

# **Computations in Support of Analysis of Dart Dispense Configurations**

**Final Report**

**Contract Number: N00014-07-C-0240**

**James Y. Baltar  
Kevin Losser  
Morris Morell**

**Digital Fusion Solutions, Inc.  
5030 Bradford Drive  
Building 1, Suite 210  
Huntsville, AL 35806**

**William E. Dietz  
Director, Engineering Analysis  
Phone: 256-327-8132  
Fax: 256-327-8120  
Email: [bdietz@digitalfusion.com](mailto:bdietz@digitalfusion.com)**

## **LONG-TERM GOALS**

Current approaches to beach and surf zone mine clearance depend on the dispensing of large numbers of darts from a parent missile or projectile. The mine clearance mission requires a uniform distribution of darts over the target area. The dispersal pattern is affected by many factors including the angle-of-attack, dispense velocity, rotational rate of the parent vehicle, the aerodynamic design of the darts, dart collisions, and the different aerodynamic regimes that exist in the vicinity of the dispenser. In the overall effort, computational modeling and simulation is used to provide insight and understanding of the dispense event. The primary long-term goal of the present effort is to understand and characterize, through simulation and analysis, the important physics affecting dart dispersal during large-dart-pack dispense events.

# REPORT DOCUMENTATION PAGE

Form Approved  
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<b>1. REPORT DATE (DD-MM-YYYY)</b> DD-MM-YYYY		<b>2. REPORT TYPE</b> Final Report		<b>3. DATES COVERED (From - To)</b> 1/29/07 - 1/28/08	
<b>4. TITLE AND SUBTITLE</b> Computations in Support of Analysis of Dart Dispense Configurations				<b>5a. CONTRACT NUMBER</b> N00014-07-C-0240	
				<b>5b. GRANT NUMBER</b>	
				<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> James Y. Baltar Kevin Losser Morris Morrell				<b>5d. PROJECT NUMBER</b>	
				<b>5e. TASK NUMBER</b>	
				<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> Digital Fusion Solutions, Inc. 5030 Bradford Drive, Bldg. 1, Suite 210 Huntsville, AL 35805				<b>8. PERFORMING ORGANIZATION REPORT</b>	
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Office of Naval Research One Liberty Center 875 N. Randolph St., Suite 1425 Arlington, VA 22203-1995				<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
				<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b> Distribution Statement A. Approved for public release; distribution is unlimited					
<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> <p>Current approaches to beach and surf zone mine clearance depend on the dispensing of large numbers of darts from a parent missile or projectile. The mine clearance mission requires a uniform distribution of darts over the target area. The primary long-term goal of the present effort is to understand and characterize, through simulation and analysis, the important physics affecting dart dispersal during large dart-pack dispense events. In this effort, the MODS (Mine Obstacle Defeat System) configuration is considered. The MIDS configuration consists of packs of darts arranged along the longitudinal axis. A current configuration under investigation consists of 9 packs, with each pack consisting of hundreds of darts mounted in a hexagonal close packing arrangement. The aggregate number of darts is beyond what can be reasonably computed using existing viscous CFD approaches. Accordingly, deriving useful data on full-sized MODS configurations requires modeling that includes the relevant geometric efforts on the flowfield without necessarily modeling every dart. The results of efforts for 2007 are presented in this document. The three main efforts were:</p> <ul style="list-style-type: none"><li>• Determination of Scaling Effects on Rotating MODS Dart Pack</li><li>• CFD/Tunnel Test Validation</li><li>• HPC Challenge Project</li></ul> <p>All simulations used the OVERFLOW-2 code, which is the premier overset-methods Navier-Stokes code developed by NASA.</p>					
<b>15. SUBJECT TERMS</b>					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b> 20	<b>19a. NAME OF RESPONSIBLE PERSON</b> Sandra Fossett
<b>a. REPORT</b>	<b>b. ABSTRACT</b>	<b>c. THIS PAGE</b>			<b>19b. TELEPHONE NUMBER (include area code)</b> 256-327-8161

## OBJECTIVES

Multiple-dart dispense systems are characterized by collisions between the darts, the presence of darts in the shock and wake regions of other darts, and darts at high angles of attack. In this effort, the MODS configuration is considered. The MODS configuration consists of packs of darts arranged along the longitudinal axis. A current configuration under investigation consists of 9 packs, with each pack consisting of hundreds of darts mounted in a hexagonal close packing arrangement. The aggregate number of darts is beyond what can be reasonably computed using existing viscous CFD approaches. Accordingly, deriving useful data on full-sized MODS configurations requires modeling that includes the relevant geometric effects on the flowfield without necessarily modeling every dart.

## APPROACH

The results of efforts for 2007 are presented in this document. The three main efforts were:

- **Determination of Scaling Effects on Rotating MODS Dart Pack**

This is a continuation of an effort begun in 2006 to compute the loads on a static MODS dart pack by taking advantage of geometric symmetry conditions. This effort extended the analysis to rotating dart packs.

- **CFD/Tunnel Test Validation**

This effort served as a validation of CFD methods applied to dart pack configurations. Configurations tested in the wind tunnel in late 2006 were analyzed through CFD methods and the results compared to experiment to develop a “best practices” CFD approach to dart pack analysis. In addition, an effort was included to determine how closely the tunnel test simulates a full ring of darts distributed around the centerbody.

- **HPC Challenge Project**

This effort supported participation in the HPC Challenge Project that was awarded to the Indian Head Division of the Naval Surface Warfare Center. Under this effort, computations were undertaken on the HPC MSRC machines on a high-priority basis. The computations consisted of various dart dispense scenarios on configurations consisting of large numbers of darts.

All simulations used the OVERFLOW-2 code, which is the premier overset-methods Navier-Stokes code developed by NASA. Dr. Pieter Buning of NASA Langley is the main developer. Collision modules developed by Dr. Robert Meakin of NASA Ames have been incorporated into OVERFLOW-2 and provide an important basis for the present effort.

## **WORK COMPLETED/RESULTS**

### **Determination of Scaling Effects on a Rotating MODS Dart Pack**

Computations have been conducted on large MODS dart packs to determine the relationship between the radial size of the pack and the expulsive force on the outer layer of darts. The study concluded that with each increasing layer of darts, the expulsive force on the outer layer increased and asymptotically approached a constant value. The work conducted on the scaling effects of a MODS dart pack assumed that the pack was static; this is not the case for the actual dart pack. When the MODS dart pack is dispensed, the pack is rotating due to the rotation of the dispense vehicle. An approach was made to model the effects of rotation on a dart pack.

In the OVERFLOW-2 CFD code, rotational source terms were added to the momentum equations to impose rotation on the free-stream fluid. This approach is commonly used in the rotorcraft community to model rotors in hover. However, due to numerical instabilities between the current periodic flow boundary conditions used in the code and the newly implemented rotation modifications, the modeling approach similar to that of the scaling study was abandoned in favor of a new representation.

The new rotational pack model closely resembled the model used in the wind tunnel test in 2006 rather than the actual MODS dart pack. The model consisted of a large center body that was used to simulate the blockage effect caused by the inner darts in the pack. A ring of darts was then added circumferentially around the center body. The distance between the darts and the center body was 0.1 inches; the same height used in one of the tunnel test validation cases. Also, an angular separation of 12 degrees between darts was used to evenly distribute darts around the center body. Additional layers of darts were then added to the model to determine how the effects scale with various rotational rates. Figure 1 shows the configuration with one, two, and three rings of darts around the center body.

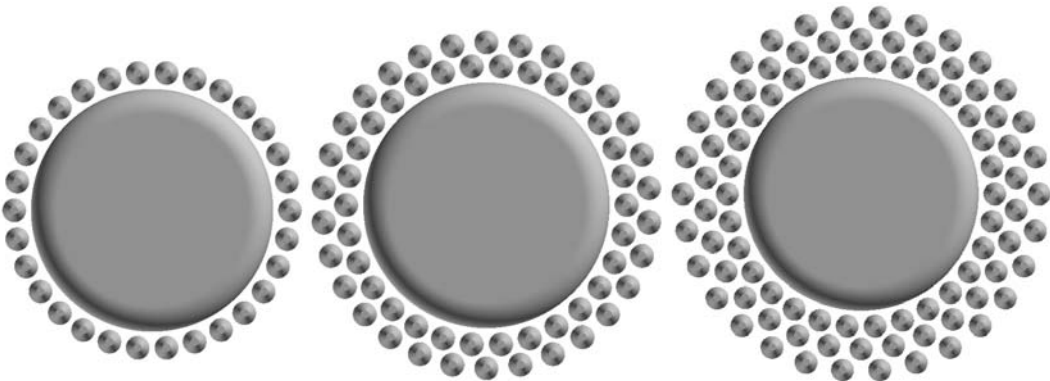
Simulations were conducted on the new rotational pack model to determine the effects of varying rotational rates. The rotational rates used in this study were 4.5, 9, and 18 Hz. The results of these computations are shown in Figure 2. The results show the radial force coefficient as a function of rotational rate. The rotation modifications made in OVERFLOW-2 essentially imparts a rotation on the free-stream flow. This allows rotational effects to be computed as a steady state-problem. By imparting rotation to the flow itself, the force coefficients computed in Figure 2 are strictly aerodynamic forces. This implies that any increase or decrease in the magnitude of the radial force is due only to the effects of rotation. In this case however, radial force coefficients remain constant over the range of rotational rates.

