data for all further trajectory simulations.

Next, the rocket booster profile was updated to include a transient at the beginning of the launch, as well as varying the mass properties of the store as the propellant is expended. Figure 4 shows the HSAD at 0.7 seconds after release for three cases: without the CG/Thrust Offset (**purple**); with the corrected offset (**green**); and with the offset as well as the updated booster profile (**orange**).

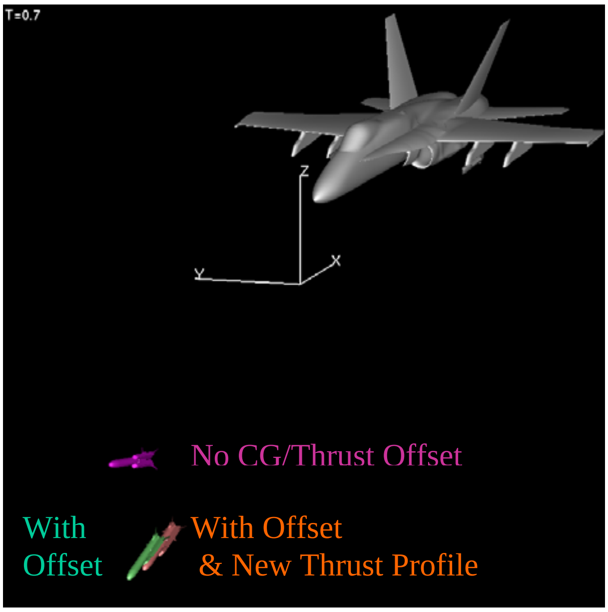

Figure 4. HSAD Trajectory Modeling Improvement.

3 Autopilot Integration

HSAD utilizes an advanced guidance section to control four moving control surfaces mounted on the rear fins of the vehicle. At release, the fins are initially locked. Fin unlock occurs 0.6 seconds after release as the autopilot takes active control of the HSAD vehicle. The behavior of the store when the autopilot initially begins to control the fins is of primary concern. Both TGP and NAVSEP required the addition of a separate subroutine for autopilots if the behavior of the HSAD vehicle during fin unlock was to be simulated computationally. A description of the autopilot functionality was supplied in the form of MATLAB/SIMULINK diagrams.[4,5].

An approach was taken that incorporated the SIMULINK realization of the autopilot with the Navy's store separation code. MATLAB has the capability to incorporate legacy FORTRAN code in its computational environment. Therefore, it was decided to modify the NAVSEP code to run as an executable subroutine in the MATLAB environment. Typically, the opposite approach is taken with most of the effort being expended in porting the autopilot algorithms into the 6DoF environment. A functional block diagram of the combined MATLAB/NAVSEP environment is shown in figure 5.

The autopilot integration and Monte-Carlo simulation of the HSAD release are described in detail in reference 6. Based on these analyses, a flight clearance for the HSAD missile for the F-18C/D aircraft was approved.

