

Article

Simulation and Stability Analysis of a Coupled Parachute–Payload System [†]

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[†] This article is an extended version of the paper entitled “Simulation and Stability Analysis of a Coupled Parachute-Payload System”, presented at AIAA AVIATION FORUM AND ASCEND 2024, Las Vegas, NV, USA, 29 July–2 August 2024, AIAA Paper 2024-4514.

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Abstract: High-fidelity simulations are used to study the stability of a coupled parachute–payload system in different configurations. A 8.53 m ring–slot canopy is attached to two separate International Organization for Standardization (ISO) container payloads representing a Twenty Foot Equivalent (TEU). To minimize risk and as an alternative to a relatively expensive traditional test program, a multi-phase design and evaluation program using computational tools validated for uncoupled parachute system components was completed. The interaction of the payload wake suspended at different locations and orientations below the parachute were investigated to determine stability characteristics for both subsonic and supersonic freestream conditions. The DoD High-Performance Computing Modernization Program CREATETM-AV Kestrel suite was used to perform CFD and fluid–structure interaction (FSI) simulations using both delayed detached-eddy simulations (DDES) and implicit Large Eddy Simulations (iLES). After analyzing the subsonic test cases, the simulations were used to predict the coupled system’s response to the supersonic flow field during descent from a high-altitude deployment, with specific focus on the effect of the payload wake on the parachute bow shock. The FSI simulations included structural cable element modeling but did not include aerodynamic modeling of the suspension lines or suspension harness. The simulations accurately captured the turbulent wake of the payload, its coupling to the parachute, and the shock interactions. Findings from these simulations are presented in terms of code validation, system stability, and drag performance during descent.

Keywords: chute stability; CFD; airdrop; cargo extractions; supersonic flow; bluff bodies



Academic Editor: Konstantinos Kontis

Received: 12 December 2024

Revised: 24 January 2025

Accepted: 29 January 2025

Published: 31 January 2025

Citation: Bergeron, K.; Ghoreyshi, M.; Jirasek, A. Simulation and Stability Analysis of a Coupled Parachute–Payload System. *Aerospace* **2025**, *12*, 116. <https://doi.org/10.3390/aerospace12020116>

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1. Introduction

Cargo airdrop operations have been dominated by operations in subsonic environments, typically at altitudes less than 7.62 km, but the recent interest in commercial space applications have warranted a resurgence in developing robust and economical earth reentry capabilities. A system of systems, such as demonstrated in many manned and unmanned programs, is commonly used to slow the payload from initial speeds on the order of Mach $M = 25$ to below 8.53 m/s. While the parachute system for the manned Orion crew vehicle uses eleven parachutes in a four-stage sequence to decelerate [1] the

vehicle, other unmanned systems have used a combination of inflatable aerodynamic decelerators in conjunction with a single parachute to enable payload recovery [2]. Several private companies have proposed alternative deceleration sequences using proprietary technologies, for example Sierra Space's Ghost vehicle (Figure 1), a cutting-edge vehicle engineered to deliver essential supplies from orbit to any location on Earth within 90 min. Created through Sierra Space's Axelerator incubator program, the Ghost is equipped with a deployable decelerator to protect pre-staged payloads during atmospheric re-entry. Capable of remaining in orbit for up to five years, it stands ready to provide critical resources, including survival kits, medical aid, and logistical support, exactly when and where they are required [3].



Figure 1. Sierra Space Ghost [3].

However, due to their mass and packed volume, parachutes still provide an efficient means of addressing certain portions of the reentry deceleration range. Hyperflo parachutes function at hypersonic speeds, but are restricted to relatively small sizes Knacke [4]. Alternatively, ribbon canopies have an upper limit of $M = 3$ while being capable of supporting payloads on the order of 45,000 lbs Pepper and Maydew [5]. More recently, the Disk–Gap Band (DGB) and Supersonic Ring–Sail (SSRS) parachute designs have been extensively tested for supersonic descent in support of Mars exploration missions. Xue and Wen [6].

Beyond basic parachute design, the payload characteristics significantly influence the efficiency and stability of the reentry system. For a given freestream velocity, slender-body wakes are much smaller than those of bluff or blunt bodies; thus, the dynamic pressure experienced by the parachute will be greater for the slender body. In addition, the interaction between the highly unsteady wake of a bluff body and the parachute bow shock is stronger than that associated with a slender body.

The computational investigation presented in this article is motivated to further refine a baseline capability and process for a systems sweep across parachute types and payloads for supersonic descent through the Earth's atmosphere as well as to investigate a system comprised of a commonly used parachute with a commonly used shipping container. Specifically, the model system consists of a rigid 8.53 m ring–slot parachute model coupled to a twenty-foot equivalent ISO container (TEU) in two configurations, and the flow conditions include both subsonic and supersonic velocity test cases. After a brief overview of prior DEVCOM Soldier Center (SC) research on the aerodynamics of prisms (rectangular boxes) and rigid ring–slot parachutes and a more general overview of supersonic parachute applications, the article follows with a section focusing on the simulation setup, resources, and initial validation and verification (V&V). The next section includes the preliminary results of this research campaign, including integrated forces and moments and flow field results showing the effects of TEU orientation and positioning upstream of the parachute

with freestream velocities of $M = 0.5$ and $M = 2.0$. An initial look at dynamic stability completes this section, then the article closes with plans for future work. This study presents a novel approach to analyzing the stability of a coupled parachute–payload system using high-fidelity simulations. Responding-body motions and cables are used to present the dynamic stability of the payload–parachute system under different conditions.