The model used in this study has the darts positioned in a circular pattern around a 5 inch center body. The MODS configuration, however, is packed in a hexagonal close packing (HCP) arrangement. It was found that as the number of layers of darts increased with the HCP arrangement, the radial force on the outer layer of darts also increased asymptotically to a certain value. This was not the case with the circular pattern arrangement. Instead of the radial force increasing in value as the layers increased, the force actually dropped. This drop

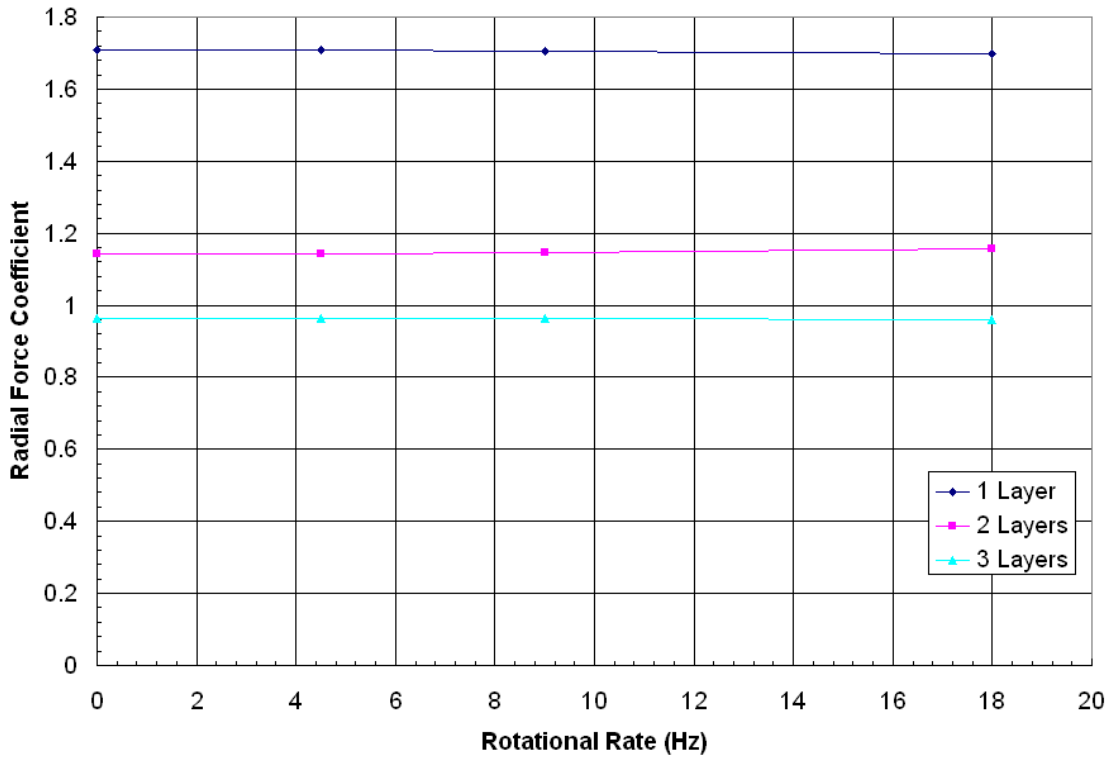
occurs because as the next layer of darts are added, the circumferential distance between darts increases resulting in a pressure relief on the darts in the outer ring.

For the case with a single layer of darts around the center body, two rotational rates of 36 Hz and 72 Hz were added to determine the effects of an increased rotational rate. Figure 3 shows the results with the additional rotational rates. The side force continues to show an increasing trend which is expected due to the increase in the tangential velocity component. The radial force however, continues on constant value trend.

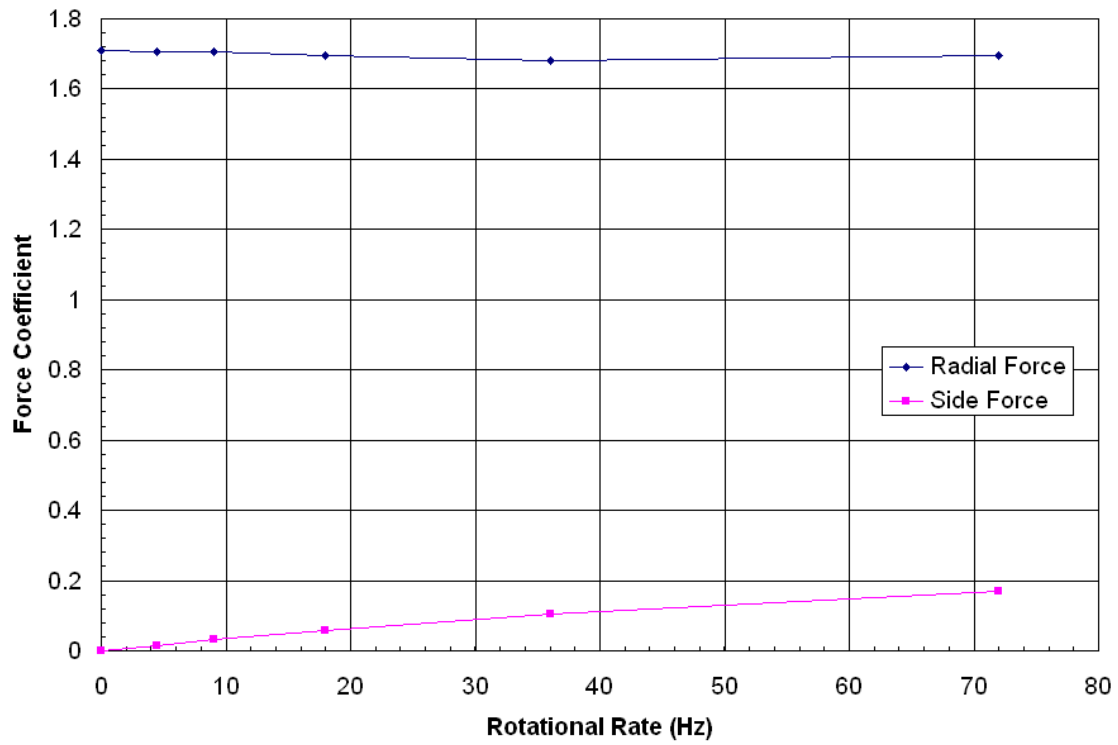
**This leads to the conclusion that for the given rotational rates in this study, pack rotation has a negligible effect on the aerodynamic expulsive force on the outer ring of darts.**



**Figure 1 Computational models used to determine the effects of rotation.**



**Figure 2 Effect of rotational rate on radial force coefficients.**



**Figure 3 Radial and side force coefficients for one layer of darts.**

## CFD/Tunnel Test Validation

Wind tunnel tests were conducted in late 2006 using the new .49 caliber dart. The first part of the test consisted of measuring aerodynamic forces and moments on single finned and finless darts in freestream during an alpha sweep from  $+42^\circ$  to  $-42^\circ$ . Also tested in the wind tunnel was the dart configuration depicted in Figure 4. The configuration consists of a center body and three finless darts. The two outer darts, or dummy darts, are static; the center dart is a metric dart on which forces and moments are measured at 3 axial locations while varying the vertical position. The tests were designed to provide insight into dart pack behavior by simulating a centerbody (modeling the inner darts) and three darts representing part of the outer layer. By adjusting the radial locations of the metric and dummy darts, and the diameter of the centerbody, the effects of radial location and centerbody diameter can be assessed.

A CFD effort using the OVERFLOW-2 code was performed on the dart configurations tested in the wind tunnel. The purpose of the CFD effort was to 1) verify the fidelity of CFD computations on single dart and multiple dart pack configurations, and 2) assess the differences in forces and moments between the tunnel configuration and the more realistic configuration that consists of a completely populated circumferential distribution of darts.

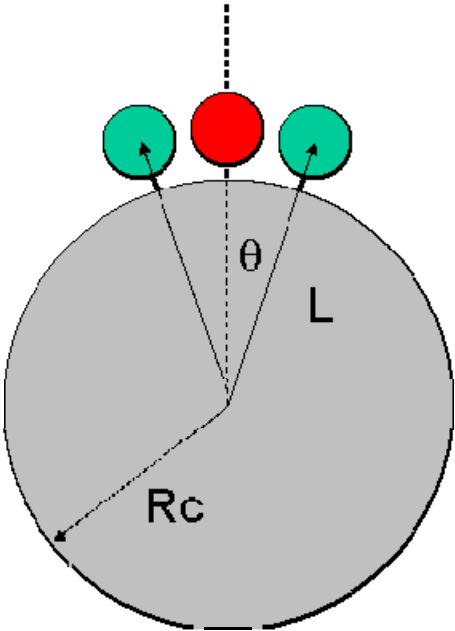
In Figures 5 and 6, the normal force and pitching moment comparison between OVERFLOW-2 predictions and wind tunnel results are presented for a single finned and finless dart in freestream. The accurate predictions for a single dart show that the grid resolution and turbulence model is adequate to model the .49 caliber dart across the expected angle-of-attack range.

