Store Separation Current Capabilities

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ABSTRACT

The difficulty in using any method to predict the carriage and subsequent release of a weapon is not only in an ability to accurately simulate the complex component interactions, but also in providing this information quickly enough to authorize the clearance of the weapon. An Integrated Test and Evaluation (T&E) approach to store separation was introduced that combined wind tunnel testing, analysis methods, and flight testing almost two decades ago. CFD, which was only occasionally used at that time, now has often replaced the wind tunnel for external store separation.

Many current and all new attack aircraft, both manned and unmanned, are designed for internal weapons carriage. The problems of using CFD, wind tunnel and flight tests for store separation from internal weapon bays are also considered.

1.0 INTRODUCTION

In an attempt to minimize the time and cost of the flight certification process advanced Computational Fluid Dynamic (CFD) methods to support and supplement wind tunnel and flight testing were developed [1,2,3,4]. CFD methods were also used for older aircraft, where no sub-scale wind tunnel models were available [5].

A cooperative effort between the US Air Force, Army and Navy called "Improvement of High Performance Computing (HPC) Applications to Air Armament (IHAAA) was instituted by the DOD in 2002. One IHAAA project was to determine if CFD could predict [6] store trajectories from bomb bays. The results of this effort helped develop the approach to support of the store separation flight clearance for the P-8A aircraft.

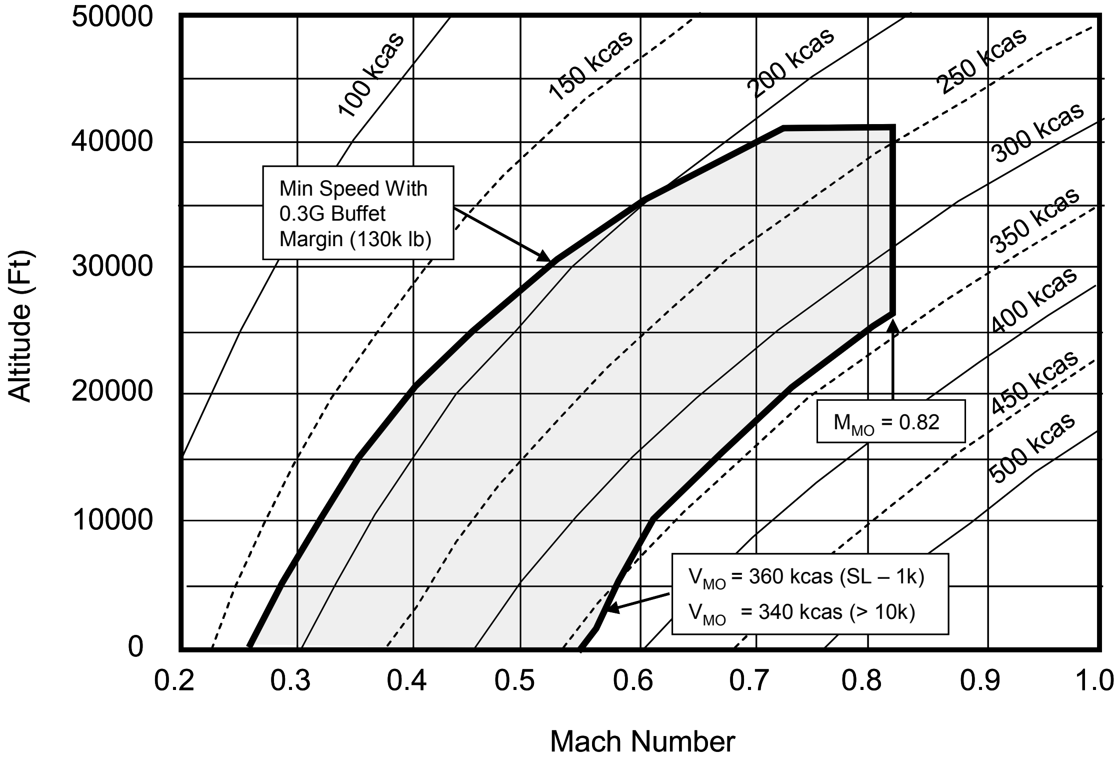
In January and February 2006 Boeing conducted a P-8A store separation wind tunnel test at the Arnold Engineering Development Center (AEDC) 16 Foot Propulsion Wind Tunnel (16T). All the test objectives were achieved in a little more than half of the original test plan. The P-8A program decided after the test was concluded that the MK-83 bomb, rather than the MK-63 mine would be flight tested.

Since grid and freestream wind tunnel data were available for the MK-63 store, and since a separate wind tunnel entry to acquire grid data for the MK-83 store would have required a program delay of 6 months at a cost of $500,000, it was decided to use CFD increments to the MK-63 data to predict MK-83 trajectories.

The MK-83 stores have a much smaller tail section than the MK-63 stores that were tested. CFD predicted MK-63 store loads for three different configurations were compared with the wind tunnel test data. CFD was then used to predict the MK-83 store grid loads for the same configurations. These grid load predictions were used in conjunction with MK-83 freestream data in a six-degree-of freedom program to simulate the MK-83 trajectories from the P-8A bomb bay.

2.0 P-8A AIRCRAFT

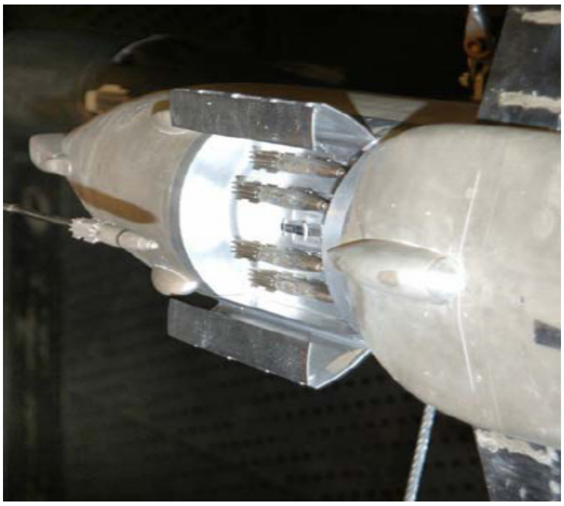
Two primary missions for the P-8A are armed Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASuW). Primary stores types to be carried and released by the P-8A include Air-to-Subsurface, Air-to-Surface, Air-to-Ground, naval mines and sonobuoys. To accommodate these stores, the P-8A incorporates two external wing pylons on each wing, two external pylons on the forward fuselage, a weapons bay internal to the fuselage, and sonobuoy launch ports. Safe separation of these stores must be assured throughout the desired P-8A flight envelope shown below:



The primary objective of the P-8A store separation wind tunnel test program was to evaluate the separation characteristics of the following stores and to provide an aerodynamic database suitable for post-test separation analyses:

- AGM-84D Harpoon.
- AGM-84H SLAM-ER.
- MK-46 Torpedo.
- MK-50 Torpedo.
- MK-63 Torpedo.
- MK-62 Quick Strike Mine.
- MK-63 Quick Strike Mine.
- MK-65 Quick Strike Mine.

