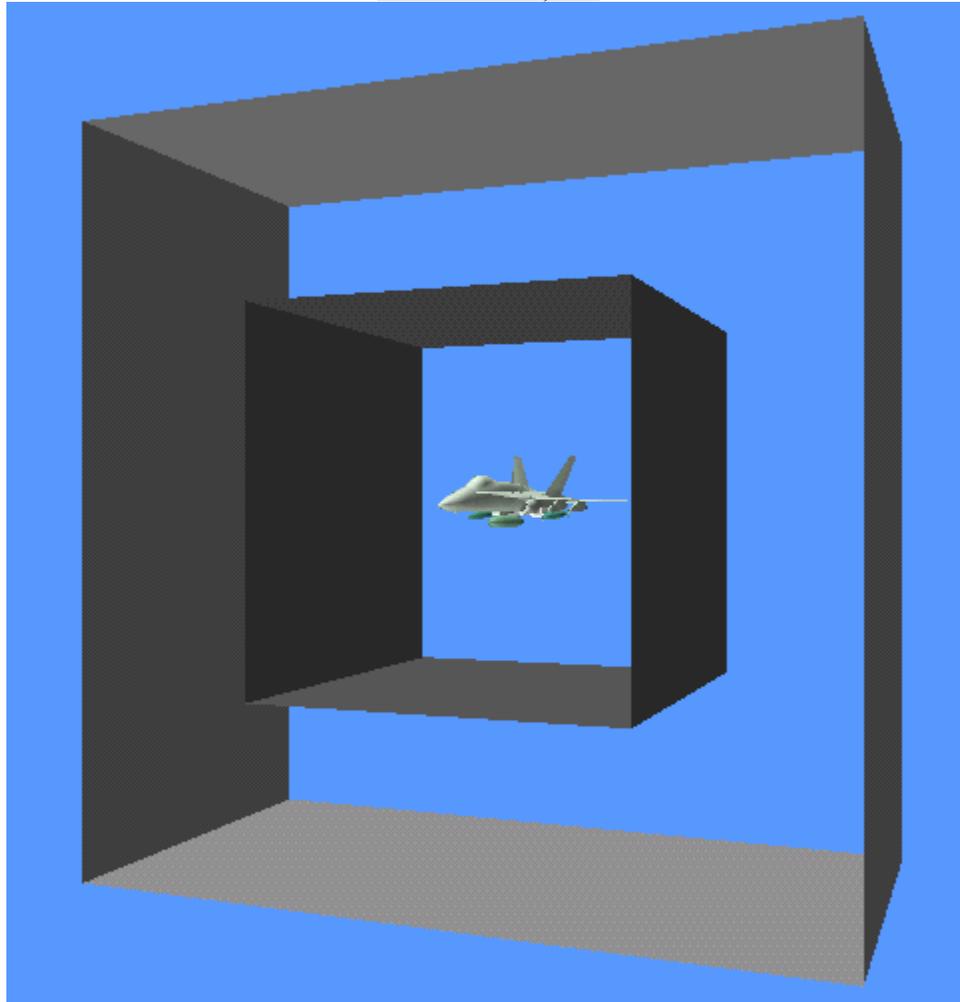


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**COMPARISON OF AEDC 4T AND CALSPAN
8-FT WIND TUNNELS FOR FA-18C/JDAM**

E. Ray
Naval Air Warfare Center – Aircraft Division
Patuxent River, MD



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**COMPARISON OF AEDC 4T AND CALSPAN 8-FT WIND TUNNELS
FOR F/A-18C/JDAM STORE SEPARATION**

E. Ray*
Naval Air Warfare Center – Aircraft Division
Patuxent River, MD

Abstract

Flight test results obtained for MK-84 Joint Direct Attack Munition (JDAM) separation from the F/A-18C allow for direct comparison between the Arnold Engineering Development Center 4 ft X 4 ft and CALSPAN 8 ft X 8 ft transonic wind tunnel data. Both freestream and flowfield grid surveys were compared. Wind tunnel data tended to agree well between wind tunnels.

Wind tunnel data were input into the Navy Generalized Separation Package store separation simulation software. Comparisons were made between the flight paths derived from both wind tunnels to actual flight test data. Trajectory data were then used to calculate minimum miss distances between the JDAM and F/A-18C.

While it was expected that using data from the larger tunnel would result in simulations closer to flight testing, both data sets resulted in similar results. Most differences can be attributed to Mach number sensitivity.

Nomenclature

ψ , PSI	Store yaw angle, positive nose right, deg
θ , THE	Store pitch angle, positive nose up, deg
ϕ , PHI	Store roll angle, positive right wing down, deg
Z	Store CG location, positive down, ft
M	Mach number
C_l	Rolling moment coefficient, positive right wing down

C_m	Pitching moment coefficient, positive nose up
C_n	Yawing moment coefficient, positive nose right
C_N	Normal force coefficient, positive up
α , Alpha	Angle of Attack, deg
β , Beta	Sideslip angle, deg
AEDC	Arnold Engineering Development Center
CTS	Captive Trajectory System
PANAIR	Panel-Method Computational Fluid Dynamics Code
JDAM	Joint Direct Attack Munition
NAVSEP	Navy Generalized six-degree-of-freedom Separation Package

Introduction

In wind tunnel testing, there is always a tradeoff between the size of the tunnel and the accuracy of results. Decreasing the size of a wind tunnel generally reduces cost, but could lead to prohibitive wall interference effects, reducing accuracy. This may be especially important during transonic testing, where it is possible for the wind tunnel walls to reflect shockwaves back at the model. For example, several studies⁽¹⁾⁽²⁾ have addressed the differences between the Arnold Engineering Development Center 4 ft X 4 ft (AEDC 4T) and 16 ft X 16 ft (AEDC 16T) wind tunnels, showing that the smaller wind tunnel can provide a viable alternative to the larger tunnel.

Portions of the Joint Direct Attack Munition (JDAM) separation testing from the F/A-18C were conducted at AEDC 4T Wind Tunnel and the CALSPAN 8-ft Transonic Wind Tunnel. While the

* Aerospace Engineer, Member AIAA
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AEDC test concentrated on the BLU-109a JDAM, it also included a series of runs with the MK-84 JDAM variant, which partially overlapped with the more extensive MK-84 JDAM tests performed in the CALSPAN tunnel. This provided an opportunity for direct comparison of flow-field data. In both cases, Captive Trajectory System (CTS) separation testing was performed on the same 6% scale model.

