IHAAA STORE SEPARATION FROM CAVITY (SSC) PROJECT

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Keywords: *B-1, GBU-38, Cavity, IHAAA*

Abstract

The Air Force, Army, and Navy have long-term, proven wind tunnel and CFD modeling and simulation experience that has supported advanced weapon development and integration. Each uses unique CFD codes to augment wind tunnel testing. These techniques have been extensively validated for external store separation. During the past three years, the three services, under the auspices of the DoD High Performance Computing (HPC) Modernization Program Office have combined their efforts to establish an Institute for HPC Applications to Air Armament (IHAAA). One of the first IHAAA tasks undertaken by the store separations team was the Store Separation from Cavity (SSC) project. The goal of this project was to determine CFD application best practices for the separation of stores from weapons bays. The results of this project were presented at a special invited session at the AIAA Annual Meeting in Reno, Nevada, on January 7, 2008. This paper summarizes the results of this special session.

1 Introduction

Internal weapons carriage is being used to improve the aircraft aerodynamic performance and low observable characteristics. All new attack aircraft in the US, such as the F-22, F-35, P-8A, and the Unmanned Combat Air System (UCAS), employ weapon delivery from bomb bays. The issue of whether the flowfield in weapon bays is unsteady or can be treated as quasi steady is of critical concern for flight clearance purposes. If the flowfield is truly unsteady, then not only is the principal tool for flight clearance purposes (the wind tunnel) of limited use, but any flight clearance issued for such a case would have to be extremely conservative since the trajectories would not be repeatable.

The separation of stores from a weapons bay may be significantly impacted by the unsteady flow in the bay. It is clear to anyone that has seen wind tunnel smoke traces from the aft end of blunt bodies that the store separation problem, even from external pylons, is an unsteady phenomenon. However, for all practical purposes, external store separation is repeatable as best it can be measured (within one inch in displacement and one degree in attitude after 250ms). Clearly, any unsteadiness in the flowfield may have minimal impact on the resultant trajectories.

2 Background

The SSC project was performed by AEDC, AFSEO and NAVAIR. The intent of the SSC project was the computation of GBU-38 trajectories from the aft bay of the B-1B using both time-accurate CFD and quasi-steady methods that use time-averaged CFD aircraft flow-field data and compare these predictions with wind tunnel and flight test results.

The SSC project was completed in October of 2007, and the results were presented at a special AFM session at the AIAA Annual meeting in Reno, Nevada, on Jan. 7, 2008 chaired by Dr. Lijewski, the AFM Conference Chairman. At the end of the special session, there was a discussion by a panel of experts on CFD applications to stores separating from weapons bays.

2 .1 AIAA Special session: Store Separation from Aircraft Bomb-Bays (Invited)

- AIAA-2008-0184
  "Flight Test Results of a GBU- 38 Separating from the B- 1B Aircraft," D. Atkins, TYBRIN Corporation
- AIAA-2008-0185
  "Quasi-Steady Computations of GBU-38 Trajectory from B-1B Aft Bay," J. Lee and A. Cenko, US Navy, Patuxent River, MD
- AIAA-2008-0186
  "High Fidelity Time Accurate Store Separation Simulations from a B1- B Bay,"
  W. Stickles, Aerospace Testing Alliance, Arnold AFB, TN
- AIAA-2008-0187
  "Time- Accurate Numerical Simulation of GBU- 38's Separating from the B- 1B Aircraft With Various Ejector Forces, Store Properties, and Load- Out Configurations," R. Spinetti, TYBRIN Corporation and B. Jolly, Jacobs Engineering, Eglin AFB, FL

In addition, one paper that was not part of the SSC project was also invited to be presented at the session. This paper was included because it specifically concentrated on wind tunnel and flight test results of stores separating from bomb bays that were considered unsteady.

