One CFD calculation to end point flight testing

(Has CFD finally replaced the wind tunnel?)

A. Cenko
Naval Air System Command
Patuxent River, MD,
USA

ABSTRACT

Any time a new aircraft is introduced into service, or an old aircraft undergoes substantial modifications or needs to be certified to carry and employ new stores, the store separation engineer is faced with a decision about how much effort will be required to provide an airworthiness certification for the aircraft and stores. Generally, there are three approaches that have been used: wind-tunnel testing, computational fluid dynamics (CFD) analyses and flight testing. During the past twenty years there have been considerable advances in all three areas. In particular, there has been a considerable improvement in the speed and validity of CFD results for store separation. The Holy Grail of CFD has long been the reduction/replacement of wind-tunnel testing. This would mean in store separation the ability to go from a CFD calculation to flight testing at the end point. The paper will describe how this was achieved for the F/A-18C/Litening pod program.

NOMENCLATURE

ATFLIR	advanced targeting forward looking infra red
BL	aircraft buttline, positive outboard, in
C_l	rolling moment coefficient, positive rt wing down
C_m	pitching moment coefficient, positive nose up
C_N	normal force coefficient, positive up
C_n	yawing moment coefficient, positive nose right
C_p	pressure coefficient
C_Y	side force coefficient, positive right
JDAM	joint direct attack munition (GBU-31 is MK-84 and GBU-38 is MK-82 variant)
JSOW	joint stand-off weapon
KCAS	knots calibrated airspeed, knots/hr
M	Mach number
MMA	maritime multi-role aircraft (P-3 replacement)
P	store roll rate, positive rt wing down
Q	store pitch rate, positive nose up
R	store yaw rate, positive nose right
TACMAN	tactical manual
Z	store CG location, positive down, ft
α	angle of attack, deg
ϕ	PHI store roll angle, positive rt wing down, deg
ψ	PSI store yaw angle, positive nose right, deg
θ	THE store pitch angle, positive nose up, deg

1.0 INTRODUCTION

Since the time that CFD was first capable of representing the geometric complexity of an attack aircraft with external stores, there has been the desire to replace/reduce the need for wind tunnel testing. The three detriments for full utilisation of CFD in this fashion were computational speed, computer resources and accuracy of the solution. For the AWACS(1) configuration, one solution using a linear code with 1,000 panels required full utilisation of the super-computer of that time (CDC 6600) for 24 hours. Clearly, the wind tunnel was in no danger. As a metric of where we are, the same solution will now run in minutes on a PC.

Paper No. 2998. Manuscript received 5 August 2005, accepted 28 March 2006.

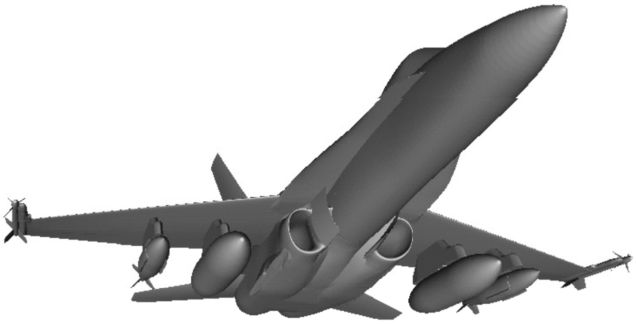

Figure 1. F-18C/GBU-31 configuration.

Figure 2. F-18C/MK-83 configuration.

Over the past 15 years, the US Air Force and Navy have made an effort to validate and accelerate the insertion of CFD methods into the store certification process. There have been several organised international conferences for this purpose.

The first of these was for the wing/pylon/finned-store, which occurred in Hilton Head, SC in the summer of 1992. One of the important results from this initial conference was the discovery that full potential methods(2) gave answers equivalent to those provided by an Euler(3) code for the wing lower surface in the presence of the store.

The second conference was sponsored by the Office of the Secretary of Defense (OSD) funded Applied Computational Fluid Dynamics (ACFD) program. This was for the F-16/Generic Finned Store; the conference took place in New Orleans in the summer of 1996 (ACFD Challenge I). For this meeting lower order(4) solutions again exhibited good agreement with Euler and Navier Stokes codes.

The last ACFD sponsored conference was the F-18/Joint Direct Attack Munition (JDAM) CFD Challenge (ACFD Challenge II). Large sets of wind tunnel and flight test data existed for the F/A-18C JDAM configuration, Fig. 1, and all the participants showed excellent correlation with both the wind tunnel and flight test results. A detailed summary of the results for ACFD Challenge II is available(5). This configuration has become the standard for store separation code validation, with several new participants during the past two years.

The last CFD Challenge was conducted under the auspices of The Technical Cooperative Program (TTCP) Key Technical area (KTa) 2-18 for the F-18C/MK-83 store, Fig. 2. Comparisons were made with pressure sensitive paint (PSP) data as well as flight test store trajectories. Again, all the participants demonstrated good comparisons(6) with the store trajectories and surface pressures. The best pressure comparisons were obtained using the FLUENT code run in a viscous mode. This seemed to imply that while viscous calculations were needed to correctly predict store pressures, inviscid results were adequate for predicting the trajectories. This is a very important consideration, since running a trajectory simulation requires many separate computations, either in a time dependent or grid mode.

It appears that CFD for external stores has reached a mature phase. Lockheed has recently demonstrated that CFD can be used to design an aircraft to be 'store friendly', and that the aircraft performance is actually improved by the process, while Boeing used CFD in the design phase for its MMA aircraft/store integration.

The US Air Force, Army, and Navy have long-term, proven CFD modelling and simulation experience and software development expertise that has supported advanced weapon development and integration. Each uses unique CFD codes to augment traditional sources of engineering data such as flight and wind-tunnel testing. In the past year, the three services, under the auspices of the High Performance Computing (HPC) Center have combined their efforts to establish an Institute for HPC Applications to Air Armament (IHAAA).