AEDC 4T, located at Arnold AFB in Tennessee, is a closed-loop, continuous flow, variable-density wind tunnel with a Mach number range between 0.2 to 2.0. The test section has a 4 ft square cross-section and a length of 12.5 ft. Test section walls are perforated with 60 degree inclined holes with variable porosity of approximately 0% to 10%. The top and bottom walls are movable up to 1/2 degree from a position parallel to the test section centerline. The porosity and wall angle schedules are based on Mach number. For store separation testing, the aircraft model is inverted and located about 6 inches below the tunnel centerline.⁽²⁾

The CALSPAN Transonic Wind Tunnel, located in Buffalo, New York, has been in use since 1947. The facility has a variable density, closed circuit, single return design with a Mach number range from 0.1 to 1.3. The test section has an 8 ft square cross-section. Boundary layer growth is controlled by an auxiliary compressor and 22.5% porous walls.⁽³⁾

The greatest concern is the validity of wind tunnel data at transonic and supersonic flight speeds, critical portions of the separation envelope. Because the shock wave produced by the model at Mach 1 is nearly normal, there is the possibility that the walls of a wind tunnel will reflect the shock wave back to the aircraft and store. It is therefore expected that the larger CALSPAN tunnel would provide more accurate results.

In order to validate results, mutual-interference grid data from both tunnels were used in the six-degree-of-freedom Navy Generalized Separation Package (NAVSEP) trajectory simulation software for comparison with flight test results.

Wind Tunnel Freestream Comparison

The first step in wind tunnel testing is to provide a baseline of force and moment coefficients of the model at various angles relative to the freestream. Figures 1 through 5 show the MK-84 JDAM freestream moment coefficients as recorded by both the CALSPAN 8-ft and AEDC 4T wind tunnels at Mach numbers from 0.80 to 1.20. These were all taken with the 6% model, where the sting causes the aft end to be blunted. In addition, MK-84 JDAM freestream data from a 10% scale model were taken at AEDC 16T as part of the F/A-18E/F program. Because of its size and the larger model scale used, data from the AEDC 16T would generally be considered a reliable comparison. The data are recorded as a function of AOA (α) with a sideslip angle (β) of zero degrees. Because $\beta = 0$ degrees, only the normal force (C_N) and pitching moment (C_m) are shown.

At the transonic Mach numbers, the data from AEDC 4T and CALSPAN 8-ft data agree well with each other. At Mach 1.05 (Figure 4), the pitching moment data diverge at high angles of attack. Figure 5 shows a noticeable difference in the freestream pitching moments at Mach 1.20. Unfortunately, data were not taken at AEDC 16T for this Mach number.

