F/A-18C/JDAM Applied Computational Fluid Dynamics Challenge II Results

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BACKGROUND

During the past ten years, the United States Navy (USN) has considerably improved its capabilities in aircraft/weapon integration. In 1989 it took more than 400 hours of wind tunnel testing, which cost $1,5000,000, and 20 flights[1] to clear the JSOW from the F-18 up to Mach 0.95. This year the MK-83 JDAM was cleared after only 60 hours of wind tunnel testing and five flights to the full F-18 aircraft envelope up to Mach 1.3. This reduction occurred not only because the USN learned to test smarter, but also developed an integrated approach[2] to Modeling & Simulation (M&S), wind tunnel and flight testing which allowed lessons learned on previous programs to be applied to new ones. However, the present approach still requires a fairly large commitment of time and financial resources to accomplish the mission.

The present approach has optimized the use of available resources; any further gains will have to come not by improving existing techniques, but by bringing new resources into the process.

Several years ago the United States Office of the Secretary of Defense (OSD), under the Central Test and Evaluation Investment Program (CTEIP) funded a tri-service research project termed Applied Computational Fluid Dynamics (ACFD) for store separation. This project is meant to provide analysis tools that effectively use Computational Fluid Dynamics (CFD) for store certification analysis. ACFD will provide the needed tools that will reduce USN dependence on wind tunnel and flight-testing.

ACFD is not intended to replace the wind tunnel in the near future; rather it will be used to determine the critical regions of the flight envelope to help structure the wind tunnel test, and to explain any wind tunnel anomalies and help structure the flight test program. The objective of the program is to provide upgraded analysis tools that will support store certification requirements at less cost and in less time.

NOMENCLATURE

BL: Aircraft Buttline, positive outboard, in.
C_l: Rolling moment coefficient, rt wing down
C_m: Pitching moment coefficient, positive up
C_N: Normal Force coefficient, up
C_n: Yawing moment coefficient, nose right
C_Y: Side force coefficient, right
FS: Aircraft Fuselage Station, positive aft, in.
l.e. F-18 Wing leading edge flap
t.e. F-18 Wing trailing edge flap
M: Mach number
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.
WL: Aircraft Waterline, positive up, in.
Z: Store C.G. location, positive down, ft.
α: Angle of attack, deg.
α_ι : Upwash angle, positive up, deg.
δ_ι: Sidewash angle, positive outboard, deg.
Note: all wind tunnel data shown are right wing, flight test left (negative PSI, PHI, Y)

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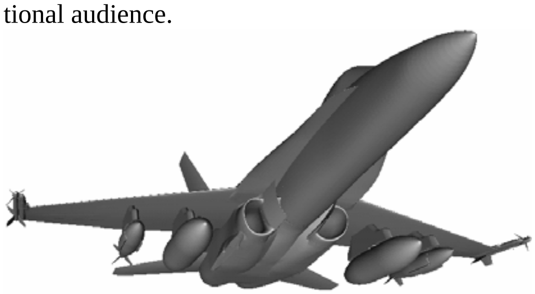
ACFD CHALLENGE

Over the past several years there have been several organized efforts to validate, demonstrate and accelerate the insertion of CFD methods into the store certification process for external stores carriage and release. Several significant efforts have been documented in AIAA conference proceedings. The first ACFD sponsored conference was the F-16/Generic Finned Store[3-8] which occurred in New Orleans in the summer of 1996 (ACFD Challenge I).

Many important lessons were learned; however, the experimental test case did not include flight test data ("real" store trajectories). Because of this limitation, store certification engineers continue 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 is a desire within the ACFD[9] program to reconcile these issues by conducting additional analysis by using a data set that includes both wind tunnel and flight test data.

SELECTION OF TEST CASE

Large sets of wind tunnel and flight test data existed for the F/A-18C JDAM configuration as a result of a recent USN store certification effort. 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.



F/A-18C/JDAM Test Configuration

TEST CASE PARAMETERS

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

For these two test cases, the configuration geometry for the wind tunnel and flight test are as shown above. The JDAM is mounted on the outboard pylon, with the 330-gallon fuel tank on the inboard pylon. The SUU-63 BRU-32A/A ejector rack provided a nominal peak force of 7,000# for both fwd and aft cartridges. However, the implementation of ejector force modeling was left at the discretion of the participants.

FLIGHT TEST RESULTS

TEST FLIGHT #13

Flight test #13 was conducted on July 10, 1996. The store was released in a 43 degree dive at 6,382 ft. at M = 0.962. The telemetry and photogrametric data were not in good agreement with each other for the vertical displacement. Since inertial effects (store mass and ejector force) largely drive the vertical displacement, the relative Z displacement is usually the easiest to predict. The discrepancy in Z was attributed to the effects of aircraft motion caused by store release.

Both Captive Trajectory System (CTS) grid data, and store aerodynamic force and moment data measured on the wing pylon were available for this aircraft configuration. These data were input into a six-degree-of-freedom trajectory code before the flight tests were performed. Parametric variations on flight conditions and store aerodynamic forces were performed to ensure that the flight test could be safely accomplished. After the flight tests were completed, the trajectory simulations were again performed, with the actual flight conditions used to try to match the flight test results.

JDAM FLIGHT 13
M = 0.962 6382 FT 43 DIVE

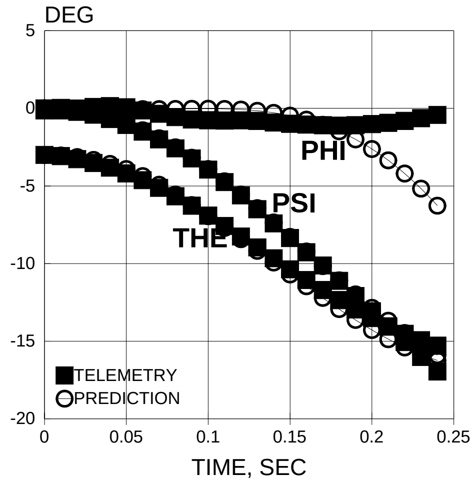


FIGURE 1 JDAM ATTITUDES

JDAM FLIGHT 14
M = 1.055 10832 FT 44 DIVE

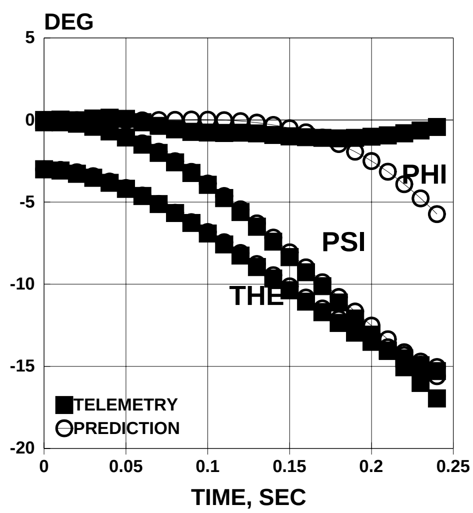


FIGURE 2 JDAM TRAJECTORY

As may be seen in Figure 1, the predicted pitch and yaw attitudes at M = 0.962 were in excellent agreement with the flight test results. The roll attitude was not well predicted. However, roll attitude, which is the hardest to predict, fortunately has a minimal impact on the trajectory. The photogrametric results are not shown, since they are considered to be less accurate than the telemetry data.