2.0 IHAAA

Two of the three services top priorities are to more rapidly meet wartime warfighter requests and to reduce development effort risks. The IHAAA holds the promise of meeting both of these shortfalls. IHAAA will enable delivery of increased flight envelopes with decreased flight test resulting in rapid delivery of war-winning capability during the next Operation Enduring Freedom or Iraqi Storm. Developmental efforts will also benefit as HPC-based simulations developed by the IHAAA mitigate developmental risk by subjecting designs to the severity of the flight environment (in an HPC model) early enough in the acquisition cycle to positively influence the design. The AMRAAM, JDAM, and JSOW programs all experienced schedule-expanding and cost-multiplying fin failures during flight test that could have been predicted if the goals of the IHAAA were realised and applied in the concept and design phases.

The mission of the IHAAA is to provide US warfighters with enhanced combat capability through application of HPC techniques for air armament design, integration, and evaluation. The vision is to be a sustainable enterprise ensuring HPC technology transition and application to provide quick reaction to warfighter needs and reduce acquisition cost, schedule, and risk. The strategic goals of the Institute are: to establish a customer-oriented enterprise integrating laboratory, development, test and evaluation organisations; to guarantee technology transfer; to broaden applicability of HPC tools; and to build acquisition community confidence in HPC capability. A key Institute strategy is to become the research-to-customer bridge by pulling relevant technology from researchers and integrating it into the air armament acquisition process. During the first year, the IHAAA institute decided to concentrate the three services efforts in the areas of store separation, unsteady flow, and aircraft/store geometry library.

The store separation team picked two areas of air armament where conventional, wind tunnel based techniques have not always provided a good prediction of flight test results. These were in the areas of weapons bay flowfields, and moving control surfaces.

2.1 Weapons bay flowfields

Internal weapons carriage is being used to improve the aircraft aerodynamic performance and low observability characteristics. The separation of small, light stores from a weapons bay may be significantly impacted by the unsteady flow in the bay. These temporal effects are not captured during wind tunnel testing and in conventional engineering methods analyses. Computational tools need to be validated for predicting the unsteady aerodynamic effect of the weapons bay on the trajectory of a store through the bay and flow field.

B-52, B-1B, B-2, F-22, F-35, MMA, and J-UCAS all use internal carriage systems for weapons delivery. All of these aircraft will carry a variety of small smart weapons in their bays. These new weapons will be more sensitive to the acoustical environment and the unsteady flow-field in the weapons bay.

There are currently a number of techniques used to predict the separation characteristics of a weapon from an internal bay. Some rely entirely on experimental flow fields beneath the aircraft and on store free-stream databases. These techniques may be deficient because it is often impossible to obtain data in the shear layer and in the internal region of the bay. Other techniques rely on a mixture of steady state CFD and experiment to predict the separation characteristics. Again these techniques are quasi-steady, and temporal effects are not modelled. However, techniques relying on fully time accurate CFD simulations do attempt to capture the temporal nature of the flow field. The need to model the temporal character of the flow for this class of light weapons has not been established. Both quasi-steady and time-accurate techniques represent the full range of tools necessary for store separation analysis. They complement each other with each having their strengths and weaknesses. For many of these techniques, different organisations are utilising different tools. These techniques need to be further evaluated to determine the advantages and disadvantages of each approach and tool for addressing this class of weapons.

Computed store separation trajectories from the weapons bay of the B-1B will be compared at conditions matching existing wind-tunnel and flight test data. Comparison data will be supplied once the computations are completed. Both fully time-accurate CFD trajectories will be performed as well as trajectories simulations using quasi-steady engineering methods utilising computationally generated grid data, flow-field data, and free-stream store aerodynamics. Work will be performed initially using local tools and then using tools from the other organisations.

2.2 Moving control surfaces

Control surface movement and deployment are being utilised and proposed for a variety of weapons including the JSOW, GBU-10, 12, 16, 24, SDB, and MALD. Use of control surfaces can be for a variety of reasons including control stability during separation, control effectiveness during fly away, increased ballistic accuracy and range, and loitering. Control surface movement and deployment can occur during the separation phase or later during the fly away phase. Of primary concern is the deployment during the separation event and its effect on the near parent trajectory. The behaviour of these stores during this early stage is difficult to simulate in a wind tunnel environment and usually must be simulated computationally. Wind tunnel testing of weapons with free-floating canards typically involves acquiring a large database of free stream, grid, and trajectory data with fixed canards and without canards. This can be costly and still does not precisely simulate the aerodynamics of the store. Another potential area of concern is the lack of good aerodynamic wind tunnel data to predict the aerodynamics of the store with the floating canards, particularly in the non-uniform flow of the aircraft. Even at moderate angles of attack, the local flow may cause the floating canards to reach their physical stops, which significantly alter the aerodynamic contribution of the canards and the overall aerodynamics of the store. Control surface deployment has been computationally simulated, but the deployment was assumed to occur instantaneously, i.e. the control surfaces stowed configuration followed immediately by a fully deployed configuration. The transient behaviour of the surface during deployment and its effect on separation has not been totally investigated. The accuracy of instantaneous deployment has been challenged but not quantified. Although the control surface deployment issue is important, the current effort will focus on the moving, floating canards, which has immediate application to an upcoming flight test of the GBU-12 separating from the F-18/C/D. The uncertainties associated with the current testing and predictions methods for floating canards needed to be investigated.

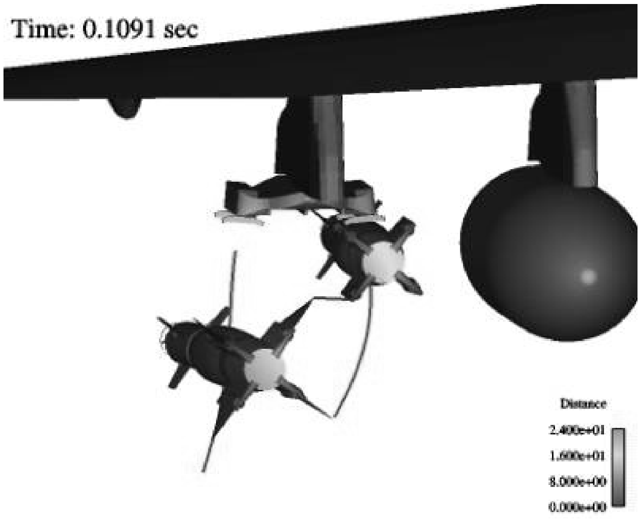

Figure 3. F-18C/GBU-12 outboard trajectory.