In Figure 7, the normal force and pitch moment coefficients of the metric dart in the presence of a 5-inch diameter center body and two dummy darts is presented. The dummy darts are at an offset angle of 11.8 degrees from the metric dart and are at a distance of 0.1 inches from the center body. All of the bodies are at the same axial position, with the darts aligned with the front of the parent. Normal force and pitching moment coefficients of the metric dart are presented as a function of vertical displacement. Moments and the direction of forces are defined by the right hand rule where positive  $C_N$  is toward the center body, and positive  $C_M$  is nose toward the center body. In general, CFD predictions are in good agreement with the data. The predictions show a slight discrepancy in normal force and pitching moment coefficients when the metric dart is in close proximity to the center body. At this position, the metric dart is at its closest proximity to the dummy darts as well. As the metric dart's distance increases, the normal force coefficient follows the increasing trend of the wind tunnel data. Force and moment coefficients are in best agreement when the metric dart is at 2 inches and 2.5 inches above the parent body. Figure 8 shows predicted surface pressures for the metric dart at a distance of 0.4 inches.

The objective of the wind tunnel test was to simulate the outer ring of darts in a dart pack. This configuration could not be tested under the technical and financial constraints of the test. The fully distributed configuration more closely represents the actual MODS configuration and is modeled quite easily using CFD. By modeling a wedge and using the same three dart configuration, symmetry boundary conditions are added to simulate the fully populated circumferential distribution. The approach used for this configuration is illustrated in Figure 9.

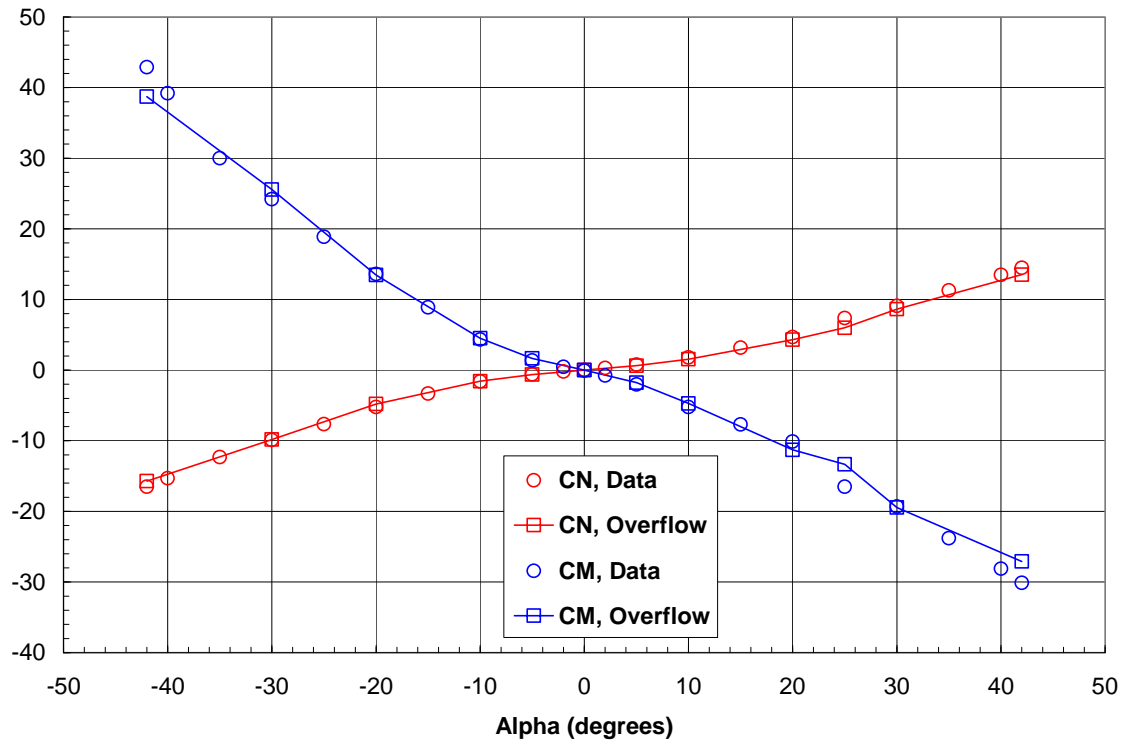
Using flow visualization software, the model is copied and rotated so that the full view is visualized. In Figure 10, a pressure plot of the simulated circumferentially complete configuration is presented.

The An analysis of these simulations shows that the metric dart on the complete configuration (symmetry model) experiences a slightly larger expulsive force when the darts are in close proximity that can be seen as a more negative normal force in Figure 11. The larger force is caused by a buildup in pressure surrounding the metric dart. Because the wind tunnel model was only a three dart configuration, the metric dart, the dummy darts and the centerbody experiences 3-D pressure relief that can be seen by the cross flow velocity vectors in Figure 12a. In the simulated complete configuration (Figure 12b), the increase in pressure below the metric dart does not get 3-D relief because of the presence of the next dart around the circumference (simulated by the symmetry boundary condition).

