Evaluation of the Capabilities of CFD to Predict Store Trajectories from Attack Aircraft

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Abstract:

This paper explores the advantages of using computational fluid dynamics (CFD) to predict store trajectories. The focus will be on comparing CFD based store separation predictions with experimental data derived from wind tunnel and flight tests. Of particular interest are the abilities of new engineers to use various CFD packages to accurately predict store captive loads and separation forces, moments and trajectories in support of real stores clearance processes. The first phase made use of existing CF-18 Aircraft/MK-83 trajectory data from on-going flight-tests by the Canadian Airforce.

NOMENCLATURE

ACFD Applied Computational Fluid Dynamics
BL: Aircraft Buttline, positive outboard, in.
C_m: Pitching moment coefficient, positive up
C_n: Yawing moment coefficient, nose right
C_N: Normal Force coefficient, positive nose up
FS: Aircraft Fuselage Station, positive aft, in.
M: Mach number
OSD Office of the Secretary of Defense
P: Store roll rate, positive rt. wing down
Q: Store pitch rate, positive nose up
R: Store yaw rate, positive nose right
PHI: Store roll angle, positive rt. wing down, deg.
PSI: Store yaw angle, positive nose right, deg.
THE: Store pitch angle, positive nose up, deg.
VER Vertical Ejector Rack
WL: Aircraft Waterline, positive up, in.
α: Angle of attack, deg.

1 INTRODUCTION

Over the past fifteen years, the US Navy has made an effort to validate, demonstrate and accelerate the insertion of CFD methods into the store certification process[1,2]. There have also been several organized conferences with the same purpose. The first of these was for the Wing/Pylon/Finned-Store[3-8], which occurred in Hilton Head, SC in the summer of 1992.

The second conference was sponsored by the OSD funded ACFD program. This was for the F-16/Generic Finned Store[9-14] which occurred in New Orleans in the summer of 1996 (ACFD Challenge I). At the end of the meeting, the ACFD tri-service technical leads evaluated the CFD tools that were used to predict the F-16 Generic store carriage loads.

Their consensus was that although many important lessons were learned, the experimental test case did not include flight test data ("real" store trajectories). Because of this limitation, store certification engineers continued to express skepticism towards the accuracy of CFD methods. Also, the CFD community raised concerns about the credibility of portions of the wind tunnel test data, criticizing scale, model support interference, and wall effects. Therefore, there was a desire within the ACFD[15] program to reconcile these issues by conducting additional analysis using a data set that included both wind tunnel and flight test data.

The last ACFD sponsored conference was the F-18/JDAM CFD Challenge (ACFD Challenge II). Large sets of wind tunnel and flight test data existed for the F/A-18C JDAM configuration, Figure 1. During the flight test phase, both photogrametrics and telemetry were used to track the position of the store during releases. Out of these tests, two release conditions were selected for this CFD Challenge. The basis for these two cases included the following considerations: 1) matching aircraft and store geometry in both wind tunnel and flight tests, 2) correlation between wind tunnel data and flight test data, 3) possession of both high transonic and low supersonic cases with interesting miss distance time histories, 4) ability to publicly release the wind tunnel and flight test data to an international audience.

The test cases selected were M = 0.962 at 6,382 ft. (flight 13) and M = 1.05 at 10,832 ft. (flight 14). Both cases were for the aircraft in a 45-degree dive.

Eight papers[16-23] were submitted for ACFD Challenge II. The meeting was held at the AIAA Annual meeting in Reno, Nevada on January 12th, 1999. Two other papers[24,25] that were not ready in time were presented at the AIAA 2000 meeting in Reno.

The principal drawback of CFD Challenge II was that all the CFD results, using both Euler and Navier Stokes, as well as a simulation that ignored the JDAM canards, gave similar results. Did that mean that Navier Stokes formulation did not have to be used, or were the test cases selected fortuitous for the inviscid formulation. Indeed, Welterlen[20] showed that his inviscid calculation was superior to the viscous one. Since diagnostic data were not available, it was impossible to say whether the SPLITFLOW viscous formulation was at fault, or that the inviscid results had a fortuitous canceling error. It was the consensus[26] of the ACFD principals that another CFD Challenge, one that would have diagnostic data (store and wing pressures) was merited.