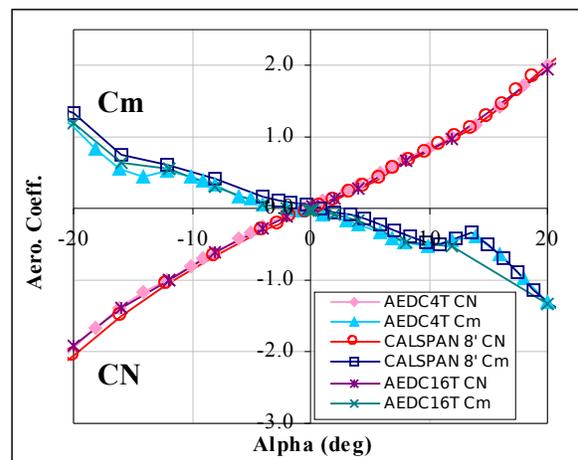


Figure 1: JDAM Wind Tunnel Freestream Comparison for M = 0.80, $\beta = 0^\circ$

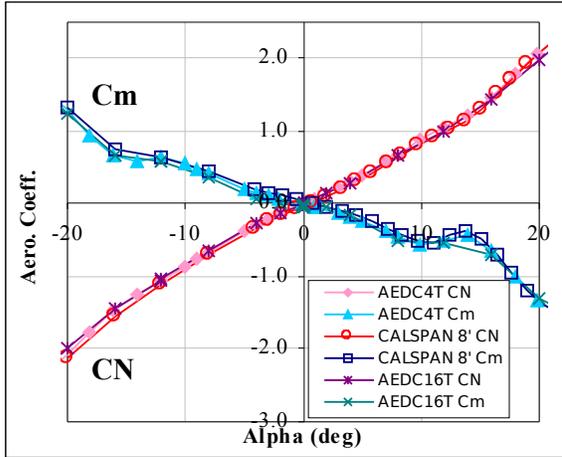


Figure 2: JDAM Wind Tunnel Freestream Comparison for $M = 0.90, \beta = 0^\circ$

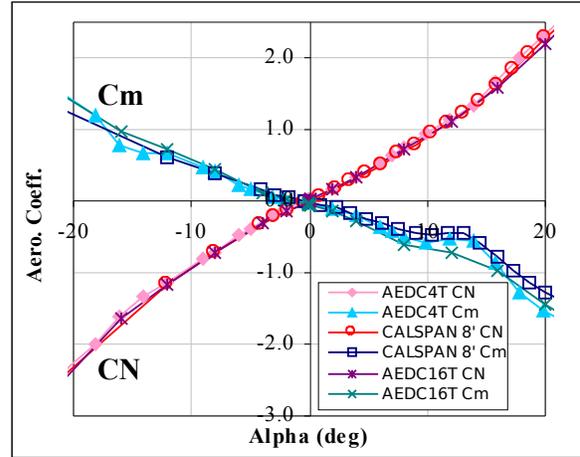


Figure 4: JDAM Wind Tunnel Freestream Comparison for $M = 1.05, \beta = 0^\circ$

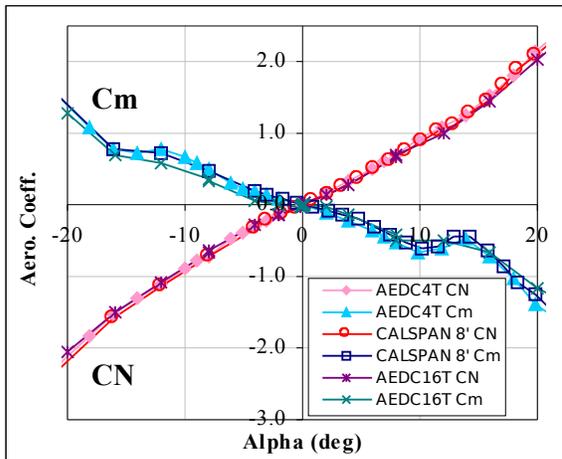


Figure 3: JDAM Wind Tunnel Freestream Comparison for $M = 0.95, \beta = 0^\circ$

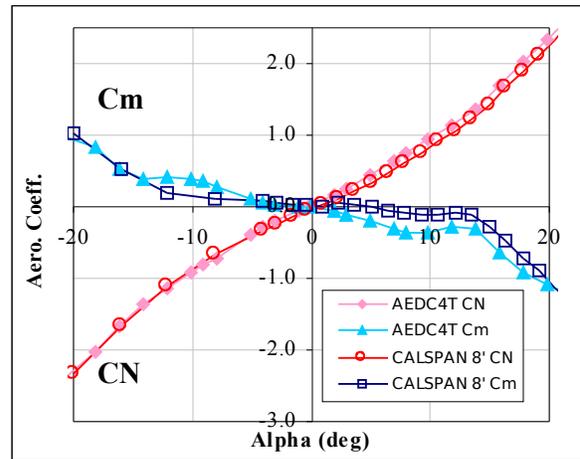


Figure 5: JDAM Wind Tunnel Freestream Comparison for $M = 1.20, \beta = 0^\circ$

Wind Tunnel Grid Comparison

A standard comparison for the CTS method is the variation of store aerodynamic moment coefficients with Z directly under the store carriage position. The aircraft models in both wind tunnels were in Configuration 1, shown in Figure 6, with each metric MK-84 JDAM at station 3 (left inboard pylon). Figure 7 displays the moment coefficients encountered in both the CALSPAN and AEDC wind tunnels for a Mach number of 0.80 and

aircraft $\alpha = 0$ degrees. For the grid comparison, only the coefficients of pitching moment (C_m) and yawing moment (C_n) are plotted. In this case, the results of both wind tunnels appear nearly identical.

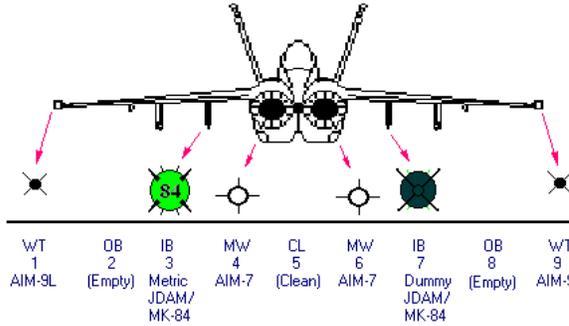


Figure 6: Wind Tunnel Configuration 1 Loading

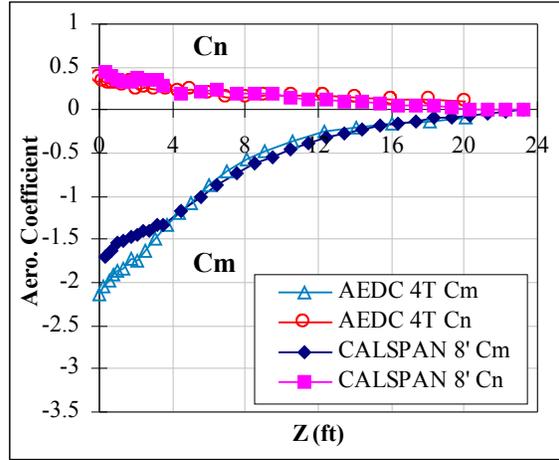


Figure 8: JDAM Wind Tunnel Grid Comparison for $M = 0.90, \alpha = 0^\circ$

As the Mach number is increased to 0.95 (Figure 9), the tunnels disagree on C_n up to $Z = 4$ ft. In this instance, the CALSPAN C_m curve is shifted above the AEDC curve past about $Z = 4$ ft.

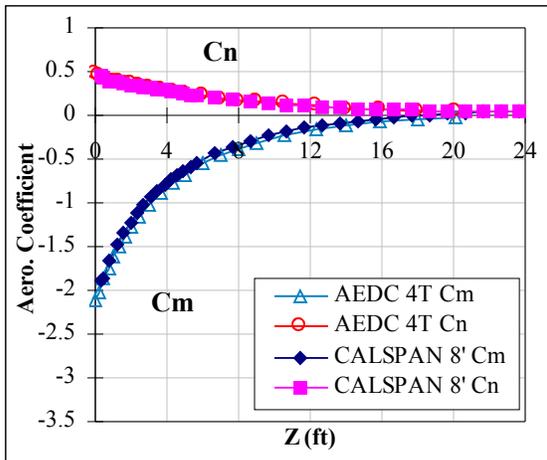


Figure 7: JDAM Wind Tunnel Grid Comparison for $M = 0.80, \alpha = 0^\circ$

The differences between the two wind tunnels begin to be seen at $M = 0.90$, as shown in Figure 8. The yawing moment coefficients still match relatively well over the test range. However, there is a discrepancy between the pitching moments approaching the carriage position ($Z = 0$). The CALSPAN tunnel measured a smaller C_m in magnitude up through $Z = 4$ ft, while the AEDC C_m is consistently smaller in magnitude than CALSPAN from about $Z = 5$ ft to $Z = 16$ ft.