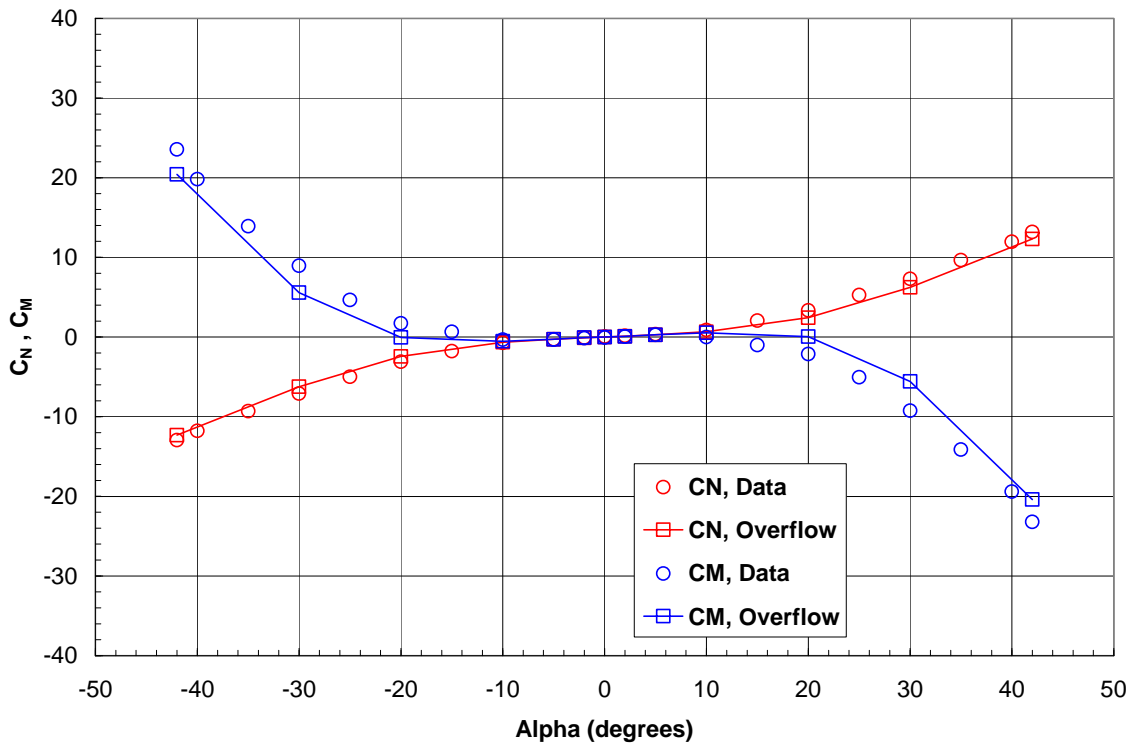


**Figure 4. Configuration of Tunnel Model Represented in CFD Validation Simulations**

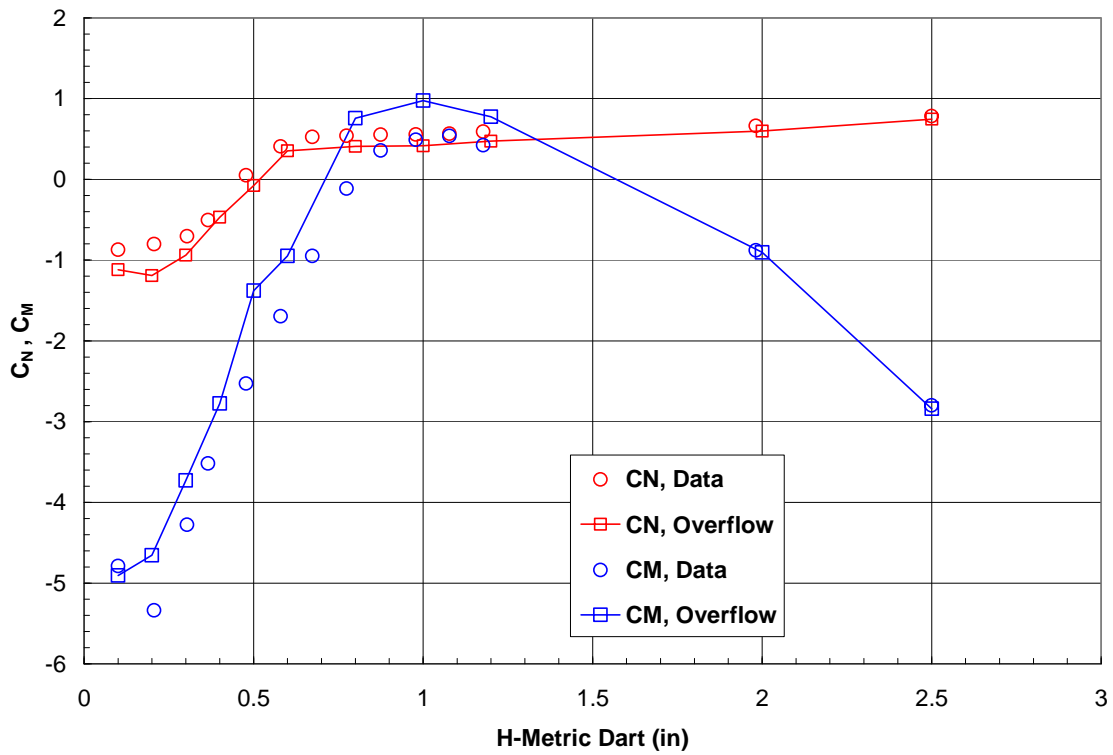




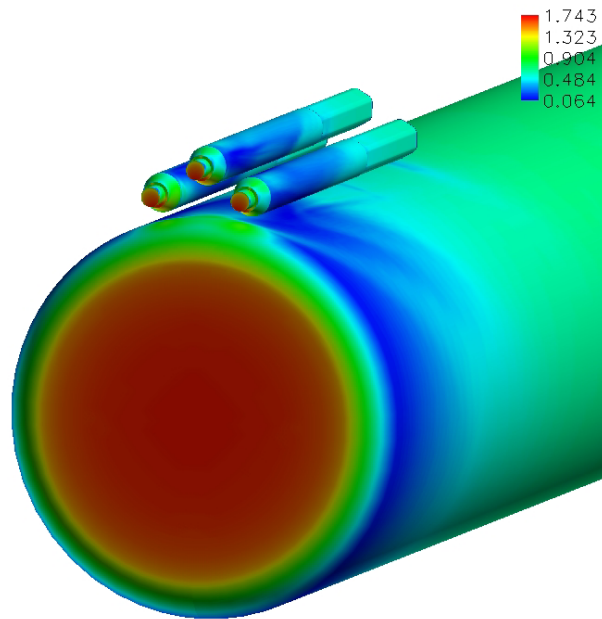
**Figure 5. Freestream Normal Force and Pitch Moment Coefficients of a Finned .49 Caliber Dart**



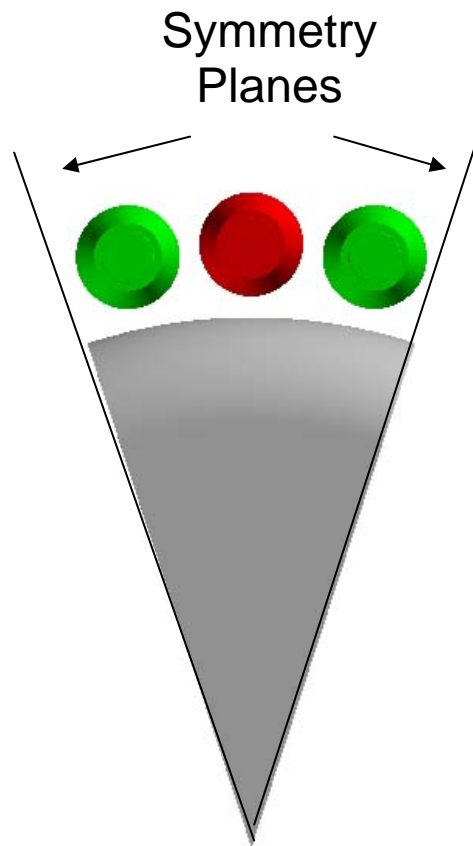
**Figure 6. Freestream Normal Force and Pitch Moment Coefficients of a Finless .49 Caliber Dart**



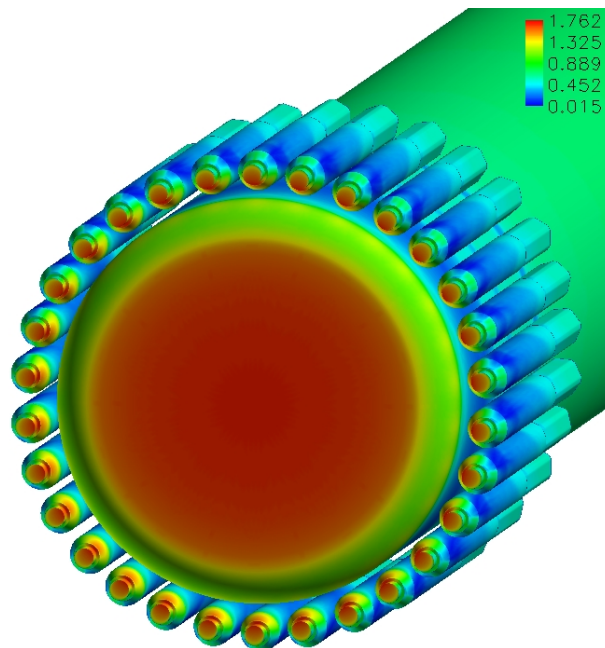
**Figure 7. Interference Normal Force and Pitch Moment Coefficients (5-inch parent, dummies at  $h = 0.1$  inches,  $X_{metric} = 0$  inches)**



**Figure 8. Pressure Plot of Wind Tunnel Model (Metric Dart at 0.4 inches above center body, dummy darts at 0.1 inches above center body)**