- AIAA-2008-0188
  "Store Separation Trajectory Deviations Due to Unsteady Weapons Bay Aerodynamics ," R. Johnson, M. Stanek and J. Grove, Air Force Research Lab, WPAFB, OH

At the end of the meeting, there was an invited panel of experts in Store Separation and Unsteady CFD Flowfields:

Dr. John Benek, Director, Computational Sciences Center of Excellence, AFRL/VAAC
Dr. Ronald Deslandes, Expert Advisor Store Separation, EADS, Munich, Germany
Dr. Marnix Dillenius, President, NEAR Inc., Mountain view, CA
Dr. M. Stanek, Associate Technical Advisor, AFRL/VAAI

All the papers were provided to the panel members and reviewed prior to the meeting. The two questions posed to the panel were

1) whether/when/and by how much would store trajectories from bomb bay be unsteady

2) How CFD could best be used to supplement/interpret/correct wind tunnel data.

Their comments can bee seen in detail in:

- AIAA-2008-0189 "Unsteady Weapon Bay Aerodynamics - Urban Legend or Flight Clearance Nightmare,"A. Cenko, NAVAIR, Patuxenx River, MD, R. Deslandes, EADS, Munich, Germany, M. Dillenius, NEAR, Mountain view, CA and M. Stanek, AFRL , WPAFB, OH.

3 Discussion of the Papers Presented

3.1 AIAA-2008-0184

Atkins described the B-1B/GBU-38 flight test program and the flight test results. The SSC project concentrated on two (out of 18) GBU-38 stores released from the B-1B aft bay. These were the C21 and D22 locations, Figure 1.

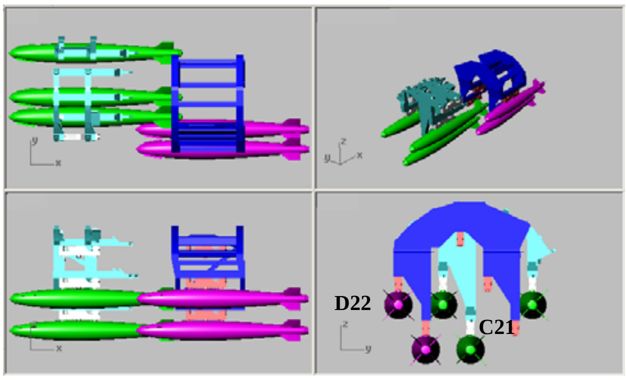

Figure 1 B1-B/GBU-38 Carriage

These two stores were selected because they were expected to experience the worst case for store acceptability (large pitch down attitude).

The flight test had instrumented ejector racks, and photogrammetric and telemetry results were available for the two releases.

The ejector racks had string potentiometers on the ejector feet and load cells under the ejector feet. Time averages were taken of the total forces – however, these turned out to be less than the true values, as was demonstrated by the integrated telemetry test data, and these data were deemed unusable.

These flight test results also were the first production use of high speed digital cameras on a bomber. Twelve cameras with 1024x1024 resolution and a capture rate of 1000 frames were used. Unfortunately, the quality of the results was somewhat disappointing. This might be due to improper survey of store positions and lens calibrations. These are presently being addressed.

The telemetry data provided excellent trajectory results, both in displacement and attitude, as well as diagnostic information from the accelerations and rates. However, it can be limited by cost and frequency availability issues.

The paper also evaluated the IHAAA papers presented, and suggested that the modeling and simulation capability of store trajectories from bomb bays could be further improved.

3.2 AIAA-2008-0185

Lee used the Beggar[1] code in both the time accurate and quasi steady formulation. He determined that the ejector force formulation that was provided could not properly match the flight test results. He therefore used the flight test telemetry accelerations to determine what the proper ejector force input should be, Figure 2.

Lee also calculated the GBU-38 carriage loads, and compared them to B-1B/MK-82 wind tunnel test data (the GBU-38 store is a smart bomb version of the MK-82, and has minimal geometric differences. The calculated results were in good agreement with the test data.