2. Prior Work

Several factors affect the integrated performance metrics, such as C_P , C_D , and C_{M_α} , which characterize drag efficiency as well as static and dynamic stability for parachute–payload interaction analyses. Rigid models for the parachute coupled with independent 6-DoF dynamic modeling allow for a focus on the system flow fields related to variations in canopy and payload geometries, relative proximity of canopy and payload, Mach number (M), Reynolds number based on the parachute nominal diameter (Re_{D_0}), effective angle of attack α , fluid density ρ , and geometric porosity λ_g . However, several important factors not included in this analysis are related to parachute textile characteristics such as structural mechanical dynamics and fabric permeability, which can be modeled as an effective porosity λ_e , as done by Heinrich [7]. Finally, aerodynamic heating becomes an increasingly important consideration as the Mach number increases, especially beyond $M > 5$. For the current work, because the airspeed remains below the hypersonic cutoff, the heating associated with air compression and viscous dissipation of kinetic energy is not included in the analyses.

2.1. SC Subsonic Rigid Ring–Slot Parachute Modeling

To increase the understanding of parachute flow physics and stability, the authors have worked on several computational cargo airdrop projects based on the ring–slot design, including Noetcher et al. [8], Bedwell et al. [9], Bergeron and Ghoreyshi [10], [11] and the citations therein. Care was taken to validate the models using pressure-based fluid–structure interaction (FSI) simulations to capture accurate inflated geometries, with results compared against published wind tunnel data for rigid models. Additional simulations extrapolated the associated flow physics and the interactions with external flows, whether freestream or aircraft. One engineering observation, specific to the current application, was the ability to optimize pack volume while maintaining very close agreement (approximately 1%) with respect to C_D and C_{M_α} for relatively large changes (4%) in geometric porosity. This benefit was seen specifically for a “baseline” canopy with $\lambda_g = 16.9\%$ by strategically placing “windows” in the ring–slot design, Figure 2 Bergeron et al. [11].

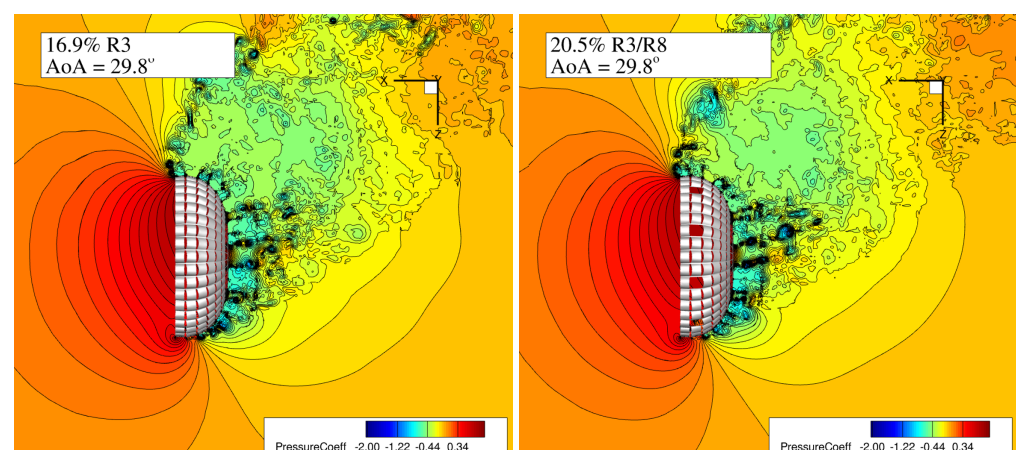


Figure 2. Center-plane pressure contours: $\alpha = 29.8^\circ$.

2.2. SC Prismatic Shape Aerodynamics Studies

While significant efforts have been associated with coupled parachute–payload systems with relatively aerodynamic shapes, for example Ewing et al. [12], Sengupta et al. [13], and O’Farrell et al. [14], the associated parametric investigation for non-aerodynamic shapes has not received the same attention. The TEU is chosen as a representative generic prism shape due to its widespread use in standard freight transport. Along with the ISU-90, it represents containers designed to standardize and facilitate packing/stacking for transport vehicles, including trains and ships as well as freight storage facilities. As such, this work complements recent studies of aerodynamic stability for prisms used for helicopter sling loads Bergeron et al. [15], Benson et al. [16], and Metzler et al. [17].

Figure 3 shows results from Benson et al. [16] depicting the integrated forces and moments as functions of the angle of attack. As with the parachute simulations, a rigorous V&V was conducted. Indeed, while many flow fields can support a given set of integrated metrics, the comparison of surface streamlines between experiment and simulations matches within the degree of uncertainty associated with the very small amount of wind tunnel angularity. Therefore, the volumetric flow field can be assumed to correlate equally well. Figure 4 illustrates the surface and volume streamlines for the condition with $\alpha = 15^\circ$ and $M = 0.2$.