2.1 Wind Tunnel Results



The separation data were obtained using a 0.062 scale P-8A model and associated store hardware as shown above. Pseudo-freestream, captive trajectory (CTS) and aircraft proximity (grid) data were obtained at the Arnold Engineering Development Center (AEDC) 16 Foot Propulsion Wind Tunnel using the Captive Trajectory Support (CTS) system. P-8A pseudo-freestream data (freestream data with the aircraft present in the tunnel) were also obtained at constant yaw angles at selected Mach number and angle of attack combinations. A digital computer routine used the balance-measured loads and other pertinent physical, ejector, thrust, or controls data to compute the time-variant separation trajectory for the CTS runs. Grid data were obtained along pre-selected rays emanating from the store carriage point. Internal weapons bay testing utilized both strut- and sting-mounted stores to permit surveys within the bay without contacting the aircraft and or support equipment. External stores used a sting support only.

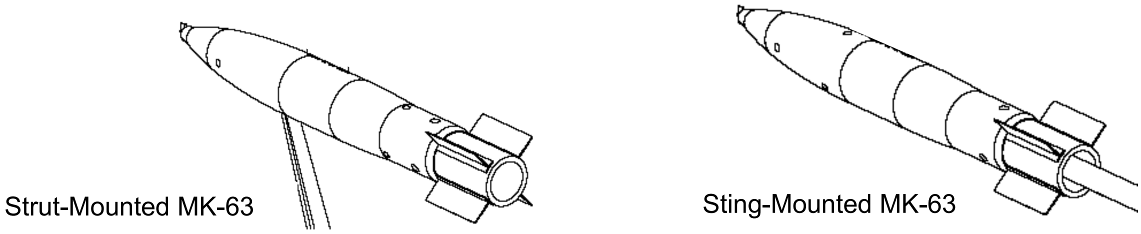


Figure 1: Strut and Sting Mounted MK-63 Stores.

2.1.1 Freestream Data

Both strut and sting-mounted wind tunnel freestream data were acquired for the MK-63 mine to determine the effects of the mounting system on the store aerodynamic characteristics.

As seen in Figure 2, there is little difference in the Normal Force (CN) values at low store angle of attack (Alphas) for M = 0.85. The Pitching Moment (CLM) values for the strut match the sting data by subtracting out an offset coefficient of 0.2. Since all the trajectory simulations use incremental grid data (grid data with the freestream values subtracted out), these differences should have no impact on the trajectory predictions.

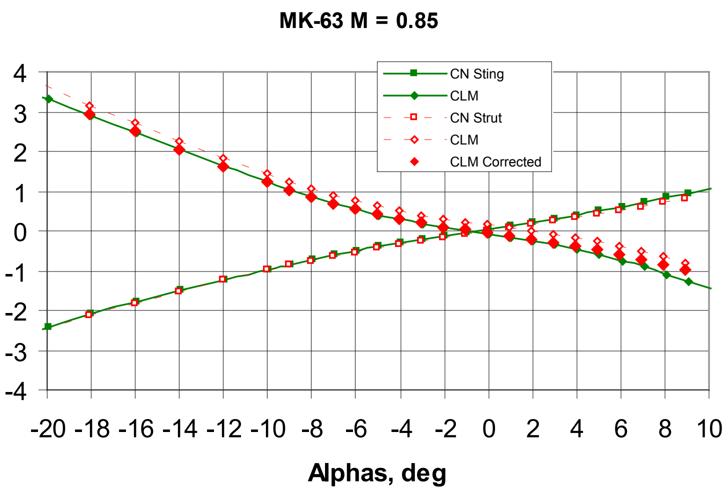


Figure 2: Strut and Sting CN and CLM Comparison.

However, there is a large discrepancy in Side Force (CY) and Yawing moment (CLN) at store sideslip angle (Betas) of -5 degrees, which increases with increasing Alphas, Figure 3. Only these four aerodynamic coefficients are considered important, since axial force (CA) and rolling moment (CLL) have little effect on store trajectories. This was not unexpected, since the strut mounting was expected to affect the forces and moments in the yaw plane. Clearly, strut mounted data at yaw angles exceeding 5 to 6 degrees are questionable, since the freestream data were only taken at +/- 5 degrees of Betas.

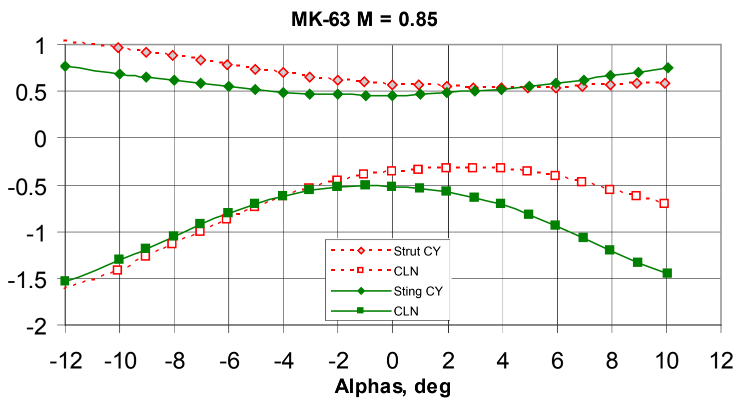
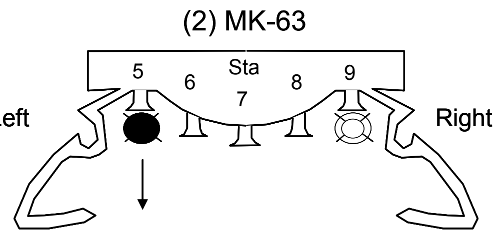


Figure 3: Strut and Sting CY and CLN Comparison at Betas = -5.

2.1.2 Grid Data

As seen in Figures 4 and 5, the incremental (freestream subtracted out – i.e., the CLM correction of 0.2 is accounted for) strut normal force and pitching moment are in reasonably good agreement with the incremental sting data for the overlapping region from carriage (Z = 1.5 to 5 ft.).