2 TTCP Panel WPN-TP 2 KTa 2-18

The Royal Australian Air Force (RAAF), Canadian Forces (CF), and the US Navy use, and will continue to use for some time, variants of the F/A-18A/B/C/D Hornet aircraft as their primary fighter weapons delivery platform. For stores clearance purposes, all these countries use similar approaches to performing Aircraft/Stores Compatibility (ASC) based on the methodology of MIL-HDBK-1763 which has traditionally relied heavily on the use of prior analogous stores results, wind tunnel and flight testing. Based on the demonstrated capability of CFD to predict aircraft store aerodynamics and trajectories in realistic timeframes, it appears that CFD has the possibility to dramatically reduce wind tunnel and flight test costs and time. In order to reduce duplication and redundancy in the US Navy's Flight Clearance, Australia's ASC Clearances and Canada's Stores Clearance processes, a new Key Technical area (KTa) was proposed under the auspices of The Technical Cooperation Program (TTCP) subgroup W.

The large wind tunnel PSP data set and store captive loads data sets from NRC/IAR's high speed tunnel were reviewed and the appropriate data were prepared for use in comparative studies. To date, specific subsets of the PSP data for the CF-18/MK-83 test case have been provided to interested participants under the auspices of the TTCP for KTa 2-18. It should be noted that the empirical data related specifically to the test case under analysis were intentionally not released to participating countries until February 2002. This comparative data were not furnished until CFD computations were completed, in an effort to demonstrate/evaluate the true capability of CFD in solving real-world stores separation problems.

CF-18/MK-83 stores separation flight-testing is ongoing at the Aerospace Engineering Test Establishment (AETE) in Cold Lake, Alberta Canada. Flight test trajectory data were provided for the first test case to be analyzed under this KTa.

Figure 2 provides an overview of the first test case configuration investigated by the participants. This paper presents the results of the first part of the US Navy effort for the KTa 2-18 program.

3 THE CODES USED

3.1 USM3D

The NASA Tetrahedral Unstructured Software System (TETRUSS) was developed during the 1990's to help provide a rapid aerodynamic analysis and design capability to aerodynamicists. The system is composed of several different integrated software pieces.

3.1.1 Grid Generation

The grid generation is done through a program named GridTool. This program helps to change the Computer Aided Design (CAD) into a grid representation, which can be used by the rest of the programs. The process of geometry and grid parameter preparation with GridTool constitutes 50 – 90 percent of the total grid-generation time. It also provides the input file for VGRID, which is the next software package in the process. VIDRIDns is a program for automatic generation of tetrahedral unstructured grids suitable for computing Euler and Navier-Stokes flow solutions. The process is based on an Advancing front and an Advancing layer method. Both of these techniques are based on a marching process in which tetrahedral cells form on top of each other.

3.1.2 Flow Solver

USM3Dns[27,28] is a tetrahedral cell-centered, finite volume Euler and Navier-Stokes (N-S) flow solver. Inviscid flux quantities are computed across each cell face using Roe's[29] flux-difference splitting (FDS). Spatial discrimination is accomplished by a novel reconstruction process[30], which is based on an analytical formulation for computing solution gradients within tetrahedral cells. The solution is advanced to a steady state condition by an implicit backward-Euler time-stepping scheme[31]. Flow turbulence effects are modeled by the Spalart-Allmaras (S-A) one-equation model[32], which is coupled with a wall function to reduce the number of cells in the sub layer region of the boundary layer.

The USM3Dns code is designed for the easy addition/modification of boundary conditions (B.C.). It supports the standard B.C.'s of flow tangency or no-slip on solid surfaces, characteristic inflow/outflow for subsonic boundaries, and freestream inflow and extrapolation outflow for supersonic flow. Some additional special boundary conditions are available as well.