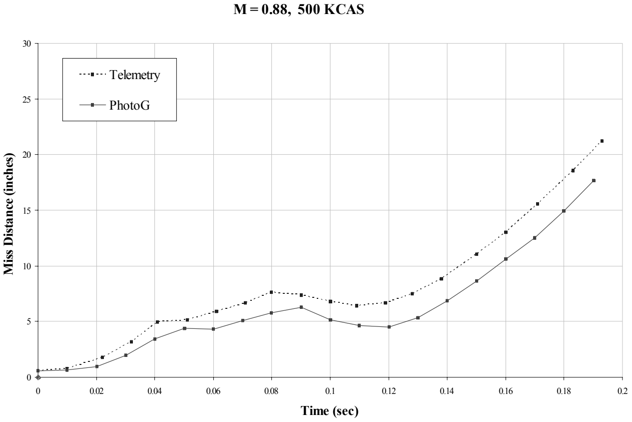

Figure 4. F-18C/GBU-12 outboard miss distance.

3.0 EXAMPLES OF CFD APPLICATIONS

3.1 F/A-18C/GBU-12 adjacent tank

Due to urgent requirements for Operation Iraqi Freedom, a flight clearance for the GBU-12 on CVER adjacent to the 330 gallon tank was requested. Since the time frame didn't allow for a wind tunnel test entry, and the Navy did not have a computational model of the GBU-12 store, it was decided that the 'hit-or-miss' method would be employed. The hit-or-miss method involves dropping the store at increasing airspeeds (by increasing M at the same altitude), until it is felt that it is no longer safe to proceed.

Although the results for the first flight (M = 0·88, 5,000ft) were relatively benign, the close distance between the fins of the first store and second store, and the fins of the second store and fuel tank raised flight safety issues.

Note that there is very little clearance between the tail of the outboard store, which is open to 20°, and the inboard store, Figs 3 and 4.

There is also minimum clearance between the inboard store and fuel tank during the separation, Figs 5 and 6.

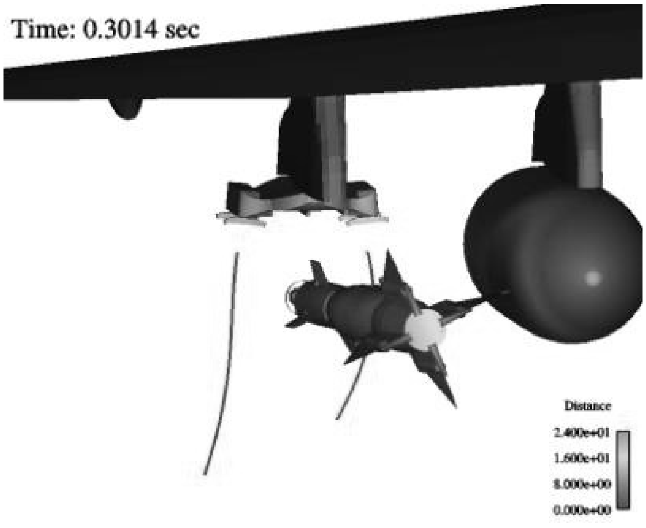

Figure 5. F-18C/GBU-12 inboard trajectory.

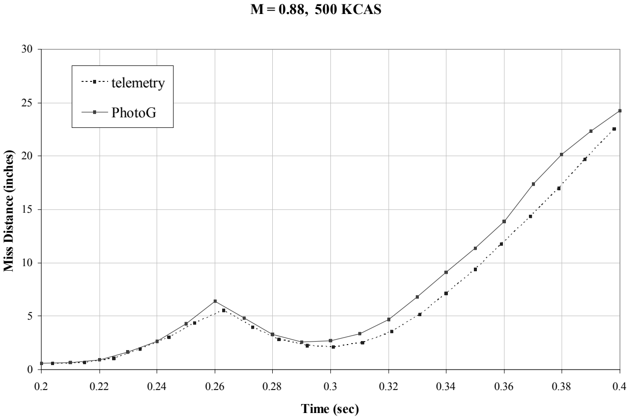

Figure 6. F-18C/GBU-12 inboard miss distance.

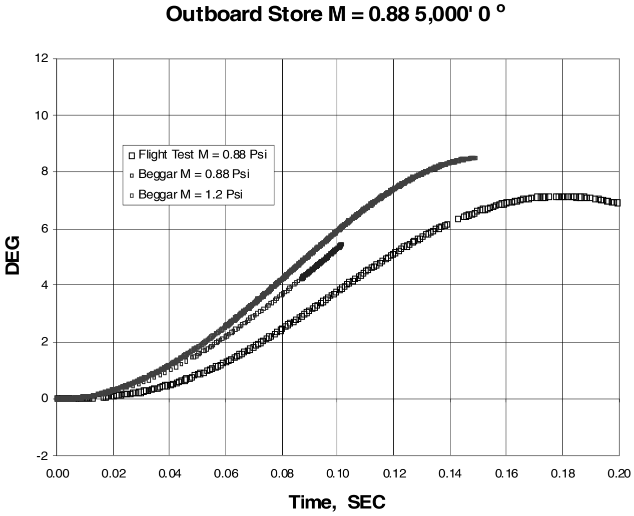

Figure 7. F-18C/GBU-12 Beggar prediction.

