STORE SEPARATION LESSONS LEARNED DURING THE LAST 30 YEARS

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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 thirty years there have been considerable advances in all three areas. In particular, the US Navy has developed a method for combining the three approaches in a process called the Integrated Test and Evaluation Approach to Modeling & Simulation for Store Separation. This paper describes how this process has evolved over the past thirty years.

Nomenclature

BL:	Aircraft Buttline, positive outboard, in.
C_m:	Pitching moment coefficient, positive up
C_N:	Normal Force coefficient, positive up
C_n:	Yawing moment coefficient, positive nose right
CVER	Canted Vertical Ejector Rack
KCAS	Knots Calibrated Airspeed
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
Z:	Store C.G. 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 Introduction

In the early days, store separation was conducted in a hit or miss fashion - the stores would be dropped from the aircraft at gradually increasing speeds until the store came closer to or sometimes actually hit the aircraft. In some cases, this led to loss of aircraft, and has made test pilots reluctant to participate in store separation flight test programs.

During the 1960's, the Captive Trajectory System [1] (CTS) method for store separation wind tunnel testing was developed. The CTS provided a considerable improvement over the hit or miss method, and became widely used in aircraft/store integration programs prior to flight testing. However, CTS was not utilized in an integrated approach, since the group conducting the wind tunnel test was generally separated both in organization and location from those responsible for conducting the flight test program and determining the safe separation envelope. Furthermore, since fairly small scale models had to be used in the wind tunnel tests, in many cases the wind tunnel predictions did not match the flight test results. No mechanism was then in place to resolve the wind tunnel/flight test discrepancies.

During the late 1970's and early 1980's, Computational Aerodynamics had finally matured to the point of providing a solution [2,3,4] for a store in an aircraft flowfield. However, instead of leading to a renaissance in store separation methodology, it mostly led to an ongoing argument among the three groups. The Computational Fluid Dynamic (CFD) community claimed they could replace the wind tunnel, the Wind Tunnel (WT) engineers said (correctly, since one CFD calculation is useless in calculating a store's trajectory) the CFD'rs were unaware of the complexity of the problem, and the Flight Test engineers (FT) said neither group could provide them with the necessary data to conduct a successful flight test program.

During the same time period the Influence Function Method (IFM) was also developed[5]. This method allowed for a straight forward estimate of store loads based on the aircraft induced flowfield the store sees. It seemed to offer a bridge to the disagreement between the CFD and WT community, since it could provide store loads in the entire aircraft flowfield with just one CFD calculation. However, except for Grumman and the Air Force, this method did not readily gain acceptance in the store separation community. Furthermore, even then an integrated T&E approach was not truly implemented, since the FT community was still separated both physically and organizationally from the CFD and WT community.

2 Discussion

Originally, the Navy utilized either aircraft or weapon contractors to perform the testing and analysis necessary to clear a new aircraft/weapon configuration. This approach had several drawbacks, not the least of which was that the contractor's involvement usually ended with the start of the flight test program. The contractors had no mechanism for using the flight test results to improve their store separation methodology. Furthermore, no two contractors used the same approach to predict safe weapon separation prior to the flight test.

About twenty years ago, the Navy decided to develop an in-house capability at the Naval Air Warfare Center, Aircraft Division (NAWCAD) to conduct the analyses necessary for a store separation flight test program. Not being burdened by any pre-existing capability in this area, the Navy was able to pick among the best attributes of the techniques used by contractors and the Air Force.

NAWCAD realized that the three legs of an integrated approach: analysis, wind tunnel and flight test are intimately related to each other and provide essential information that can improve the product of each group. Not only is the entire program conducted by the same group, but ideally by one individual. The computational aerodynamics, wind tunnel test planning, trajectory simulation and flight clearance for each point in the flight test program are all managed by the same person, who does not seek to be an expert in CFD methods or wind tunnel testing, but is competent in their use and knows their limitations. This individual not only has the authority, but also the responsibility for ensuring that the flight test program is conducted both safely and cost effectively.