The version of the program that was used included parallel processing. The tetrahedral grid was divided into a certain number of pieces and communication between these partitions was accomplished through Message Passing Interface. This speeds up the solution process better then the number of processors used. The solution is also unaffected by the splitting process.

3.2 SPLITFLOW

The other CFD code used for this study was the propriety code developed by Lockheed Martin Aeronautics Company SPLITFLOW[9,20].

SPLITFLOW is a Cartesian-based, unstructured, adaptive Euler/Navier-Stokes solver. The Cartesian approach generates hexahedral cells that are aligned with the Cartesian coordinate axes. Grid refinement involves recursively sub-dividing each cell into two, four or eight cells, which become "children" to the initial cell. Triangular faces, or facets define boundary geometry. At boundaries, cells are "cut" to account for volume and flux changes. This feature allows SPLITFLOW to handle extremely complex geometries, and little care need be taken by the user to prepare or maintain the grid. Initial grid cell sizes are scaled from geometry facet sizes and are then refined or derefined, at specified iteration intervals, by the solver based on the user's choice of gradient adaptation functions (Mach number, pressure, etc.). The refinement applies statistical methods, and searches for high gradients to determine where cells need to be added. Since the code is "smart" enough to place cells where they are needed, the best initial grid is usually sparse and the flowfield is used to determine where new cells should be placed. With a sparse initial grid, flowfield information can propagate in fewer iterations, each of which take less time because there are fewer cells. For example, a grid limited to 800,000 cells, is appropriately initialized to about 100,000 cells. Another benefit of cutting boundary cells is that geometry changes can be made easily while salvaging a developed solution. For example, if the user has a converged solution of an aircraft with undeflected control surfaces, a new geometry model with deflected control surfaces can simply be substituted.

4 Results and Discussion

The work presented in this paper is the culmination of two years of effort by Midshipmen at the US Naval Academy. Results for the aircraft wing, tank and store pressures[33], as well as comparisons[34,35] with the Overflow[36] code, were presented previously. This paper concentrates on the trajectory comparisons.

Both freestream and aircraft/store carriage loads were computed. All of the tests were run with the same test case parameters. The USM3D grids used in both of these had the grids varying from 1 to 1.3 million cells. SPLITFLOW used an adaptive grid, varying from 300K to 1.5 million cells. The original aircraft model did not include the vertical ejector rack. This was modeled for the present study, in an attempt to determine the importance of the ejector rack on the store trajectory.

4.1 Freestream Comparisons

Splitflow and USM3D comparisons for the MK-83 freestream characteristics are shown in Figure 3. Both codes show excellent agreement with the test data, although the SPLITFLOW code required less than a third the number of cells (300,000 vs. 1,000,000).

4.2 Force and Moment Predictions

Due to time constraints, the original USM3D and SPLITFLOW aircraft models neglected the VER geometry. For this study, the VER geometry was modeled; unfortunately, the USM3D license at the Academy expired before the computations were concluded. Since the original aircraft models for the two codes gave practically identical results[34,35], it is anticipated that the USM3D results for the VER effect on store loads would be similar.

As may be seen in Figures 4 and 5, the VER has a significant impact on the Mach number distribution on the store surfaces. This effect can be quantified by the differences seen in store pitching and yawing moment, Figure 6. Since the VER effect is to increase both moments, and since the moments drive the trajectory, it is clearly important to model the aircraft and suspension equipment as accurately as possible.

4.3 Trajectory Predictions

Although there were significant differences between the VER induced store pressures, the true test of the solution's validity is the capability of the code to predict the store trajectory. As was previously shown[34,35], the two Euler methods predict essentially the same trajectory as the OVERFLOW code. These trajectories were calculated using the approach described by Davids[37], with the input loads and moments predicted by the two codes.

Comparisons with the flight test results for this case are shown in Figures 7 and 8. The large yaw predicted for the store tail during the first 0.14 seconds of the trajectory is supported by the photogrammetric data, for both M = 0.90 and 0.95. The outboard store tail actually contacted the inboard store for the M = 0.95 flight, Figures 9,10. The predicted trajectory indicated that the inboard upper fin of the outboard store would hit the lower fin of the inboard store.