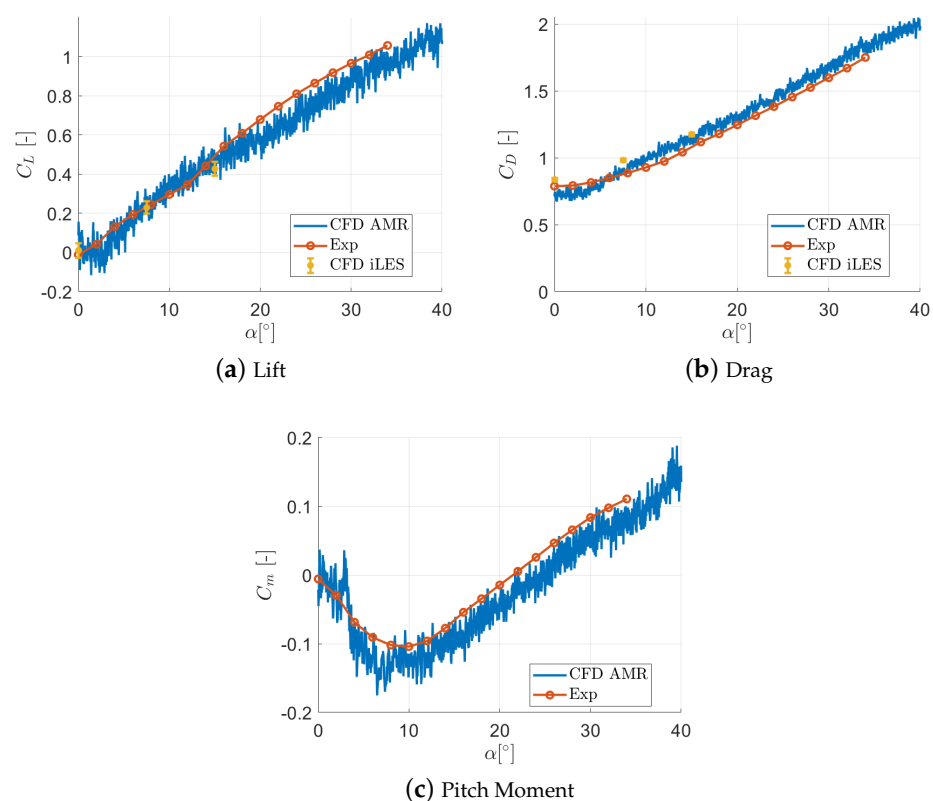


Figure 3. Comparison of forces/moment data for experiments (red markers) and simulations (blue curve) for the axial configuration of the TEU.

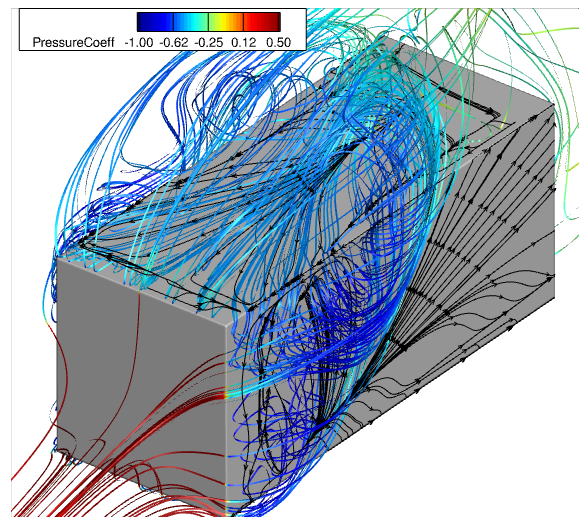


Figure 4. Surface and volume streamlines of TEU for the condition with $\alpha = 15^\circ$ and $M = 0.2$.

The complexity of these bluff-body flow fields naturally increases with supersonic speeds and the introduction of shocks. Thus, the downstream influence of the wake on the parachute becomes more pronounced, as we discuss in the results section below.

2.3. Recent Supersonic Computational Analyses

While testing of supersonic parachutes can be traced back to the 1950s, the last two decades have seen a concentrated effort in the domain of computational research and development programs. This is mainly attributable to interest in Mars exploration missions, though some commercial companies, most notably SpaceX, have increased their launch rates, and consequently their need to address re-entry and the supersonic environment. Using Detached Eddy Simulations (DES), Fan et al. [18] were able to capture the “pulsation” flow mode observed in experiments for relatively close trailing distances between the canopy and the capsule. Recently, Xue and Wen conducted a review of efforts extending as far back as NASA’s 1976 Viking program [6]. The majority of parachute designs have been based on the DGB, with extensive testing of a Supersonic Ring–Sail (SSRS) through NASA’s Low-Density Supersonic Decelerator (LDSD). In particular, the testing of the SSRS design led to a reexamination of the structural testing process of conducting proof loading at subsonic speeds using ground tests to bound the supersonic inflation loading. Subsequently, the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) project focused on heritage DGB designs and structural strengthening. Of particular note, NASA has supported several computational teams which have significantly advanced the state of Fluid–Structure Interaction (FSI) modeling by using embedded/immersed boundary methods in deployment analyses Rabinovitch et al. [19], Boustani et al. [20], and Yu et al. [21].

3. Physical and Computational Setup

For detailed presentation of the meshing, numerical approach (including, turbulence models), time step, Newton sub-iterations, and temporal damping, the authors refer the reader to material in [9,16,22,23] and the references therein. This section highlights components of the simulation that are unique to the presented results, specifically the setup and orientation of the payload–parachute system and RANS grids used in the simulations.