There have been considerable advances in the three principal tools used for store separation.

2.1 Advances in Computational Aero

2.1.1 1980's

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 utilization of CFD in this fashion were computational speed, computer resources and accuracy of the solution. For the AWACS[3] configuration, one solution using a linear code with 1000 panels required full utilization of the supercomputer of that time (CDC 6600) for twenty-four 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.

The most critical feature that determines a store's separation trajectory are the carriage moments, which are principally caused by the aircraft flowfield. For this reason, the first step in separation analysis is to estimate the region of the flight envelope that might have the worst carriage moments. This is done by deriving an estimate of the aircraft flowfield. The primary analytical tool for this purpose to evaluate the aircraft aerodynamics in the early 1980's was the linear potential flow technique (PAN AIR[3]).

Although the potential flow codes have demonstrated the ability to predict complex aircraft flowfields in the linear speed regime, yaw head probe flowfield test data, when available, were always used to validate the analytical aircraft models. The yaw head probe test data are usually acquired at the AEDC 4x4 and 16x16 foot transonic wind tunnels or the CALSPAN 8x8 foot wind tunnel.

Due to the time required for one computation, a technique that could use the clean aircraft flowfield was developed at Grumman under an Air Force contract. The Influence Function Method (IFM)[5,6,7] was used to determine the effect of the aircraft flowfield on the store loads and moments. Using the aircraft flowfield and store influence coefficients, an estimate of store aerodynamic coefficients was made everywhere in the flowfield, including carriage. The store aerodynamic coefficients were then input in a six-degree-of-freedom program to simulate the store's trajectory prior to the wind tunnel test. The simulated trajectories were used to help design the wind tunnel test to ensure that the most critical regions of the store separation envelope are tested. This approach was the principal technique for inserting computational aerodynamics in the flight clearance process during the 1980's, and it's derivative (FLIPTGP) is still used by the Air Force.

2.1.2 1990's

Over the past twenty 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 organized 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[8] gave answers equivalent to those provided by an Euler[15] 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 [10] 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, Figure 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[11]. This configuration has become the standard for store separation code validation, with several new participants during the past two years.

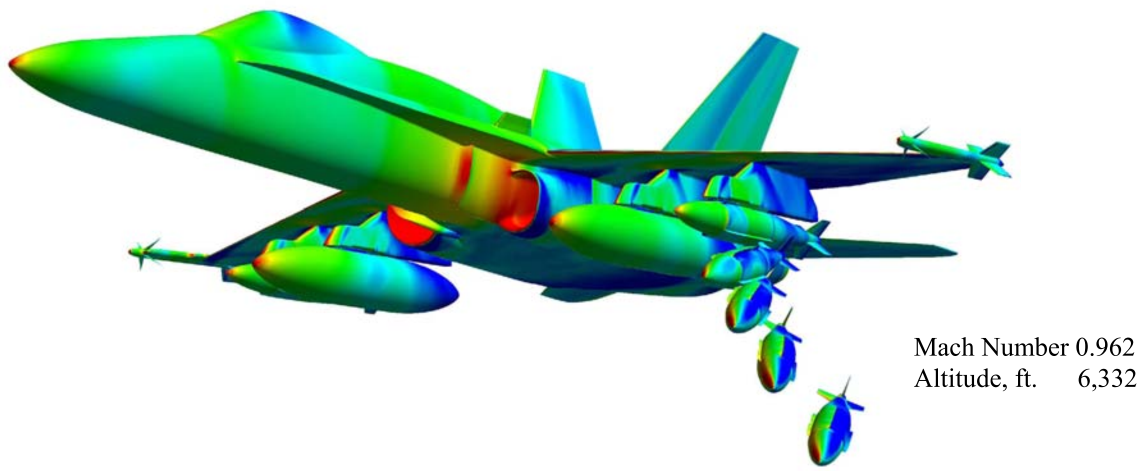

Figure 1 F-18C/GBU-31 Transonic Trajectory Simulation

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, Figure 2. Comparisons were made with Pressure Sensitive Paint (PSP) data as well as flight test store trajectories. Again, all the participants demonstrated good comparisons[7] 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.