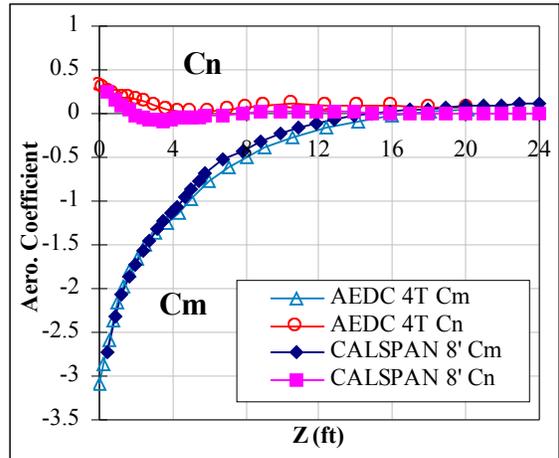


Figure 9: JDAM Wind Tunnel Grid Comparison for $M = 0.95, \alpha = 0^\circ$

The coefficients measured at Mach 1.05, shown in Figure 10, agree well. A second AEDC test confirmed these results.

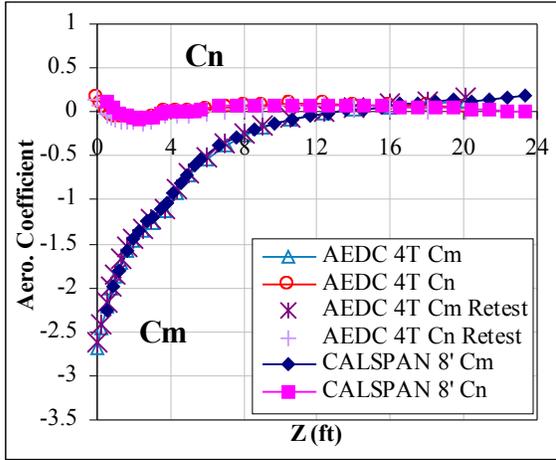


Figure 10: JDAM Wind Tunnel Grid Comparison for $M = 1.05, \alpha = 0^\circ$

At Mach 1.20, the tunnels begin to show some variation. As seen in Figure 11, the first AEDC yawing coefficients are shifted slightly above the CALSPAN yawing coefficients. However, yawing results from the AEDC retest are nearly identical with the CALSPAN results. Of more concern is how the AEDC pitching moments are all shifted below the CALSPAN pitching moments. The pitching coefficients from the second AEDC test tend to lie between the other two pitching curves. This suggests a calibration error in addition to any potential blockage effects or shock wave interactions with the wind tunnel wall.

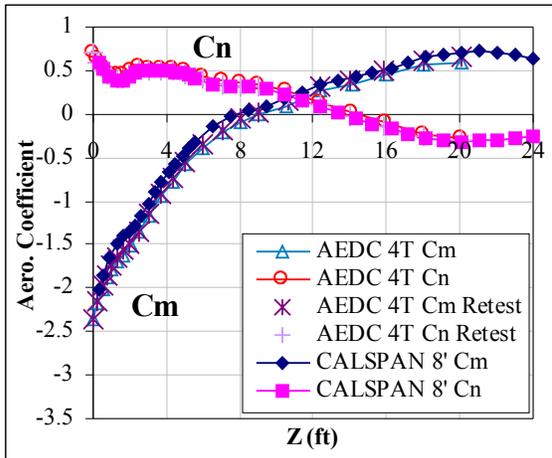


Figure 11: JDAM Wind Tunnel Grid Comparison for $M = 1.20, \alpha = 0^\circ$

Simulation Comparison With Flight Testing

While there is some discrepancy between tunnels, neither set of flowfield data set can be preferred until compared with another independent source, in this case, flight test trajectory data. Trajectories for applicable flight conditions were evaluated by applying grids from each tunnel into the grid-based option of the six-degree-of-freedom NAVSEP trajectory simulation code. These simulated trajectories were then compared to both telemetry and photogrammetric flight test data. Several flight configurations were compared with CALSPAN-derived trajectories, but because the AEDC test had only one MK-84 configuration, only six flight tests were applicable to data from both tunnels. While grid data were available from Mach 0.80 to 1.20, these test flights were performed at Mach numbers ranging from 0.896 to 1.303.

Parameters such as Mach number, altitude, and dive angle were recorded for each test flight and can be placed into the trajectory simulation. However, some variability is associated with the parameters of carriage loads and aircraft angle of attack. The procedure was to first run a trajectory using the CALSPAN grid data for some estimated parameters. The store carriage loads used in the simulation were recorded from internal balance data from captive carriage testing. Next, these variable parameters were adjusted slightly in order to match the flight test data as closely as possible. Once values for these parameters were locked in, NAVSEP used the AEDC freestream and grid data to generate trajectories. Because the MK-84 JDAM test at the CALSPAN tunnel was more extensive, there was significantly more grid data available. While one would generally place all available data into NAVSEP, in order to make a fair comparison, only CALSPAN grids taken at the same positions as the AEDC tests were used in these simulations.

The aircraft configuration for Flight Tests 1 and 2 is shown in Figure 12. This configuration differs from the wind tunnel test (Figure 6) by the replacement of wing tip AIM-9 missiles with wing tip cameras and the absence of the starboard fuselage AIM-7.

M = 0.896, 4624 ft, Level Release

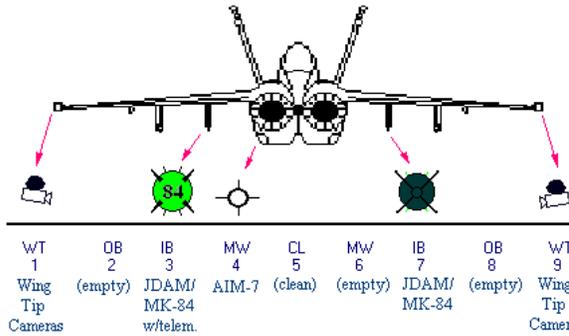


Figure 12: Aircraft Loading for Flight Tests 1 and 2

JDAM NAVSEP trajectories for the first 300 msec after release from both wind tunnel grids are compared with the telemetry data for Flight Test 1 in Figure 13. Because of the limitations of camera angles, photogrammetric attitude data are not plotted. This flight involved straight and level release at Mach 0.896 at an altitude of 4,624 feet. The simulation was not expected to simulate roll effectively because off-axis ejector forces can cause unpredictable roll rates.⁽⁴⁾ Therefore, the roll angle (PHI) is not plotted. Both simulated yaw angles in Figure 13 match quite well with the flight test telemetry data. The AEDC 4T simulations disagree for the pitch angle. This difference in trajectory is due to the wind tunnel discrepancy with pitch coefficient at Mach 0.90 (Figure 8). It appears that the AEDC pitching moment is incorrect.