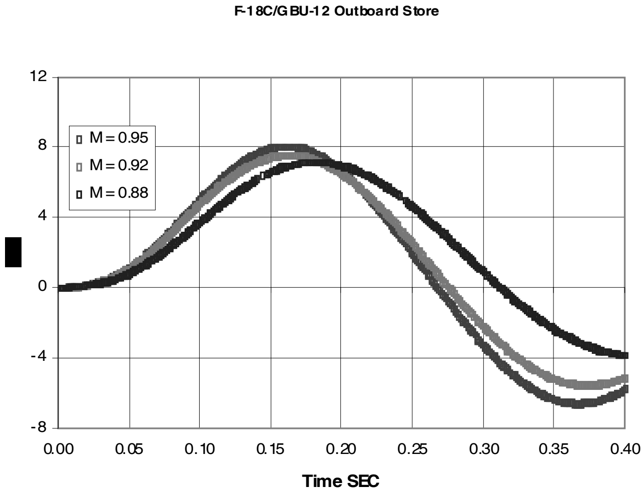

Figure 8. F-18C/GBU-12 yaw.

Usually, when the miss distances get within six inches there is a reluctance to proceed with the next flight test point, unless wind tunnel data indicates it's OK to go ahead.

Fortunately, the Air Force SEEK EAGLE office had the geometry of the F-18C/D available, since they participated(7) in ACFD Challenge II. They were also experienced in performing trajectory calculations for the GBU-12 store, and offered to perform CFD calculations simultaneously with the flight test program.

The US Air Force uses the Beggar(8) Code as its primary tool for store separation calculations. The philosophy behind Beggar is to use a Chimera, or overlapped, grid system so that the components of a problem may be girded independently of each other and then assembled to form the complete system of computational grids. By automating the Chimera assembly process and incorporating an algorithm to solve the rigid-body equations of motion, the code has become a user-friendly platform ideal for store separation calculations. To further increase the applicability of the code, a coarse-grain parallelisation of the code has been implemented that significantly reduces the amount of wall clock time needed for complex problems. Recently, (6+) DOF has been successfully implemented into the Beggar code to allow the simulation of stores with moving components such as rotating fins.

Beggar is capable of numerically approximating the solution to either the three-dimensional curvilinear form of the Reynolds averaged Navier-Stokes (RANS) equations, the thin-layer Navier-Stokes equations, or the Euler equations. Additionally, separate sets of equations may be solved in different blocks of the grid system. For example, a grid of a wing section may be evaluated based on the RANS equations while an outer Cartesian grid representing the free-stream may use the Euler equations to model the pertinent physics. The set of governing equations is discretised using a finite-volume formulation. The linear system of equations is solved with a symmetric Gauss-Seidel relaxation scheme, while Newton's method is used to advance the solution in time as well as synchronise the solution at the block boundaries. Upwinding is accomplished through either Steger-Warming flux vector splitting or Roe flux vector differencing of the inviscid flux vectors. The viscous flux vectors are discretised using central differencing. Available turbulence models include the Baldwin-Lomax algebraic model, the Baldwin-Barth one-equation model, the Spallart-Almaras one-equation model and the two-equation K-ε with wall functions. For the analyses presented in this paper, only inviscid solutions were used.

The Beggar predictions are compared with the flight test results in Fig. 7. The store yaw behaviour is of principal concern for this case.

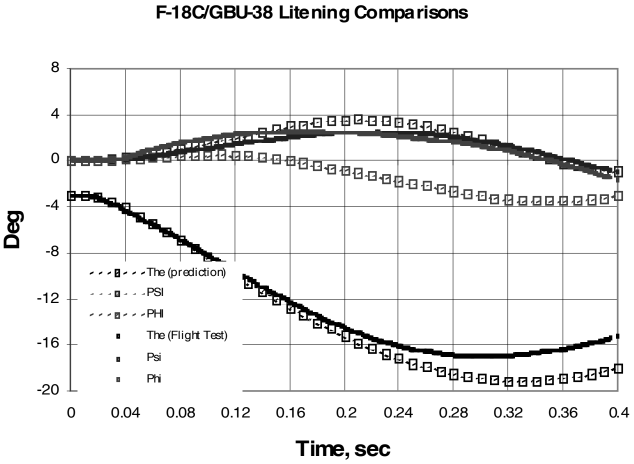

Figure 9. F-18C/GBU-38 Litening Pod trajectory M = 0·80.

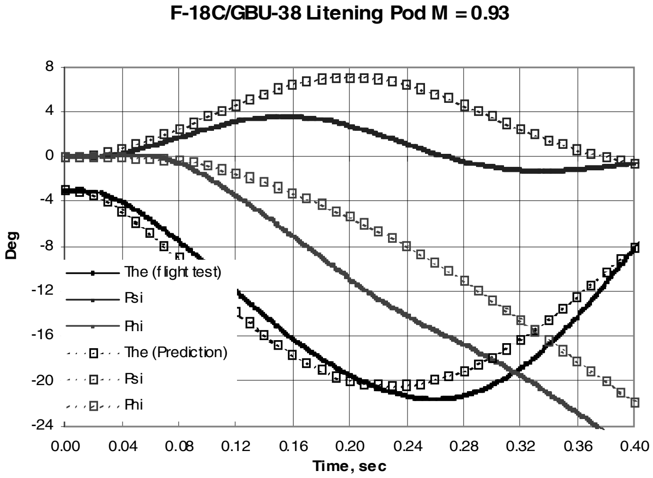

Figure 10. F-18C/GBU-38 Litening Pod trajectory M = 0·93.

The fact that the Beggar predicted a very small increase in the store's yaw behaviour with a considerable increase in Mach number indicated that is was safe to proceed to the next test point. The CFD predictions were validated with the flight test results, as may be seen in Fig. 8.

The integration of CFD results produced by the Air Force with the flight test programme enabled the Navy to issue a flight clearance for this configuration in a month after the start of the program.

3.2 F/A-18C/Litening Pod

In support of Northrop Grumman's efforts to market the Litening Pod to the Australian and Canadian governments for use on their F/A-18 aircraft, Northrop Grumman contracted NAVAIR to support flight certification of the Litening Pod and associated pylon mounting system on Station 4. The flight certification should permit operation of the Litening Pod mounted on the pylon and operation of the pylon mounted without the pod. Northrop Grumman desired to obtain a flight certification to operate the pod on the station without restriction to the flight envelope and manoeuver capability of the F/A-18 A/B/C/D aircraft using F/A-18 OFP load 17C.