2.1.2 2000's

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 their MMA aircraft/store integration.

The Air Force, Army, and Navy have long-term, proven CFD modeling 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).

There have been several improvements in utilizing CFD for store separation analysis since that time. Under one of the IHAAA projects, the Air Force provided the Navy with CFD predictions that enabled the flight clearance process to proceed in a timely fashion.

Due to urgent requirements for Operation Iraqi Freedom, a flight clearance for the GBU-12 on Canted Vertical Ejector Rack 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.

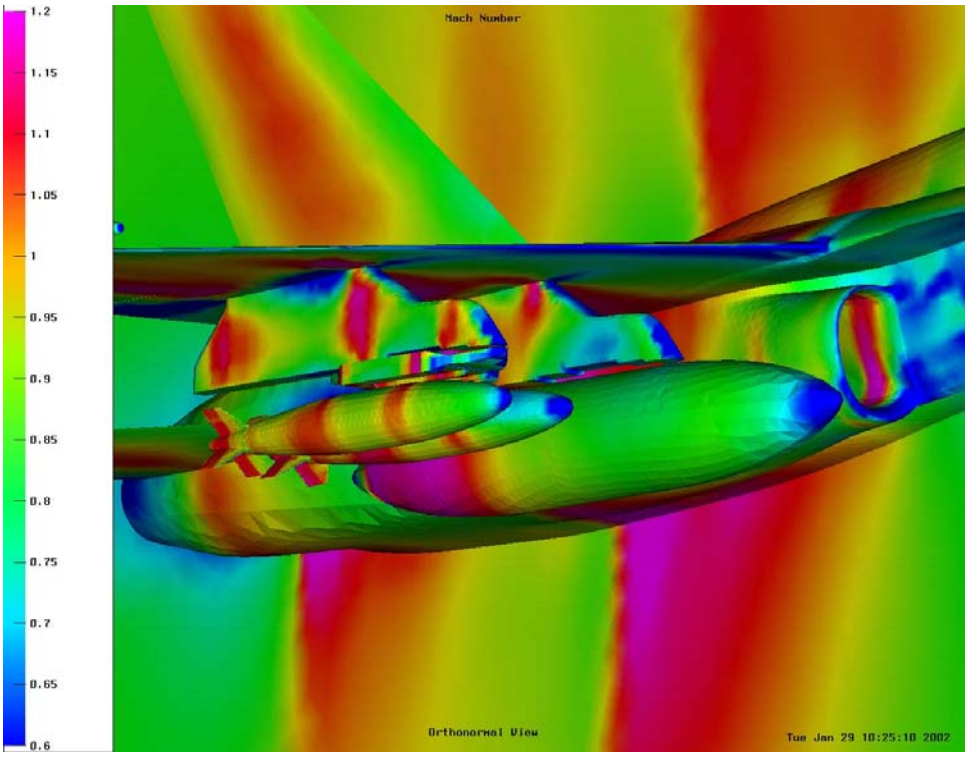

Figure 2 F-18C/MK-83 Transonic Pressure Prediction

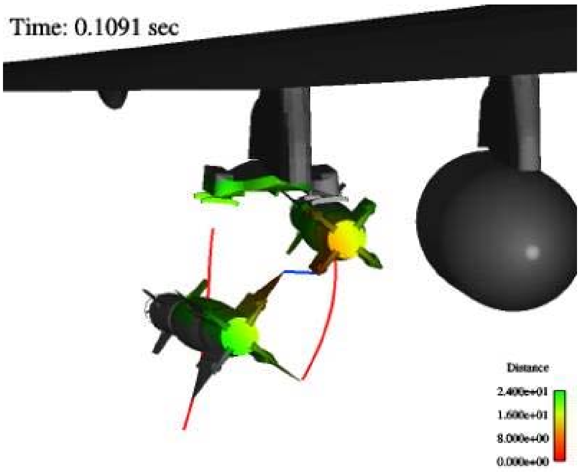

Figure 3 F-18C/GBU-12 Outboard

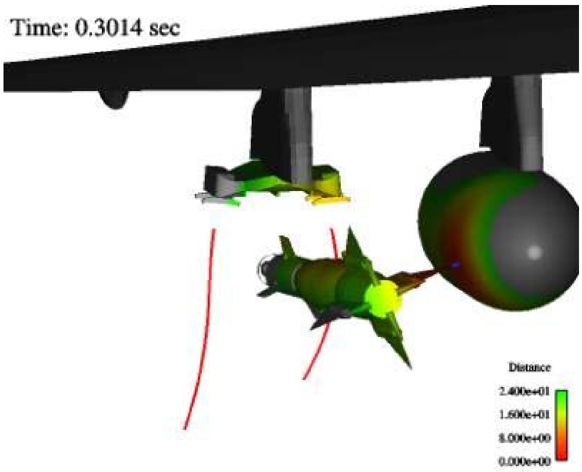

Figure 4 F-18C/GBU-12 Inboard

Although the results for the first flight (M = 0.88, 5000') 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 twenty degrees, and the inboard store, Figure 3 and between the inboard store and fuel tank, Figure 4.

available, since they participated[7] in ACFD performing trajectory calculations for the GBU-12 store, and offered to perform CFD calculations simultaneously with the flight test program. Their predictions were in excellent agreement with the flight test data, and the flight test program was able to proceed to the desired end point.