<u>TEST FLIGHT #14</u>

Flight test #14 was conducted on August 29, 1996. The store was released in a 44 degree dive at 10,832 ft. at M = 1.055. The telemetry and photogrametric results for the displacement again showed a large discrepancy in Z.

The predictions using the wind tunnel test data were again in excellent agreement with the flight test data, Figure 2.

MISS DISTANCES

The most important parameter for safe store separation is the ability to accurately predict the store miss distance, which is the smallest distance between any part of the store and aircraft during the early part of the trajectory. Early in the flight test program, it was evident that the predicted miss distances were smaller than the flight test results. This was attributed to the fact that the aircraft moves away from the store during the ejector stroke.

The USN is in the process of incorporating aircraft motion into its trajectory simulations. As a first step, it was assumed that the energy produced by the total ejector force causes the absolute displacement between the store and the aircraft. Therefore, the ejector force used in the trajectory simulation was the force measured for ejection from the F-18 centerline, which was 25% larger than that measured on the pylon during the pit tests.

As may be seen in Figures 3 and 4, the miss distance predictions were in excellent agreement with the test data. The disagreement between the photogrametric and telemetry predicted miss distance is attributed to the fact that the telemetry could not take aircraft motion into account.

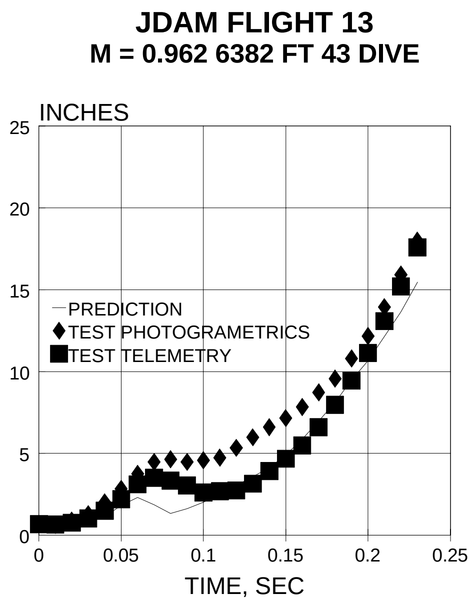


FIGURE 3 JDAM MISS DISTANCE

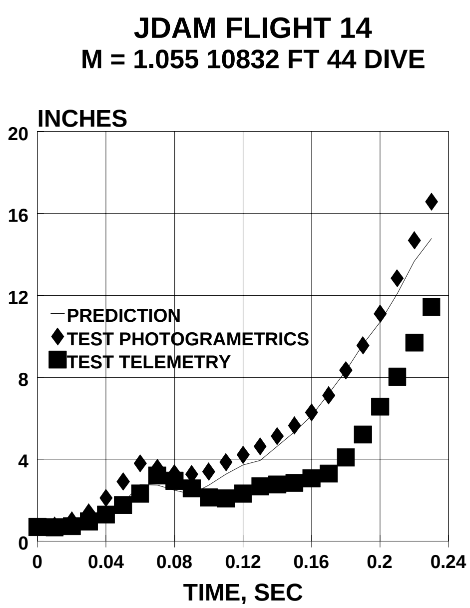


FIGURE 4 JDAM MISS DISTANCE

ACFD CHALLENGE II PAPERS

General

Each participant was requested to include in their paper:

1) a description of the CFD and trajectory integration methods used to produce the estimates of the trajectory;
2) a description of the methods and resources required to produce the computational grid;
3) estimates of carriage loads, the position and attitude of the store throughout the computed trajectories and an estimate of the miss distance versus time; and
4) metrics of the CFD process used, including convergence rate, man-hours and time required for grid generation, computer resources used and an estimate of the expertise of personnel required to replicate the results.

Eight papers by Cenko[10] , Hall[11], Tomaro[12], Woodson[13], Welterlen[14], McGroy[15], Fairlie[16], and Fortinwere[17] submitted for the ACFD Challenge II. The meeting was held at the AIAA Annual meeting in Reno Nevada on January 12th, 1999. Due to the interest in the Challenge the timing of the session and the venue were changed to enable seating for around 200 people; despite this, the room was filled to capacity with over 50 people having to stand in the back for four hours.

The first paper[10] described the wind tunnel and flight test results, while the other seven described the application of seven different CFD codes to the problem. Two of the papers[11, 15] were not ready in time to be included in the meeting proceedings, but all eight papers were either presented at the meeting, or the results were provided at a later date.

ACFD Challenge II Overview paper

Cenko outlined the background to the Challenge and the sources of the data used. The wind tunnel data consisted of both CTS grid and carriage force and moment data measured on the wing pylon conducted in the CALSPAN 8-ft. transonic wind tunnel. The grid and carriage data were 6%, while the freestream data at both 6% and 22% were available. As was seen in Figures 1 and 2, the wind tunnel data were in excellent agreement with the flight test results.

Early in the flight test program it was noticed that the miss distances, despite the excellent correlation in store attitudes, were smaller than the flight test results. Cenko attributed this to the aircraft also moving away from the store during the ejector stroke. The USN is therefore in the process of incorporating aircraft motion into it's trajectory simulations. As a first step, it was assumed that the energy produced by the total ejector force causes the absolute displacement between the store and the aircraft. Therefore, the ejector force used in the trajectory simulation was the forced measured for ejection from the F/A-18 centerline, which was 25% larger than that measured on the pylon during the pit tests[i]. Some discussion concerning the correct specification of the variation of ejector force with time resulted, as it seemed at least two different sets of data were used.

CFD Research Corporation.

L. Hall[11] presented the results of the CFD research code for the F-18/JDAM configuration. These results were significantly different from the other seven codes presented, since the trajectory calculations were run in a time dependent mode. At the time of the meeting, the trajectory had run for only .05 seconds; however, the predictions shown were in good agreement with the test data. One drawback of using time dependent (as opposed to quasi-steady state) trajectory calculations is that it takes a very long time to get one solution, and, if any of the parameters change, another solution would take the same amount of time.