NAVAIR agreed to provide pre flight analysis and flight test support of five stores on station three with Litening Pod on station four: GBU-38, GBU-12, MK-84, Dual AIM-120 and FPU-8 external fuel tank. The purpose of the flight test program was to clear these stores to their TACMAN limits.

Extensive wind tunnel and flight test data existed for the GBU-38 store at Station 3 with an ATFLIR located on Station 4. Excellent results were achieved with this wind-tunnel data in the F-18C/GBU-38 flight test programme(9). Preliminary Euler CFD calculations(10) indicated that the Litening Pod would have similar aerodynamic effects to the ATFLIR. It was decided that an incremental CFD approach would be used for this configuration. The wind tunnel data for the GBU-38 next to the ATFLIR would be corrected by the CFD predicted increments in aerodynamic coefficients for the effects of Litening Pod relative to the ATFLIR.

3.2.1 *F/A-18C/GBU-38 Litening Pod*

The first GBU-38 flight test occurred at M = 0·80, 450 KCAS. At this low Mach number, it was felt that linear method would be applicable. The PAN AIR1 code was used to determine the Litening Pod increments for this case.

As may be seen in Fig. 9, excellent match between pre flight predictions and flight test results was achieved. Since F-18/ATFLIR flight test data (modified by PAN AIR predicted increments) were used for these predictions, it appeared that at subsonic speeds the Litening Pod flowfield effects were similar to those for the ATFLIR. This validated the incremental approach used.

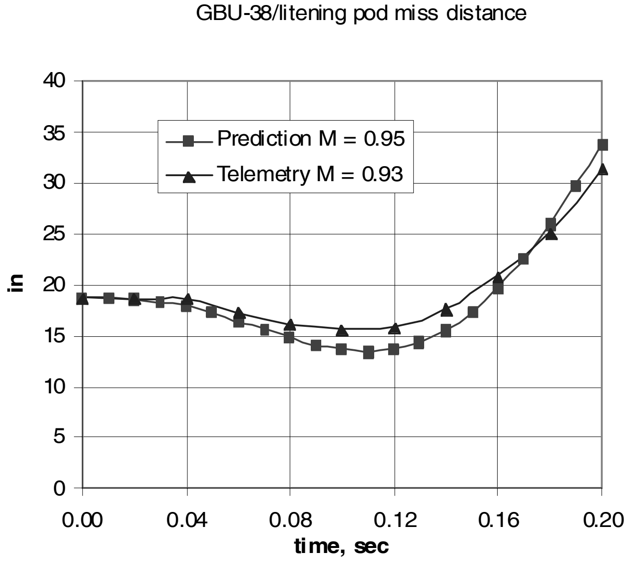

Figure 11. F-18C/GBU-38 Litening Pod miss distance.

A flight at the transonic endpoint was therefore recommended to better determine Litening Pod flowfield effects.

The second GBU-38 flight test occurred at M = 0·93, 575 KCAS. As may be seen in Fig. 10, excellent match between pre flight predictions and flight test results was achieved for the first 0·12 seconds of the trajectory, which is the region of most concern.

The trajectory was benign, as may be seen by the miss distance presented in Fig. 11.

Since F-18/ATFLIR flight test data were again used for these predictions, it appeared that at transonic speeds the Litening Pod flowfield effects are similar to those for the ATFLIR.

Based on the results of these two flights, the GBU-38 adjacent to

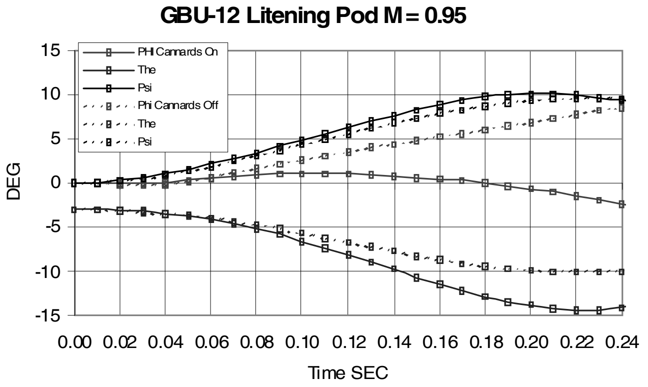

Figure 12. F-18C/GBU-12 Litening Pod trajectory.

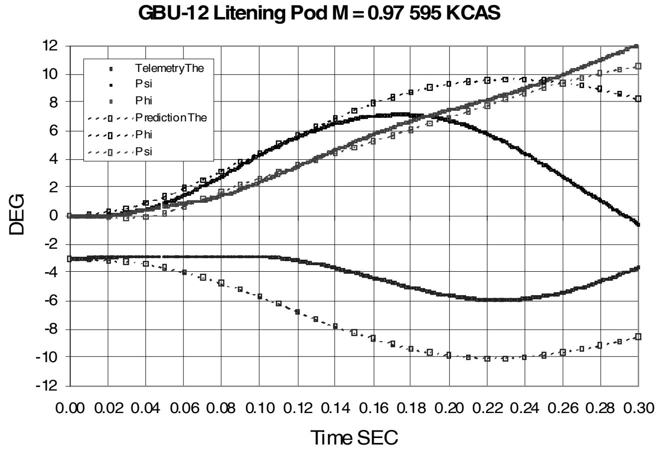

Figure 13. F-18C/GBU-12 Litening Pod trajectory comparison.