This, as well as several other IHAAA projects, are explained in greater detail in

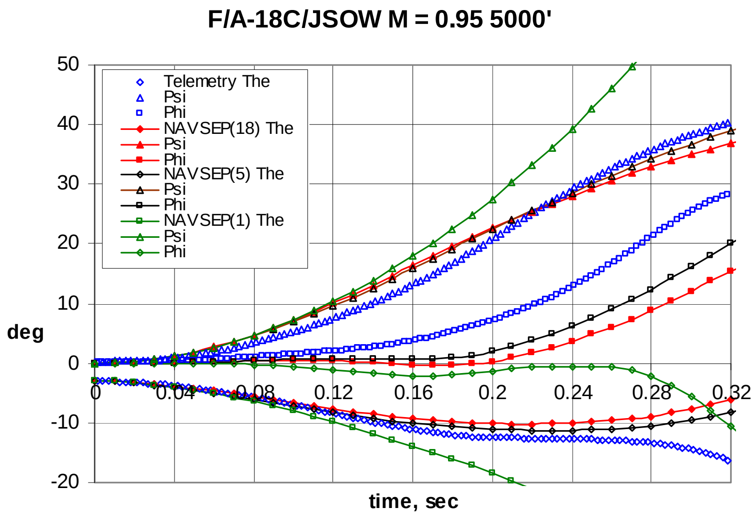

Figure 5 F-18C/JSOW Grid Effects on Trajectory Prediction

Usually, for the US Navy, 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 references 13-15.

Although CFD applications to external store separation problems are well documented, such is not the case for stores separating from bomb bays. There have been two recent attempts to determine how CFD can be best used to address this problem. For the case of the Small Smart Bomb (SSB) separating from the F-111 aircraft Australia, Canada, the UK and the US Air Force and Navy participated in a TTCP project to determine whether CFD could be used to determine the discrepancies between the wind tunnel test data and the flight test results. The participants agreed that some of the differences between the wind tunnel and flight test data could be attributed[16] to the fact that no wind tunnel aerodynamic data were taken inside the cavity. However, the flight test data were not sufficiently accurate to determine which CFD tools gave the correct answer. One interesting result was that Reynolds Averaged Navier Stokes (RANS) results appeared to be in better agreement with the wind tunnel test data than a DES solution.