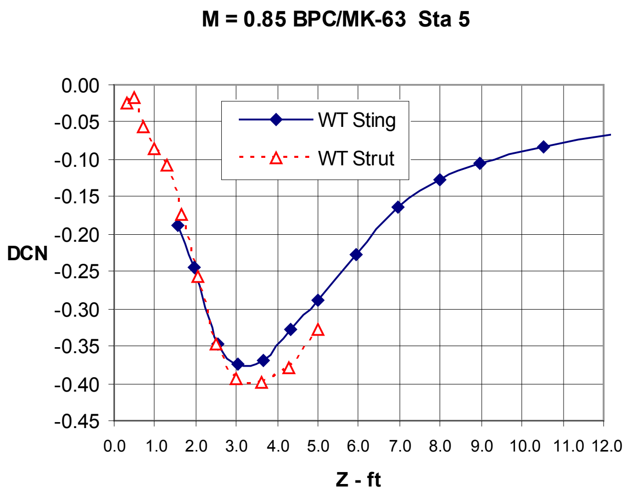


Figure 4: MK-63 Incremental Normal Force.

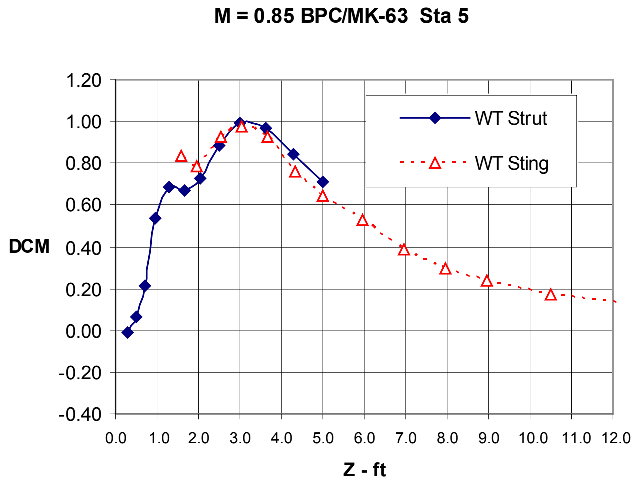


Figure 5: MK-63 Incremental Pitching Moment.

The incremental Side Force and Yawing moment also compare reasonably well for this same region, Figures 6 and 7. The comparisons between the strut and sting grid data for the other stations were similar. Since the trajectory simulations use incremental grid data with the appropriate freestream data, using the strut and sting grid data with sting freestream should give the best results. The Six Degree of Freedom (SDoF) code used strut grid data for the first 1.5 feet of the trajectory, and then sting data for the rest.

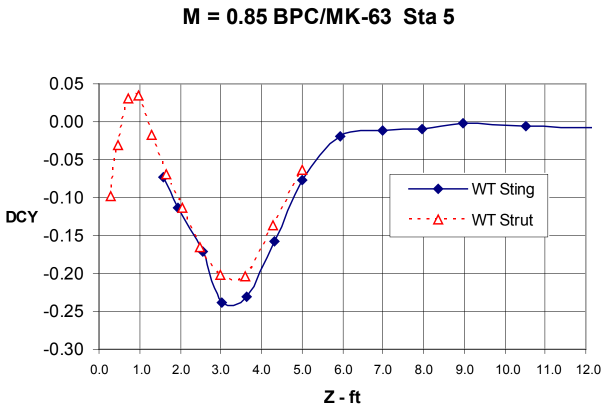


Figure 6: MK-63 Incremental Side Force.

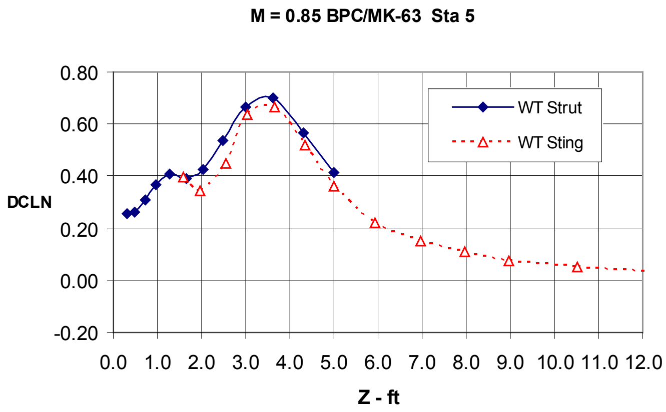


Figure 7: MK-63 Incremental Yawing Moment.

2.1.3 K-63 CFD Predictions

To determine the increments that need to be applied to the MK-63 grid data the CFD code Overflow predicted MK-63 data were compared to the wind tunnel test results. The solution for a MK-63 on stations 5 and 9 is shown in Figure 8.

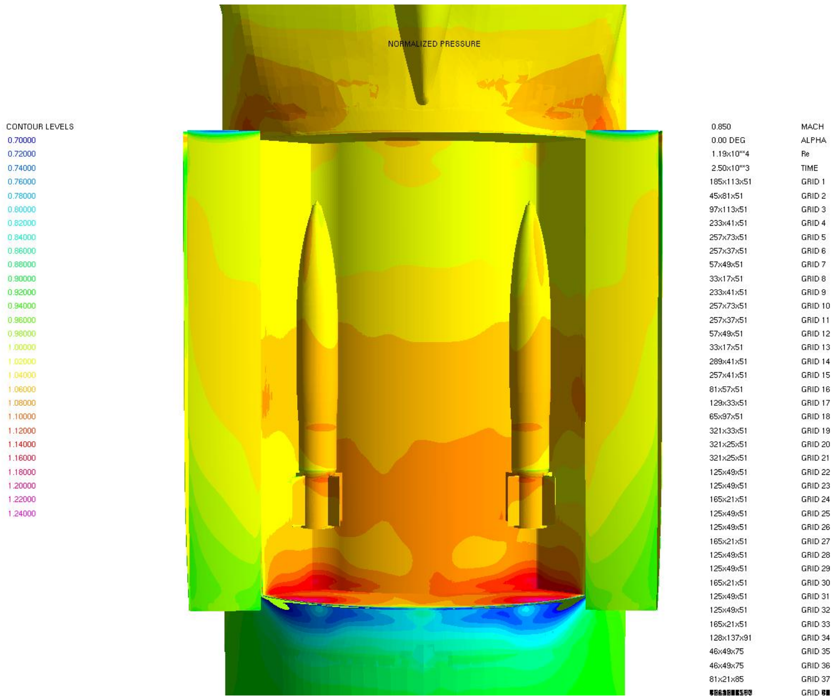


Figure 8: P-8A Pressure Distribution for MK-63 at STA 5-9.

The CFD to wind tunnel comparisons with the grid data normal force and pitching moment are shown in Figures 9 and 10. The predicted trends are in good agreement with the wind tunnel grid data. Also shown in Figures 9 and 10 are the effects of having only one store in the cavity. It appears that the effect of having a store on one side does not significantly impact the normal force and pitching moment on the other side of the bomb bay.