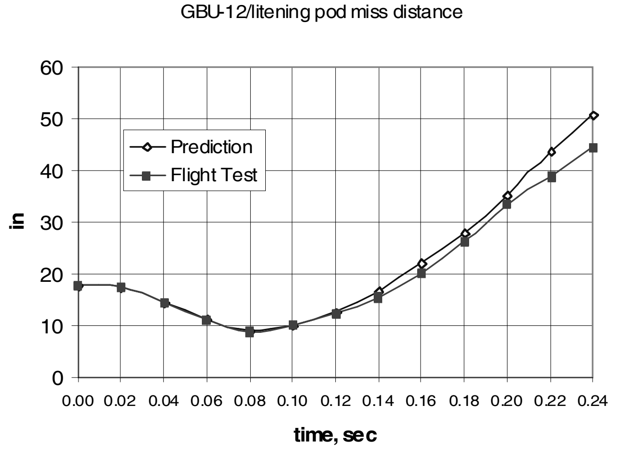

Figure 14. F-18C/GBU-12 Litening Pod miss distance.

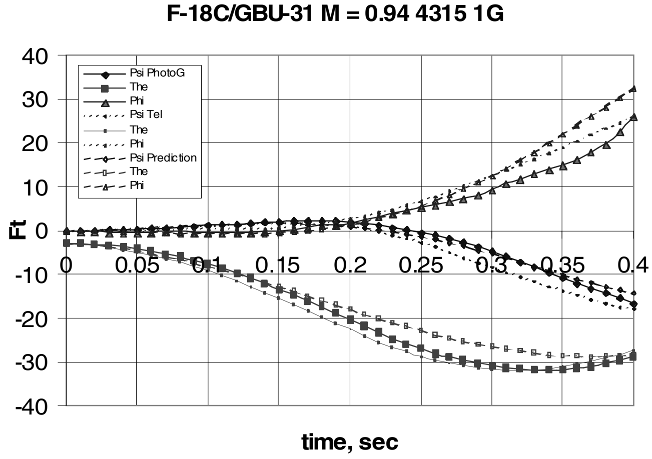

Figure 15. F-18C/GBU-31 Clean trajectory comparison.

the Litening Pod was cleared to the TACMAN limits.

3.2.2 *F/A-18C/GBU-12 Litening Pod*

No wind-tunnel data were available for the GBU-12 store in the aircraft flowfield. The excellent match for the Beggar CFD trajectory predictions with the GBU-12 flight test data previously discussed gave us the confidence to proceed to the flight test programme with no wind-tunnel testing. Originally, a build up program of two flights (M = 0·90 and M = 0·95) was planned.

Since the Beggar CFD predictions for the GBU-12 next to the 330 gallon tank predicted more pitch and yaw than was seen in the test data, the Beggar code was run using both the floating canard option, and with the canards removed. Wind-tunnel test data for the canards removed have shown a better match with flight test results(11).

The Beggar predictions for the two canard models at M = 0·95 are shown in Fig. 12. There was a considerable difference in the trajectory prediction caused by the floating canard model deflecting to the limit.

Both sets of predictions at M = 0·90 and 0·95 were similar and indicated a benign trajectory. For this reason, the M = 0·90 flight test was eliminated, and the testing begun at the transonic end point, M = 0·97, 595 KCAS.

As may be seen in Fig. 13, the canard off pre flight predictions were in excellent agreement with the test data. It appears that not modelling the canards gives a better approximation of flight test results. The predicted miss distance was also in close agreement with the flight test results, Fig. 14.

This represents the first occasion that the US Navy was willing to go from a CFD calculation to flight testing at the endpoint. This saved the program $70,000 by eliminating one flight test point; however, it also save the program more than $500,000 since no wind-tunnel testing was required.

This approach was possible because the IHAAA funded effort had validated the Beggar code for the GBU-12 trajectories next to the fuel tank. Otherwise, the build up in airspeed approach would have been used.

3.2.3 *F/A-18C/MK-84 Litening Pod*

Flight test data existed(12) for the MK-84 store at Station 3 with an ATFLIR located on Station 4. Extensive wind tunnel and flight test data for the GBU-31 (MK-84 JDAM) on Station 3 with an AIM-7 on Station 4 were also available.

Preliminary Euler CFD calculations(10) indicated that the Litening pod would have similar aerodynamic effects to the ATFLIR. It was decided that an incremental CFD approach would be used for this configuration. The wind-tunnel data for the GBU-31 next to the AIM-7 would be corrected by the CFD predicted increments in aerodynamic coefficients for the effects of Litening Pod relative to the ATFLIR.

As may be seen in Fig. 15, an excellent match with flight test was achieved using the wind tunnel test data to predict the GBU-31 trajectory at M = 0·94. Since no wind-tunnel test data were available for the MK-84 on Station 3, an approach(13) using MK-84 freestream data combined with GBU-31 grid data was used. The MK-84

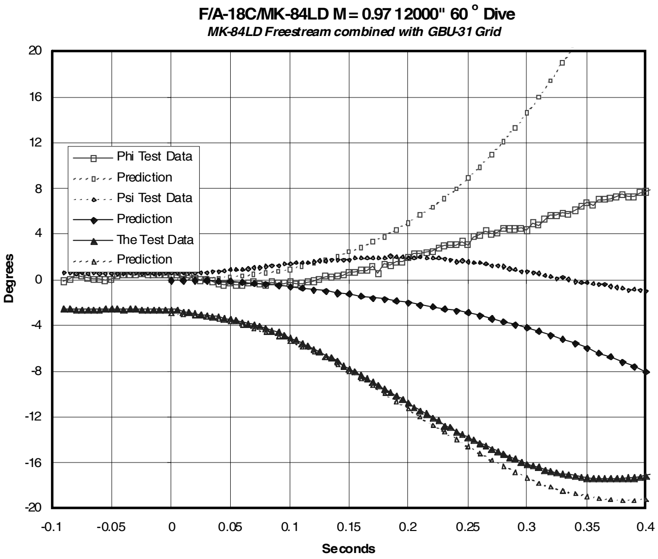

Figure 16. F-18C/MK-84 Clean trajectory comparison.

