AIAA 2015-2102

Aerodynamic Decelerator Systems Technology Conferences
30 Mar - 2 Apr 2015, Daytona Beach, FL
23rd AIAA Aerodynamic Decelerator Systems Technology Conference

Optimizing Extraction Parachute Operational Parameters

Richard D. Charles*
U.S. Army Natick Soldier Research, Development, & Engineering Center, Natick, MA 01760-5017

A current area of interest in the operational and test community is the application of aerial delivery at high speed and at relatively low altitudes. The High-Speed Container Delivery System (HSCDS) is such a program intended to address this type of operational need. In conjunction with this program, a series of simulations have been conducted that attempted to cover a *parameter space* of operational variables such as aircraft type, aircraft flight speed, extraction line length, and drogue parachute design and size. The objective here is that with validated and verified modeling and simulation results anchored to actual flight test data, future exploratory test and development work may be performed with increased reliance on information derived from modeling and simulation with potential savings in the use of airdrop assets. In this effort a series of payload and parachute extraction scenarios were simulated using high fidelity computer simulation models and the Cobalt CFD (Computational Fluid Dynamics) software code. Simulations were conducted for full aircraft configurations with the rear cargo doors open. The "overset" capability of this software was used that allowed a surface geometry for the drogue parachute to be the basis for a subgrid around the parachute and for this subgrid to be set within the larger geometry grid developed around the aircraft. Different aircraft domains and grids were then used with different drogue parachute configurations while different drogue line lengths were accounted for by the appropriate displacements between the two grids. Numerically-derived resultant aerodynamic forces on the drogue parachute are compared with experimental flight force data obtained from a tow plate attached to the lower cargo door of the aircraft. This tow plate was used to anchor a tethered drogue parachute to the test aircraft. One of the operational goals of the HSCDS program was to meet the desired operational parameters of the system while operating within and managing the extraction environment within safe limits for the aircraft and its crew.

*Senior Research Aerospace Engineer, Associate Fellow, AIAA

I. Introduction

THERE has been interest recently in the topic of aerial delivery applications at limits of the operational flight envelope of the aerial delivery aircraft, namely, the extremes of low altitude and high speed that tend to help minimize the threat to the safety of the aerial delivery aircraft but which also tend to challenge the robustness of the hardware and the strength and the durability of the components of the aerial delivery systems. Past investigations have examined several of the aspects of this problem, from container subsystem specification to cargo extraction methodology.[1-3] Other past investigations have also examined the nature of flowfields behind aircraft characteristic of those used in aerial delivery and have shown that for level, steady flight, the flowfield aft of the aircraft is dominated by the geometric characteristics of the aft ends of the aircraft[4-5]. Furthermore, for situations where the aircraft is undergoing steady level flight and does not encounter cross-winds the effect of the propulsion systems is minimal on the region proximate to the open aft cargo door or ramp and was subsequently not part of the numerical simulation. In addition, there have been efforts to systematically apply numerical simulation techniques to parachute dynamics and mechanics[6]. The capability of computational tools to model and simulate complex aircraft situations, up to and including dynamic maneuvers has also been document recently.[7-8] It is then a logical step to attempt to apply the simulation techniques to predict and bound the aerodynamic force environment expected to be present in aerial delivery operations. The current investigation focused on the central issue, that for a set of given flight conditions could the aerodynamic forces be predicted numerically? And if so, what was the effect of varying the various system parameters? And where appropriate, how did the numerically determined results compare with the results obtained from flight tests?

II. Problem description

The objective of this effort was to explore the utility of numerical simulations of full aircraft in flight for the purpose of predicting operational conditions expected to be encountered during flight tests of new cargo extraction methods for aerial delivery applications.

In order to simplify the exploration, the case of a drogue extraction parachute attached to a tow plate was selected as the simulation configuration. In this scenario the drogue parachute was assumed to be fully inflated for the duration of the simulation with an attachment point to the aircraft through the extraction line connected to the tow plate. This simplification allowed a static geometry for the drogue parachute to be used within the duration of the simulation. A single ring-slot (R-S) geometry was used to approximate the drogue parachute. It was scaled as required to correspond to the test drogue parachute used in the test flight testing.