**Figure 9. CFD Model with Symmetry Plane Boundary Conditions**



**Figure 10. Pressure Plot of Circumferentially Complete Configuration**

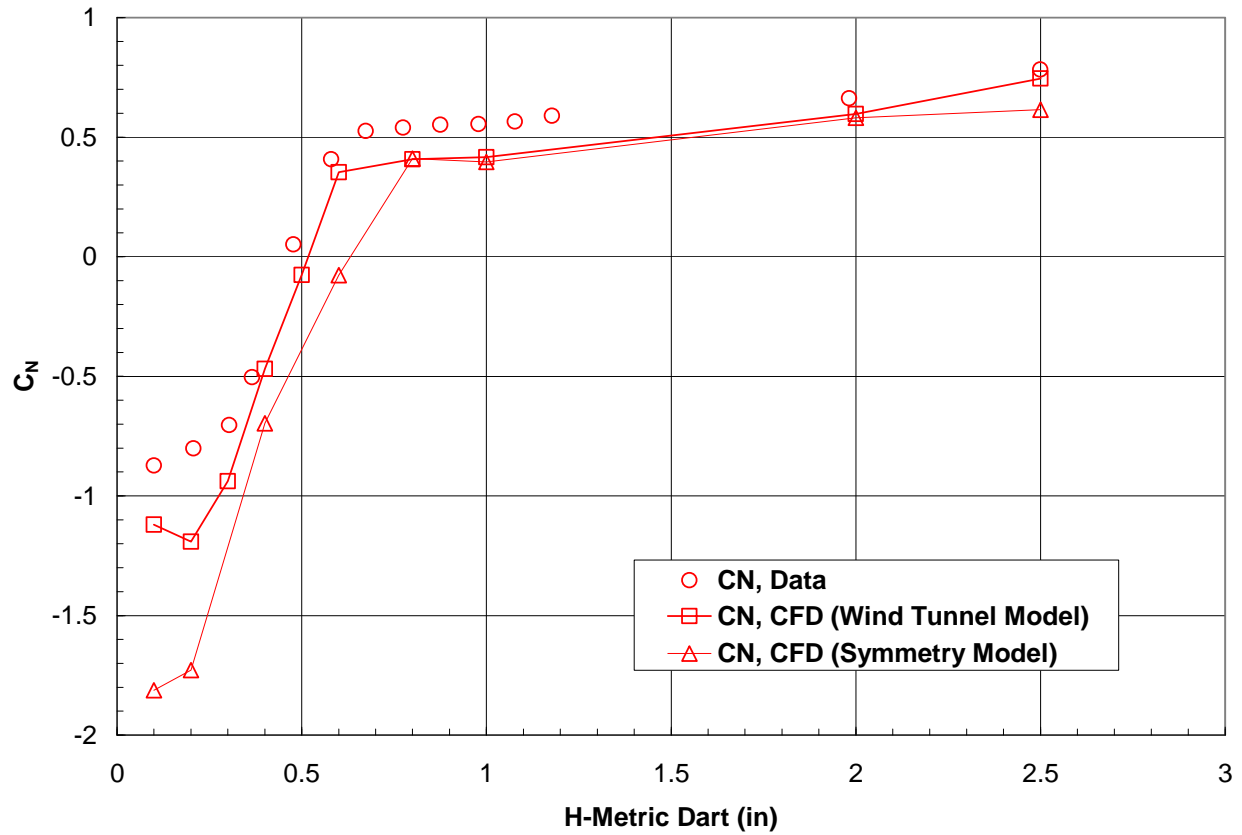


Figure 11. Normal Force Coefficient Comparison

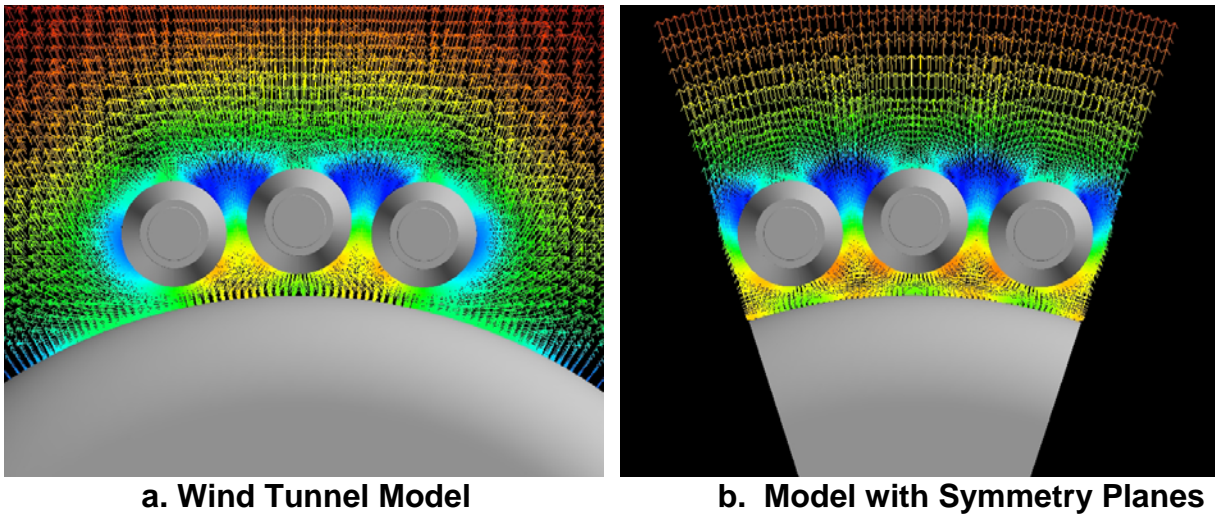


Figure 12. Cross Flow Vectors Colored by Pressure

## Computations in Support of HPC Challenge Project

The Indian Head Division of the Naval Surface Weapons Center was awarded an HPC Challenge Project for FY2007 through FY2009. The goals of this HPC Challenge project are 1) to accurately model the dispense of multiple dart packs, approaching the full MODS payload, 2) to determine how many darts need to be modeled to capture the overall dispense dynamics, and 3) determine whether the dispense of 4000+ darts can be modeled given enough computing resources, or to determine the maximum number of darts that can be simulated given the available HPC resources. After preliminary dart pack configurations were run, DFSI was assigned to run dart pack dispense simulations on a 273-dart pack at a Mach number of 1.2 at rotational rates of 6, 12 and 18 Hz.

The primary HPC resource for the DFSI simulations is *kraken*, which is located at NAVO at Stennis Space Center, MS. *kraken* is an IBM Cluster 1600 system assembled with 368 nodes of eight 1.7GHz Power4+ processors each, for a total of 2944 processors. Most nodes have 16 Gbytes of memory or 2 Gbytes of memory per processor. The processor limit on the Challenge queue is 1024 processors, which gives access to 2048 GB on memory.

Several sample simulations were run to determine the proper OVERFLOW-2 settings for the large dart pack simulations. To set up all the OVERFLOW-2 simulations, a FORTRAN program was written to duplicate the single dart grids and orient the forward-fin and rear-fin darts into the configuration, shown in Figure 13. The *over.namelist* input file for the complete dart pack is also created by this program.

A one-dart simulation was performed as a convergence study to assure that the solution was converged for each time step. A single aft-fin dart was set at a 15° angle of attack and released with freestream conditions of Mach 1.2 and Re of 8.0e6/ft. OVERFLOW-2 runs were made with 3, 6, 10 and 13 Newton iterations (NITNWT) per time step at CFLMAX of 2, 5, and 10. Since the dart is aerodynamically stable, the dart oscillates through positive and negative angle-of-attack until the alpha goes to zero. The aerodynamic dampening was monitored using the dart alpha calculated from the OVERFLOW-2 *sixdof.out* file. Figure 14 shows the comparison from the six different simulations. A NITNWT of 6 and a CFLMAX of 5 was used during the 273-dart simulations, since the maximum dart oscillation was captured with the least amount of computational time.

A two-dart simulation was performed in order to determine the proper non-dimensional physical time step (DTPHYS) at angular rotation rates of 6, 12, and 18Hz. Both darts were aligned along the X-axis at 0° angle of attack, one dart was translated six inches along the Z-axis. A tangential velocity due to the angular rotation rates was calculated and applied to the dart on the X-axis in the positive Z direction. If the DTPHYS was too high for the simulation, the OVERFLOW-2 contact model allowed darts to intersect as shown in Figure 15. The DTPHYS determined in this study was applied to the 273-dart simulations.

The initial configurations shown in Figures 16 and 17 were set up to check out the OVERFLOW-2 settings and estimate the size of the largest dart pack that could be run on *kraken* within the CPU time and memory constraints of the HPC Challenge project. Figure 16 is a 57-dart pack consisting of three axial rows and two radial layers. Each axial row is

rotated  $15^\circ$  (the angle of one-half of a dart) relative to the upstream axial row, to increase randomness in the dart collisions. Figure 17 is a 111-dart pack consisting of three axial rows and three radial layers. Both of these dart packs were initialized at the chosen spin rate and then released to free flight. After grid adaptation, the 57-dart case used 130 million grid points and required up to 48 processors on *kraken*. The 111-dart case used 300 million grid points and required up to 240 processors on *kraken* after the darts were released and the grid was adapted. Both simulations ran until the solution failed due to a bug in the OVERFLOW-2 grid adaptation. A bug fix was received from Pieter Buning that was used in the 273-dart simulations.

Based on these two simulations, the 273-dart pack was chosen for the large dart simulations. The 273-dart pack, shown in Figure 18, consists of three axial rows and five radial layers. To study the effect of angular rotation rate on dart dispersal, DFSI was tasked to run three 273-dart simulations at angular rotation rates of 6, 12, and 18Hz. Free stream conditions correspond to a Mach number of 1.2 at sea level.

As the darts separate from each other, the OVERFLOW-2 grid must be adapted to maintain the proper grid resolution as the darts move into the off-body grid. At each adaptation, the number of mesh points increases and thus the amount of memory required by OVERFLOW-2 increases. On *kraken*, each node of 8 processors has 16 Gbytes of memory. The only way to increase memory available to OVERFLOW-2 is to request more processors. The 12 and 18 Hz simulations were run until the processor limit on the Challenge queue of 1024 processors was met. The 12 Hz simulation was run to about 0.025 sec after release and the 18 Hz simulation was run to about 0.015 sec after release. To completely simulate the flight dispense event, the OVERFLOW-2 simulation should be run to about 0.1 seconds after release. The 6 Hz simulation was run to about 0.01 sec after release and failed due to another problem.

Figure 19 shows a four shot sequence of the dart release for the 12Hz case, which is typical for all cases. Animations of the dart packs spinning and the darts released to free-flight are available and are used in the analysis of the OVERFLOW-2 results. Individual dart positions, velocities, force and moments can be analyzed using OVERFLOW-2 output files and Tecplot. As a sample, figures 20, 21 and 22 show the individual dart radial distance, velocity and cross-plane angle-of-attack for the outer layer darts for each of the three rows. Also shown on the dart radius and velocity plots is the average radius and velocity of the outer layer of darts. The first row of outer layer darts is seen to move outward at the higher radial velocity due to the large expulsive force in the outer layer of darts. The maximum alpha for a dart is seen to be about  $20^\circ$  until later in the simulation when collisions in the last row of darts cause the angle-of-attack to go up to about  $40^\circ$  for a small number of darts.

Figures 23 and 24 show the average radius and average velocity of the outer layer of darts for the three rotation rates that were simulated. As expected, the darts with the higher rotation rate move out farther and faster than the darts at the slower rotation rate.

## **IMPACT/APPLICATIONS**

Many configurations of interest involve moving bodies. While much of CFD analysis is considered mature technology, the approaches required for accurate computations of time-dependent moving-body simulations are considered groundbreaking work. The current effort represents a major increase in computational capability that has many applications, including but not limited to store separation, missile and aircraft dynamics, air vehicle performance evaluation, control surface modeling, and missile staging.

Additional documentation of the wind tunnel test results and dart dispense modeling presented herein is available from the following references:

Watson, K., et al, "Wind Tunnel Measurements of Transonic Aerodynamic Loads on Mine Clearing Darts," AIAA Paper No. 2008-346, 46<sup>th</sup> AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 2008.