5 Summary

The Euler versions of the USM3D and SPLITFLOW codes have shown the potential of predicting complex flowfield aerodynamics at transonic speeds. The OVERFLOW predictions were performed by a CFD expert, while undergraduate students originally learned to use the unstructured Euler codes, and were able to produce useful results, in a short time frame. Comparisons with actual flight test data, which were not available earlier, seem to indicate that unstructured Euler has matured to the point where it can predict aircraft store aerodynamics and trajectories in a realistic timeframe. It certainly could have been used to predict the fin-to-fin contact prior to the flight test. The work is continuing, and further wind tunnel, flight test and predictions are planned as part of the TTCP effort.

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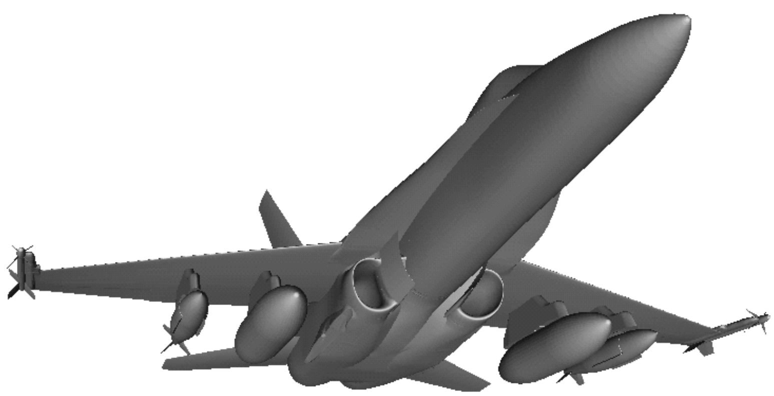