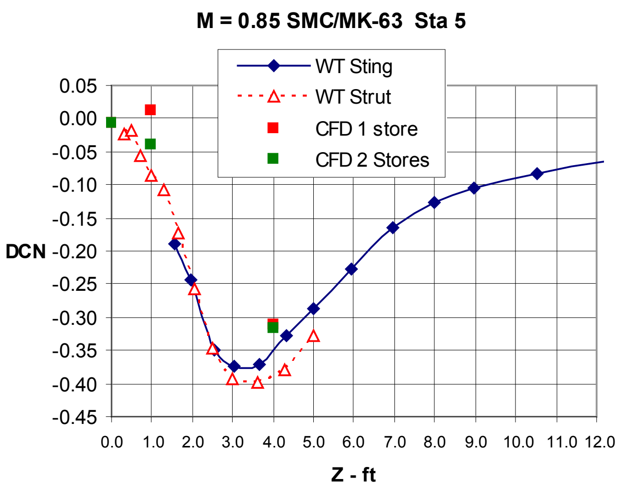


Figure 9: MK-63 Incremental Normal Force.

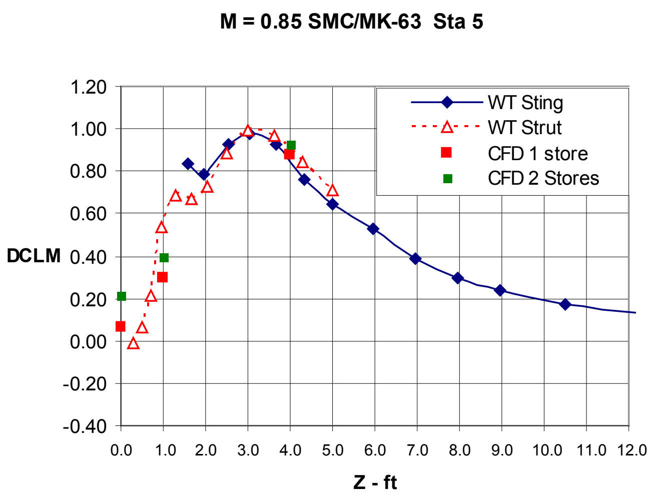


Figure 10: MK-63 Incremental Pitching Moment.

The side force comparison is shown in Figure 11. The trends are again in good agreement with the test data, including the reversal in sign between 0 and 1 ft. The CLN comparison, shown in Figure 12, indicates that the CFD result is also in good agreement with the test data except for Z = 0. For this position the CFD predicted yawing moment is much larger and of opposite sign to the test data.

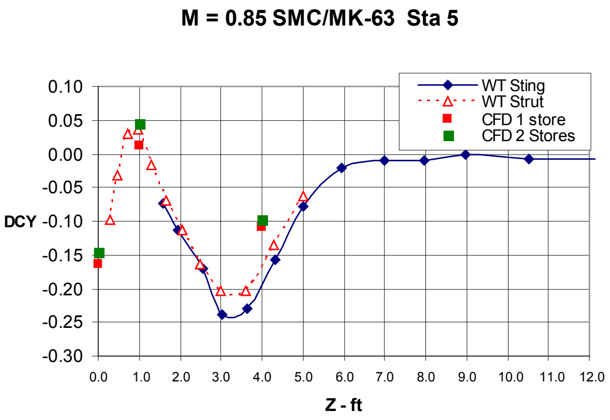


Figure 11: MK-63 CY Comparison.

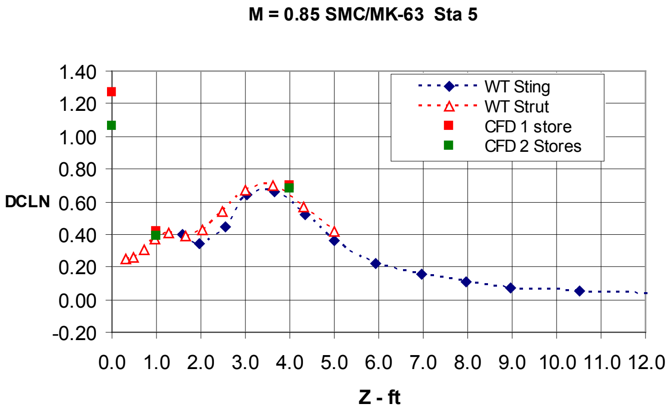


Figure 12: MK-63 CLN Comparison.

This behaviour is unexpected, since the forces on a store tend towards zero [6] when the store is close to the cavity bottom, particularly for intermediate L/D cavities. However, since the store is constrained in yaw during the ejection stroke, even a large yawing moment at carriage should have little impact on the resulting trajectory.

2.2 Flight Test Considerations

All of the CTS trajectories during the test, and the trajectory simulations conducted off-line after the test, indicated that the P-8A aircraft should not have any difficulty releasing all of the P-8A Performance Based Specification (PBS) stores required by the contract.

Most encouraging was the fact that increasing the MK-63 yawing moment grid data by 1 (which represents a 100% increase to the largest values seen in the wind tunnel test) to simulate MK-83 trajectories made a minimal impact on the predicted miss distances.

However, wind tunnel test predictions have been known to not always match flight test results, particularly for stores released from bomb bays. In particular, there is concern that Reynolds number effects in bomb bays may change the store release characteristics.

The incremental effects of the support mechanism on store freestream aerodynamics are shown in Figure 13. Note that the strut effects are most significant for negative pitching moments.

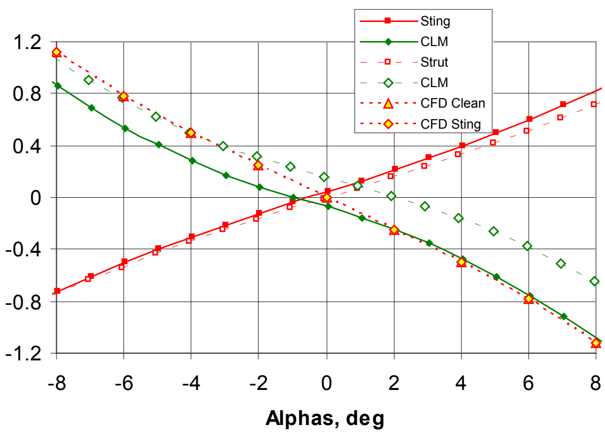


Figure 13: CFD Predicted Sting Effects on Pitching Moment.

All the trajectory simulations were done using the wind tunnel ejector force characteristics, and assuming yaw and roll constraint during the ejector stroke. When pit testing is completed and the ejector characteristics are better quantified, these simulations will have to be redone. Furthermore, since yaw and roll constraint for store trajectories has never been demonstrated in flight, the ejector characteristics will have to be modified after the first flight.