Another attempt to apply CFD to store separation from bomb bays was under an IHAAA funded project examining the separation of the GBU-38 bomb from the B-1 aft bay. Two major findings[17,18] from this project were that for well designed spoilers the cavity flowfield had negligible affect on the trajectory, and that quasi-steady techniques work equally well to time accurate for these cases. These were the first bomb bay flight test data telemetry that have been released, and demonstrated that, at least for this case, there were no unsteady flowfiled effects inside the cavity. Further details for this project are avialable[19-22].

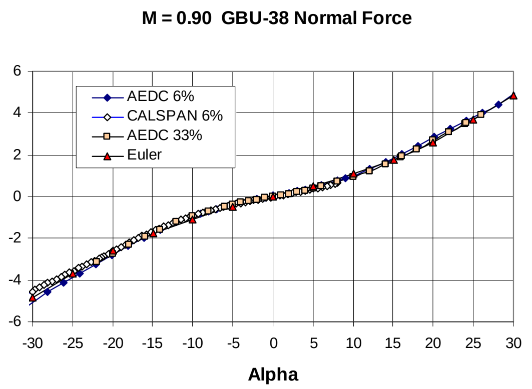

Figure 6 GBU-32 C_N

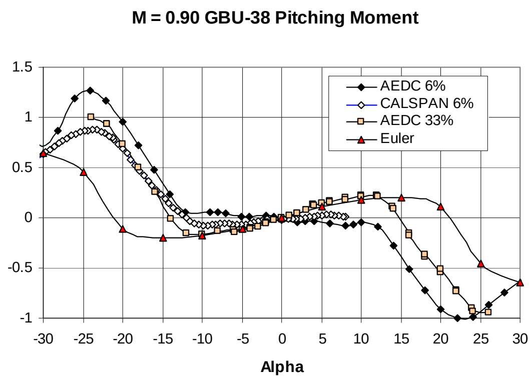

Figure 7 GBU-32 C_m

3.1 Advances in Wind Tunnel Testing

3.1.1 Carriage Loads

There have been four developments in wind tunnel testing that have improved the process. The first was the determination that store loads measured with the store on the carriage pylon could vary considerably from those measured from an aft mounted sting. Comparison with flight test data demonstrated that pylon measured loads gave better trajectory predictions[23], particularly at transonic Mach numbers.

3.1.2 Store Attitude Effects for Grid Testing

The second improvement in wind tunnel testing occurred as a direct result of the close integration between the wind tunnel and flight test community. Flight test data had demonstrated that store attitude effects were critical to getting a good trajectory match with flight test results. Flight test data were then used to determine which of these effects were dominant.

Originally[5], for every data point (i.e. Mach number, aircraft angle of attack) three values of x and y (coupled), three of θ and ϕ, and five of ψ were taken for every z position (18 grids). At the end of the flight test program, it was discovered that if only one value of x, y and ϕ and two values of θ and ψ had been taken (5 grids), the results would have been similar, while reducing the size of the wind tunnel test program by more than a factor of 3. As may be seen in Figure 5, the prediction using a grid of 5 variables was just as good as that using the original 18. However, using only one grid variable, the prediction departs from the test data when the attitudes exceed 10 degrees in pitch and yaw.

Recently, the GBU-31, GBU-32 and GBU-38 (GBU refers to Glide Bomb Unit) stores certification programs were successfully completed using one value of x, y, and roll angle, and three values of yaw and pitch angles (7 grids), and excellent correlation was achieved between the predictions and test data[24].

3.1.3 Store Model Geometry Effects

Store separation wind tunnel testing is usually done with small scale models (5-10%). It is hard to accurately model all the geometric effects in such small scale. For that reason, the freestream coefficients are subtracted from the grid data at the appropriate angle of attack and Mach number to produce incremental coefficients, to which the freestream increment at the appropriate angle of attack is added to compute the quasi-static trajectory.