Figure 1 F/A-18C/JDAM Test Case

FIGURE 2 CF-18/MK-83 Configuration

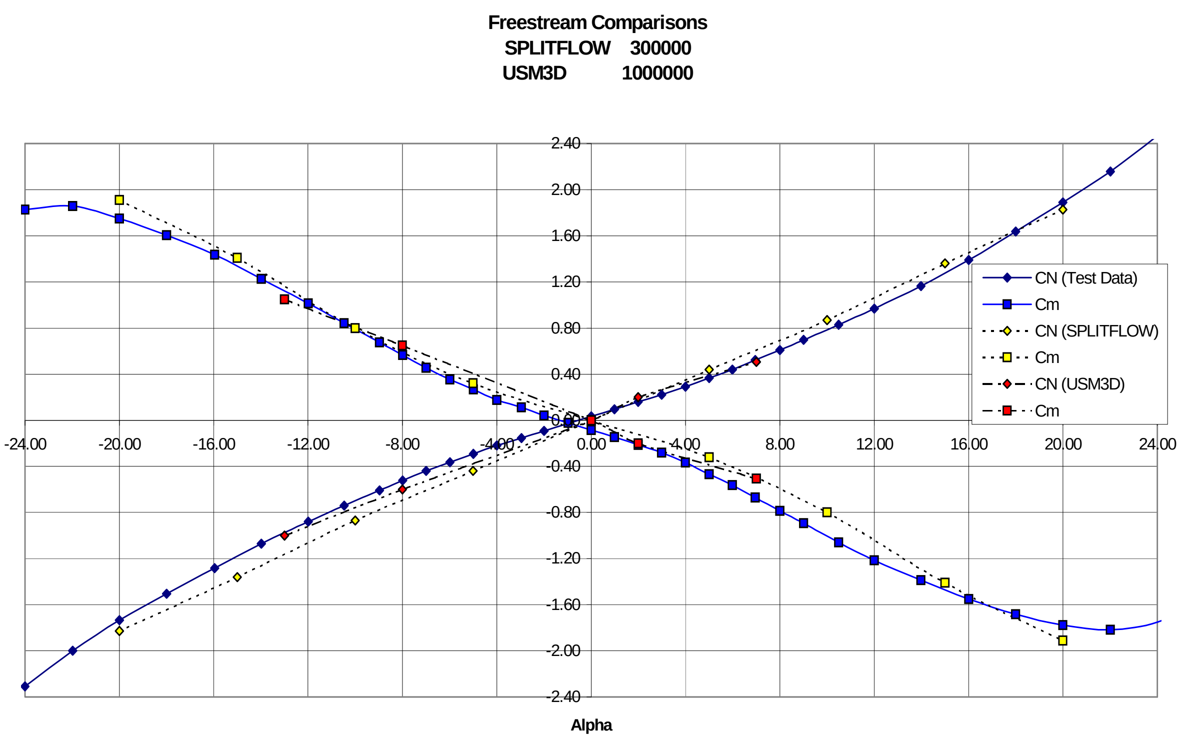

Figure 3. SPLITFLOW/USM3D Comparisons for the MK-83 bomb

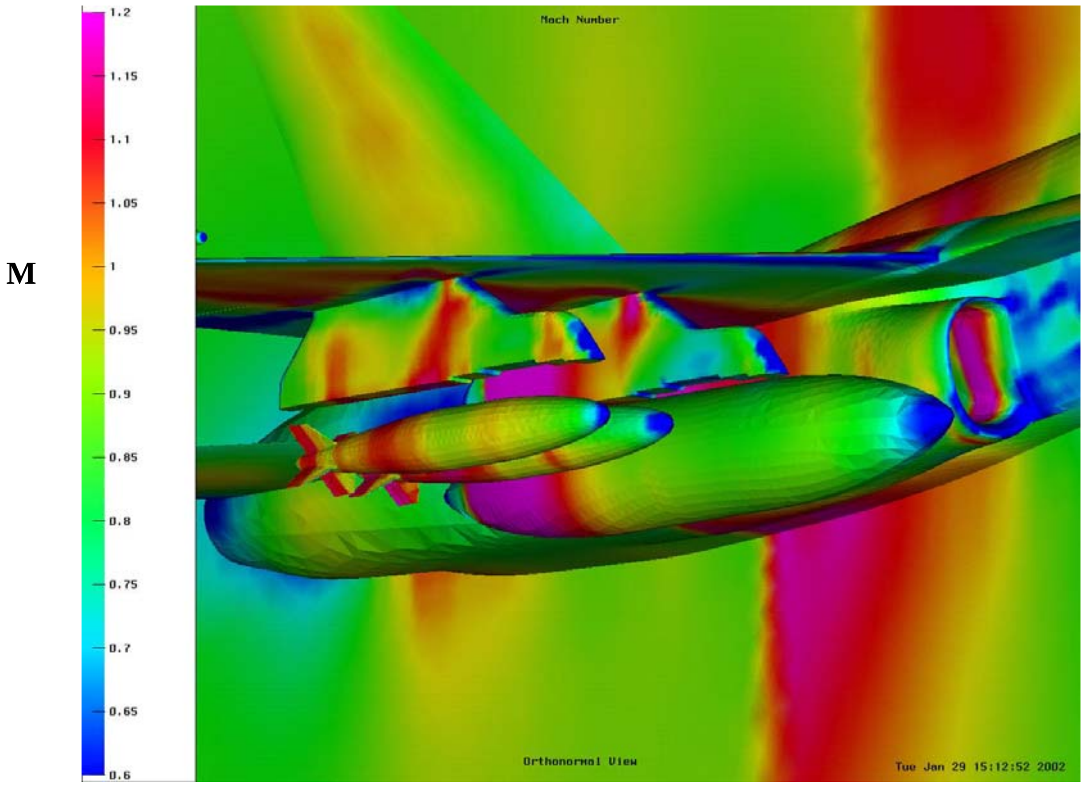

Figure 4: SPLITFLOW Mach distributions on Outboard Mk-83 for F-18 without the VER