3.1. Models

The chute geometry definitions are shown in Figure 5. The 8.53 m ($=D_O$) ring–slot parachute (RS) model has a geometric porosity of $\lambda_g = 11.5\%$, which correlates well with the range of the DGB parachutes discussed in Xue and Wen [6]. The ratio D_P/D_O of

the projected diameter to the nominal diameter is 0.775. The TEU is 6.06 m long, 2.44 m wide, and 2.59 m tall. The initial goal of the study was to compare the efficiency and stability of two different payload orientations for trailing distances between the payload and parachute X/d based on predefined distances of $X = 10, 20, 30$ m. Using the height of the TEU as the reference distance $d = d_h$, Figure 6 denotes the simulated payload–parachute configurations. While this nondimensional definition permits analysis based on configuration, it does not correlate with the standard ratio definition of X/d , where d represents the largest diameter. Alternatively, a comparison between the results of this article with respect to the standard definition would result in a ratio for the TEU2 configuration that needs to be defined using the length of the TEU such that $d = d_l$ and $X/d_l = 4.95, 3.30, 1.65$, respectively, for the TEU2 configuration.

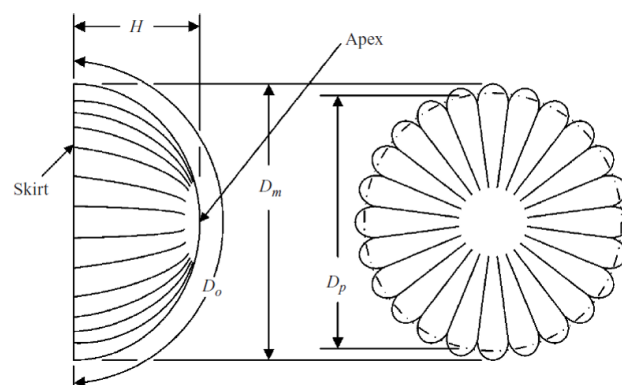


Figure 5. Chute geometry definitions.

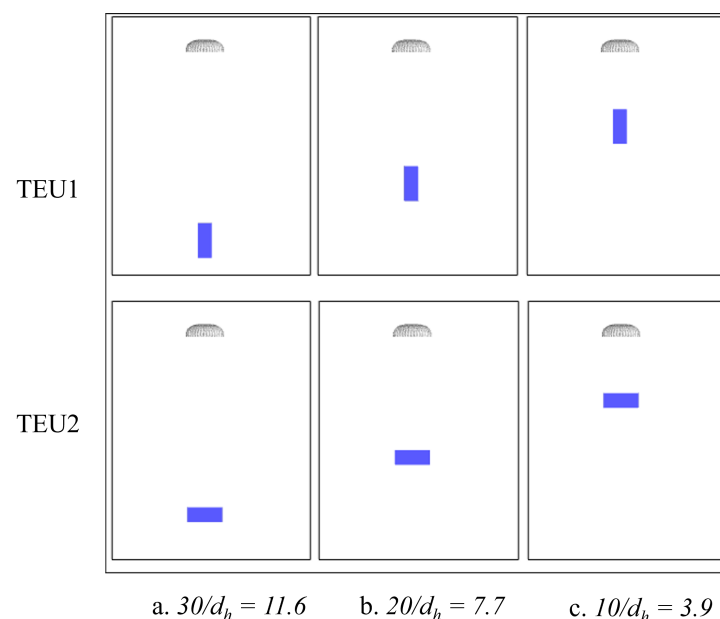


Figure 6. Configurations of payload to canopy skirt based on d_h .

In addition to fixing the geometry configurations to be simulated, the project was limited for this first analysis to two Mach numbers, namely, $M = 0.5$ and $M = 2.0$. The simulation altitude was 30 km, and standard atmosphere modeling was assumed.

To assist with the analysis of the efficiency of the payload–parachute system, Figure 7 indicates the position of “tap” locations for interrogating the flow velocity to indicate the various wake deficits. Tap points were placed both upstream and downstream of the parachutes and their positions remained fixed across all simulation setups, making them independent of the distance between the payload and the chute. The tap points span a

region of $1D_p$ (where D_p is the parachute's projected diameter), with each row consisting of ten points spaced at intervals of $0.1D_p$. Upstream tap locations were positioned at $0.5D_p$, $1D_p$, $1.5D_p$, and $2D_p$. From the chute skirt, while downstream tap locations were situated at $1D_p$, $1.5D_p$, $2D_p$, and $2.5D_p$ from the chute skirt.

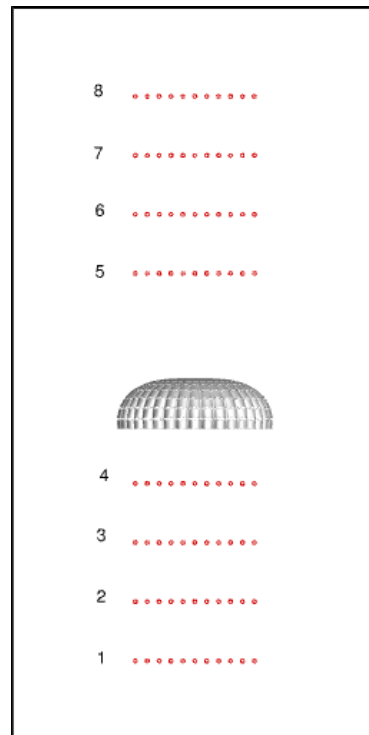


Figure 7. Tap locations aligned with the transverse mid-plane of the flow.