The simulations were anchored to flight test data acquired through the HSCDS (High Speed Container Delivery System) Program conducted by the U.S. Army Natick Research, Development, & Engineering Center (NSRDEC). For this test program several aircraft flew at a variety of test conditions (speeds and altitudes), using a variety of different drogue parachute constructions and sizes, and used a range of drogue parachute line lengths.

The key output parameter of the simulations was the magnitude of the drag forces encountered on the Drogue Parachute. The Drag force for these investigations was specified as the component of force on the parachute oriented along the major axis of the aircraft model (the x-axis of the Computational Grid). There were also several aircraft used in the HSCDS flight test program that included the C-17 Globemaster, and several variants of the C-130 Hercules (C-130H, C-130J, C-130J-30, MC-130, MC-130H). For the purposes of the simulations a subset of these aircraft configurations was used.

The simulations were run on computational resources supplied by the Department of Defense High Performance Computational Modernization Program (DoD HPCMP) and used the Overset capability within the Cobalt Computational Fluid Dynamics (CFD) software package supplied by and supported by Cobalt Solutions, LLC. The use of this capability allowed the simulations to be based upon the appropriate pairings of Computational Grids based upon the relevant Drogue Parachute geometry and Aircraft Geometry. The length of the Drogue Parachute Line was accounted for by adjusting the spacing between the aircraft and parachute grids, respectively. The aircraft airspeed was accounted for by specification of the airflow speed at the inlet portion of the computation domain using the Cobalt input file convention of specifying the inlet Mach number. The Cobalt CFD software was capable of simulating the flow of a gas governed by the compressible Navier-Stokes equations. The reference gas properties were set consistent with the operational altitudes of the reference flight tests.

The following figures display characteristic images of the Computational Grids used for each aircraft and the Drogue Parachute as well as displaying the smaller Drogue Parachute Computational Grid as it was placed within the larger computational grid for the aircraft. For the C-130 aircraft a Computational Grid of approximately 37 M cells was used. The C-17 computational grid possessed approximately 47 M cells. In both cases, the boundaries of the Computational Domain were on the order of two orders of magnitude away from the aircraft, which was placed approximately in the center of the Computational Grid. This spacing is shown graphically in Fig. 4 and the grid spacing is portrayed graphically in Fig.5. The Computational Model used for the Drogue Parachute is displayed in Fig. 3 with its corresponding grid boundaries indicated in the figure. The two Computational Grids, aircraft and parachute, were composited utilizing the 'overset' methodology, which is displayed in Figs. 4 and 5.

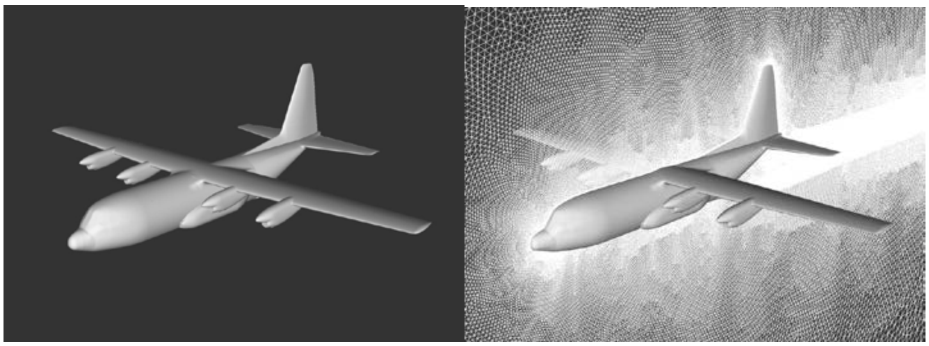

Figure 1. Computational Geometry and Computational Grid around the C-130 aircraft