Air Force Wright Research Lab

Tomaro presented the F/A-18C/JDAM carriage loads and trajectory analyses[12] conducted by AFRL/VAAC included the use of computational aerodynamic (CFD) and 6DOF rigid-body, trajectory generation techniques. The two methods were not coupled into a single simulation package: the CFD method simply provided the aerodynamic loads database to the trajectory generator which was run independently in a carriage-loads decay manner. This approach required the CFD method to produce carriage loads and a series (alpha and beta sweeps) of isolated, JDAM freestream solutions. Many resulting JDAM trajectories could be generated for varying decay parameters, ejector characteristics, altitudes, etc. A fully integrated moving-body/mesh CFD method would require complete, expensive simulations each time a parameter was varied.

The CFD portion of these analyses used the AFRL/VAAC 'Cobalt' flow solver. Cobalt is a parallel, implicit, unstructured-grid Euler/Navier-Stokes code developed for routine application in the design and analysis of aerospace vehicles. The unstructured grids may consist of completely arbitrary cell types, such as hexahedral, tetrahedral and prismatic, and more than one type may exist in the same global grid.

For the F/A-18C/JDAM carriage cases, several tetrahedral grids were produced with the NASA GridTool/VGRIDns unstructured mesh generation system. The primary grid used in subsequent carriage loads analyses consisted of 6.62 million cells (half-model for symmetry) with viscous boundary layers (approx. 4 million cells) about all components of the F/A-18C and JDAM. About one-month of calendar time was required to generate an 'appropriate' mesh, i.e. no negative volumes, crossed faces, etc. Subsequent Cobalt solutions required about 10.1 GBytes of main memory and the following timings:

M = 0.962	M = 1.055
50 nodes (CPU's) IBM SP2	32 nodes IBM SP2
17.69 hours wall-clock	26.87 hours wall-clock
17.22 hours CPU/node	6.27 hours CPU/node
(861 total CPU hours)	(841 total CPU hours)

Isolated freestream JDAM viscous grid generation and flow solutions (alpha and beta sweeps) required less than 3 weeks turnaround for both Mach numbers. Thus, within two months calendar time, the CFD portion of the Challenge was completed.

After the carriage and isolated, freestream JDAM aerodynamics were provided by Cobalt, trajectories were generated using the NAWCAD NAVSEP[2] program. The carriage-loads decay method was used to account for mutual interference effects between the F/A-18C and JDAM. In addition to aerodynamic forces and moments, NAVSEP requires the JDAM inertial properties, damping coefficients, ejector-model characteristics, and then it calculates trajectories in a matter of seconds on any computer platform.

As may be seen in Figure 5, the predictions for the pitch and yaw motion of the store for the M = 0.962 are in excellent agreement with the test data, although the pitch attitude is somewhat overpredicted. This implies that the predicted carriage pitching moment was larger than that in flight. The roll motion is not well predicted. However, since rolling motion has traditionally been the hardest part of the trajectory to predict, and generally has little influence on store miss distances, the lack of rolling motion correlation is of small consequence.

JDAM FLIGHT 13
M = 0.962 6382 FT 43 DIVE

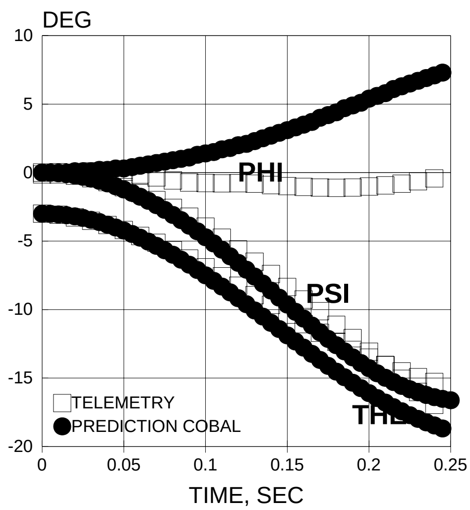


FIGURE 5 JDAM ATTITUDES

Figure 6 presents the comparison at M = 1.055. Again, the pitch and yaw motion are in excellent agreement with the flight test data, with the pitch attitude somewhat overpredicted. The roll motion is similar to that at M = 0.962. There was little difference in the agreement between the test data and the carriage loads calculated using either inviscid or fully viscous codes. This was reflected in comparisons of the calculated and measured trajectories being quite good for both cases.

JDAM FLIGHT 14
M = 1.055 10832 FT 44 DIVE

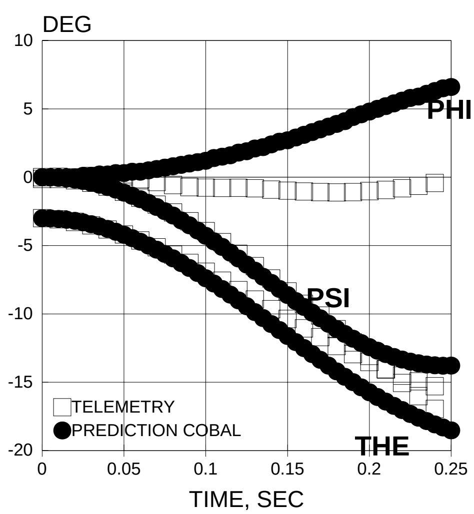


FIGURE 6 JDAM ATTITUDES

Naval Air Warfare Center.

Woodson[13] presented comparisons for SPLITFLOW[18], USM3D[19], and PUMA, an unstructured, viscous code developed at NAWCAD.

Only viscous-store results were computed using the USM3D code. The code for both cases was run for 2000 iterations using a CFL of 0.1 initially ramping up to 100 over the first 500 iterations and then continued at 100 for the remaining 1500 iterations. The solutions converged to a steady state value in approximately 500 iterations with the residual reduced about three orders of magnitude. The solutions were run on a Cray C90 and required 315 MW of memory and a total of 48.44 hours of CPU time for case 1 and 57.46 hours for case2. Multitasking was employed using ten processors for a wall clock time of approximately six hours for case 1 and eight hours for case 2 (average concurrent CPUs = 7.5 and 6.96, respectively).

USM3D results for the two cases are shown in Figures 7A and 8A.