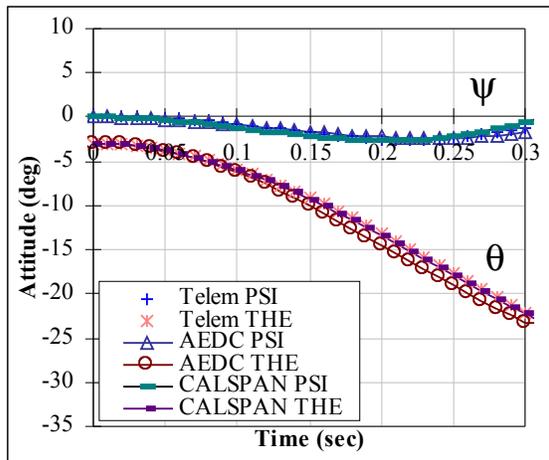


Figure 13: Flight Test 1 Attitude Comparison,

Given data on the store position and attitude, as well as geometry models, it was possible to compute miss distances. The miss distance code used models in the same format as the PANAIR code ("A502" format) and simply calculates the minimum distance of any point on the store to any point on the aircraft pylon. In the case of photogrammetrics, it is possible to determine miss distances directly from the images. However, it was decided to indirectly use the photogrammetric data to determine positions and attitudes for input into the miss distance code, in keeping with the other data sources. Figure 14 shows the simulated miss distances for Flight Test 1 compared to those determined from flight test telemetry and photogrammetrics.

In this case, the AEDC 4T miss distances are slightly more conservative than those from the CALSPAN 8-ft trajectory. The difference in pitch angle between AEDC and CALSPAN data caused little difference with the miss distance prediction.

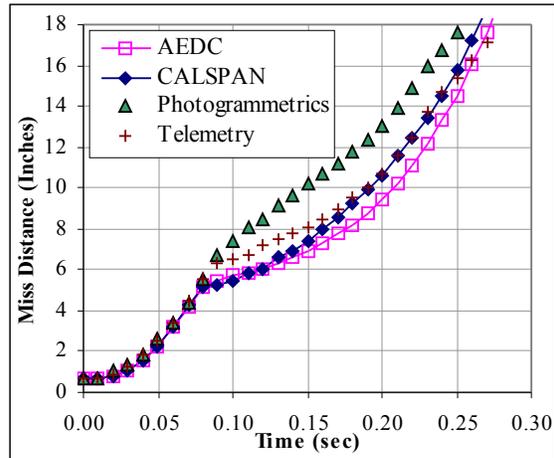


Figure 14: Flight Test 1 Miss Distance to Pylon, M = 0.896, 4624 ft, Level Release

Flight Test 2 was a release from straight and level flight at Mach 0.961 and 5,203 feet. The NAVSEP simulations are compared with Flight Test 2 telemetry data in Figure 15. Neither simulation pitches down as much as the actual flight test. The pitch angles from both simulations agree well with each other because the wind tunnel data for pitch coefficient agreed well near carriage at Mach 0.95 (Figure 9). The difference in wind tunnel yaw

readings, however, becomes evident in a divergence from telemetry yaw angle after about 200 msec. The CALSPAN simulation slightly overpredicts yaw while the AEDC simulation underpredicts yaw.

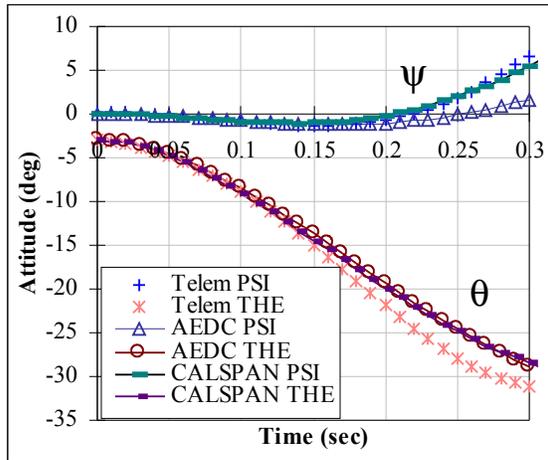


Figure 15: Flight Test 2 Attitude Comparison, M = 0.961, 5203 ft, Level Release

Figure 16 displays the miss distance histories for Flight Test 2. After about 60 msec, the miss distance based on telemetry is shifted below the miss distance based on photogrammetrics. The telemetry miss distance is probably too conservative since it does not account for aircraft motion.⁽⁴⁾ The CALSPAN tunnel produced more conservative miss distances than AEDC. Both sets of wind tunnel data do an excellent job of predicting the store's initial tendency to separate cleanly and come back.

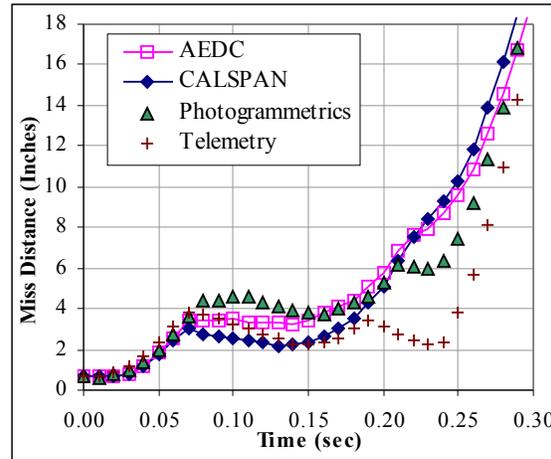


Figure 16: Flight Test 2 Miss Distance to Pylon, M = 0.961, 5203 ft, Level Release

Unlike Flight Tests 1 and 2, the remaining tests included a 330 gallon external fuel tank on the centerline station, as shown in Figure 17. While the CALSPAN tests did include testing with a centerline fuel tank, it was decided to only use grids produced in the same configuration as AEDC for computing trajectories to maintain an applicable comparison. However, it has been established that the centerline tank has little effect on the flowfield of the station in question.⁽⁵⁾