However, since the CTS is done with the store at the aircraft model scale, it's important to use small scale models representative of the full scale geometry. As may be seen in Figure 6, small scale models closely match the large scale results for the GBU-32 store. However, Figure 7 shows the error that using slab tail (AEDC 6%) in the small scale model to the pitching moment. The GBU-32 pitching moment appears to be neutrally stable, while the large scale and CALSPAN results indicate the store is unstable at low angles of attack. This was attributed[25] to the vortex shed by the GBU-32 strakes on the tail. The CALSPAN 6% geometry attempted to model the GBU-32 tail by using a faceted tail geometry. Note that the Euler results reproduce the large scale pitching moment at low angles of attack.

3.1.4 Mach Sweep Effects

A third change in the method of store separation testing was the development of the Mach sweep technique.

Originally, wind tunnel testing would be conducted at pre-specified points in the flight envelope, i.e. M = 0.6, 0.80, 0.9, 0.95, 1.05, 1.1, 1.3. However, at transonic speeds, the aerodynamic coefficients can change substantially and non-linearly for small Mach number increments.

The Mach sweep test technique uses a small incremental build up in tunnel Mach number in the transonic range (i.e. M=0.02). As may be seen in Figure 8, the yawing moment for the GBU-32 store changes by more than 100% between M = 0.90 and 0.92. Furthermore, aircraft configuration changes have a significant impact on the store aerodynamics. The large yawing moment effect of the Targeting Forward Looking Infrared (TFLIR) can also be easily seen in Figure 8.

One major advantage of the Mach sweep technique is that it is easy to identify the critical Mach numbers for the remainder of the test. For the GBU-32 and GBU-38, most of the grid data were taken only at M = 0.85, 0.95 and 1.20;

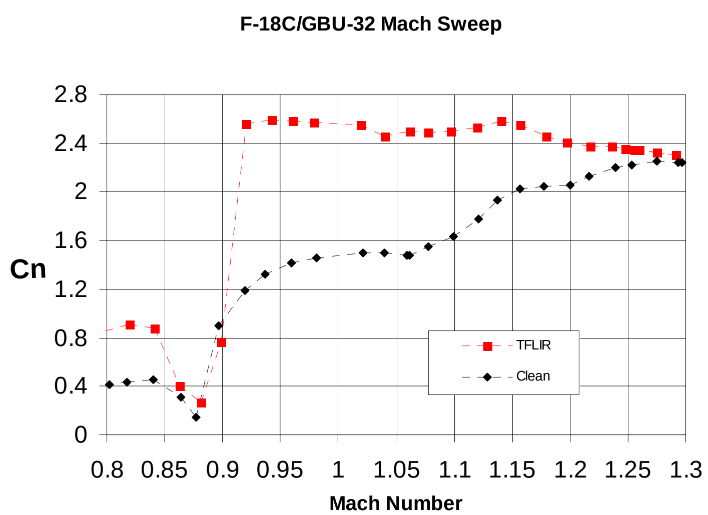

Figure 8 GBU-38 Yawing Moment vs. Mach Number

an excellent match with the flight test data were achieved[24].

4.1 Advances in Flight Testing

The flight test process is the most expensive part of store separation testing, and thus can lead to the most overall savings.

As may be seen in Figure in Figure 9, the Navy has developed an Integrated Test and Evaluation (T&E) approach to store separation[26, 27] that uses CFD to design the wind tunnel test, which in turn is used to design the flight test matrix. The process has been continuously improved, since the wind tunnel test results are used to validate the CFD predictions, and the flight test results are used to both check the wind tunnel test data, as well as the original CFD predictions.

Two developments in flight testing have considerably improved the efficiency of the integrated T&E approach to store separation process. These were the development of high quality acceleration and angular rate telemetry data, and testing from both sides of the aircraft in a single flight. Telemetry data enabled a continuous improvement in the T&E process and real-time decision making, while testing from both sides of the aircraft enabled twice the number of tests to be conducted for a given flight.