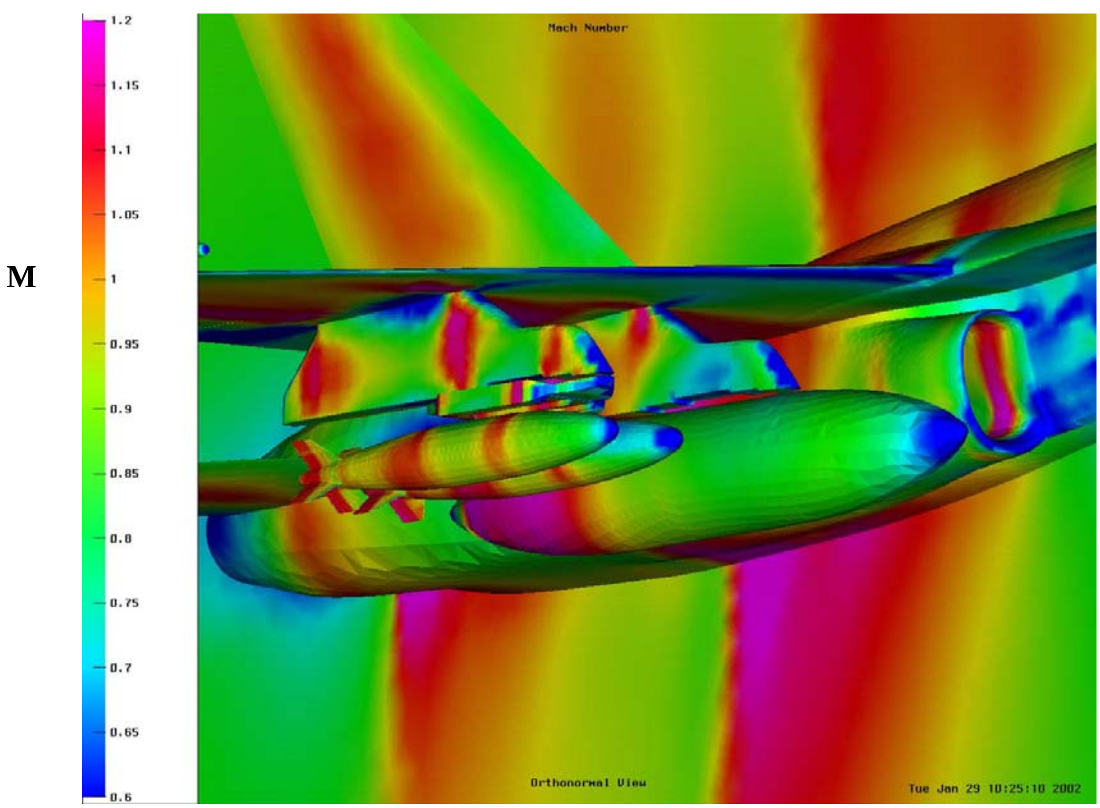

Figure 5: SPLITFLOW Mach distributions on Outboard Mk-83 for F-18 with the VER

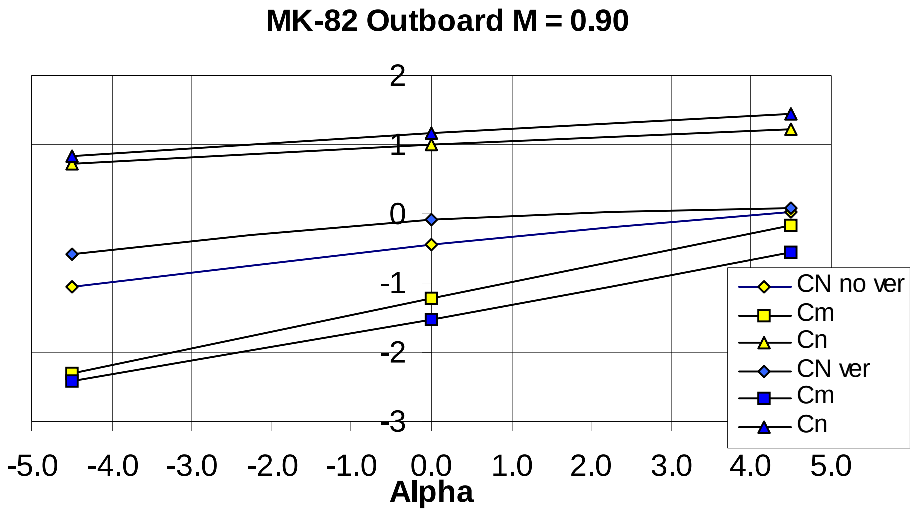

Figure 6: SPLITFLOW Comparison of Carriage Loads