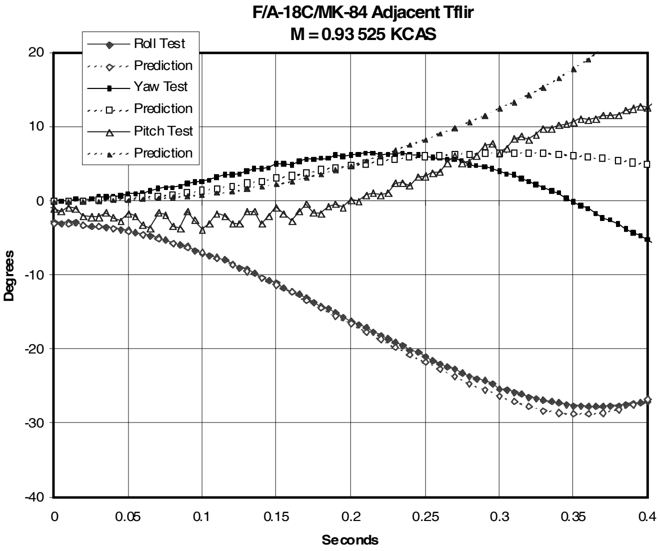

Figure 17. F-18C/MK-84 ATFLIR trajectory comparison.

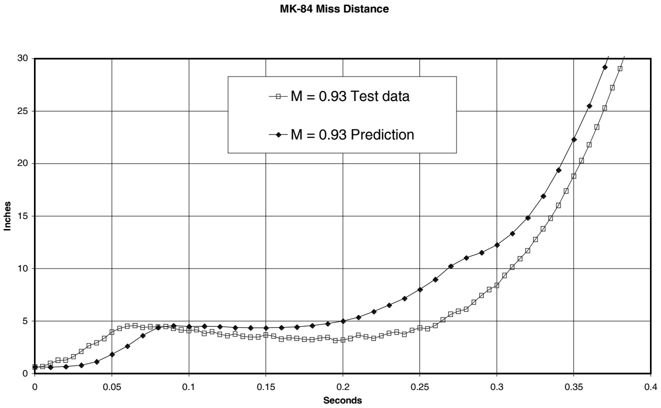

Figure 18. F-18C/MK-84 ATFLIR miss distance comparison.

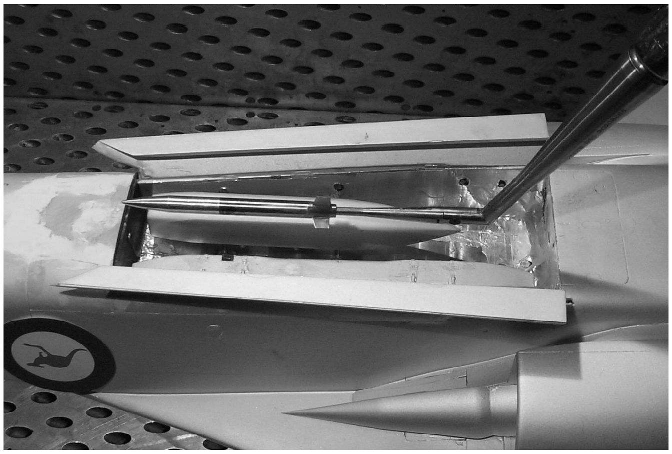

Figure 19. F-111/SSB wind-tunnel test model.

trajectory predicted using this approach was an excellent match with the flight test data, Fig. 16.

The final step was to use the CFD predicted ATFIR induced increments (– 1 in C_m and 1 in C_n) and the GBU-31 clean aircraft grid data to predict the MK-84 trajectory next to the ATFLIR. An excellent match with the flight test was obtained, Fig. 17.

One might ask why, for the GBU-12, one CFD calculation was sufficient to permit a flight test at the end point, while for the MK-84 a much more elaborate, incremental approach was used. The reason for this is evident in the miss distance for the MK-84 to the pylon shown in Fig. 18. As is clear from this Figure, the MK-84 trajectory has a much better chance of impacting the aircraft than did the GBU-12. For this reason, the standard build-up (hit or miss) approach was taken for this configuration, and the flight testing started at M = 0·90.

4.0 FUTURE CHALLENGES

It appears that aircraft external store testing has reached a mature phase. Lockheed has recently demonstrated(14) that CFD can be used to design an aircraft to be 'store friendly', and that the aircraft performance is actually improved by the process.

The next generation of strike aircraft is expected to employ munitions from internal bays under subsonic, transonic and supersonic flight conditions. Current simulations for such weapon separations are immature and have not yet been validated. A lack of flight test data, combined with the inherent difficulties of modelling separation from aircraft cavities in the wind tunnel, have slowed the development of simulation codes necessary to predict weapon trajectories from internal weapon bays. The absence of validated trajectory simulation codes will increase the risk and cost of store certification efforts for aircraft such as the F-22, F-35 Joint Strike Fighter (JSF) and unmanned combat air vehicles (UCAV).

There are several issues involving store separation from internal bays that differ from those of external carriage. The first of these is the appropriate way to test these in a wing tunnel. Conventional aft sting supports, Fig. 19, do not allow the store loads inside the cavity to be measured. This might have led to the disappointing match between the wind tunnel and flight test results for the F-111/SSB configuration(15).

It has been shown that store loads can vary substantially from outside to inside the cavity(16). There is a large change in the store pitching moment from outside to inside the cavity (Z/D = 1 is the cavity face), Fig. 20. However, using a strut mounted sting, which was used in this case, can induce its own errors, particularly for cases where the store yaws. One approach that has been used is to mount the store from the top of the cavity; although this should give

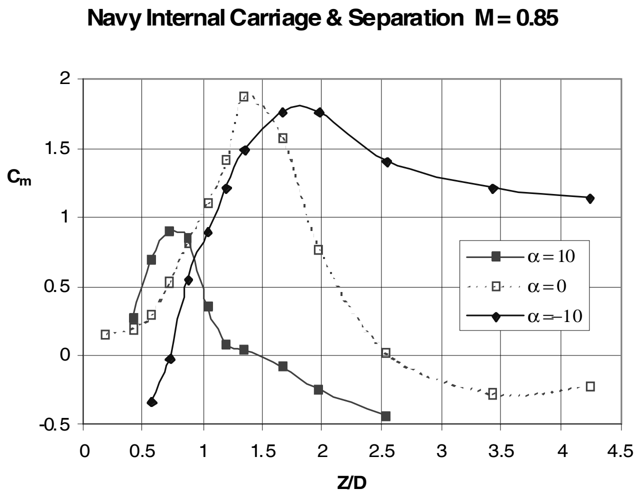

Figure 20. MK-82 pitching moment.

the best answers, this type of testing requires a separate model change for each test point.