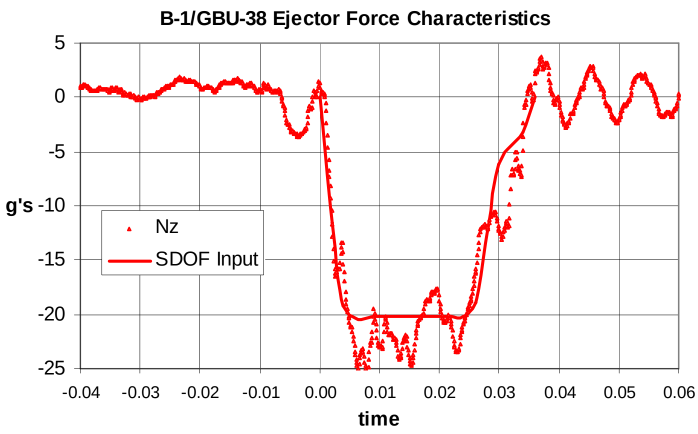

Figure 2 B1-B Ejector Force

However, the store loads, both CFD and wind tunnel, were very close to zero. This means that the flowfield inside the cavity has very little impact on the resultant trajectories.

3.3 AIAA-2008-0186

Sickles used the NXAIR code in a time accurate approach,. Sickles also described how accurately representing the ejector forces was essential to matching the flight test results. However, while Lee relied on the flight test telemetry data to correct the ejector force characteristics, Sickles proposed a novel approach to addressing this problem. Since F = ma, and since for the first 40ms the ejector forces dominate the trajectory characteristics, he developed an algebraic expression to correct the ejector force characteristics:

$$F_{z_1} = \left(\frac{\omega I_{yy}}{t} - F_{z_2} r_2 \right) / r_1$$

where r_1 and r_2 are the distances of the forward and aft ejector from the cg, F_{z_1} and F_{z_2} are the corresponding forces, ω is pitch rate, t is the duration of the ejector force, and I_{yy} is the store pitch moment of inertia. This approach gave comparable results to using the actual telemetry test data. However, this approach would suffer if the photogrammetric results were in substantial error.

Sickles also calculated the trajectory assuming the aerodynamic loads inside the bomb bay were zero. As may be seen in Figure 3, this showed little difference to the trajectory computed using the time accurate approach, again implying the aerodynamic flowfield inside the B-1B aft bay is very benign.

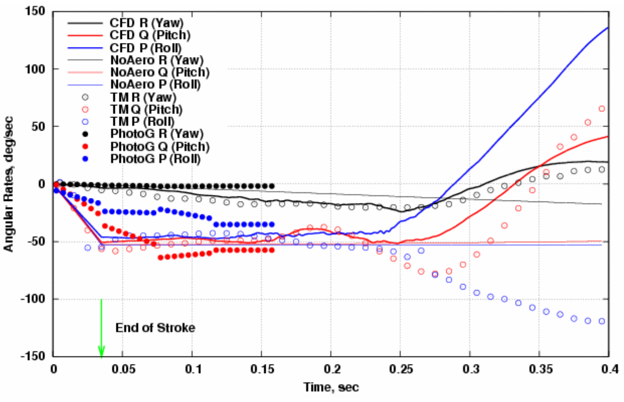

Figure 3 GBU-38 Pitch, Yaw and Roll rates

3.4 AIAA-2008-0187

Spinetti used the same code as Lee (actually, AFSEO provided NAVAIR with the BEGGAR code and the B1-B/GBU-38 grid). He also ran the code in a time accurate mode and reported in an earlier paper (AIAA-2007-1654) that good agreement between the computed results and the flight test data could not be obtained with the ejector force characteristics that were provided. Jolly used the flight test telemetry data to determine the ejector force locations and the ejector-stroke time intervals that resulted in better agreement between the computed store orientation (and translational displacements) and the flight test data. These results are reported in the earlier paper and again in the current paper (AIAA-2008-0187) with the details of Jolly's technique because of their significance; basically, accurate ejector forces are critical to obtaining an accurate numerical simulation of the store trajectory.