3.0 BOMB BAY WIND TUNNEL SUPPORT MECHANISMS

Because of the strut support interference effects seen for the P-8A, a long term study was conducted at the United States Naval Academy (USNA).

Wind tunnel tests were available [7] for the Navy Internal Carriage and Separation (NICS) cavity. The MK-82 was used to measure forces as it traversed the longitudinal axis of the cavity at several different bay depths. One such configuration is shown in Figure 14.

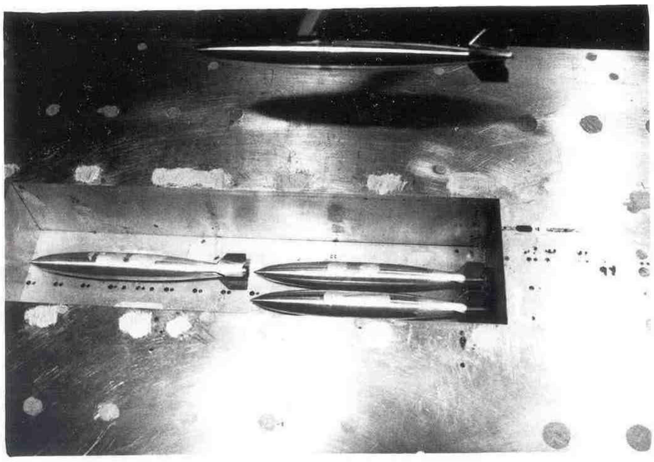


Figure 14: NICS Cavity Geometry.

The geometry of this configuration was reproduced and used to generate unstructured grids for the purposes of generating flow solutions using the USM3D code. In particular, comparisons of store forces and moments as it traversed the shear layer were desired. Reasonable agreement [8] between the predictions and test data were seen.

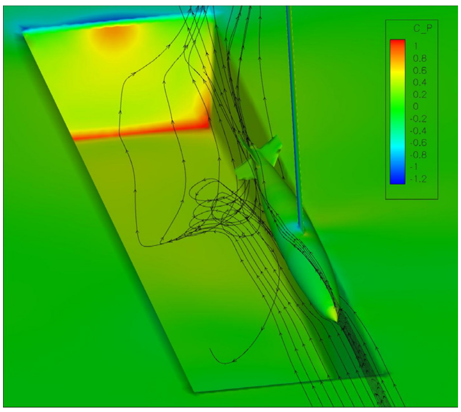


Figure 15: USM3D Solution for Empty NICS Cavity.

As may be seen in Figure 16, the strut attachment hardware has a significant impact on the store aerodynamics, particularly at non zero angles of attack.

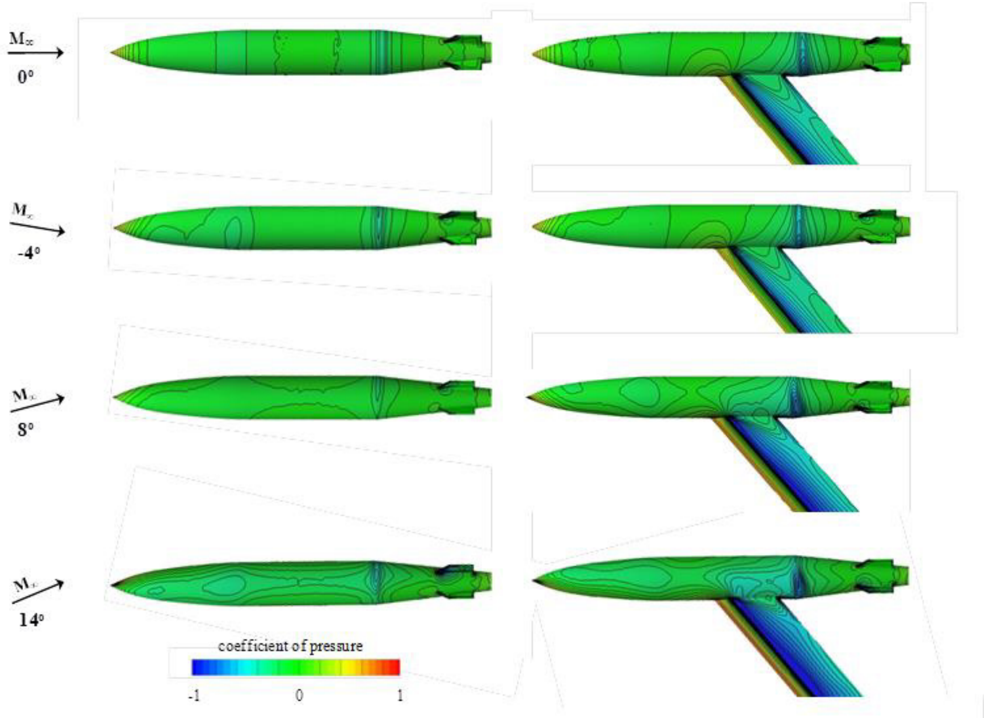


Figure 16: Strut Effects on MK-83 Pressure Distributions.

Snyder [9,10] and Doig [11] did an extensive study using both the USNA wind tunnel and CFD to determine if strut designs could mitigate the interference effects.

As may be seen in Figure 17, the shock wave from the strut attachment interferes with the store tail, significantly affecting the store pitching and yawing moments.

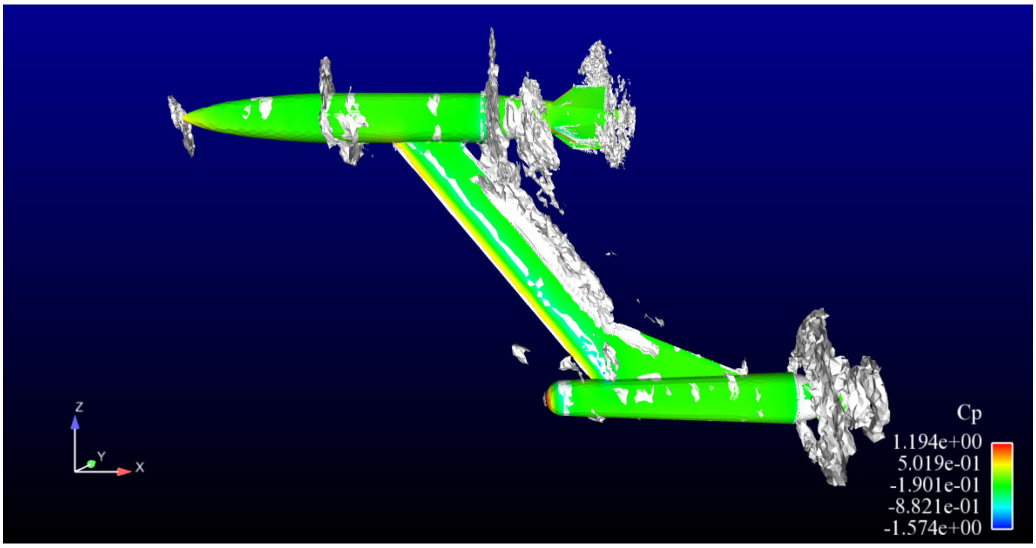


Figure 17: Shock Pattern on Generic Strut Store at M = 0.85.