JDAM FLIGHT 13
M = 0.962 6382 FT 43 DIVE

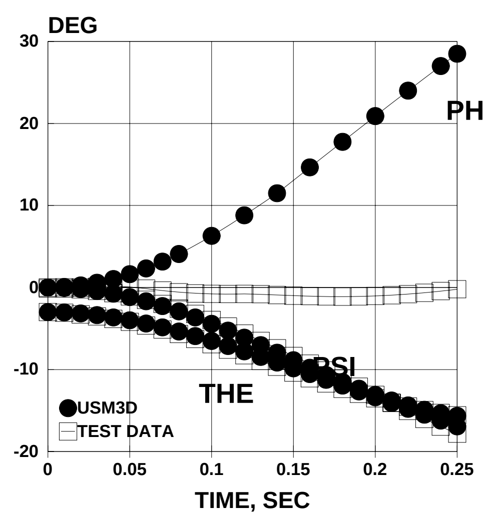


FIGURE 7A JDAM ATTITUDES

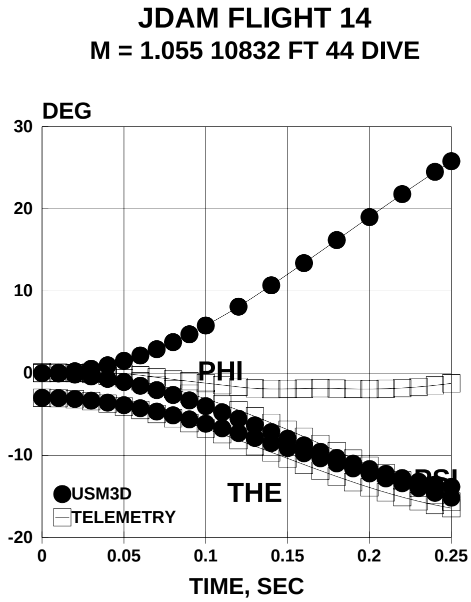


FIGURE 8A JDAM ATTITUDES

Two solution approaches using SPLITFLOW were conducted: (1) inviscid, and (2) viscous around the JDAM store. By assigning different material numbers to the various components of the configuration (i.e. wings, pylons, stores, etc.) different boundary conditions may be applied so that the prismatic grids may be generated only on those parts of the geometry where viscous effects are anticipated to be important and neglected elsewhere. Both cases were run for 2000 iterations using a CFL number of 1.0 and a turbulent CFL number of 0.1. The solutions were run on a Cray C90 requiring 256 MW of memory and a total of 58.56 CPU hours for case 1 and 81.29 hours for case 2. Multitasking was employed using four processors for a wall clock time of approximately 34 and 48 hours (average concurrent CPUs = 1.75 and 1.7, respectively). The longer run time for case 2 was caused by sliver cell problems aft of the shock at the pylon trailing edge so a smaller global cell size was employed which resulted in the code reaching its maximum number of cells much sooner than it did for case 1. Both cases achieved about three orders of magnitude reduction of the residuals. The inviscid solutions required about one half the run times of the viscous store results (26.50 and 40.56 CPU hours, respectively).

SPLITFLOW results for the two cases, using SPLITFLOW calculated angularities and wind tunnel freestream data in NAVSEP, are shown in Figures 7B and 8B.

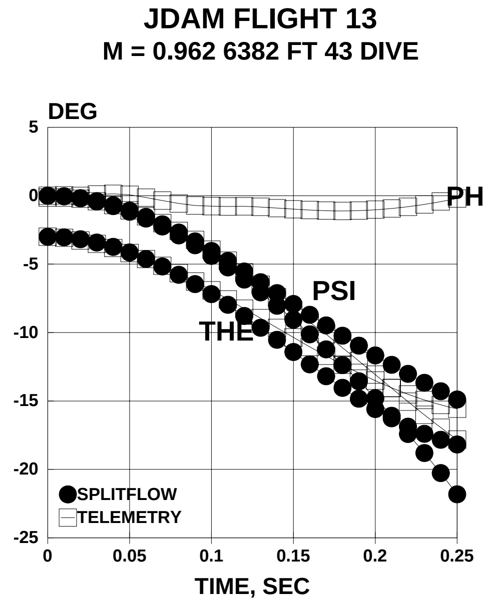


FIGURE 7B JDAM TRAJECTORY

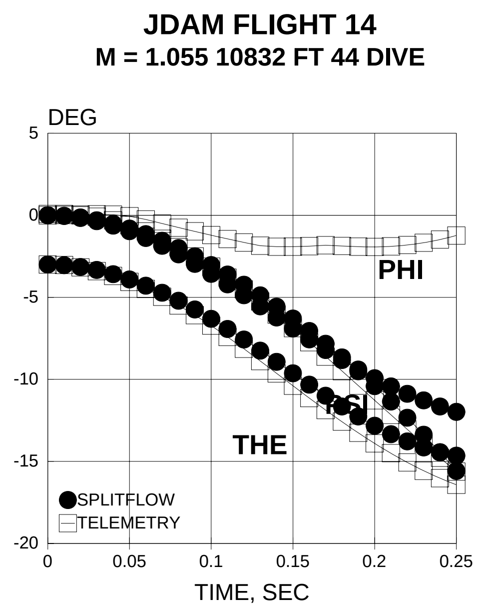


FIGURE 8B JDAM ATTITUDES

Both of the PUMA runs were inviscid and were performed using between 32 and 64 nodes of the IBM SP-2. Each run was converged two orders of magnitude using first order spatial accuracy. Then this first order solution was used to initialize the second order runs. Unfortunately, it was possible to converge the second order solution only about 1-2 orders in the residuals.

PUMA for the two cases are shown in Figures 7C and 8C.