Spinetti also demonstrated the sensitivity of the computed store trajectory to the store properties; specifically, the axial moment of inertia and the location of the center of gravity, and concluded that (like the ejector forces) accurate store properties are critical to obtaining an accurate numerical simulation of the store trajectory. In addition, the lateral offset to the store center of gravity was removed, and any roll that was computed was, therefore, indicative of a pure aerodynamic effect. The effect on roll was shown to be relatively small within the weapons bay of the aircraft.

The effect of the load-out configuration (partially-full aft rack vs. empty aft rack) on the computed store trajectory also was examined (Fig. 4) and, unlike the relatively small, pure aerodynamic effect on roll within the weapons bay that resulted from removing the lateral offset to the store center of gravity, significant differences were observed both in yaw and roll indicating the dependence of the store trajectory on the flow field within the bay.

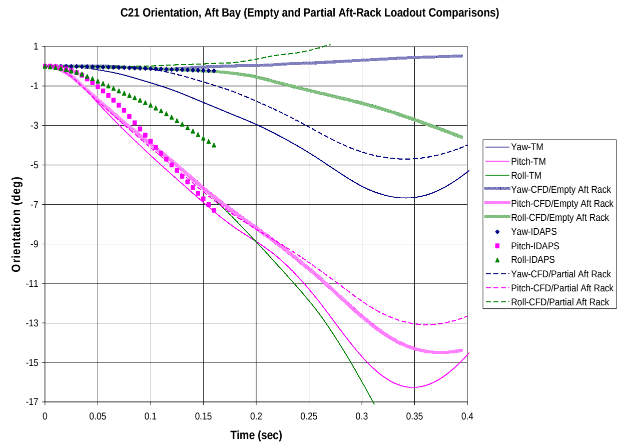

Figure 4 Effect of Load-out Configuration

3.5 AIAA-2008-0188

Johnson cites three cases where the store trajectories from bomb bays were non-repeatable. For one of these, the F-111/SSB[2,3], he indicates that CFD calculations that occurred at multiple release times showed different trajectories. However, a multi-national effort to determine whether the SSB trajectories from the F-111 bomb bay were non-repeatable did not agree[4] with the unsteady conjecture. Part of the problem with these flight test results was that the photogrammetric data were of poor quality, and could not quantifiably determine whether trajectories under the same conditions exhibited any non-repeatability.

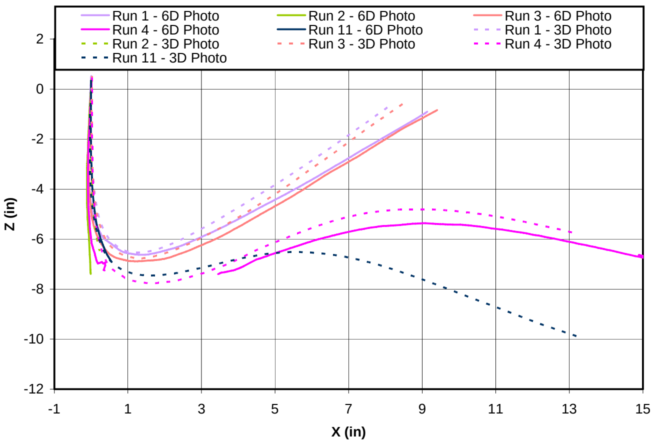

Figure 5 GBU-38 Drop Testing

The second case described the trajectory of a GBU-12 separating from the B-52 bomb bay. Freeman had shown[5] that multiple release times produced substantially different trajectories. However, none of these trajectories actually reproduced the actual flight result, in which the GBU-12 actually came back to hit the aircraft. Since the only way that the incident could have occurred was if the GBU-12 tails had failed to deploy, another possible contributor to this incident could have been a mechanical failure of the lanyard used to deploy the fins and its influence on the resultant trajectory.