4.0 TELEMETRY INTEGRATION

One of the most difficult and time consuming tasks in the development of a new combat aircraft is ensuring that the ordnance delivered by the aircraft separates safely and predictably from the carriage aircraft. Store separation simulations, wind tunnel tests, and flight tests account for many thousands of hours of analysis for a combat aircraft. Store Separation engineers employ a number of methods to record the exact position of the weapon as it departs the aircraft on a test flight. One method, termed photogrammetrics, utilizes multiple cameras and post-processing algorithms to compute the trajectory of the weapon based on high-speed imagery of the release. Another method involves capturing telemetry from the weapon as it is released. The telemetry is produced by a miniature Inertial Measurement Unit (IMU), termed a 6DoF or TM unit that broadcasts the sensor readings to a ground station utilizing an RF link.

Each method has its strengths and weaknesses. The photogrammetrics is accurate in displacement, but not in attitude, particularly roll, and requires extensive preparation of the weapon and carriage aircraft, and complex post-processing of the video. The telemetry method has become more affordable, as the 6DOF units have become cheaper and smaller, and also allows the store separation engineers to track the weapon for a longer period of time than does the photogrammetrics. Typically, the certification of a new weapon on an aircraft will make use of a combination of both methods, and it is important that both methods accurately determine the true trajectory. Of course, the true trajectory is not perfectly known using either method, so a good technique is to compare the results of both methods for validation.

More than 25 years ago, the US Navy began developing small and affordable 6DoF units for store separation. After success with what began as an in-house effort, the manufacturing of the 6DoF units was transitioned to the commercial sector. Currently the most commonly used 6DoF unit used is manufactured by Summit Instruments and is pictured in Figure 18. These third-generation units have impressive capabilities in terms of battery life, sensor performance, and cost over earlier units. As a result, the inclusion of a 6DoF for most store separation tests is the standard rather than the exception to the rule.

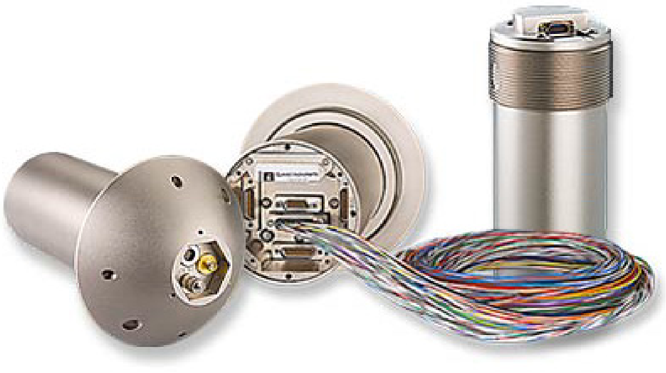


Figure 18: 6DoF Telemetry Inertial Measurement.

While the use and manufacturing of the 6DoF units have become more standardized, the processing of the telemetry form the units in order to determine the store displacement relative to the carriage aircraft has remained somewhat ad-hoc depending on which office and at what desk the data reduction was done.

USNA developed a process to analyse telemetry data from the 6DoF units. This allows the determination of store displacements and attitudes real time, allowing for the store separation engineer to make go/no go decisions during the flight test. Further details on this code may be obtained in Reference 12.

Telemetry units have an obvious advantage for bomb bays. Camera locations inside the bomb bays may have restricted views for some of the separating stores. As was described in Reference 6, telemetry units determined that the ejector forces used to predict GBU-38 trajectories from the B-1 aircraft had to be modified.

5.0 TELEMETRY DETERMINATION OF STORE AERODYNAMIC FORCES AND MOMENTS

The store pitch, yaw and roll rates are a derivative of the store aerodynamics. This means that the store attitudes are a double integral of the underlying moments that cause the trajectory. It appears that comparing CFD predictions to the time varying store forces and moments during a trajectory would be a better way of evaluating the CFD capabilities.

The telemetry unit in the store provides the body axes pitch, yaw and roll rates (q, r, and p) in degrees/sec, and the body axes accelerations along the three coordinate axes. These may be used to evaluate the store aerodynamic coefficients by using the following equations of motion:

- $M_x = I_{ZZ}\omega_x$ where $M_x = 1/2\rho V^2$ ScCLL and $\omega_x = dp/dt$.
- $M_x = I_{zz}\omega_y$ where $M_x = 1/2\rho V^2$ ScCLM and $\omega_y = dq/dt$.
- $M_x = I_{ZZ}\omega_z$ where $M_x = 1/2\rho V^2$ ScCLN and $\omega_z = dr/dt$.

Note that the accelerations are also a function of the pitch, yaw and roll rates if the unit is not at the store CG as described in detail in Reference 12 (usually, it's in the nose or tail).

Flight test telemetry data were available from Reference 13 for the MK-84 store separating from the F/A-18C aircraft at two separate Mach numbers, Figure 19.

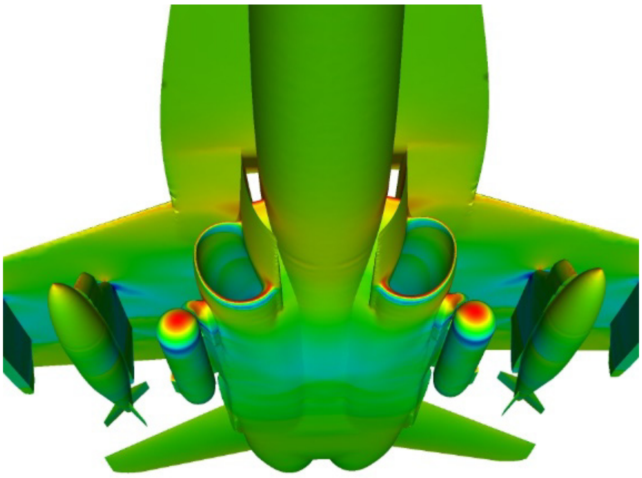


Figure 19: F-18C Aircraft with Litening Pod.