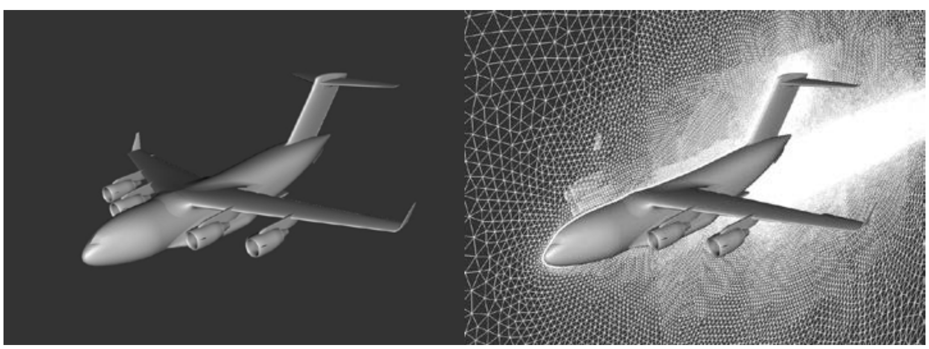

Figure 2. Computational Geometry and Computational Grid around the C-17 aircraft.

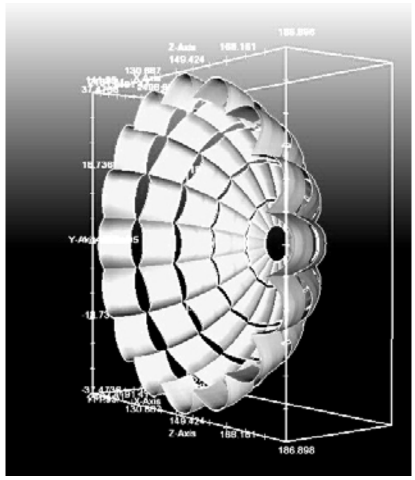

Figure 3. Computational Geometry and Computational Grid Domain for the ring-slot Drogue Parachute used.

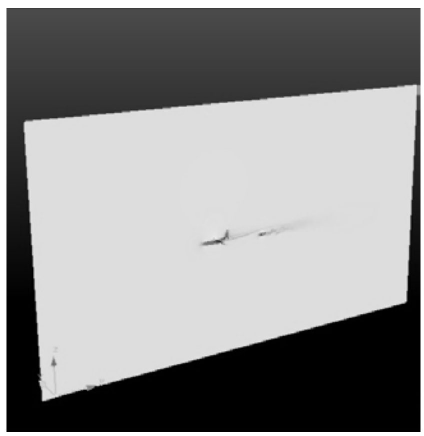

Figure 4. Scope of computational flowfield domain.

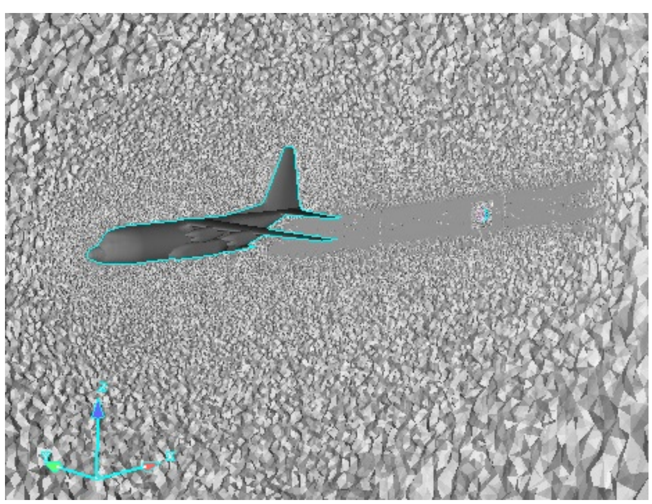

Figure 5. Combined Geometry and Computational Grid of aircraft (C-130) and Drogue Parachute Grids.

The Computational Grid used for the Drogue Parachute component was comprised of 7.6 M cells. The Computational Geometry used for the Ring-Slot Drogue Parachute is represented in Fig. 3. (A cutting plane of data through the flowfield local to the Drogue Parachute for a typical simulation is displayed in Fig. 9. The flow results around the Drogue Parachute, but imbedded within the context of the overall flowfield, are displayed in Figs. 8 and 9.)