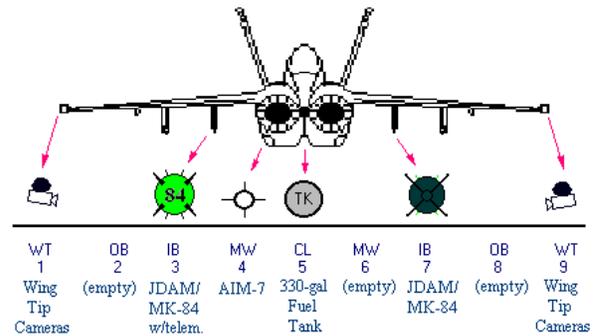


Figure 17: Aircraft Loading for Flight Tests 3, 4, 5 and 7

Figure 18 is for Flight Test 3, a level release at Mach 0.943 and altitude of 4,315 feet. As with Flight Test 2, the telemetry shows a steeper pitch than either simulation. Again, the AEDC yaw angle is less than that derived from the CALSPAN data.

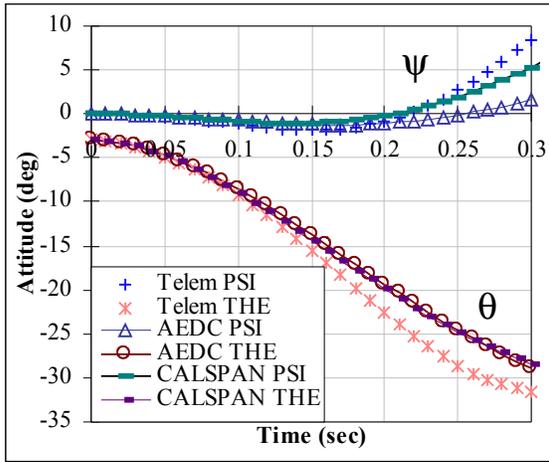


Figure 18: Flight Test 3 Attitude Comparison, M = 0.943, 4315 ft, Level Release

The corresponding miss distances for Flight Test 3 are plotted in Figure 19. This is the only case where the photogrammetric miss distance is more conservative than telemetry. Some investigation revealed that the photogrammetric timing was early by approximately 0.015 seconds relative to telemetry. Generally, the telemetry is used to determine the beginning of store ejection when there is a large spike in acceleration. The simulations tend to compromise between telemetry and photogrammetrics until about 100 msec. After this, the simulations tend to be less conservative than the telemetry flight test data. The double dip seen at M = 0.961 (Figure 16) is again evident and well predicted by both sets of data.

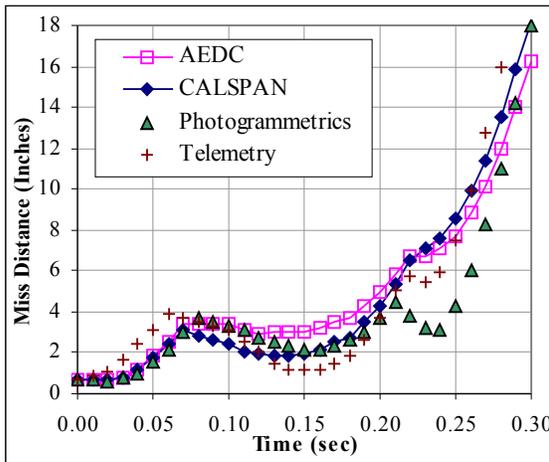


Figure 19: Flight Test 3 Miss Distance to Pylon, M = 0.943, 4315 ft, Level Release
NOTE: Timing Error Between Telem. and Photo.

Flight Test 4 involved a 45 degree dive (relative to the horizontal) at Mach 0.95 and an altitude of 7,004 feet. The attitudes in Figure 20 are all similar to the corresponding plots from Flight Tests 2 and 3. This is most likely because each of these tests were at similar Mach numbers. In addition, the same carriage loads and aircraft angle of attack were used in all three simulations.

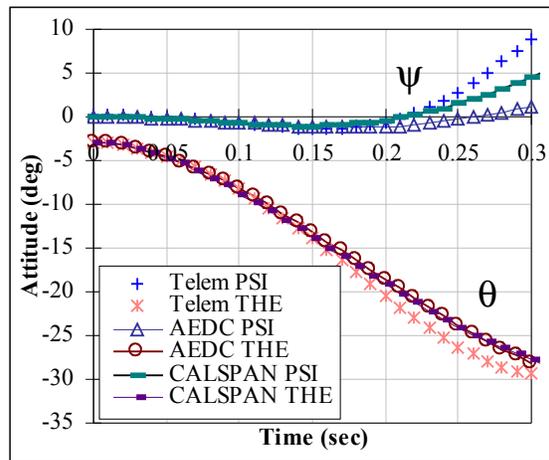


Figure 20: Flight Test 4 Attitude Comparison, M = 0.95, 7004 ft, 45 deg Dive

The miss distances for Flight Test 4, shown in Figure 21, tend to show that both wind tunnels were conservative until about 180 msec, at which time the larger pitch shown in the telemetry causes a rapid decrease in miss distance at 220 msec. The CALSPAN prediction matches this trend, but AEDC does not. The telemetry shows the store hitting the aircraft, which did not happen. This is because the telemetry does not reflect the wing reaction dynamics at store ejection.

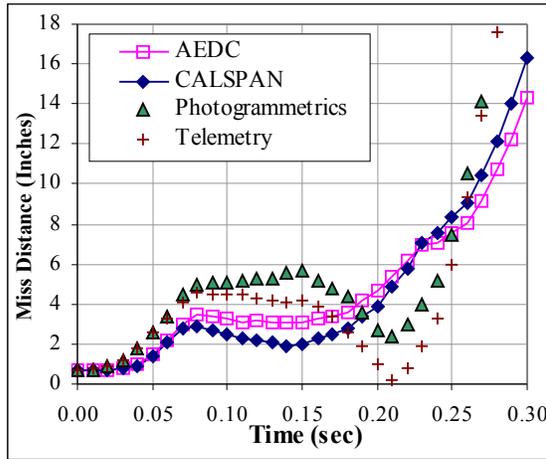


Figure 21: Flight Test 4 Miss Distance to Pylon, M = 0.95, 7004 ft, 45 deg Dive

Figure 22 goes along with Flight Test 5, a 44 deg dive at Mach 1.078 and 13,476 feet. The pitch angles from both simulations agree well with the telemetry pitch. This is because both wind tunnels had nearly identical pitching moment curves at Mach 1.05 (Figure 10). Both simulations tended to overpredict the yaw angles relative to the yaw telemetry.