The last case described, GBU-38 drop testing, shown in Figure 5, clearly exhibited non-repeatable trajectories. However, as the author correctly points out, drop testing techniques cannot properly model the store mass properties and aerodynamics at the same time. One possible way to determine whether the scaling laws were at fault would be to repeat the drop tests using heavy scaling laws, and then use CFD to determine whether the non-repeatability could have been predicted.

4 Expert Panel

After all the papers had been presented, there was an invited panel of experts in Store Separation and Unsteady CFD Flowfields. Their written comments are available in AIAA 2008-1089. Their oral presentations are summarized below:

4 .1 Dr. Ronal Deslandes

4.1.1 Definition of Unsteadiness:

- All trajectories are unsteady in the sense of time dependency, independently of internal or external Installation. If unsteady effects turn to become dominant , Trajectories might become non-repeatable. (if an ejector fails but the locks open, the external store motion will react to unsteady stochastic constraints and boundary conditions not usually considered and predicted)

4.1.2 Non-repeatable means:

- unpredictable
- uncontrollable
- unsafe

4.1.3 Potential of Wind Tunnel for Dynamic Testing of Cavity Separation

- CTS type approach does not satisfy:
  - complexity of unsteadiness
  - interference due to sting effects
- Freedrop approach has shortfalls in:
  - compressibility at high speeds
  - unmatched gravitational effects

- angular rate deficiency

4.1.4 Similarity Rules of Flight Physics

• *Physical Similarity*	*Density*	*(1) mass geo.*
• *Kinematics*	*Mach Number* *Reynolds Number* *Strouhal Number*	*(2) speed* *(3) viscosity* *(4) frequency*
• *Dynamics*	*Euler Number* *Newton Number* *Froude Number*	*(5) pressure* *(6) forces* *(7) gravitation*

Realised Test Methods:	*Shorfall in:*
Froude Scaling (1+4+6+7)	*for low speeds only*
Light Body Scaling (1+2+4+5)	*gravitational error*
Heavy Body Scaling(2+4+5+6)	*moments of inertia error*

4.1.5 CFD Role

- Isolated wind tunnel analysis is considered as not efficient enough to resolve internal store separation problems.

- CFD analysis is a prerequisite for :
  - Sensitivity analysis prior to wind tunnel Testing
  - Wind tunnel test design and preparation
  - Analysis and interpretation of wind tunnel test data

4.1.6 Certification Criteria

- All trajectories are unsteady in the sense of time dependency , independently of internal or external Installation
- If unsteady effects turn to become dominant ,Trajectories might become non-repeatable.
- Non-repeatable means:
  - unpredictable
  - uncontrollable
  - unsafe
  - not certifiable
- Solution: make trajectories become repeatable by selection of appropriate separation palliatives

4.1.7 Way Forward

- High fidelity CFD closed coupled with appropriate trajectory analysis tools
  - viscosity
  - ejection constraints
  - autopilot control
- Representative wind tunnel test setup
  - Large scales for reality match
  - Force and Flow Grid surveys
- Assorted flight test programs
  - High fidelity flight test
  - Instrumentation (telemetry, electronic sensors…)
  - Accurate pre and post flight test process
- Skilled engineers

4 .2 Dr. Marnix Dillenius

- For a given bomb bay or cavity, the mean dynamic pressure should be determined (measured or computed from "good" CFD). Together with some estimate of the aerodynamic coefficients for the store in question, the dimensional forces and moments acting on the store can be evaluated. The aerodynamic forces and moments should be compared to the inertial characteristics of the store. For bombs, the inertial effects may dominate. The store will then fall ballistically from its carriage/launch position to the shear layer. If the store is light, its trajectory within the cavity/bay can be unsteady and the store may "hang up" in the cavity or bay.