3.2. Computational Setup

The simulations were completed on two HPCMP supercomputer systems: Onyx, a Cray XC40/50 system at the Engineer Research and Development Center, DoD Supercomputing Resource Center (DSRC) in Vicksburg, MS; and Narwhal, an HPE Cray EX system at the Navy DSRC, Stennis Space Center, MS.

3.2.1. Meshes

The baseline mesh (Figure 8) for the 8.53 m ring-slot canopy was a 69.5 M cell hybrid grid with a structured density box in the streamwise direction behind the canopy. An initial set of adaptive mesh refinement simulations were computed to define the wake region. The purpose of this structured density box was to better resolve the flow features within the wake of the canopy. The grid convergence was examined in a prior study by Ghoreyshi et al. [23]. In that study, the same parachute as in the current research was simulated, and grids with varying refinement levels were analyzed. Additionally, an adaptive mesh refinement was tested. The grids used in this study are comparable to “Grid 4” (the finest grid) from the referenced work. The mesh used for the ring-slot also included an isotropic layer surrounding the surface of the canopy. This layer allowed for higher resolution of the flow features within the boundary layer of the canopy. A total of 50 layers were constructed at a growth rate of 1.25. The y^+ of this mesh was ≈ 1 .

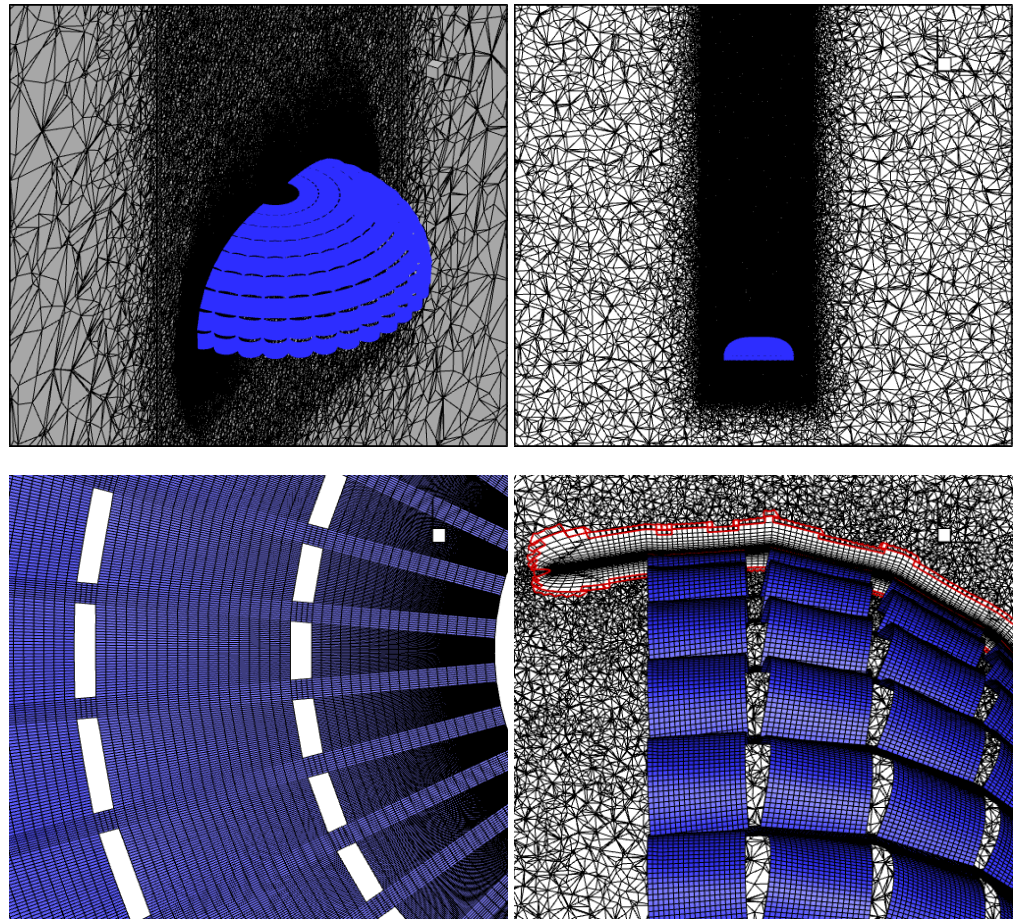


Figure 8. RANS grid.

3.2.2. Flow Solver Summary

Kestrel is the fixed-wing product of the CREATE-AV program funded by the DoD High-Performance Computing Modernization Program (HPCMP). The objective of the CREATE program is to improve the Department of Defense's acquisition time, cost, and performance by using state-of-art computational tools for the design and analysis of ships, aircraft, and antenna. Kestrel is specifically developed for multidisciplinary fixed-wing aircraft simulations, incorporating components for aerodynamics, jet propulsion integration, structural dynamics, kinematics, and kinetics [24]. The code has a Python-based infrastructure that integrates Python, C, C++, or Fortran-written components [25]. Kestrel 10.4.1 is used in this work. The code has been extensively tested and a variety of validation documents have been reported.