Shown in Figure 20 and 21 are the MK-84 store pitching and yawing moments that were obtained from the telemetry data by using the equations shown below:

- $CLM = I_{zz}\omega_y / (1/2\rho V^2 Sc)$.
- $CLN = I_{ZZ}\omega_z / (1/2\rho V^2 Sc)$.

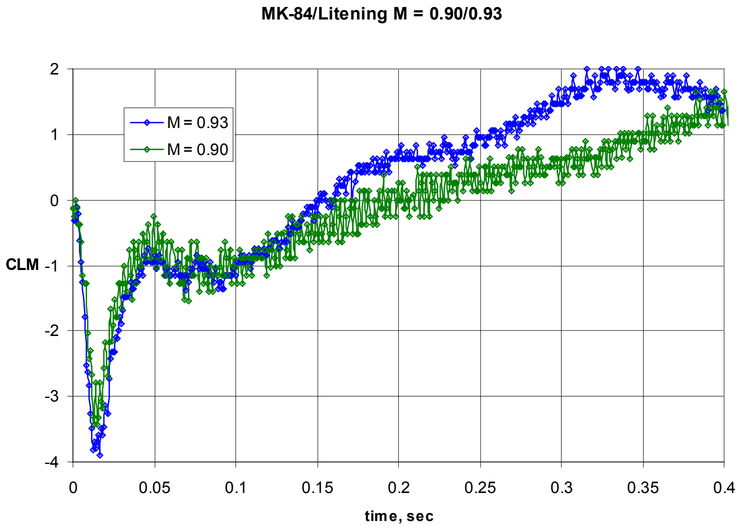


Figure 20: MK-84 Pitching Moment.

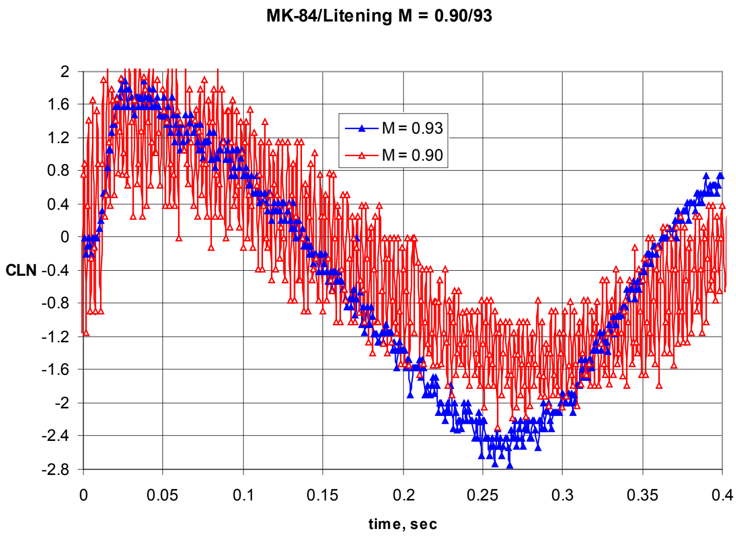


Figure 21: MK-84 Yawing Moment.

Since the telemetry data is at fixed time steps, differentiation leads to an oscillatory behaviour.

The sudden change in the pitching moment seen during the first 50 ms is due to an offset between the store CG and the ejector feet, and would be ignored in comparing the pitching moment coefficient predictions.

There is a substantial difference in the yawing moment data at M = 0.90 and M = 0.93. Obviously, a smoothing function needs to be applied to the raw telemetry data at M = 0.90.

A comparison of the pre-flight predicted yawing moment with the telemetry data averaged over three time steps is shown in Figure 22. The predicted pitching moment (using wind tunnel freestream and grid data) is in good agreement with the flight test result, and indicates a yawing moment at carriage around 1.4. The reason the telemetry data indicates a yawing moment of zero for the first 20 ms may be attributed to friction between the ejector pistons and the store.

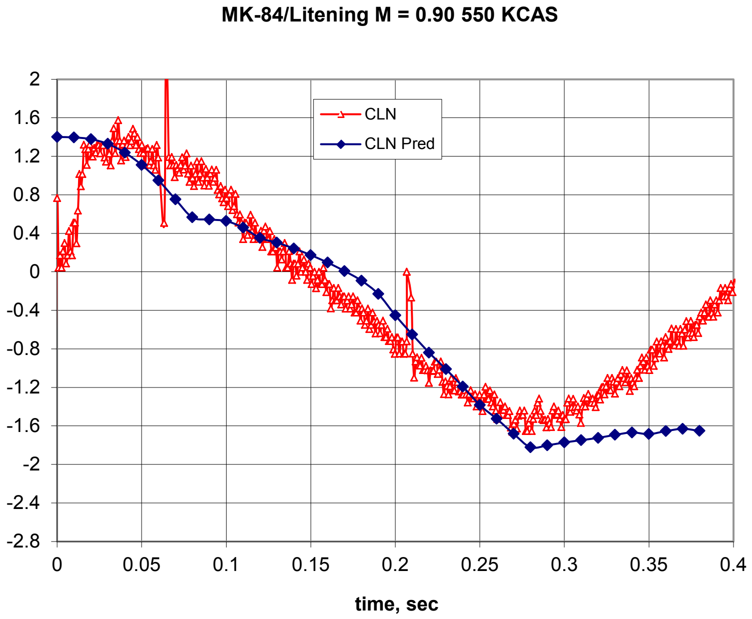


Figure 22: MK-84 Yawing Moment.

Using a similar procedure Hetereed [14] demonstrated how photogrammetric and telemetry results could be used to improve trajectory simulations from the JSF bomb bay.

6.0 SEARCH AND RESCUE (SAR) STORE SEPARATION

The Australian Maritime Safety Authority (AMSA) plans to replace Dornier 328 turboprops with Bombardier Challenger 604 special mission jets modified for search and rescue (SAR) [15]. Similarly configured CL-604 Multi-Mission Aircraft are in service with the Royal Danish Air Force.

6.1 Search and Rescue (SAR) Store Separation from Turbojet Aircraft

There are several store separation challenges posed by replacing a turboprop aircraft with a turbojet for SAR. For the 328 the rear cargo door used for store separation is well clear of the engine. For the 604 it's just underneath the nacelle, Figure 23. In addition, the minimal airspeed at which the 604 can release stores is significantly higher.

Figure 23: Bombardier Challenger 604.

Unlike military aircraft, Sea Air Rescue has rarely used wind tunnel testing, Computational Fluid Dynamics (CFD) or Six Degree-of-Freedom (SDoF) trajectory simulations prior to flight testing. This might have been due to the fact that the released stores were relatively light weight, the airspeeds low, and incidental contact with the aircraft unlikely to cause significant damage at lower airspeeds.