- If a strong shear layer is present (meaning there are no devices near the leading edge of the cavity/bay to suppress shear layer effects), the characteristics of the shear layer need to be known: its mean location and its motion in terms of amplitude and frequency (strength). The forces and moments acting on the store and its motion as it traverses through the shear layer can be calculated using CFD or some validated reduced order method(s). Note: the aerodynamic forces and moments acting on the store can be unsteady depending on "strength" of the shear layer. For repeated store releases, the location on the store where the effects of the moving and pulsing shear layer are first felt will be different even for a store released/ejected from the same carriage position and with the identical conditions (ejection schedule, cg location, inertial characteristics). As a result, for multiple store releases, the store will have different state variables after it passes through the shear layer. It may show "bifurcation" in pitch angle etc.

- Bomb bays/cavities testing in wind tunnels may be deceiving. The cavities may not generate the flow frequencies and amplitude. The shear layer characteristics may not develop because the wind tunnel may not have enough "power" (sufficiently high dynamic pressure) to make the cavity resonate. In some cases, scale mismatch may alter the resonance characteristics. Also, wind tunnels themselves generate noise by nature. This noise can affect the cavity flow characteristics. Care must be taken when validating CFD results to wind tunnel data.

- Obvious and not mentioned, all of the problems related to unsteadiness and or repeatability in the trajectory characteristics of a store released or ejected from a bomb bay can be "fixed" by employing a positive means to push the store through the shear layer by some mechanical device such as a trapeze (like used in powered missile launches from bays).

4 .3 Dr. Mike Stanek

4.3.1 Weapon Bay Unsteady Store Trajectory effects

- "Urban Legend" or "Flight Clearance Nightmare" ?
  - Real, but obscured by the clearance process, and historical practice
  - Part Nightmare / Part Opportunity
- Weapons bays are unsteady
- CTS (Captive Trajectory System) is steady
  - Unsteadiness is filtered and discarded
- The more a cavity flow can be made "steady" (flow control), the more applicable CTS is
- Sensitivity to unsteady cavity flow varies dramatically from situation to situation
- Things can be done to both model and control this

4.3.2 All Weapon Bays are Unsteady

- Weapons bay flow dynamics is a recurring issue with each new aircraft.
- Acoustic Levels Peak Between 0.9 < Mach < 1.3
  - Weapons bay acoustic levels currently approach 180 dB
  - Electronic component damage threshold could be as low as 150 dB

4.3.3 Passive Spoilers / Current Solution Bays Become "Steady" With Effective Control

4.3.4 What Do We Mean By "Unsteady Weapons Bay Effects"?

- Unsteady Weapons Bay Effects can appear as either: 1) high acoustic levels due to an unsteady shear layer, or 2) erratic store trajectories due to an unsteady shear layer.
- For Store Separation, this could mean a dramatic departure or "bifurcation" of the trajectory due to the unsteady shear layer.

- Dramatically different trajectories (into bay / or out of bay) for identical nominal release conditions.
- In other words, same ejector force, same Mach #, same angle of attack, same altitude. Different Trajectory…….

4.3.5 The Traditional Store Clearance Process

- Store-clearance is based upon a historic wind-tunnel process called Captive Trajectory Simulation (CTS). This process assumes that at each position in the flow field surrounding the aircraft, there is a single, constant , unique value for the store force and moment about each axis. A "quasi-steady" trajectory Is constructed using 6 DOF equations which uses this matrix of forces and moments. Steady, time-averaged CFD (Computational Fluid Dynamics) is used to supplement wind tunnel data.