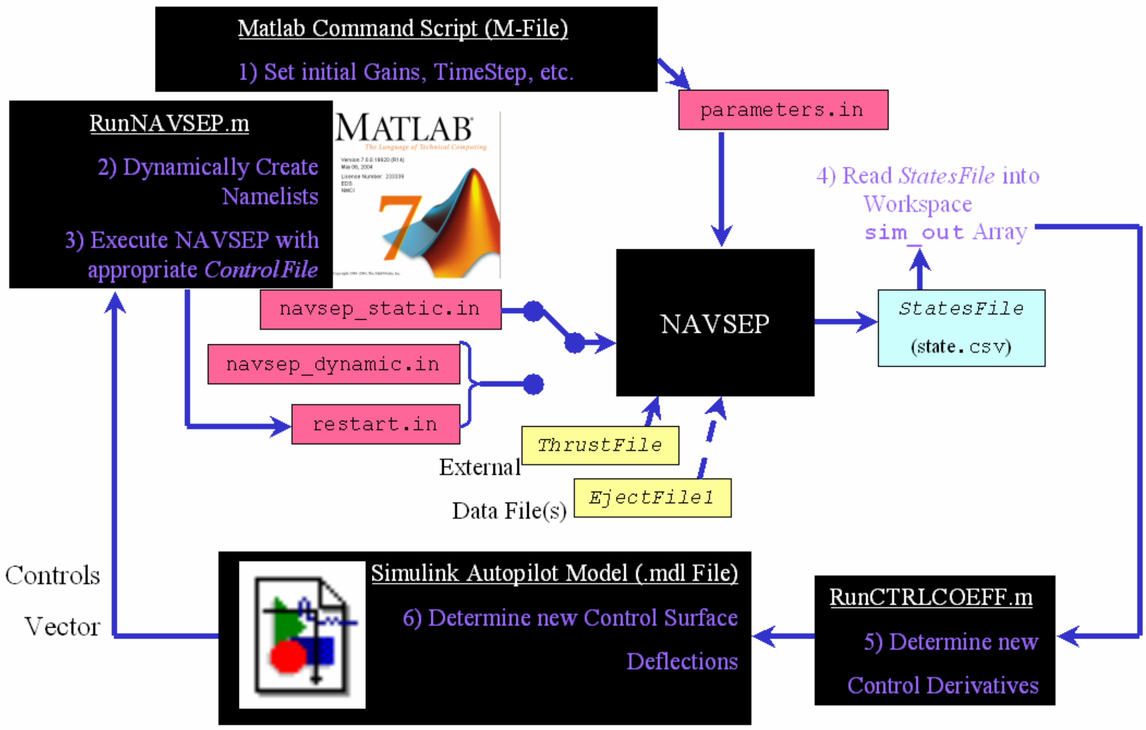

Figure 5. Functional Diagram of NAVSEP and MATLAB/SIMULINK Iterative Execution

4 QF-4 Flight Clearance

Subsequent to these analyses, it was decided that the first HSAD launch would be from the QF-4 aircraft. Since cost and time constraints precluded the possibility of conducting a QF-4/HSAD wind tunnel test, and since the US Navy has recently demonstrated CFD tools can be used to replace/complement wind tunnel flowfield data, it was decided that CFD could be used to determine whether the HSAD missile could be safely launched from the QF-4 aircraft.

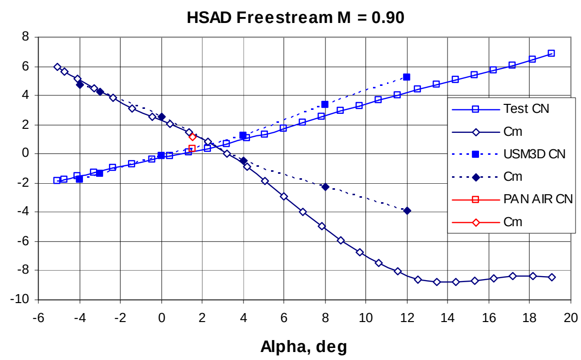

Figure 6. HSAD Freestream Comparisons

Since the HSAD missile is launched at subsonic speeds, and the rapidly accelerates to a supersonic Mach number, it was decided to conduct two independent calculations of the HSAD grid loads in the QF-4 flowfiled. The PAN AIR[7] code would be used to calculate the subsonic grid loads, while USM3D[8] would be used at transonic speeds. The PAN AIR code was selected because it's relatively easy to use, and has been previously validated at subsonic speeds.

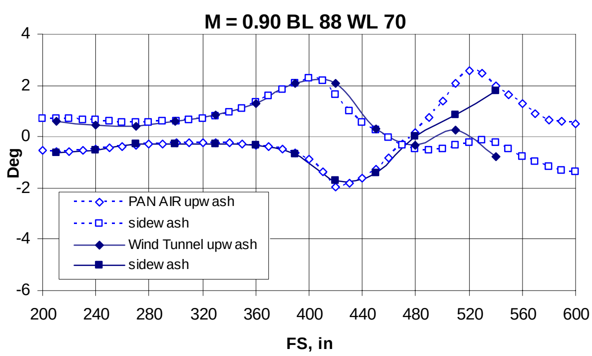

Figure 7. PAN AIR Flowfield Comparisons

As a first step, both codes were validated by comparing to HSAD freestream data. As may be seen in Figure 6, both codes show good agreement with wind tunnel data except for the pitching moment when alpha exceeds 4 degrees. This is probably due to the effects of the HSAD inlets at positive Mach numbers.

Since the freestream are subtracted from the grid data and replaced with large scale values, this discrepancy is of little concern.

The first step in developing the PAN AIR and USM3D models of the OF-4 aircraft was to determine the relative flowfield effects at the HSAD trajectory position. As may be seen in Figure 7, PAN AIR predictions are in excellent agreement with wind tunnel probe data for the upwash and sidewash at the inboard pylon location at M = 0.90 at AOA of 0 degrees.