The following figures display representative images of configurations used in acquiring the Flight Test data. In Fig. 7, sensors in the linkage to the Tow Plate measured force data representative of the longitudinal forces encountered by the Drogue Parachute.

Figure 6. Photograph of Flight Test.

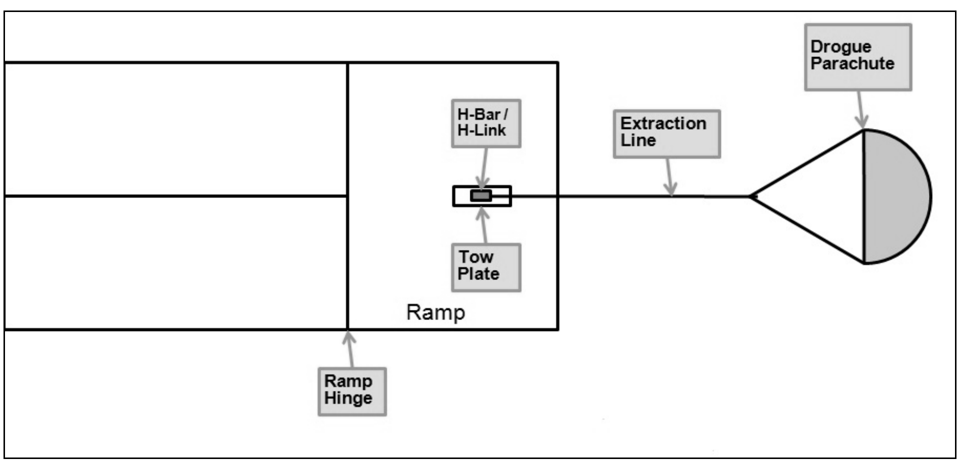

Figure 7. Tow Plate schematic of Drogue Parachute in tow configuration.

III. Results

The flow solution methodology was based upon solving the turbulent formulization of the Navier-Stokes equations where the Delayed Detached-Eddy Simulation (DDES), Spalart-Allmaras model was used. In most cases the default software turbulence model parameters were used for the simulations. The nominal default values of temporal damping were also used. Two Newton sub-iterations were used per iteration of the simulation as well as second-order temporal accuracy for the calculations.

The flight tests conducted for the HSCDS program used several different types of aircraft flying different flight profiles. In some cases the full deployment of the delivery system was tested and in some cases just the Tow Plate configuration was utilized. Only Tow Plate data was used for comparison with the numerical simulations.

The Flight Test Drag data was recorded in *CSV* (*Comma-Separated Value)* text-files and processed by Matlab script files that plotted the time record and determined the maximum Drag values for the test run.

Typical flight test airspeeds varied from 150 to 245 KIAS (Knots indicated Airspeed), while the Drogue Parachute line lengths varied from 60 to 165 feet long, and the parachute diameters varied from 100 to180 inches in diameter. It was noted after the simulations were performed that a typical Test Flight was designated by a range in indicated airspeed for the flight.

A more comprehensive treatment of the Flight Test data is being presented in a companion paper at this conference ("High Speed Container Delivery System Joint Capability Technology Demonstration" by M. R. Henry and S. Patel), where the test design, methodology, and more extensive analysis of the Flight Test are considered.[11]

Selected Flight Test Tow Force results are presented in Table 1 for the 100 inch diameter Drogue Parachute case for both the C-17 and the C-130 variants. Some general trends can be gleaned from the data. The first grouping (items 1 to 3) show the effect of increasing the aircraft airspeed results in an increase in Drag force. The second and third groupings show the trend across the aircraft where higher peak forces tend to be encountered with the C-130 as compared to the C-17 with the same line length, general airspeed, and Drogue Parachute diameter. This trend can be intuitively explained the fact that the C-17 is a bigger aircraft with a larger cross-section. The smaller size of the C-130 results in a smaller wake region. Because of this smaller wake, the towed Drogue Parachute is exposed to more of the free-stream airflow and thus encounters higher aerodynamic drag forces. The higher C-130 drag forces can also be seen in the fourth grouping (items 8 through 10). The effect of increasing the Drag Parachute line length can be seen in the last grouping (items 11 through 14) as the line length is increased from 60 to 140 feet for the C-130 aircraft, the drag forces increase. For this configuration, this trend indicates that a longer line length results in the Drogue Parachute being increasingly further extended into the near free airstream with higher relative airspeeds and larger aerodynamic drag forces.