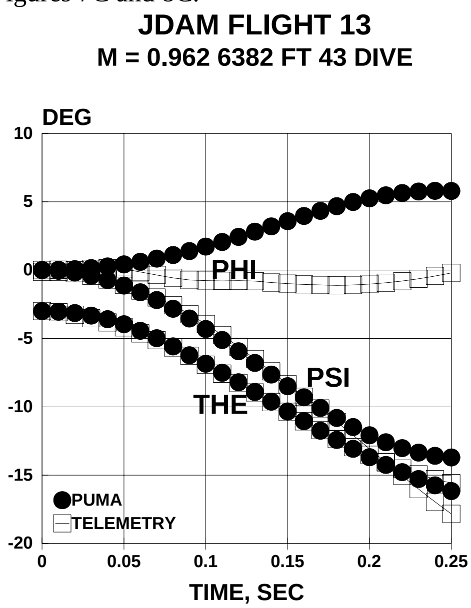


FIGURE 7C JDAM TRAJECTORY

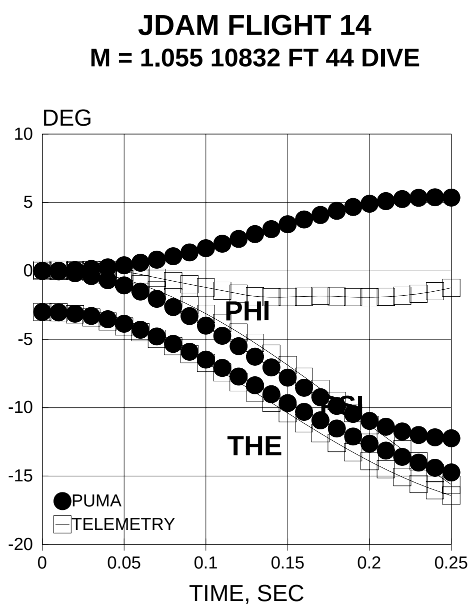


FIGURE 8C JDAM ATTITUDES

Lockheed Martin

Welterlen[14] presented both viscous and inviscid SPLITFLOW results. The viscous grid required 800,000 Cartesian Cells, and an additional 1,044,207 prismatic cells on the surface. The inviscid solution required approximately 120 CPU hours on a HP 9000 using 8 V-2250 processors. The viscous results required about 250 CPU hours on a Cray J-90.

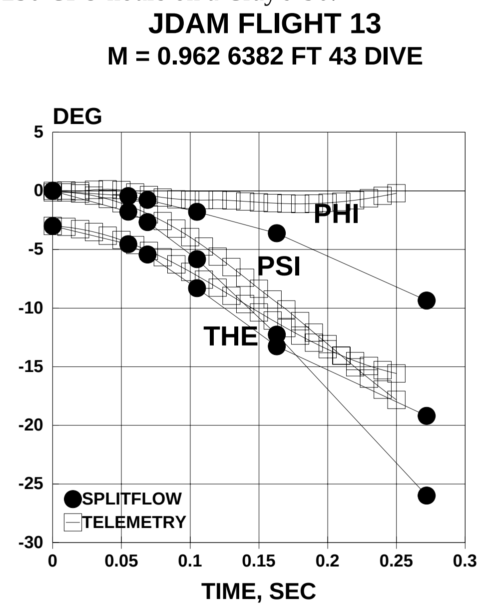


FIGURE 9 JDAM ATTITUDES

The predicted carriage loads were in close agreement with the test data; however, the inviscid results matched the carriage loads better than did the viscid. The trajectory predictions are shown in Figures 9 and 10.

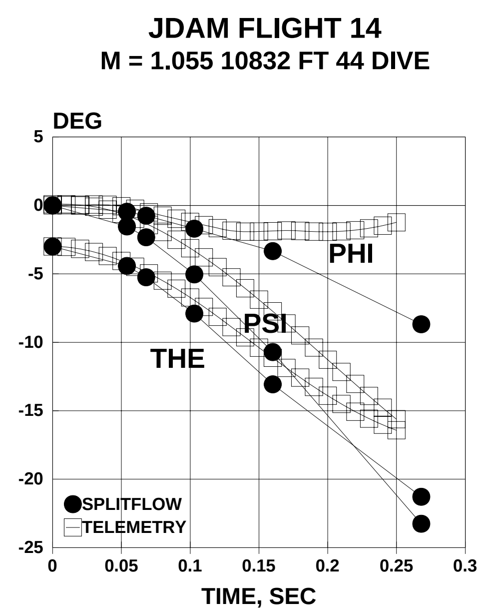


FIGURE 10 JDAM ATTITUDES

Aerosoft Inc

The sixth paper from Aerosoft Inc using the GUST solver package was withdrawn. McGroy later presented results that were similar to the others shown in this paper, but these have not been made available at this time.

DSTO Australia

Fairlie then presented computations[16] using the RAMPANT code supplied by Fluent Inc. While the Fluent suite of codes includes an unstructured grid generator, the authors chose to make use of a grid generator marketed by ICEM CFD Engineering. This code, known as ICEM CFD Tetra, creates unstructured tetrahedral grids.

The PLOT3D format geometry file of the F/A--18C JDAM configuration was read directly into ICEM CFD DDN, the CAD system associated with the mesher. This module was used to generate the surfaces, curves and points defining the features of the geometry required as input by Tetra. Only the port semi-span of the configuration was modeled, with a symmetry boundary condition imposed on the lateral plane of symmetry. A far-field boundary was provided in the form of a semi-sphere centered on the aircraft's center of gravity, with a radius of approximately five fuselage lengths.

The trajectories followed by the JDAM after its release have been simulated using the Defence Science and Technology Organization Release Evaluation Suite (DSTORES). For the present configuration, all trajectory predictions have been made using the empirical FFD method (included in DSTORES) to estimate store aerodynamic characteristics. Given a database of store free-stream aerodynamic characteristics, this method requires just two further CFD analyses to predict a trajectory: a set of CFD generated carriage loads and a computation of the flow field beneath the parent aircraft without the presence of the released store.

The initial grid as input to the RAMPANT Solver consisted of just over 1.05 million tetrahedra. A typical RAMPANT run consisted of about 200 iterations with the value of the CFL number set to 0.5, followed by about 300 iterations with CFL set to 1.0. This was generally sufficient to reduce the normalized residuals of continuity, x-, y- and z-momentum and energy by between two and one half and three orders of magnitude compared with their initial values. At this stage, the grid was adapted in regions in which the static pressure gradient exceeded a particular value (initially set to 10% of its maximum value, but varied depending on the number of tetrahedra generated in the new grid) in an attempt to better define shock waves. After adaptation, the grid generally contained somewhat more than 1.25 million tetrahedra. The solution was then iterated for up to a further 500 iterations. After an initial transient created by the adaptation of the grid, the residuals once again fell to their previous, or even lower values.

All computations were carried out on a Silicon Graphics Origin 2000 server. This machine has sixteen R10000 processors running at 250 MHz and is equipped with 4 GB of memory. Typically, the initial 500 iterations on the unadapted grid required a little less than 40 hours of CPU time on a single processor, and occupied approximately 460~MB of memory. After adaptation, the additional 500 iterations used somewhat more resources, the exact amount depending on the number of tetrahedra in the adapted grid. While the vast majority of the calculations presented here were carried out on a single CPU, the RAMPANT code may be run in parallel. Thus far, no more than four parallel processors have been used, yielding a speed-up of just over 3.8 compared with a single processor.