4.3.6 Problem With Relying Exclusively On Traditional Store Clearance Process

- CTS works best in steady flowfields
- External flows are designed to be attached (non-separated) steady flows
- CTS works well for these cases

4.3.7 Problem With Traditional Store Clearance Process Based On Averages – "Bifurcation"

- Store bifurcation could be a potentially dangerous situation. After a store is cleared for release at a certain condition (using CTS), it is checked with flight test. Because store bifurcation depends upon time of release (and the unsteady flow is usually not measured or recorded), you could clear a weapon during flight test, using multiple separation events, and then STILL have an unsafe separation event in the field afterwards (50/50 chance?).

4.3.8 Why We Should Care

- Truncated Performance of Weapon System
  - Some Store Release Boundaries

Defined By Unsteady Effects

- CTS Cannot Anticipate "Trajectory Departures"
  - Safety of Flight Issue
- Prediction, Understanding, and Screening can Enhance and Streamline the Clearance Process

4.3.9 Supporting Evidence

- Combined Asymptotic and Numerical analysis results
  - Malmuth, Shalaev, & Fedorov
- Time accurate coupled CFD/6-DOF modeling results

- 2-D Generic rectangular cavity/slender store (Jordan & Denny)
  - F-111/SSB trajectories (Coleman)
  - B-52/GBU-12 trajectories
- Wind tunnel results

- Sting mounted store response to unsteady aero loads
  - Small scale drop testing

Generic rectangular cavity/MK-82 JDAM
B-1B aft bay/CBU-105

4.3.10 Why Store Bifurcation is Not Reported

- In Flight Test - Requires REPEATED drops at same Mach Number, Angle of Attack, Altitude. Too Expensive $$$$$$ - NEVER DONE.
- Even with repeated drops, you might not observe it (if timing is wrong).
- In Wind Tunnels - Free Drop testing in wind tunnels limited to "blow down" facilities. Not industry practice. Not trivial. RARELY DONE. Limited to research.
- In Simulations - High-fidelity, time-accurate CFD (Computational Fluid Dynamics) is required to simulate this. Multiple runs at the same Mach Number, Angle of Attack, Altitude, are required. Too Expensive $$$$$$$. - RARELY DONE.
- Easier to clear weapon up to boundary of flight envelope where store behavior becomes erratic, and then to placard the aircraft (CTS process now)
- We don't know how extensive the problem is, because no one collects the data to prove / refute the existence of this behavior.

4.3.11 The Good News

- The problem CAN be studied in a systematic way.
  - Establish Periodic behavior of forces and moments in store carriage position.
  - Release store at several points in unsteady cycle.
  - Examine scatter in trajectories.
- Idea is to develop understanding of phenomena, then to develop some screening process to allow store clearance process to apply expensive
- Flow control methods OR timed-releases are potential ways to FIX the problem.

4.3.12 Path Forward

- Measure Unsteady Effects

- Capture Unsteady Balance Loads and Acoustics together (Unsteady CTS)
- Instrument free drop models with telemetry, synchronized with acoustics
  - Capture in-bay portion of flight
  - Off-body unsteady diagnostics (synchronize with acoustics)
- Model Unsteady Effects
  - Add time-dependent forces to CTS “lookup” (unsteady balance loads)
  - Validate against measurements and “proper CFD”
- Screen For Unsteady Effects
  - Focus additional attention on “bad actors” / keep current practice

5 Conclusions

Clearly, ejector force characteristics had a much larger effect on the GBU-38 trajectories from the B-1 cavity than the aerodynamic forces and moments. However, that may not be the case for all stores released from bomb bays, especially light stores released from cavities that, due to poor design or lack of spoilers or aeroacoustic suppression devices, have a strong aerodynamic effect inside the bomb bay.

The issue of whether unsteady flow effects inside bomb bays affect store trajectories has not been resolved by this study. Further analytic and experimental study is merited.

6 Acknowledgements

The authors would like acknowledge the support of the High Performance Computing Modernization Program Office (HPCMPO). The HPCMPO support was provided through the Institute for HPC Applications to Air Armament (IHAAA).

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