Aircraft	Line Length (ft)	Air speed Note (KIAS)	Peak Force (lb)
1. C-17	135	150-175	3148
2. C-17	135	175-200	4071
3. C-17	135	200-225	5248
4. C-17	110	160-245	6107
5. C-17	110	160-245	6003
6. C-130	110	160-245	6350
7. C-130	110	160-245	6523
8. C-17	2x60 (120)	160-245	6072
9. C-17	2x60 (120)	160-245	6129
10. C-130	2x60 (120)	160-245	6783
11. C-130	60	160-245	6312
12. C-130	110	160-245	6350
13. C-130	110	160-245	6523
14. C-130	140	160-245	6489

Table 1. Flight Test Drag force measurements for the 100 inch diameter Drogue Parachute.

The numerical simulations were run using the grids and input files created for the simulations as per the Cobalt software package manual[9].

The simulation data was processed by requesting the calculation of the forces to be determined for the Drag Parachute *Part* of the simulation model in the Cobalt CFD input file. A Matlab script was also used to process the simulation force data to determine maximum and mean values of the time record for the force values in the drag direction. Dimensions of the Drogue Parachute geometry were based upon those for the parachutes used in the Flight Tests. Air speeds for each simulation run were maintained at a constant for each simulation. The nominal air-speed corresponding to approximately 150 Knots flight speed was bracketed by a low bounding value of 125 Knots and a high value of 250 Knots.

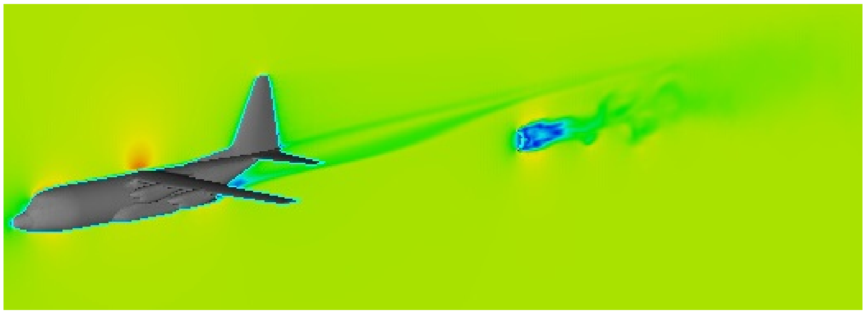

Figure 8. Detail of combined aircraft Speed in flowfield (C-130) and drogue parachute domains.

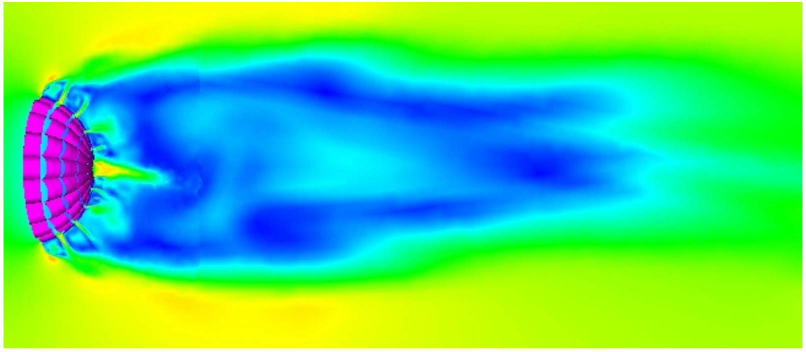

Figure 9. Detail of Speed in flowfield local to the Drogue Parachute.