For turbojets the higher stall speeds might have a larger impact on aircraft safety. The higher airspeeds might also cause an increase in the store tumbling rates. For stores that use parachute deployment, the possibility of parachute failure would increase.

6.2 Requirements for SAR Trajectory Simulations

6.2.1 Freestream

The store geometries of interest for SAR are simple rectangles and cylinders, and could be easily modelled in most Euler or NS codes. A range of solutions, especially for angles of attack above 90 degrees would be preferred. In addition, a wind tunnel test for a rectangular shape and cylindrical shape for lower angles of attach in a low speed tunnel should not be too expensive, and might make for a good University class project, and combined with a CFD class.

6.2.2 Initial Conditions

Ground testing would provide an initial estimate, which flight test photogrammetrics could then confirm.

6.2.3 Aircraft Flowfield Effects

Since the initial conditions are unknown, time accurate trajectories would make no sense. An Euler or NS model for the 604 aircraft could be developed. However, a grid of store loads in the aircraft flowfield would require a much larger data set than used for military aircraft.

Military aircraft have well defined initial conditions, and the store trajectories follow a prescribed path largely determined by the ejectors. A grid, done either in the wind tunnel or by CFD usually requires about 20 different Z locations at 2-3 pitch and yaw attitudes (around a hundred CFD calculations or wind tunnel test points) for each store at a particular Mach number and aircraft configuration.

For SAR aircraft, the trajectories are unknown. Furthermore, since the store attitudes vary from 0 to 360 degrees, the number of CFD grid points required would be in the thousands.

Panel methods have demonstrated the capabilities to estimate aircraft flowfield effects at transonic Mach numbers. Since the aircraft flowfield required is only in the effects that the upwash and sidewash have on the store at a particular location, linear theory might be adequate to provide store incremental coefficients.

The usual approach for predicting aircraft flowfield effects using wind tunnel data is to subtract the small scale store freestream data from the grid data (incremental coefficients) and use larger scale freestream data in the SDoF simulations.

Using DATCOM for the freestream characteristics of a rectangular store, with no aircraft flowfield effects, a trajectory simulation was simulated as shown in Figure 24.

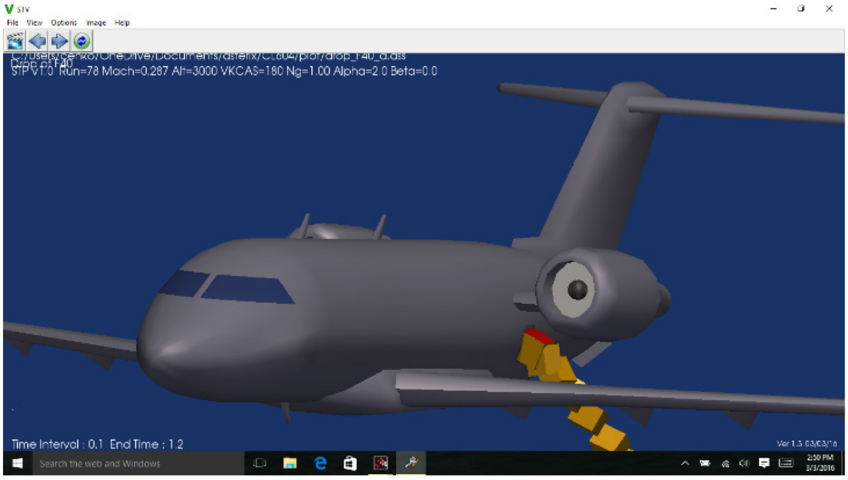


Figure 24: Simulation of a Rectangular Store Trajectory from 604 Aircraft.

A workshop on the topic of store separation from turbojet aircraft is planned for the International Aerospace Symposium of South Africa (IASSA) in Pretoria this September.

7.0 CONCLUSIONS AND RECOMMENDATIONS

There is the possibility of greatly reducing the size and scope of the store separation flight test programs. CFD can be used early in the design program to make the aircraft “store friendly”. CFD can also help design the store attachment hardware and to determine the critical test points to be covered in the wind tunnel test program. Telemetry can also be used to back out and correct the CFD and wind tunnel predictions.

8.0 REFERENCES

[1] Taverna, F.P. and Cenko, A., “Navy Integrated T&E Approach to Store Separation,” Paper 13, RTO Symposium on Aircraft Weapon System Compatibility and Integration, Chester, UK, October 1998.

[2] Sisco, B. and Cenko, A., “SPLITFLOW Prediction of MK-83 Trajectories from the CF-18 Aircraft,” AIAA Paper 2001-2430, June, 2001.

[3] Walsh, J. and Cenko, A., “USM3D Prediction of MK-83 Trajectories from the CF-18 Aircraft,” AIAA Paper 2001-2430, June, 2001.

[4] Ryckebusch, C., Niewoehner. R. and Cenko A., Sisco, B. and Walsh, J., “Evaluation of the Capabilities of CFD to Predict Store Trajectories from Attack Aircraft “, AIAA Paper 2002-0279, January, 2002.

[5] Ray, E.S., “CFD Method for Separation of SLAM-ER from S-3B and P-3C,” AIAA 2003-4226.

[6] Hallberg, E., et al. “IHAAA Store Separation from Cavity (SSC) Project,” ICAS Paper 2008.2.6.2, Sept. 2008.

[7] Cenko, A., et al., “Influence Function Method Applications to Cavity Flowfield Predictions,” AIAA Paper 89-0477, Jan. 1989.

[8] Finney, L., “An Investigation of Cavity Flow Effects on a Store In the Vicinity of the Shear Layer,” ITEA Aircraft Stores Compatibility Symposium, April 2010.

[9] Snyder, M., et al., "Strut Effects on Store Freestream Aerodynamics," AIAA Paper 2011-3159, June 2011.

[10] Snyder, M., et al., "US Naval Academy Store Separation Simulation Program," AIAA Paper 2011-7042, Sept. 2011.

[11] Doig, G., et al., "Aspects of Sting Interference for Transonic Store Release Wind Tunnel Testing, AIAA Paper 2013-0642, Jan. 2013.

[12] Hallberg, E. and Godigsen, W., "MATLAB Based Telemetry Integration Utility for Store Separation Analysis," ITEA International Symposium, November, 2007.

[13] Cenko, A., "IHAAA Applications to Reducing Store Separation Flight Testing," AIAA paper 2007-1653, Feb. 2007.

[14] Hetereed, C., "F-35 Joint Strike Fighter: Store Separation Flight Test and Analysis," 2013 MSC Software Users Conference, May 7-8, 2013, Irvine, CA.

[15] Milne, C., "Minister unveils first Challenger SAR jets for AMSA," Australian Aviation, Jan 27, 2016.