Prybyla, G., et al, "Modeling of Mine Countermeasure Dart Dispense," DoD High Performance Computing Modernization Program, 2007 Users Group Conference, Pittsburgh, PA, June 18-21, 2007

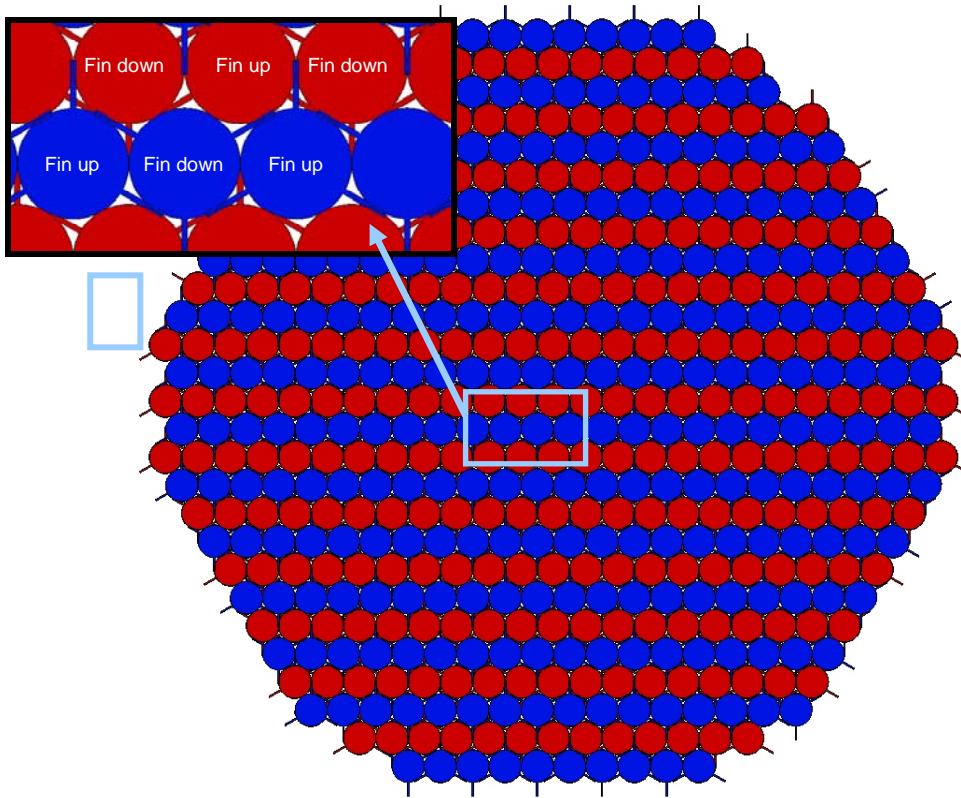


Figure 13. Single axial row of current MODS configuration, the blue darts represent aft fin darts, and the red darts represent forward fin darts.

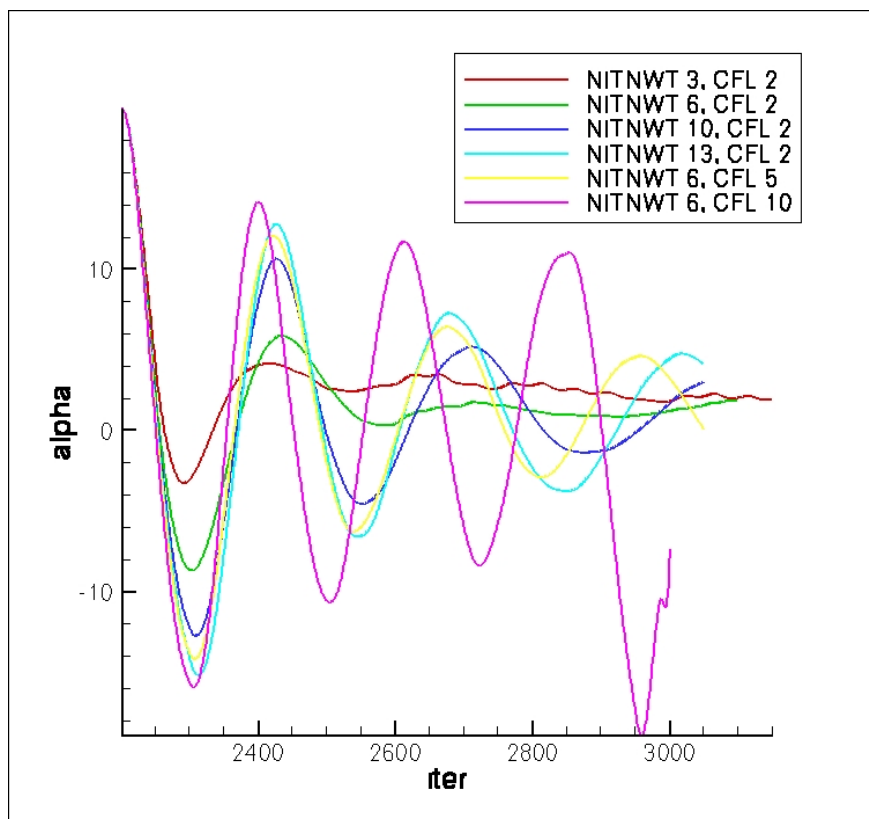
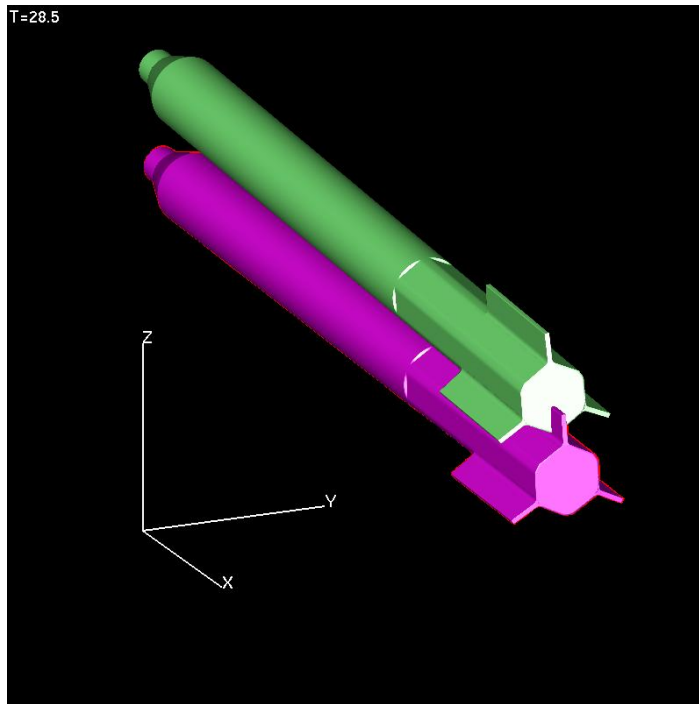
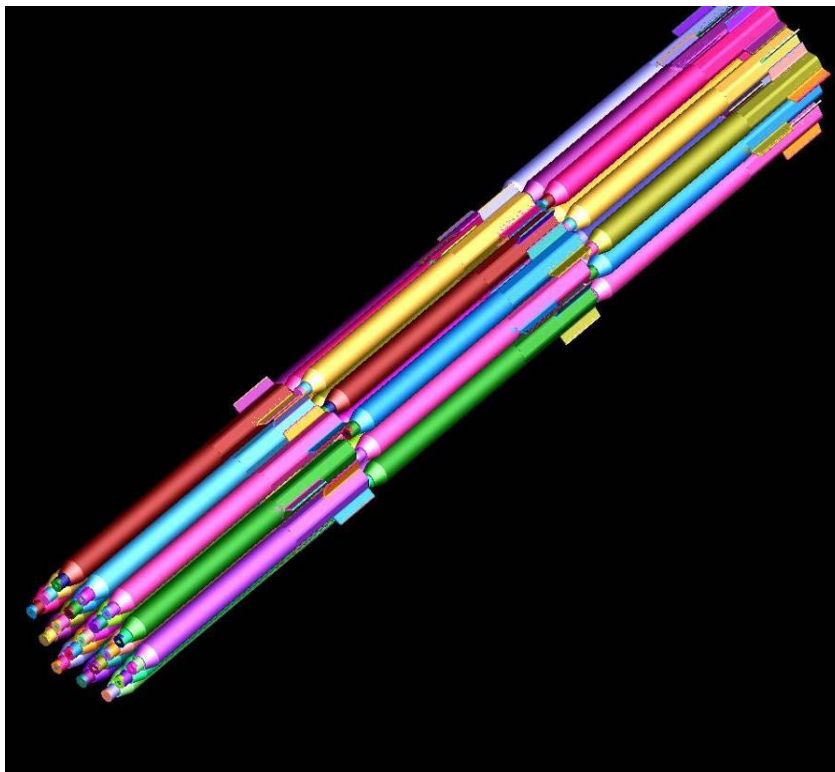


Figure 14. Dart convergence analysis.