4.1.1 Number of Flight Tests Required

The Joint Stand of Weapon (JSOW) was certified for carriage and release on the F-18C aircraft in 1994. The original flight test matrix called for testing starting at M = 0.66 (400 KIAS) and proceeding to the transonic endpoint M = 0.95 (575 KIAS) in 25 knot increments. The testing was done for three aircraft configurations – JSOW released from outboard pylon with a JSOW on the inboard pylon, JSOW released from the inboard pylon, and finally JSOW released from outboard pylon with a 330 gallon tank on the inboard pylon. Since these flights were done from one side of the aircraft, this would have required twenty four separate flights. Due to a good match with the pre-flight trajectory simulations, we were able to reduce the number of flights to fifteen. The program manager for Strike Weapons mentioned[28] these cost savings in his keynote address at the RTO meeting on Aircraft Weapon System Compatibility and integration, and said he expected we could reduce the number of flights to 8-10.

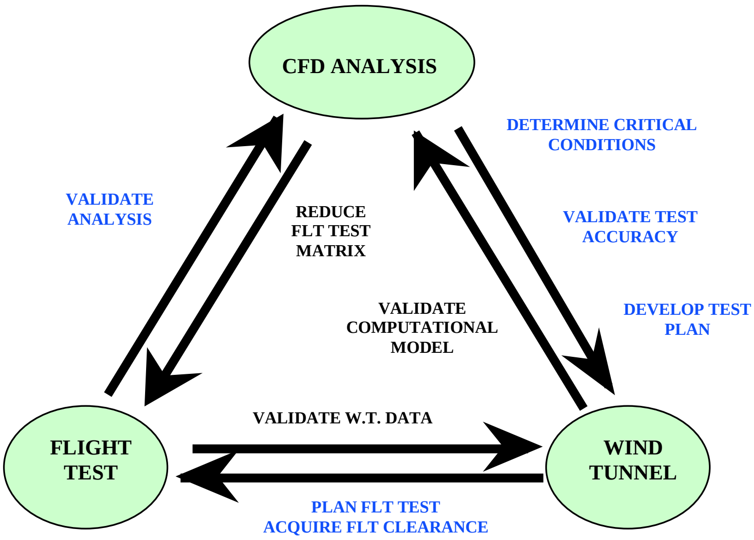

Figure 9 Navy Integrated T & E Approach to Store Separation

Were we to repeat the JSOW program at the present time, we would probably do it in 1-2 flights, with at most 4 weapons released, by dropping the stores from both side of the aircraft.

4.1.2 High Quality Telemetry

These velocities were then used as the initial conditions for the trajectory predictions.

As may be seen in Figure 10, the major cause of the discrepancies between pre-flight predictions and flight test data can be attributed to using pit stand data for ejector force calculations.