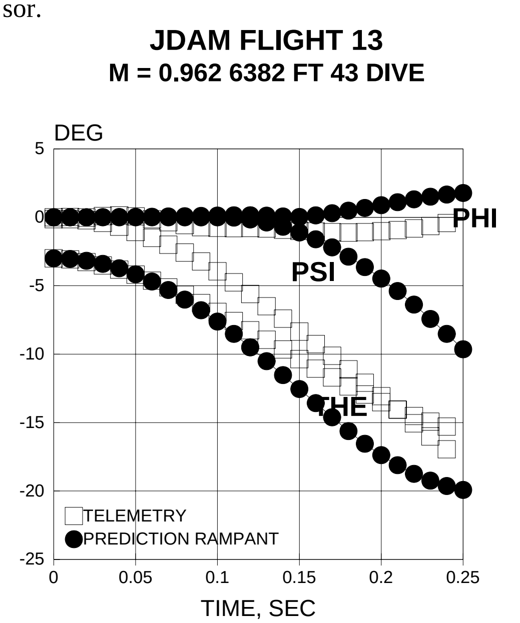


FIGURE 11 JDAM TRAJECTORY

The RAMPANT comparisons are shown in Figures 11 and 12. The predicted carriage loads were input into the Australian six-degree-of-freedom code, in conjunction with the experimental store freestream data, and the trajectories were calculated in a manner similar to those in Reference 12. The Australian code has an unusual feature that allows it to calculate a yaw restraint between the pistons and the store during the ejector stroke, which lasted for approximately 0.07 seconds.

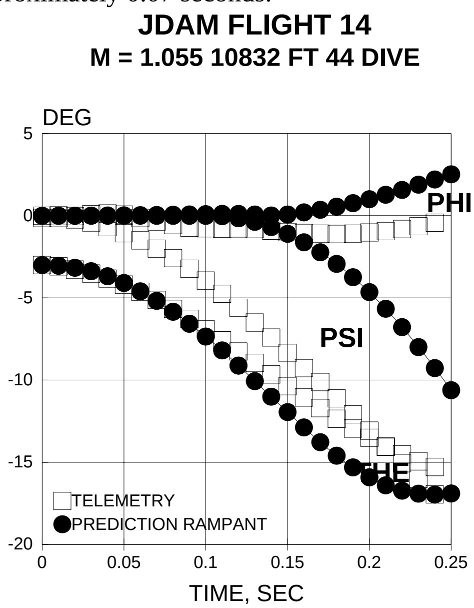


FIGURE 12 JDAM ATTITUDES

As may be seen in both Figures 11 and 12, the yaw attitude would be in excellent agreement with the flight test data if the prediction were displaced by 0.07 sec. It appears that for this case, the trajectory code did not properly account for the constraint between the pistons and store. However, there have been numerous flight test cases where the store was clearly constrained in yaw during the ejection stroke. The constraint feature will become more useful once it has been calibrated with flight results.

The pitch attitude prediction is in reasonable agreement with the test data, although it overpredicts the test data by approximately 20% at both Mach numbers. The roll attitude is in excellent agreement with the flight test results; the yaw constraint might have fortuitously helped to constrain the roll.

<u>NRC IAR Canada</u>

The last paper described[17] the quasi-steady CFD approach developed at the Institute for Aerospace Research (IAR) of the National Research Council of Canada (NRC). It consists of three different modules:

1) A steady-state 3D unstructured inviscid solver, FJ3SOLV.
2) A 6-DOF Store Separation Model (SSM), and
3) A grid motion technique.

Each of these modules could be used separately.

To apply the IAR approach to the F/A-18C JDAM CFD Challenge, the three modules were coupled in a quasi-steady mode using the following methodology:

For a given store position, compute the steady-state aerodynamic loads acting on the store using FJ3SOLV. Feed the CFD predicted aerodynamic loads into the 6-DOF SSM and, for a small time increment compute the new store CG location and angular orientations.

If grid motion is possible, move the store and grid nodes using spring analogy technique to store's new position and go to step 1. If grid motion is not possible or grid cells become inadequate after node movement, move the store to its new position, generate a new grid, interpolate the solution to the new grid from the previous one and go to step 1.

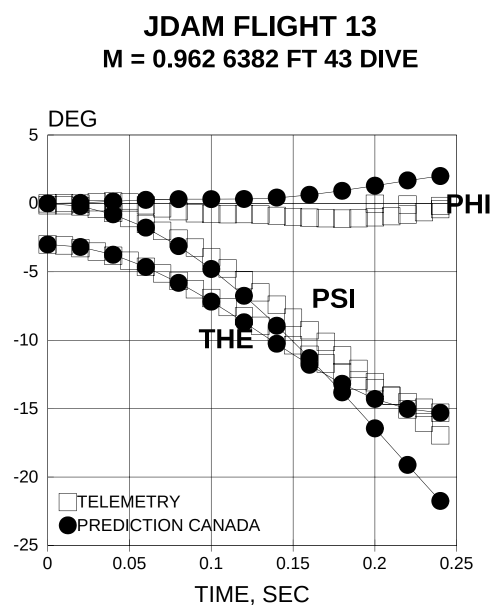


FIGURE 13 JDAM TRAJECTORY

Starting from a clean CAD geometry, it took about a week to generate an initial grid.

For the store-in-carriage position and using free stream uniform flow as initial condition, about 2000 iterations were needed to get converged carriage loads. For the subsequent store positions, the solver was only run for 1000 iterations using the previous solutions as initial conditions. The calculations were performed in a single CPU mode on a SGI OCTANE R10000 workstation. The CPU time was about 24 hours for 1000 iterations. With a time step of 0.02 sec. and a total time of 0.24 sec., the quasi-steady coupling process was repeated 12 times. The total CPU time for a complete JDAM trajectory prediction was then about two weeks.

In the case of grid motion failure, it took about 4 hours to re-generate a new grid. The Canadian results are shown in figures 13 and 14.

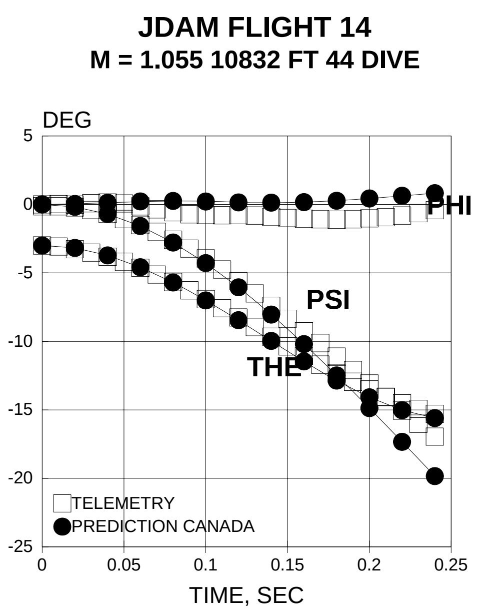


FIGURE 14 JDAM ATTITUDES

OTHER RESULTS

Two other organizations that tried to take part in the Challenge were not able to present their results in Reno. Their results are summarized below.