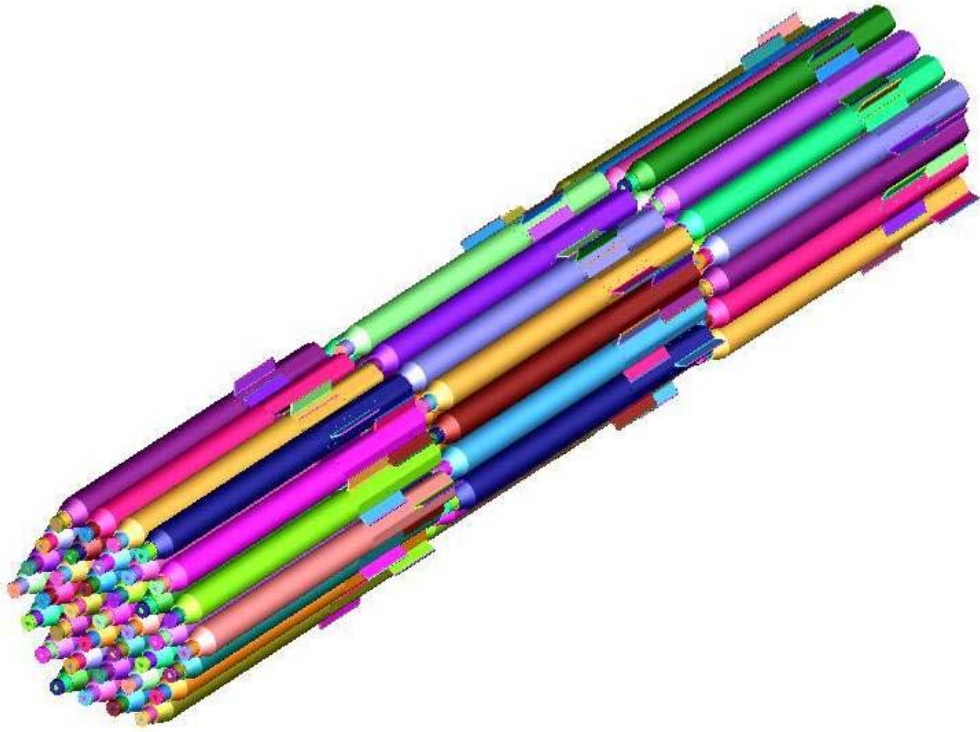




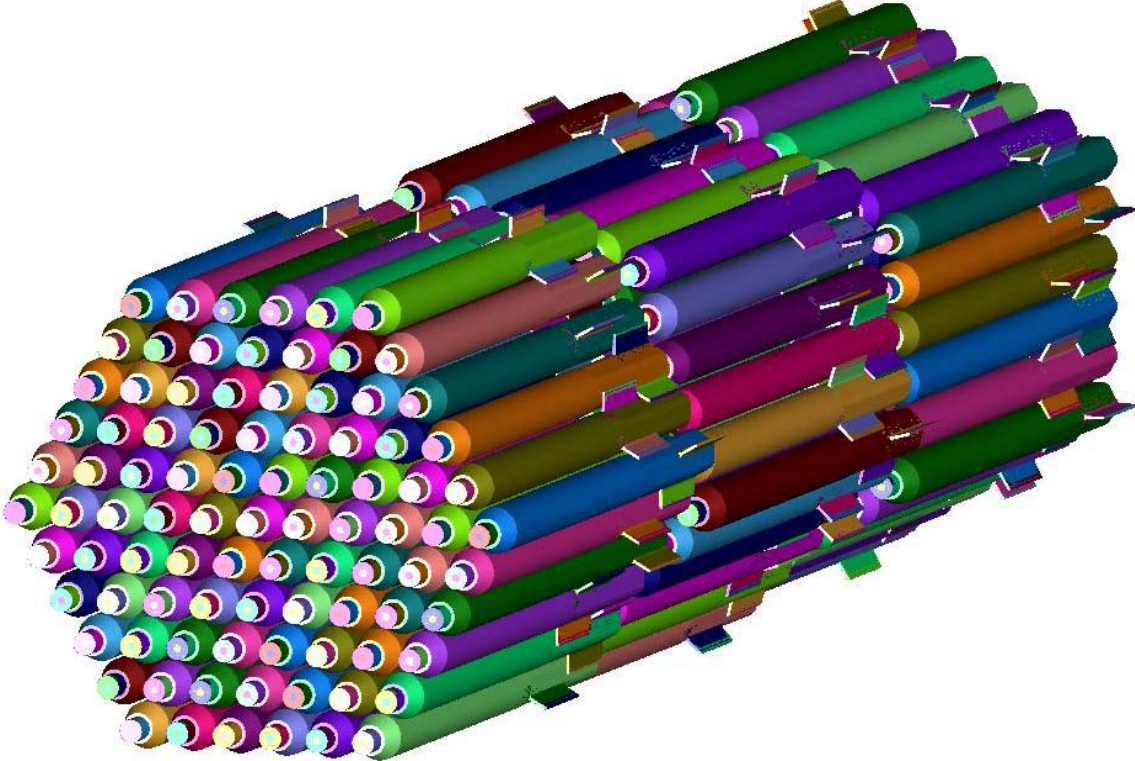
**Figure 15. Two darts intersecting due to high DTPHYS.**



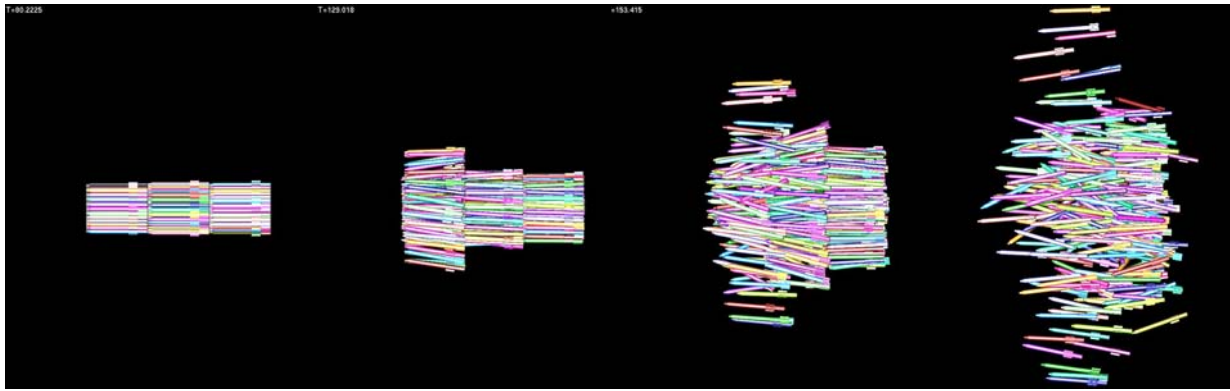
**Figure 16. 57 Dart pack consisting of three axial rows and two radial layers**



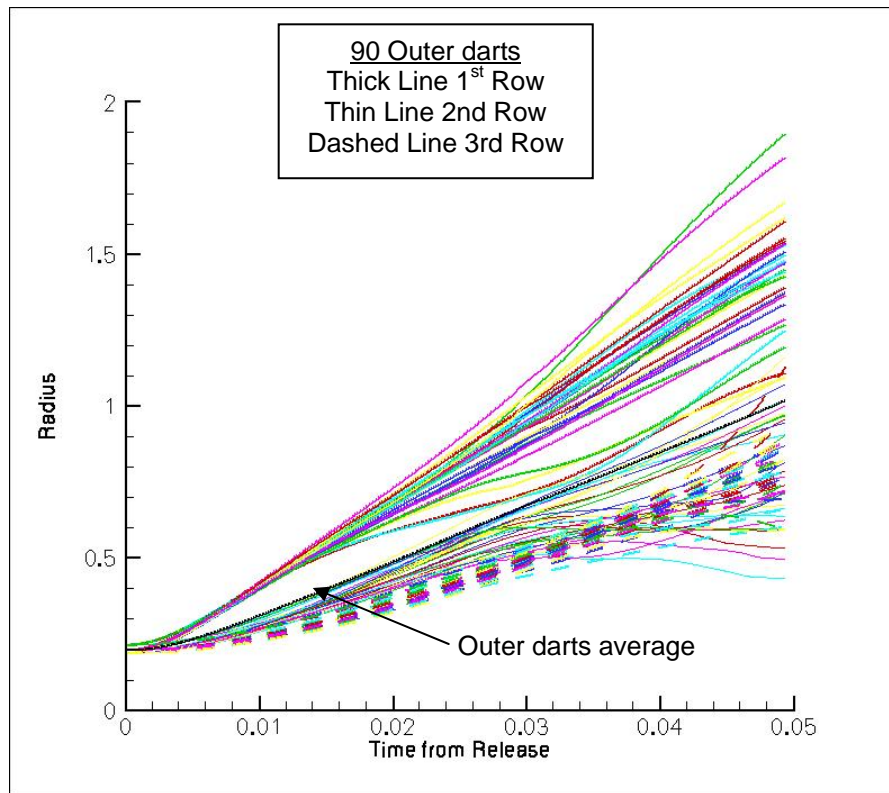
**Figure 17. 111 Dart pack consisting of three axial rows and three radial layers**