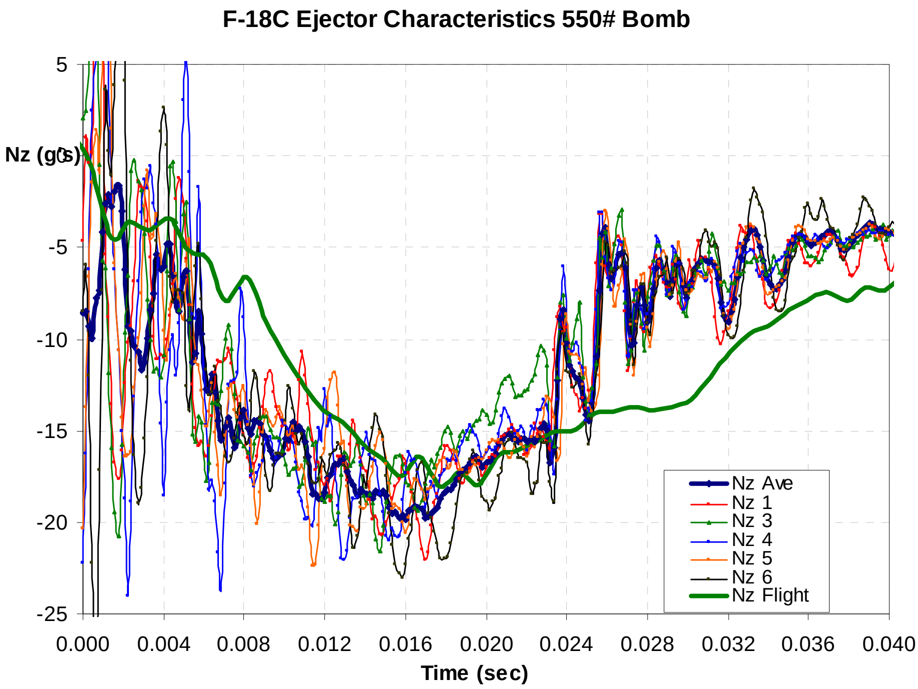

Figure 10 Pit Stand and Flight Test Ejector Force Data

There are two ways to determine flight test trajectory data. One is photogrammetrics and the other telemetry. Although both methods have their supporters and detractors, telemetry is unmatched in it's ability to improve the modeling and simulation process of store trajectories.

Since every trajectory simulation consists of a time integration, if the initial conditions are incorrect, then the trajectory can't possibly match the flight test data. Telemetry test data have been invaluable in determining the ejector force characteristics and their effects on the resultant trajectories.

Originally, ejector force characteristics were determined by using pit stand test data. The pit test data consist of parking an aircraft over a pit, and then ejecting the store into the pit and measuring its end of stroke velocity.

The solid purple line represents the average of six pit test results, while the green line represents the flight test results for the same store. Clearly, the aerodynamically loaded wing in flight behaves nothing like what is seen from the pit test data. Once telemetry data were used to determine store initial conditions, pre-flight predictions showed much better correlation with flight test results[29, 30]. Flight test telemetry data were also useful in interpreting the structural dynamic response of the rack on store separation characteristics [31].

Another advantage of flight test telemetry data is that it's available well before store release. Since the telemetry gives a time history of the forces and moments the store sees, it's possible to determine whether any unsteady effects are present. As may be seen in Figure 11, the GBU-38 store exhibits no unsteady pitch

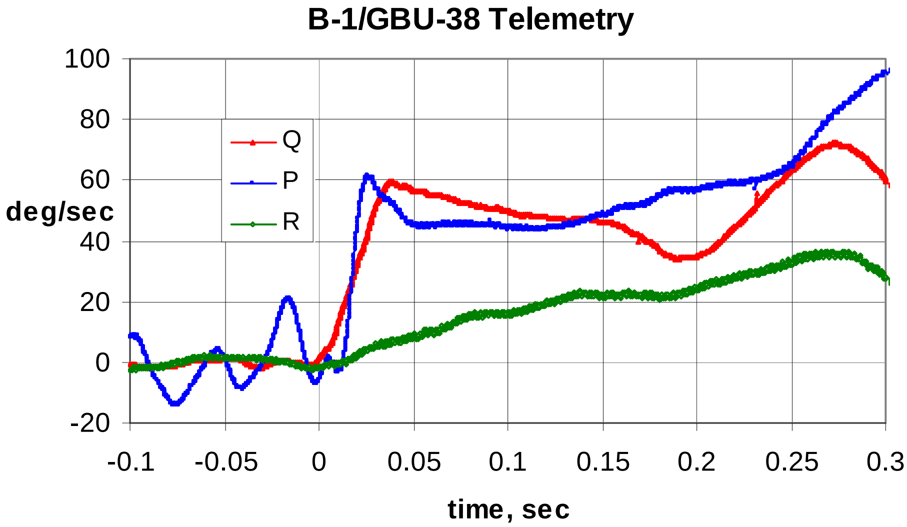

Figure 11 GBU-38/B-1 Flight Test Telemetry Data

and yaw (Q and R) behavior prior to store release. The variation in roll rate, P, is due to rack dynamics caused by the previous store.

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