A further problem with wind tunnel testing is the question of Reynold's number and scale effects. This has never been an issue for external store separation; however, since CFD shows considerable Reynold's number flowfield effects inside the cavity, this issue can not be ignored. Perhaps testing in the NTF facility at full scale Reynolds' numbers might help resolve this issue.

Another question is the proper turbulence model that needs to be used. As described in Ref. 17, LES models take too long, while DES has not been demonstrated to be sufficient.

Clearly, a CFD challenge for internal weapon separation is merited.

5.0 CONCLUSIONS

Have we finally replaced the need for the wind tunnel in store separation? Not quite yet!

The examples shown in the paper, and which probably represent the limit of CFD's applicability, had several characteristics that made the approach possible. The hierarchy of store separation difficulty, in decreasing order, can be described as follows:

1. New store on new aircraft
2. Existing store on new aircraft
3. New store on existing aircraft
4. Existing store on existing aircraft (new configuration)
5. Existing store on modified aircraft (previously cleared configuration)

All the examples shown fall in the last category. The reason that CFD was a practical alternative was that there existed substantial wind tunnel and flight test data for both the F/A-18C/D aircraft and the stores that were tested. Since the aircraft modification only affected one station, it was reasonable to calculate the incremental effects using CFD. For cases where large amounts of test data are required, the wind tunnel has no match at the present time.

Furthermore, it is not clear that CFD can actually predict the trajectory of a store from a cavity. Since a full Navier-Stokes calculation might not be feasible until(17) 2080, and DES has not yet demonstrated the capability to predict store loads (as opposed to cavity aero acoustics), it might be that CFD can best be used in an incremental approach for weapons bay flowfields. The JSF, J-UCAS and MMA programs should provide many opportunities to develop this approach.

ACKNOWLEDGEMENTS

While I was still in graduate school we used to have a saying that "the true scientific method is to have a student do all the hard work, and the professor publish the results." I would like to propose a corollary: "The true scientific method is to have the workers do all the hard work, and the manager publish the results."

In that spirit, I would like to thank the following individuals, whose hard work have made this paper possible:

Darren Grove, Jae Lee, Eric Ray, Scott Getson and Ron Schultz, NAVAIR; Bruce Jolly, AFSEO and Mike Melnyk, Northrop-Grumman.

I would also like to thank my boss, Tom Rudowsky, who painstakingly read the manuscript. Any errors/omissions are entirely his fault.

REFERENCES

1. CENKO, A., TINOCO, E.N., DYER, R.D. and DEJONGH, J. PAN AIR applications to weapons carriage and separation, *J Aircr*, February 1981, **18**, pp 129-134.
2. MADSON, M. *ET AL.* TranAir computations of the flow about a generic wing/pylon/finned-store configuration, January 1994, AIAA paper 94-0155.
3. NEWMAN, J.C. and BAYSAL, O. Transonic solutions of a wing/pylon/finned store using hybrid domain decomposition, August 1992, AIAA paper 92-4571.
4. MADSON, M. and TALBOT, M. F-16/generic store carriage load predictions at transonic Mach numbers using TranAir, June, 1996, AIAA-96-2454.
5. CENKO, A. and LUTTON, M. ACFD Applications to store separation — status report, *Aeronaut J*, October 2000, **104**, (1040), pp 459-466.
6. CENKO, A., NIEWOEHNER, R. and RYCKEBUSCH, C. Evaluation of the capabilities of CFD to predict store trajectories from attack aircraft, September 2002, ICAS paper 2.6.1.
7. NOAK, R., and JOLLY, B. Fully time accurate CFD simulations of JDAM separation from an F-18C aircraft, January 2000, AIAA Paper 2000-0794.
8. NOACK, R.W, RIZK, M., ELLISON, S. and JOLLY, B. Beggar — a store separation predictive tool, June 2002, AIAA Paper 2002-3190.
9. CENKO, A.T. Utilizing flight test telemetry data to improve store trajectory simulations, June 2003, AIAA Paper 2003-4225.
10. STATHOPOULOS, N. MK-84 store separation characteristics comparison between Litening and Nighthawk Pods, July 2004, BAES Report MAU-261-239.
11. CENKO, A. *ET AL* Integrated T&E approach to store separation — dim past, exciting future, September 1996, ICAS Paper 96-3.3.2.
12. CARRON, T.J. Advanced targeting forward looking infrared (ATFLIR) Phases I and II adjacent stores separation testing on F/A-18A/B/C/D aircraft, October 2003, NAVAIR Report #NAWCADPAX/RTR-2000/125.
13. DAVIDS, S. and CENKO, A. Grid based approach to store separation, June 2001, AIAA Paper 2001-2418.
14. HUDSON, M. External fuel tank trade study, 10 December 2003, Presentation to the Mission Systems Technical Management Board.
15. LEUGERS, J. *ET AL* Flight test demonstration of miniature munitions release from internal weapon bay — final test report, January 2000, AFRL-MN-EG-TR-2002-7011.
16. CENKO, A., CHEN, D. and TURZANSKI, R. Influence function method applications to cavity flowfield predictions, *J Aircr*, August 1989, **26**, (8).
17. MORTON, S.A. and CUMMINGS, R.M. Computing unsteady loads of fighter aircraft at high angles of attack and in maneuvering flight, 2005, RTO AVT-123 Symposium on Flow Induced Unsteady Loads and The Impact on Military Applications, April 2005.