**Figure 18. 273 Dart pack consisting of three axial rows and five radial layers**



**Figure 19. 273 Dart (12 Hz) Dispense Sequence**



**Figure 20. 273 Dart (12 Hz) – Dart Radius**

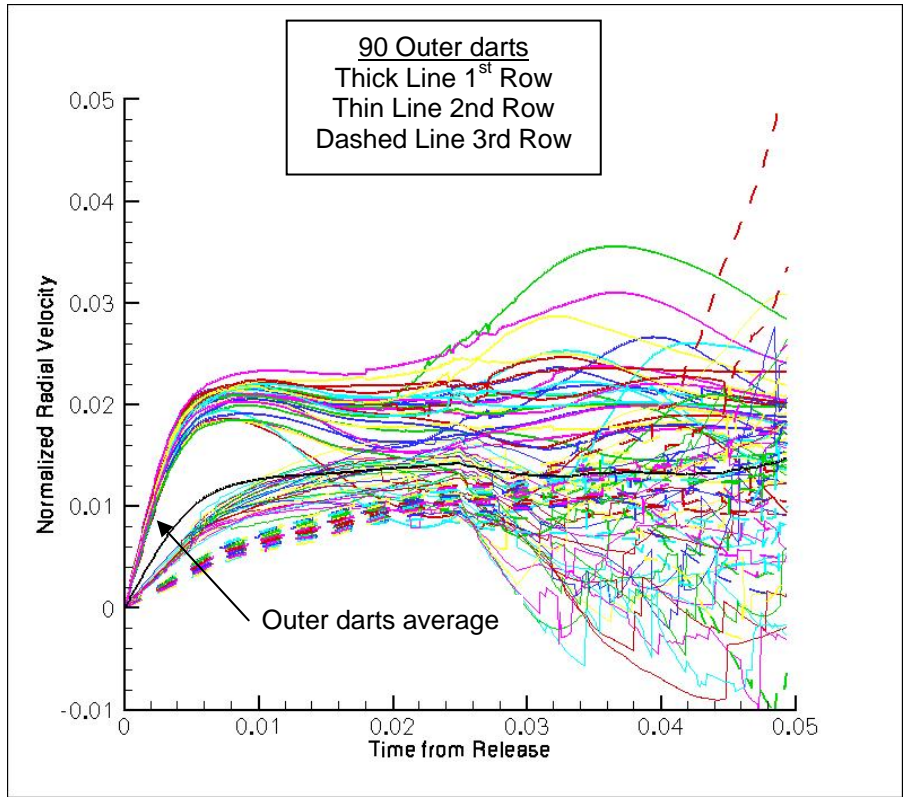


Figure 21. 273 Dart (12 Hz) – Radial Velocity

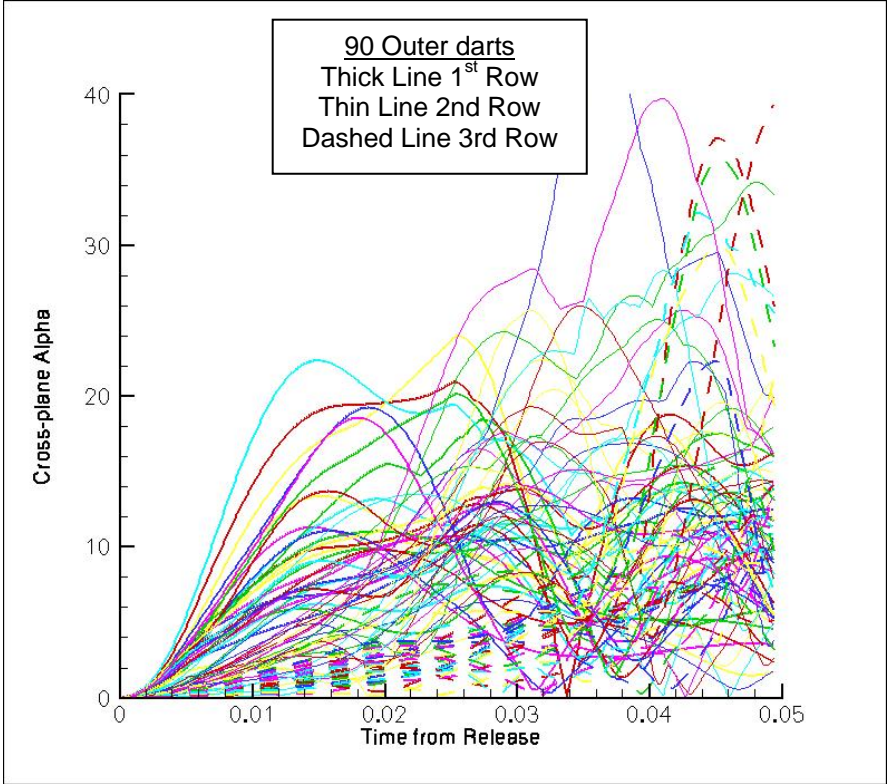
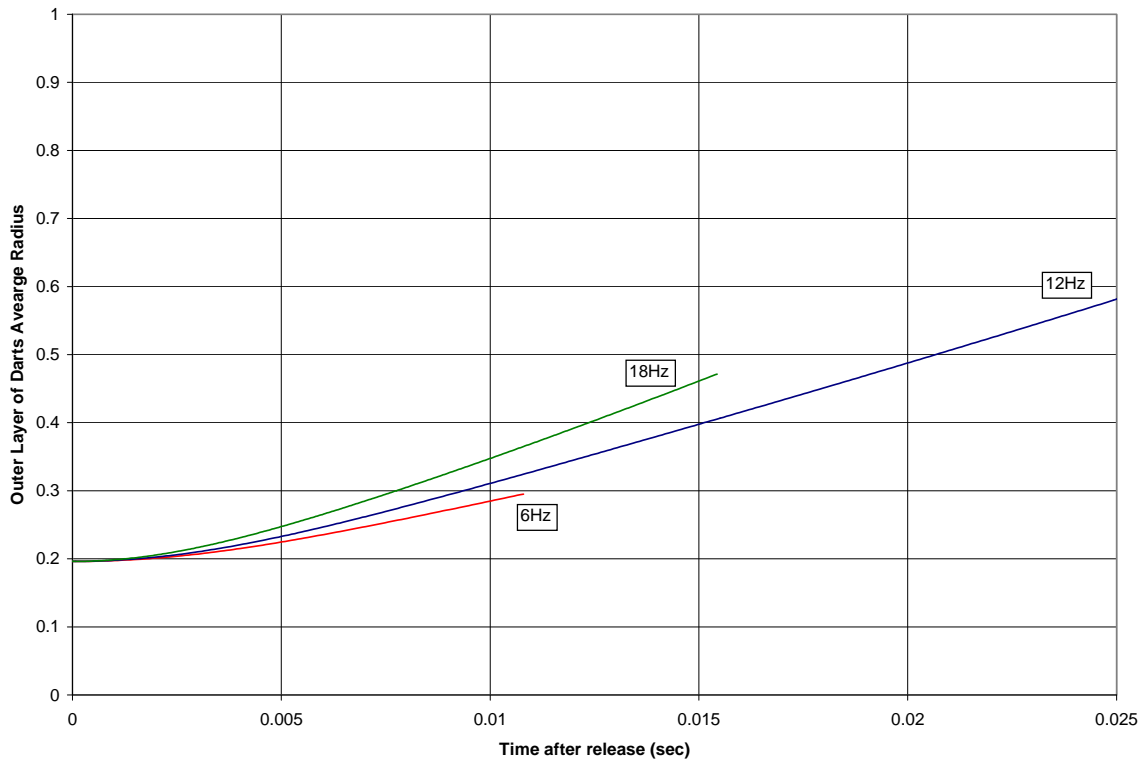
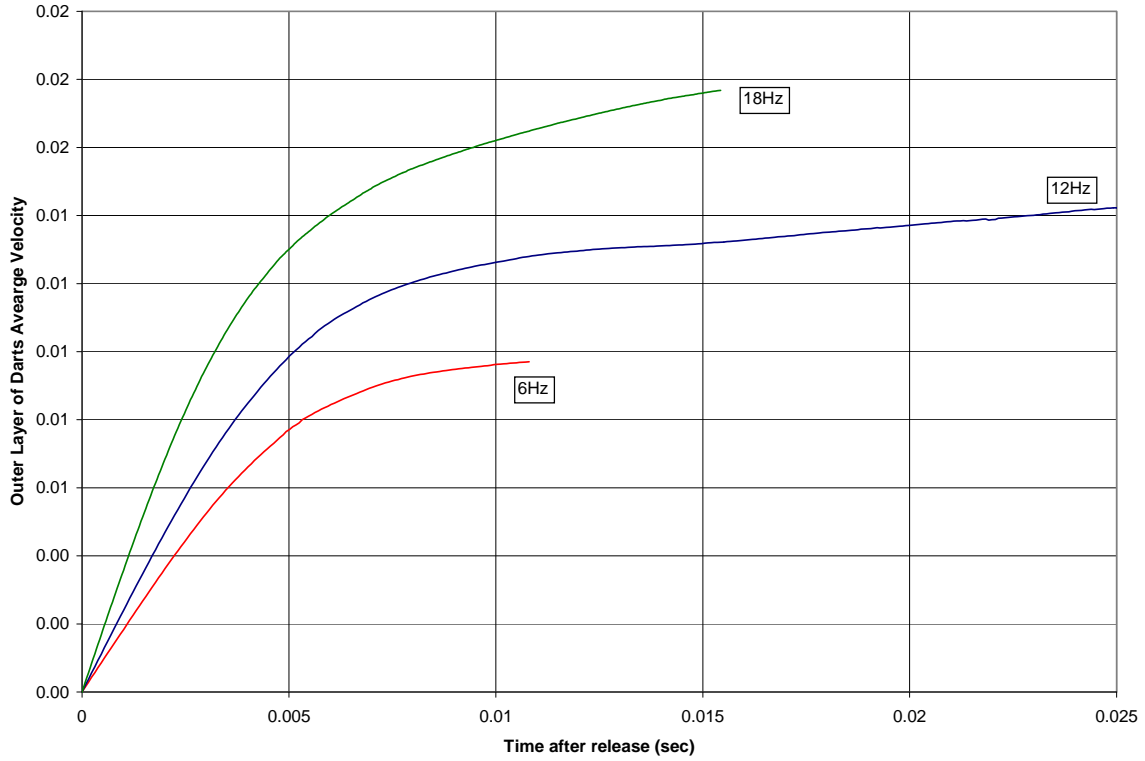


Figure 22. 273 Dart (12 Hz) – Cross-plane Angle-of-Attack



**Figure 23. 273 Darts at 3 Rotation Rates**



**Figure 24. 273 Darts at 3 Rotation Rates**