To compare the QF-4 to the F-18 flowfields, the F-18 flowfield was shifted by the difference in CG positions for the HSAD missile. As may be seen in Figure 8, the two flowfields appear similar in magnitude, except

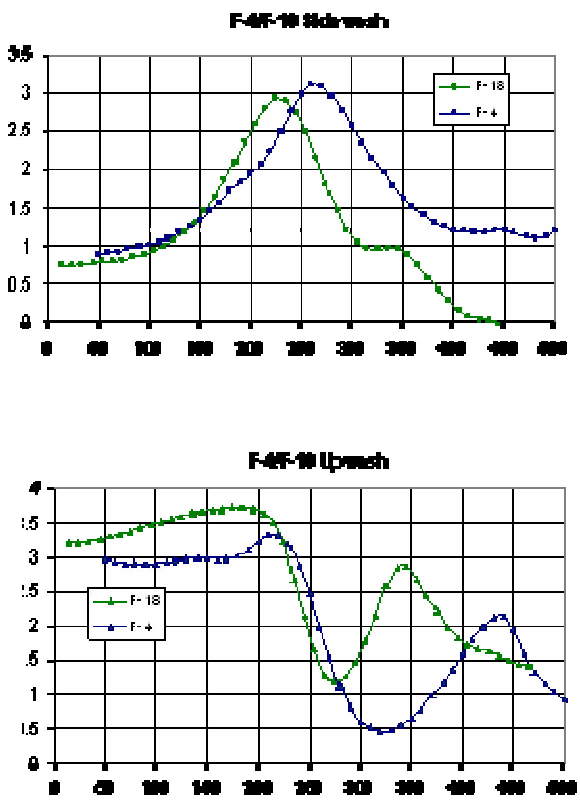

Figure 8. PAN AIR F-18C/D and QF-4 Flowfield Comparisons

that the QF-4 flowfield is spread over a wider distance. That implies that the HSAD loads would be more benign in the QF-4 flowfield that in the F-18.

The predicted HSAD forces and moments in the QF-4 aircraft flowfield are also shown in Figures 9 and 10. As expected from the flowfield comparison, the QF-4 grid data exhibits considerably less variation in forces and moments than the F-18C/D. This means that trajectories from the QF-4 would be more benign than from the F-18C/D under the same conditions.

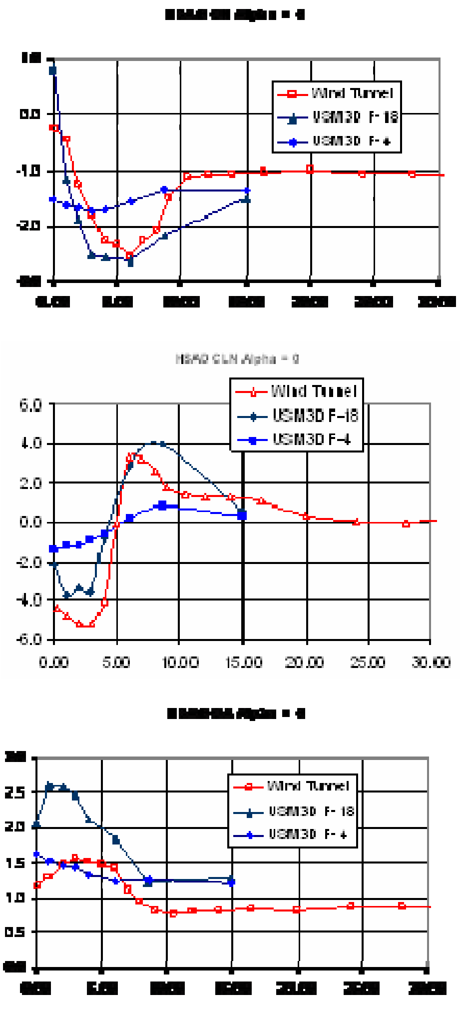

Figure 9. USM3D F-18C/D and QF-4 Force Comparisons

The only noticeable difference in the two trajectories is in the roll attitude. This is of concern, since roll attitude may affect the ability of the HSAD autopilot to recover the missile. However, since the intent is to use

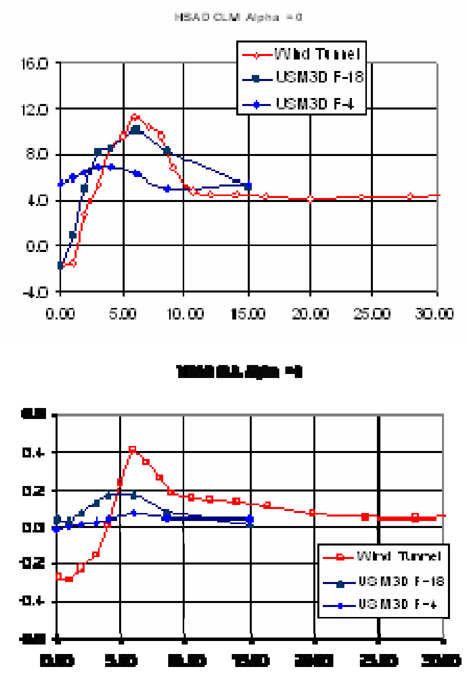

Figure 10. USM3D F-18C/D and QF-4 Moment Comparisons

trajectory predictions for the QF-4 in a relative sense to the F-18C/D, as long as the QF-4 trajectories are more benign for the same conditions they would be acceptable.