Kestrel CFD solvers include KCFD [26], COFFE [27], and KCFD/SAMAir [28]. The KCFD flow solver is used in this study. KCFD uses a second-order accurate cell-centered finite-volume discretization; however, SAMAir utilizes a fifth-order finite-volume discretization on Cartesian meshes [29]. Specifically, the KCFD flow solver discretizes the Reynolds-Averaged Navier–Stokes (RANS) equations in second-order cell-centered finite-volume form. The code then solves the unsteady three-dimensional and compressible RANS equations on hybrid unstructured grids [30]. The KCFD flow solver uses Method of Lines (MOL) to separate the temporal and spatial integration schemes [26]. The spatial residual is computed through a Godunov type scheme [31]. Second-order spatial accuracy is obtained through a least-squares reconstruction. The numerical fluxes at each element face are computed using various exact and approximate Riemann schemes, with a de-

fault method based on HLLE++ scheme [32]. In addition, the code uses a subiterative, point-implicit method (a typical Gauss–Seidel technique) to improve the temporal accuracy. Among the turbulence models available within Kestrel are Spalart–Allmaras (SA) [33], Spalart–Allmaras with rotational/curvature correction (SARC) [34], Menter’s SST [35], and Delayed Detached Eddy Simulation (DDES) with SARC [36].

Several advanced-capability components of Kestrel were used during these simulations. The laminar equation set known as implicit Large Eddy Simulation (iLES) was employed for the simulations of the ring–slot-TEU system. The time step size (T_s) was set to $1e-3$ with 8000 startup iterations. The simulations were then run for 4000 iterations. The unsteady residuals are depicted in Figure 9.

An initial dynamic stability set of simulations for these configurations was investigated using a responding-body motion between the fixed payload and the chute. For responding-body motions, the weight and balance data of the chute were estimated; the chute then responded to aerodynamic forces and its weight. A “ball” constraint was defined to keep the distance to the suspension line confluence point constant during the motion. In addition, the catenary modeling capability was tested for the static lines during the responding-body motions.

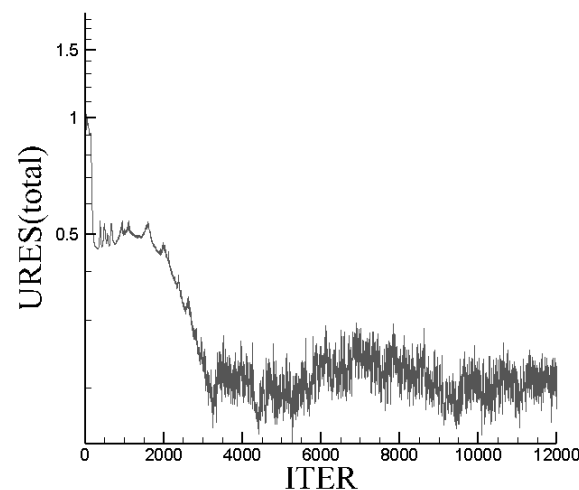


Figure 9. Unsteady residual for chute in freestream with $M = 2.0$ and 30 km altitude.

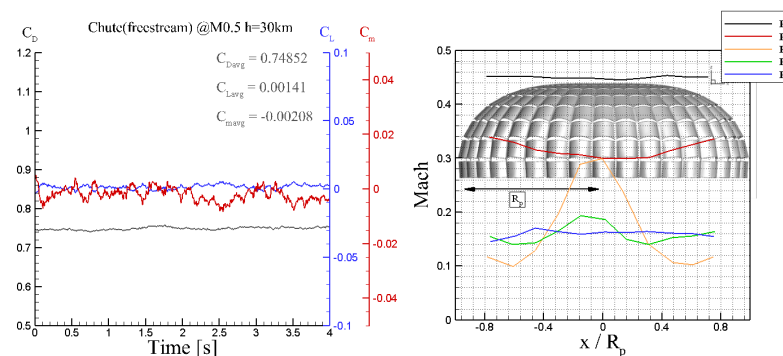
4. Results and Discussion

Table 1 summarizes the completed simulations. For clarity, the identifiers $M2$ and $M05$ are assigned to the cases with Mach 2.0 and Mach 0.5, respectively. The columns represented by $C_{D\delta}$, $C_{L\delta}$, and $C_{M\delta}$ represent the standard deviations of the time histories used to compute the averaged drag, lift, and moment coefficients, respectively. The magnitude of $C_{L\delta}$ and $C_{M\delta}$ relative to their averages reflects not only the unsteadiness but also the relatively small contribution to the dynamics compared to the dominance of drag. This is indicative of the symmetry and stability of the ring–slot parachute design. The frequency f is a measure of the dominant component of the vortex shedding.

Table 1. Time-averaged, variance, and PSD analyses of chutes under different conditions.

Case	C_{Davg}	C_{Lavg}	C_{mavg}	$C_{D\delta}$	$C_{L\delta}$	$C_{m\delta}$	f [Hz]
∞ , M2	0.9247	0.0028061	−0.0039595	0.023733	0.008716	0.012272	1.4956
TEU1-10m, M2	0.2693	−0.008386	0.01099	0.030594	0.014799	0.020636	18.533
TEU2-10m, M2	0.216	−0.00102	0.001388	0.02806	0.01243	0.017043	15.2
TEU1-20m, M2	0.5749	−0.00759	0.009995	0.04658	0.02043	0.0286	22.3
TEU2-20m, M2	0.573	0.00124	−0.00145	0.0326	0.0204	0.0284	22.7
TEU1-30m, M2	0.632	−0.0104	0.01387	0.0382	0.0164	0.0232	19.2
TEU2-30m, M2	0.6034	−0.00308	0.00398	0.02696	0.02119	0.0295	22.0
∞ , M05	0.7485	0.0014117	−0.00208	0.003479	0.0016838	0.002431	0.77813
TEU1-10m, M05	0.557	0.00302	−0.0042	0.05883	0.0349	0.05089	5.0
TEU1-20m, M05	0.617	0.003425	−0.00454	0.03892	0.01777	0.02544	7.7
TEU1-30m, M05	0.668	−0.00054	0.00093	0.03298	0.015079	0.021707	0.68
∞ , M07	0.77709	0.00012422	−0.00018692	0.0032741	0.0023439	0.0033981	0.17
∞ , M09	0.81093	0.0018863	−0.0027832	0.0039234	0.001531	0.0022253	0.30
∞ , M1.1	0.9058	0.00065987	−0.00044181	0.002662	0.000955	0.001327	0.093
∞ , M1.5	0.9096	−0.00011073	0.00017779	0.0011764	0.00069426	0.00096917	0.992