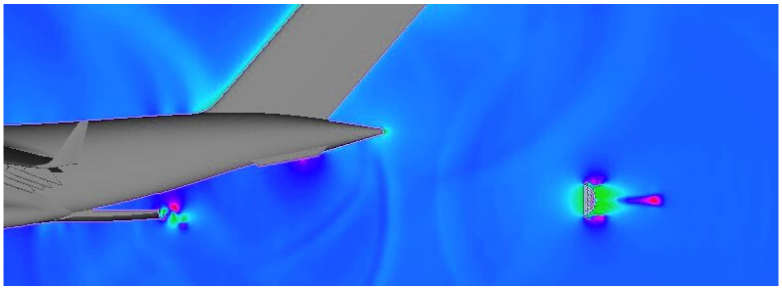

Figure 10. Dynamic pressure field detail immediately aft of the aircraft (C-17).

Selected Numerical Simulation Force results for selected conditions for the C-130 aircraft are given in Table 2. For each grouping in the table, the input parameters were held to the nominal values of a Drogue Parachute diameter of 75inches, an aircraft airspeed of 148 knots, and a Drogue Parachute Line Length of 135 ft. Additional values of Drogue Parachute Diameters of 100 and 110 inches, Line Lengths of 60 and 150 ft., and aircraft airspeeds of 125 and 250 knots, were used.

Drogue Parachute Diameter (in)	Line Length (ft)	Air speed (knots)	Maximum Force (lb)
1. 75	135	148	3338
2. 75	135	148	3344
3. 75	60	148	3513
4. 75	150	148	3340
5. 100	135	148	6018
6. 110	135	148	7249
7. 75	135	125	2334
8. 75	135	250	10530

Table 2. Drag Force values for various C-130 simulation runs.

The numerical simulation data was used to attempt to bracket the Flight Test data. A nominal airspeed of approximately 148 Knots was used and a lower value of 125 Knots and an upper value of 250 Knots were also used for various simulations. A nominal size of 75 inches was chosen for the Drogue Parachute size, but the other Drogue Parachute sizes of 100 and 110 inches were also investigated. A nominal Line length of 135 feet was used but the values of 60 and 150 feet for the Line length were included as part of the parameter space investigation. For items 1 and 2 in Table 2, slightly different values of vertical placement for the Drogue Parachute were used in order to investigate the sensitivity of the simulations to vertical placement with the results of showing that to this level of approximation that the vertical placement of the parachute within the wake region didn't have a strong effect upon the resultant Drag force value. Simulation runs 1-4 attempted to capture the first order effect of line length on the resultant Drag forces. Except for a slightly higher value for the shorter Line Length, the simulation results seemed to be rather insensitive to this parameter variation also. The comparison of items 1, 5, and 6, yielded the predictable result that an increase in the parachute size resulted in greater Drag forces. Comparing items 1, 7, and 8, showed the equally predictable trend that increased aircraft air speed resulted in greater Drag forces. Although not possible to make a direct comparison, the values for items 1, 7, and 8, of Table 2 are not inconsistent with the trend shown in comparing items 1, 2, and 3, of Table 1 for the Flight Test results for the C-17 aircraft, and items 10 and 14 of Table 1 for the C-130 aircraft.

IV. Conclusions

An essential element of Verification and Validation of simulation exercises as documented by authors on the subject[10] is the notion of viewing it as an iterative process where concerns raised in the simulation efforts are communicated to the experimenters and critical issues of interest to the experimentalists are conveyed to the numerical simulator until both efforts are robust enough to be able to minimize the uncertainty of the results to ensure rock solid agreement of the compared results. The investigation reported in this effort documents essentially the first iteration of a comparative study where experimental tests were performed in the context of drop tests from actual aircraft and the numerical simulations attempted to duplicate the test conditions. Such issues such as the definition or control of the aircraft air speeds throughout the course of test or simulation runs so that they matched their corresponding counterpart is one such area where the Verification and Validation methodology could be refined especially as the final variable of comparison, the Drag force can be seen to be at least in one of its components proportional the air speed velocity to the second power.