Since no wind tunnel data was planned to be available for the QF-4 launch, the accuracy of the CFD analysis for the QF-4 was based on comparisons of trajectory simulations using CFD and wind tunnel data for the F-18C/D. Figure 11 show a comparison of the trajectory simulations for the F-18C/D using data from CFD and data from wind tunnel testing. The agreement is generally close with the largest discrepancy being in the prediction of the roll angle of the missile. The good agreement provided confidence in the results obtained using CFD only for the QF-4. Figure 12 compares the predicted HSAD trajectories in the QF-4 flowfield to those in the F-18C/D flowfield. As expected, the trajectories from the QF-4 are more benign than from the F-18C/D.

5 Conclusions

The capabilities of CFD have matured to the point that it is an integral part of the store separation analysis process. The cost of CFD analyses is substantially lower than both wind tunnel and flight tests, so using CFD to

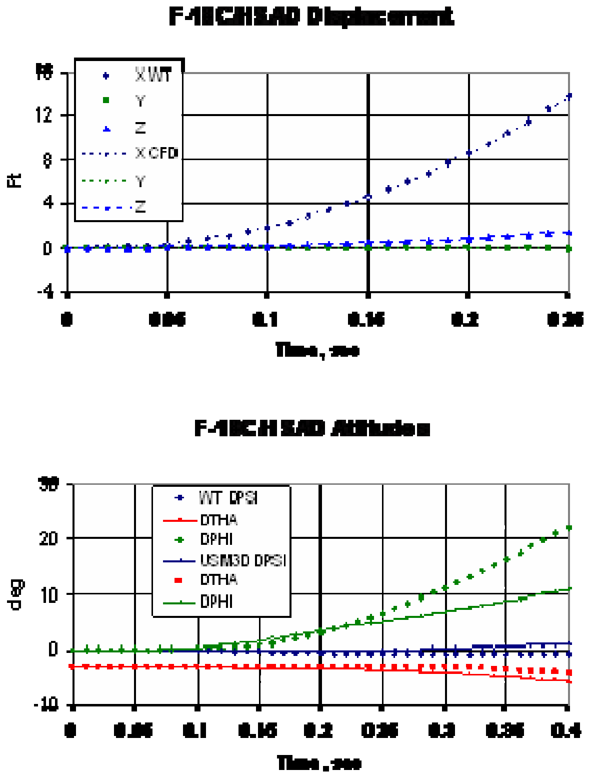

Figure 11. Comparisons of USM3D and Wind Tunnel Grid Data Effects on HSAD Trajectories

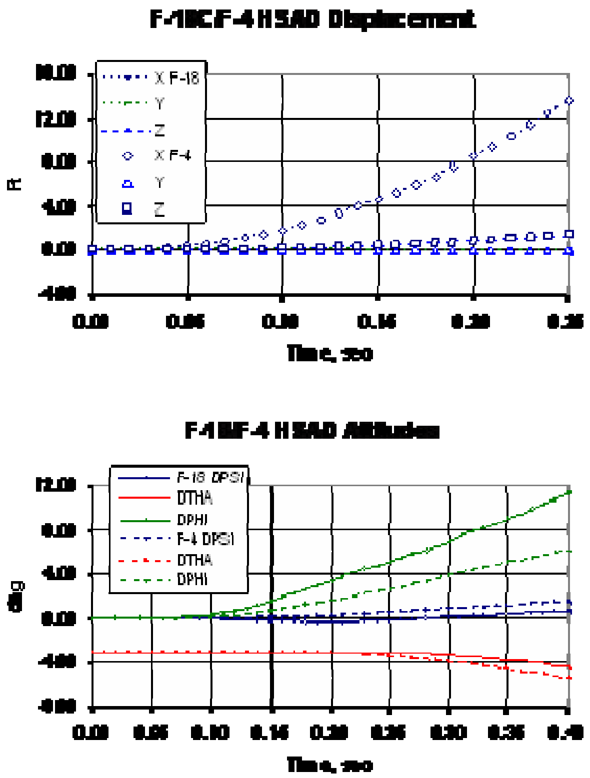

Figure 11. Comparisons of F-18 and F-4 Flowfield Effects on HSAD Trajectories

compliment wind tunnel testing makes good fiscal sense where possible. In this case, wind tunnel testing was available for the initially planned release of an HSAD from an F-18C/D aircraft. When the delivery aircraft was subsequently changed to a QF-4 aircraft, CFD alone was used to perform the trajectory simulations. In order to verify the accuracy of the CFD-based solution, the same CFD code was used to predict the release from the F-18C/D where comparisons to simulations based on wind tunnel data were available. The release from the QF-4 aircraft was determined to be more benign than a similar release from an F-18C/D aircraft, As a result a flight clearance was issued with no wind tunnel testing of the QF-4 required; a substantial savings in both schedule and money.

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