For M05, the freestream value of C_{Davg} agrees with predictions based on the validation for lower Mach numbers Bergeron and Ghoreyshi [10] and the increasing influence of compressibility. Figure 10 captures the Mach deficiency for the wake regions.

**Figure 10.** Time-averaged coefficients and tap data for chutes in freestream at M = 0.5 and 30 km altitude.

As expected, one of the major observations from Table 1 is the influence of the payload wake and shock structure on both drag and shedding frequency in the M2 case. In particular, there is a distinct jump in the M2 cases for both the TEU1 and TEU2 configurations at the 10 m payload–parachute separation.

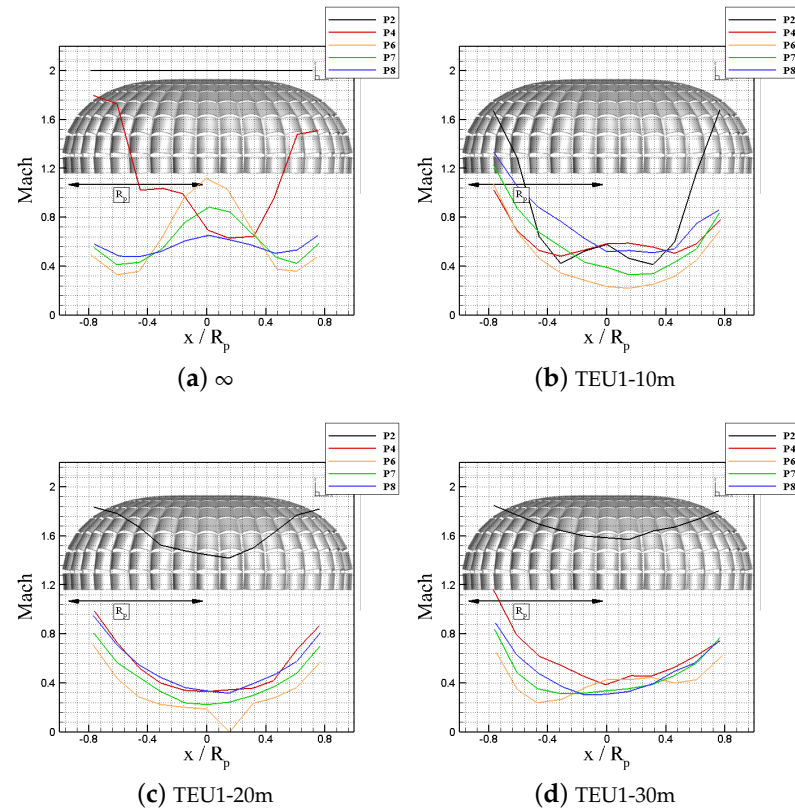


Figure 11. Effects on tap data of TEU1 upstream of chute at $M = 2.0$ and 30 km altitude.

A close inspection of Figures 11 and 12 shows the evolution of the payload wake and shock influence on the RS.

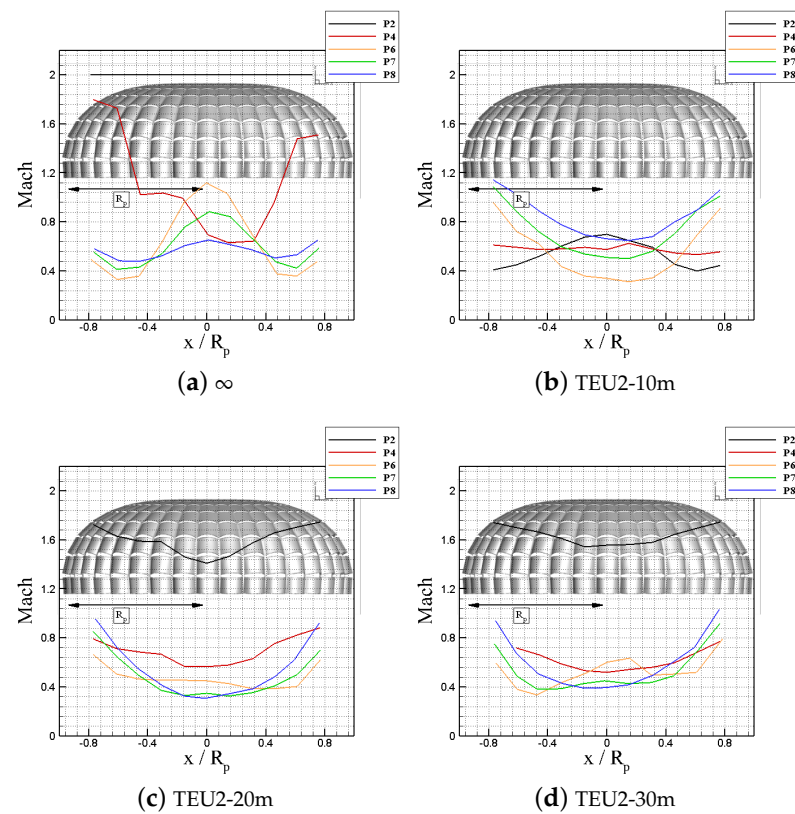


Figure 12. Effects on tap data of TEU2 upstream of chute at $M = 2.0$ and 30 km altitude.