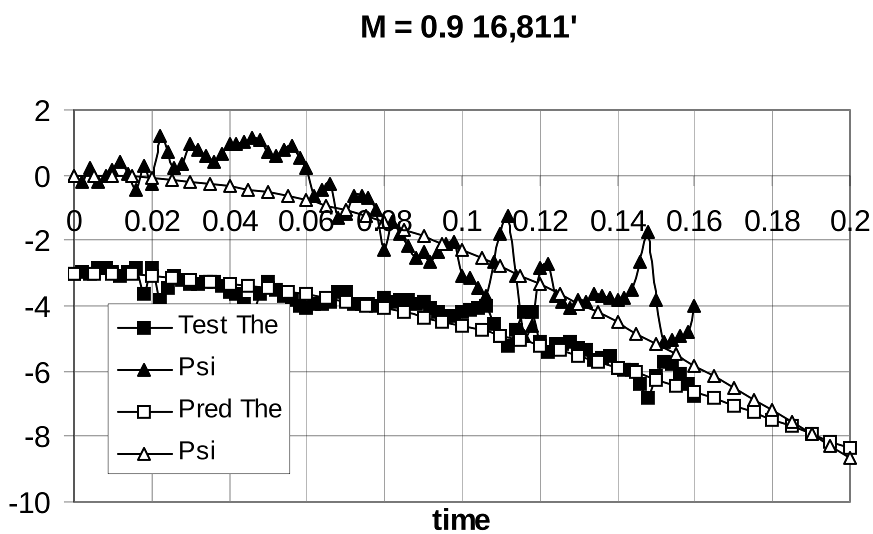

Figure 7: Trajectory Prediction M = 0.90

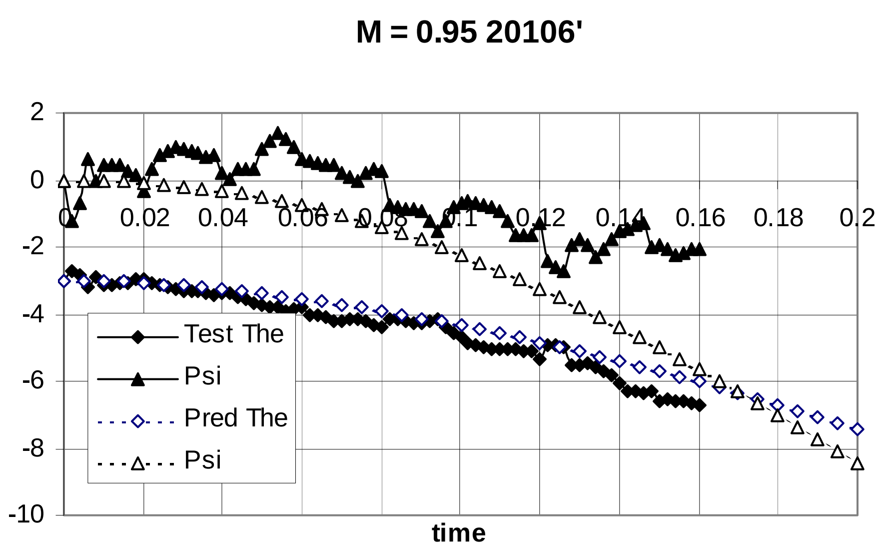

Figure 8: Trajectory Prediction M = 0.95

Figure 9: CF-18/MK-83 Carriage Position

Figure 10: MK-83 Inboard Store Fin Post Flight