AEDC

AEDC performed time-accurate viscous computations to simulate the trajectory simulations for both flight release conditions[20] utilizing the chimera overset grid approach[21]. The process for predicting time-accurate body motion relies on four codes, NXAIR[22] to solve the fluid dynamic equations, PEGSUS[23] to define the inter-grid communications, FOMOCO[24] to compute the store loads for overlapping surfaces entities, and SIXDOF[25] to solve the rigid-body equations of motion.

Enhancements to the NXAIR flow solver have significantly reduced the time required to perform time-accurate moving-body simulations. Recent algorithm improvements allow choosing time steps commensurate with that required to capture the physics, rather than that required to satisfy a numerical stability limit; thus, increasing the allowable time step size by an order-of-magnitude and greatly reducing the computer resource requirements for solving moving-body problems. Also, the code has been "parallelized" to take advantage of the chimera methodology and the architecture of new scalable shared-memory computers. POSIX threads are employed, where the code spawns the computations of several individual meshes to as many processors as allocated by the user; thus, greatly reducing the wall clock time when utilizing multiple processors.

The F-18C surface definition was prepared from a CAD definition. A significant portion of the effort involved preparing the aircraft surface from the CAD definition, which was accomplished in approximately one month. Volume grid generation and setting up the PEGSUS inputs required about two to three weeks. To reduce the number of grid points to define the boundary layer, wall functions were utilized. The overall grid system, comprised of 7.0×10^6 mesh points, is distributed over 66 individual overset meshes (5.2×10^6 points over 47 meshes for the F-18C and 1.8×10^6 over 23 meshes for the JDAM). All detail of the JDAM was modeled including the strakes and fin gaps. The aircraft engine duct was modeled to compute flow through the duct. Lateral symmetry about the aircraft center plane was assumed, and only the port side of the aircraft was modeled.

Given the release conditions and ejector model, the two separation trajectories were simulated by using the aforementioned codes. The turbulent Navier-Stokes equations were solved with the two-equation SST[26] turbulence model. Duct flow was established to a corrected mass flow rate at approximately 145 lbm/sec for both release conditions. The steady-state solutions of the flow field about the carriage configuration were performed until convergence was achieved for the store loads to approximately three decimal places. The steady-state and trajectory computations were performed on a SGI Origin 2000 R10000 and level loaded over 16 processors. Computations to determine the steady-state carriage loads required approximately 600 steps for each case. The time-accurate computations took 500 time steps to compute the 0.4-second trajectory. The total CPU time to complete one case (including both the steady state and dynamic portion of the computations) was 2900 CPU hours (1400 for the steady-state solution and 1500 for the dynamic solution). Approximately 25 percent of the time in the time-accurate portion of the problem is required by PEGSUS. Because computer resources had to be shared with other users, only part-time usage of 16 processors was available and the wall clock time to complete each trajectory simulation (steady-state and dynamic portion) was two weeks. With dedicated usage of 64 processors on an Origin 2000, the computations could be completed in less than 2 days. This is a significant speed increase from just five years ago when inviscid time-accurate separation computations took several months to complete and viscous time-accurate separation computations were not performed because they were estimated to take years. Planned improvements to PEGSUS should significantly reduce the CPU time for the time-accurate computations and for initial set-up of the problem. It is quite evident that significant strides have been made to address CFD productivity concerns and that time-accurate CFD is now a practical tool for store separation analysis.

Comparisons between computed orientation and flight telemetry data are shown in Fig. 15 for the high subsonic flow case and in Fig. 16 for the low supersonic case. For both cases, the computed orientation shows excellent agreement in pitch and roll while the computed yaw shows a slightly larger nose outboard angle. Although not shown, the computed store displacements and miss distance for the supersonic case show even better agreement with the experimental values and a slightly better agreement than for the subsonic case.

JDAM FLIGHT 13
M = 0.962 6382 FT 43 DIVE

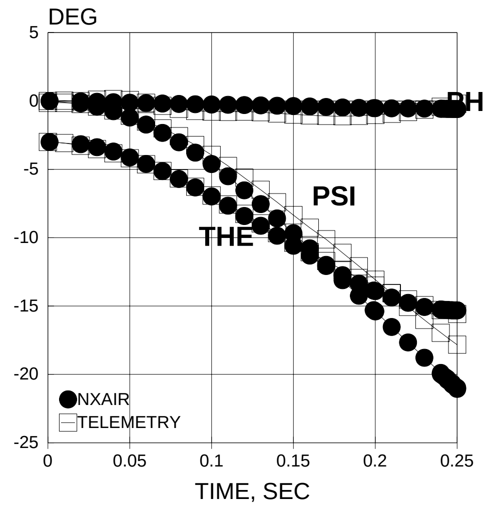


FIGURE 15 JDAM ATTITUDES

For the external releases of a single store, the benefit of a time-accurate approach is not fully realized. For these cases, the quasi-steady approach may be sufficient to accurately predict the separation event. However, for more complex releases of multiple stores and from internal bays, the temporal effects become much more important, and the quasi-steady approach may not be sufficient.

JDAM FLIGHT 14
M = 1.055 10832 FT 44 DIVE

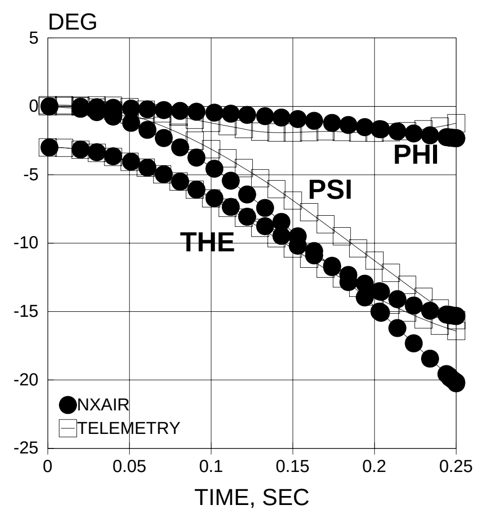


FIGURE 16 JDAM ATTITUDES

AFSEO

The Applied Computation Fluid Dynamics (ACFD) group within the Air Force Seek Eagle Office (AFSEO) also computed the F/A18C/JDAM challenge cases using a fully time accurate CFD simulation.