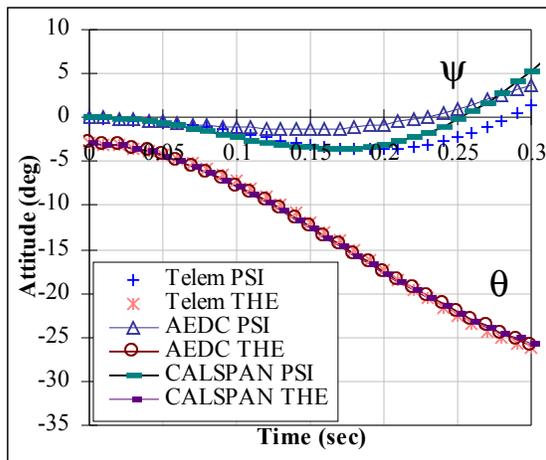


Figure 22: Flight Test 5 Attitude Comparison, M = 1.078, 13476 ft, 44 deg Dive

As with the previous flight test, the wind tunnel miss distances for Flight Test 5 (Figure 23) tend to be overly conservative relative to the flight test data, especially in the case of CALSPAN. The reason for the small miss distance in the case of

CALSPAN is best illustrated by visualization of the three trajectories in Figure 24. Store positions for CALSPAN, AEDC, and telemetry are shown 150 msec after release. Photogrammetrics and telemetry confirm that the actual flight test included much more roll than predicted by either wind tunnel. This could be a result of aircraft rolling maneuvers, wing flexure, and/or an off-axis ejector force. Even though the CALSPAN 8-ft tunnel predicted the store yaw quite well, neither tunnel could have been expected to predict this kind of roll behavior. The underprediction of yaw by AEDC, while only 2.17° different than CALSPAN at 150 msec, means that the AEDC trajectory does not swing the tail of the store close to the side of the pylon. The difference in trajectory between the wind tunnels is somewhat unexpected because the grid data at Mach 1.05 agreed quite well (Figure 10).

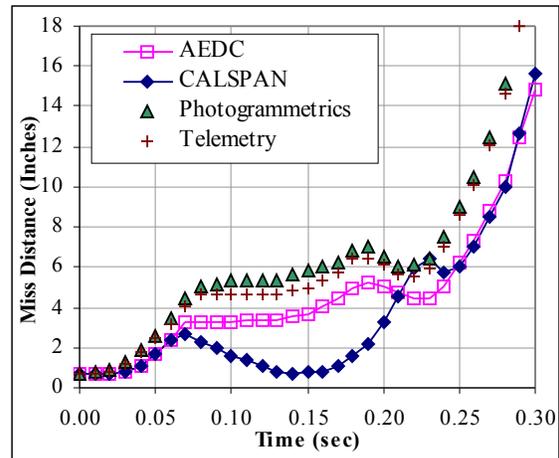


Figure 23: Flight Test 5 Miss Distance to Pylon, M = 1.078, 13476 ft, 44 deg Dive

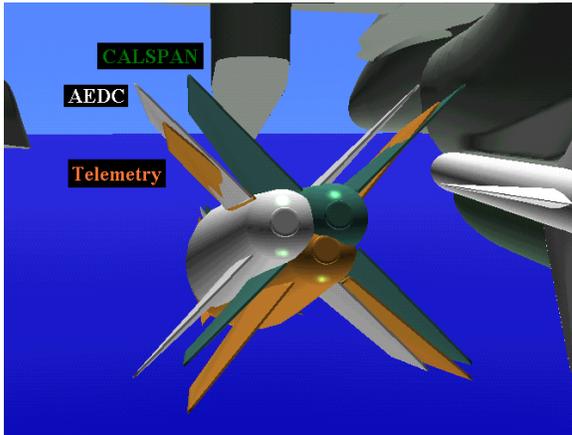


Figure 24: Flight Test 5 Trajectory Comparison for T = 150 msec. CALSPAN and AEDC disagree mainly in yaw, while Telemetry shows extra roll not predicted by either tunnel.

The final applicable sets of data are from Flight Test 7, a 51 deg dive from 20,025 ft at Mach 1.303. In Figure 25 there is a large difference between both simulated trajectories. The CALSPAN simulation has a shallower pitch angle than the AEDC simulation. This is linked to the wind tunnel pitch coefficients at Mach 1.20, where the CALSPAN pitching curve was shifted above the AEDC pitching curve (Figure 11). Figure 11 also showed that the AEDC yaw coefficients were higher than the CALSPAN yaw coefficients, leading to a higher yaw angle for the AEDC simulation.

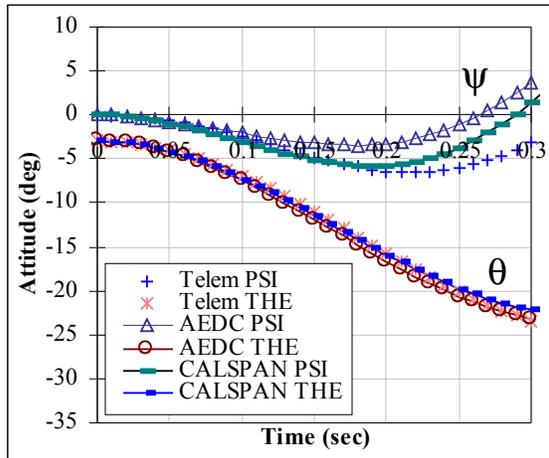


Figure 25: Flight Test 7 Attitude Comparison, M = 1.303, 20025 ft, 51 deg Dive

The corresponding miss distances from Flight Test 7 are shown in Figure 26. As usual, the telemetry miss distances are somewhat more conservative than the photogrammetric miss distances. Up to about 120 msec, the wind tunnel data are slightly more conservative than the telemetry data. Then both wind tunnel data sets lie between the flight test sets until after about 200 msec.