In general, the numerical simulation data showed satisfactory agreement to the experimental flight test data but there is great room for improvement in both methodologies in order to tighten up the agreement between the two. The level of agreement is believed sufficient to have confidence in the use of the computational techniques to provide predictive tools for future system development efforts, hopefully providing some relief from the need to perform as many flight tests in the future, although such tests will always be required for the refinement of such systems.

Acknowledgments

The computational grids were developed by personnel at Cobalt Solutions, LLC. The numerical simulations were performed at the U.S. Army Research Laboratory Department of Defense (DOD) Supercomputing Resource Center (ARL DSRC) and the U.S. Air Force Research Laboratory DOD Supercomputing Resource Center (AFRL DSRC) on computational hardware using software licenses for the Cobalt CFD software program supplied by the DoD High Performance Computing Modernization Program (HPCMP). Computational results were processed utilizing Utility Server (US) hardware at both Centers and were visualized using the Ensight software program.

The technical program was supported through U. S. Army Airdrop and Aerial Delivery Science and Technology Development program funds.

The author would like to thank the invaluable help of Mr. Kenneth Wertzler and Dr. Robert Tomaro of Cobalt Solutions, LLC, with their assistance with performing the current simulations and for their previous efforts with creating the computational grids and problem definitions for the previous, initial proof-of-principle simulations.

References

[1]Munroe, J. E., Hogseth, C. J, Billoni, D. J., and Rei, S. A., "High-Speed Container Delivery System (HSCDS): Trade-off Determination", U.S. Army Natick Research, Development, and Engineering Center, Natick Technical Report TR-92/050, September, 1992.

[2]Munroe, J. E., "High-Speed container Delivery System (HSCDS): Best Technical Approach", U.S. Army Natick Research, Development, and Engineering Center, Natick Technical Report TR-92/051, September, 1992.

[3]Behr, V. L., "The Development of a Parachute System for Aerial Delivery from High Speed Cargo Aircraft", AIAA-93-1232, *Proceedings of the 12th Aerodynamic Decelerator Systems Technology Conference and Seminar*, London, England, 10-13 May, 1993.

[4]Peake, D.J., "The Flows about Upswept Rear Fuselages of Typical Cargo Aircraft", *Quarterly Bulletin of the Division of Mechanical Engineering & the National Establishment DME/NAE 1968 (3),* July 4 – Sept. 30, 1968, pp. 31-44.

[5]Bergeron, K., Hayes, M., Aronoff, J., and Charles, R., " C-17 Low Speed Wind Tunnel Wake-Vortex Study", *AIAA 2009-1482, 47th AIAA Aerospace Sciences Meeting,* Orlando, FL, 5-8 January, 2009,

[6]Charles, R., et al. "Overview of the Airdrop Systems Modeling Project within the Collaborative Simulation and Test (CST) Common High Performance Computing Software Support Initiative (CHSSI) Portfolio," AIAA-2005-

1621, *Proceedings of the 18th Aerodynamic Decelerator Systems Technology Conference and Seminar*, Munich, Germany, 23-26 May, 2005.

[7]Clifton, James, et al. "Determining the Stability and Control Characteristics of High-Performance Maneuvering Aircraft Using High-Resolution CFD Simulation with and without Moving Control Surfaces." *50st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Nashville, TN, 6-9 January, 2012.

[8]Snyder, Murray R., et al. "Validation of ship Air Wake Simulations and Investigation of Ship Air Wake Impact on Rotary Wing Aircraft." *American Society of Naval Engineers Launch and Recovery Symposium, Linthicum, MD*. 2012.

[9]*Cobalt User Manual*, Cobalt Solutions, LLC, February 13, 2013.

[10]Oberkampf, W.L., and Tuscano, T.G., "Validation Methodology in Computational Fluid Dynamics," *Fluids 2000*, AIAA 2000-2549, Denver, CO, 19-22 June, 2000.

[11]Henry, M. R., "Extraction Parachute Development for the High Speed Container Delivery System," *Proceedings of the 23rd Aerodynamic Decelerator Systems Technology Conference and Seminar*, Daytona Beach, FL, 30 March-2 April, 2015.