The ACFD group utilized the Beggar flow solver originally developed at the Air Force Wright Laboratory at Eglin AFB with development continuing within the AFSEO by the ACFD group. The Beggar flow solver utilizes overlapping structured grids to simplify grid generation of complex geometry and to accommodate the relative motion that occurs in a store separation simulation. Beggar couples, within a single code: 1) an automated grid assembly process to determine the grid overlap and interpolation information, 2) integration of surface stresses to provide aerodynamic force and moment predictions, 3) six degree of freedom (6DOF) rigid body trajectory prediction for providing the motion of a store in response to aerodynamic and external inputs. 4) an fully implicit time accurate flow solver.

The Beggar code is a conventional cell centered finite volume formulation and can solve the Euler or the Navier-Stokes equations. It utilizes second or third order upwind differencing of the spatial terms and first order differences of the time terms. The resulting set of linear equations is solved using symmetric Gauss-Seidel iteration. A Newton iteration cycle is used to fully couple the solutions on the different grids in a solution and to remove linearization errors. The solver utilizes domain decomposition based upon the grids in the system to parallelize the execution of the flow solver.

The Beggar automated grid assembly process is fully integrated within the code and is performed at each time step. The 6DOF routines provide the new positions and rates for a moving body. The grid assembly process is also parallelized and overlaps its' execution with the flow solution to reduce wall clock time to obtain a simulation.

The separation of the JDAM from the F/A18C at Mach 0.962 was simulated using the Beggar code assuming inviscid flow. The grid system for the F/A18C, the JDAM, and assorted auxiliary grids utilized a total of 39 single block grids and 12 multi-block grids with a total of 95 grids and 2.8 million grid points. The JDAM grid alone contained 360,000 points. The grid system was generated in approximately one man month.

The separation simulation was run at a physical time step of one millisecond and was terminated at a solution physical time of 0.42 seconds. The solution was run on 16 processors for the flow field solution with another 2 processors used for the grid assembly process. The execution time varied somewhat with an average wall clock time of 160 seconds per time step on an SGI Origin 2000 with 250MHZ MIPS R10000 processors. Thus, a simulation out to 0.25 second in physical time could be performed in less than 12 hours. Each flow solver process utilized between 75 and 132 Megabytes of memory with the total memory requirements of 1.6GB for the flow solver. Each of the two grid assembly processes utilized another 512MB of memory.

Figure 17 presents the comparison of the inviscid results from the Beggar code for a fully time accurate simulation and the flight test data. The agreement in general is excellent with the inviscid results slightly over predicting the pitch and yaw angles. The preliminary viscous results show a significant improvement in the agreement with the flight test data, Figure 18. The inviscid prediction of the roll angle is generally good and captures the general trends. The viscous agreement degrades at later times when the JDAM is at large yaw and pitch angles.

JDAM FLIGHT 13

M = 0.962 6382 FT 43 DIVE

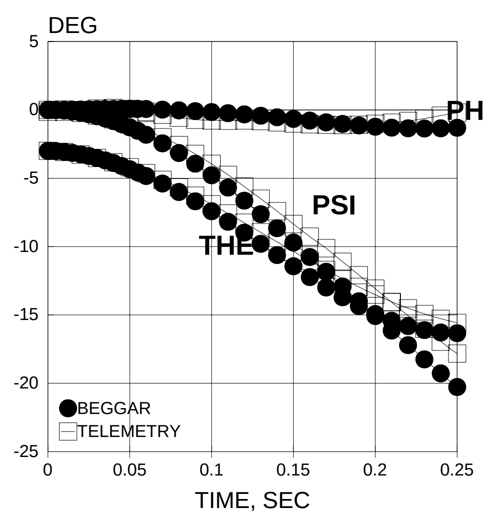


FIGURE 17 JDAM ATTITUDES

JDAM FLIGHT 13
M = 0.962 6382 FT 43 DIVE

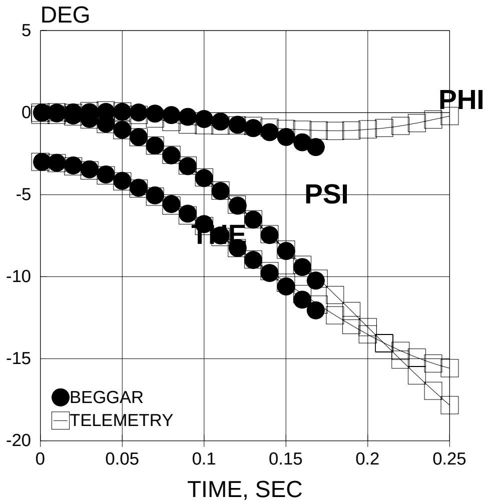


FIGURE 18 JDAM ATTITUDES

CONCLUSIONS & RECOMMENDATIONS

The quality of the invited papers and presentations reinforced the approach used by the AFCD Challenge sponsors. However, taking this presentations as representative of state of the art for applying current CFD-based tools for stores carriage and separations indicates that wind tunnels will still be relied on for the provision of the major part of the aerodynamic data on which stores certification are to be safely based. Indeed it is acknowledged that the CFD solutions were in the majority of cases within the error range of the wind tunnel and flight test data. Accuracy would not therefore seem to be issue, but rather the time required to produce a solution needs to be decreased significantly. Given this development CFD-based tools should become far more prevalent in use during Requirements Definition and Systems Engineering trade-off studies for the aircraft and stores thereby reducing the likely hood of expensive aircraft and/or store redesign after hardware has been made.

One other general result was the consensus that improvements in the ejector modeling and ejector foot/store interaction during the ejection needed to be accomplished.

One of 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. Does that mean that Navier Stokes formulation does not have to be used, or were the test cases selected fortuitous for the inviscid formulation? Indeed, Welterlen showed that the inviscid calculation was superior to the viscous one. Since diagnostic data were not available, it is impossible to say whether the SPLITFLOW viscous formulation is at fault, or that the inviscid results had a fortuitous canceling error. It was the consensus of the participants that another CFD Challenge, one that would have diagnostic data (store and wing pressures) was merited.

For this reason ACFD Challenge III, to be held at the Applied Aerodynamics meeting in Denver in 2000, has been recommended. This Challenge will make use of CF-18/MK83 Canadian PSP results, as well as CF-18/MK-83 flight test data.

ACKNOLEDGEMENTS

ACFD Challenge II was made possible by funding provided by the OSD under the CTEIP program. Australian Involvement in the Challenge was jointly funded by the Royal Australian Air Force and Dr. Richard M. Root, U.S. Office of Naval Research International Field Office Asia (ONRIFO Asia).

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