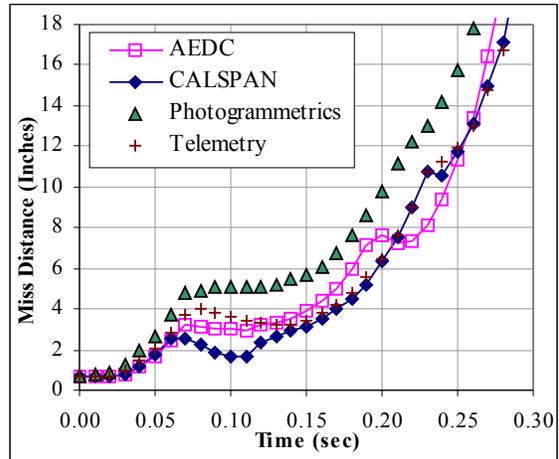


Figure 26: Flight Test 7 Miss Distance to Pylon, M = 1.303, 20025 ft, 51 deg Dive

Inaccuracies in wind tunnel data will invariably cause the simulations to diverge from flight tests. In this case, one of the largest contributions to wind tunnel inaccuracies is sensitivity of the models to Mach number. Additional CTS testing of the MK-84 JDAM at the CALSPAN tunnel has shown that the moment coefficients can vary widely over very small Mach increments. It should be noted that these carriage loads were taken for a store on the outboard pylon with a 330 gallon external fuel tank on the inboard pylon, as shown in Figure 27, while all of the flight tests released the JDAM from the inboard pylon. Figures 28 and 29 show the results of a Mach sweep on pitching and yawing carriage moments on the MK-84 JDAM as well as the standard MK-84. The pitching moment encounters a sudden drop off between 0.90 and 0.95 Mach. Similarly, yawing moments demonstrate a steep valley and peak in the transonic region. Because even a small difference in Mach number in the transonic region will result in drastically different moment readings, the customary uncertainty in Mach number

readings is most likely a major cause for different wind tunnel results between the AEDC and CALSPAN tunnels for the F/A-18C.

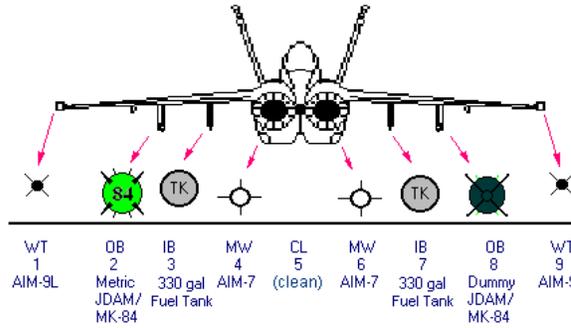


Figure 27: Wind Tunnel Configuration 3 Loading

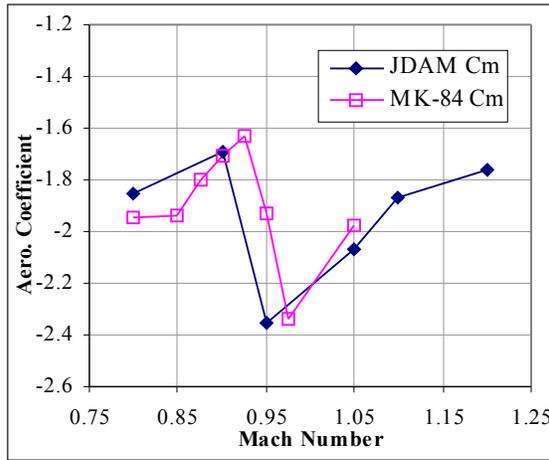


Figure 28: Pitching Moment Coefficient Sensitivity to Mach Number at Carriage, $\alpha = 0^\circ$

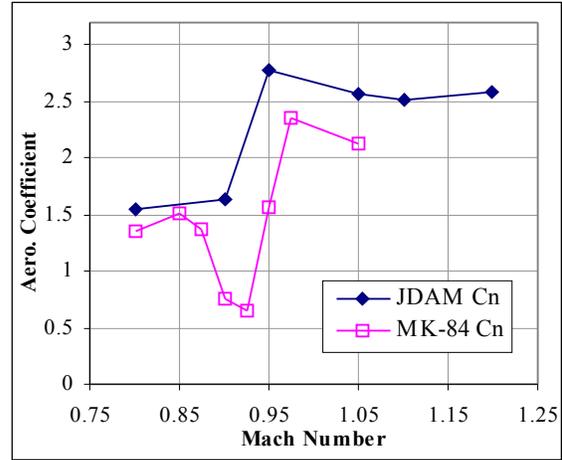


Figure 29: Yawing Moment Coefficient Sensitivity to Mach Number at Carriage, $\alpha = 0^\circ$

Conclusion

The first comparison of the AEDC 4T and CALSPAN 8-ft wind tunnels was the freestream pitching moment and normal force coefficients of the MK-84 JDAM. While the results from both tunnels tended to match for transonic conditions, there were discrepancies in pitching moment for supersonic conditions.

Next, grid data from both tunnels were compared. The most obvious difference was in the grid carriage pitching moment at 0.90 Mach. At Mach 1.20, there was a systematic shifting of results between tunnels. A possible reason for such a systematic difference is a calibration error in one of the tunnels.

The wind tunnel data were then input into the NAVSEP separation simulation, ultimately providing miss distances between the MK-84 JDAM and F/A-18C. The greatest discrepancy in miss distance was for Test Flight 5. This is confusing because the relevant data from both tunnels agree quite well for this condition.

While it was expected that wall interference effects would be the major cause of different readings in the different sized tunnels, further analysis

demonstrates that uncertainty in Mach number provides a sufficient explanation for differences between tests. This could mean that future tests in smaller wind tunnels can be just as accurate as larger tunnels, provided that adequate Mach sensitivity analyses are conducted. However, it must be remembered that there are flight phenomena (i.e. off-axis ejector strokes, wing flexure, etc.) which no wind tunnel will be able to predict.

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