This is a result of the payload wake being entrained when the payload–parachute separation distance is 10 m. The phenomenon is captured well in both the Mach contour and vorticity isosurface plots in Figures 13 and 14. The vorticity values are in units of angular velocity. Note that small isosurface values tend to capture excessive flow details, including minor separated flow structures, while overly large values can miss critical flow features of interest. Selecting the appropriate isosurface value typically relies on experience and a trial-and-error approach. The figures also show the time-averaged streamlines, which seem to indicate some asymmetry in the flow fields for TEU1-10, TEU1-20, and TEU2-20.

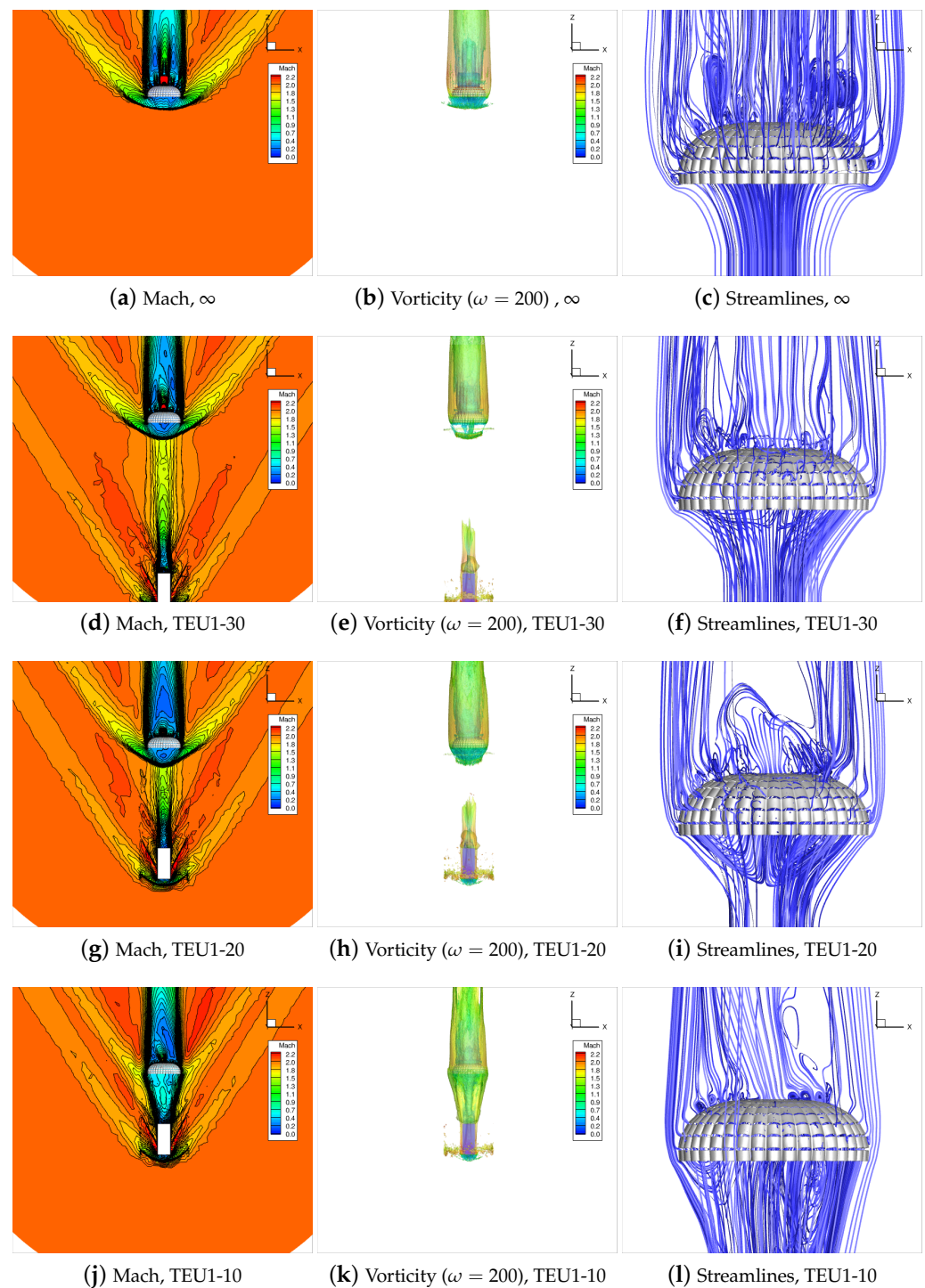


Figure 13. Mach contours, vorticity isosurfaces, and streamlines of chute in the wake of TEU1 at $M = 2.0$ and 30 km altitude.

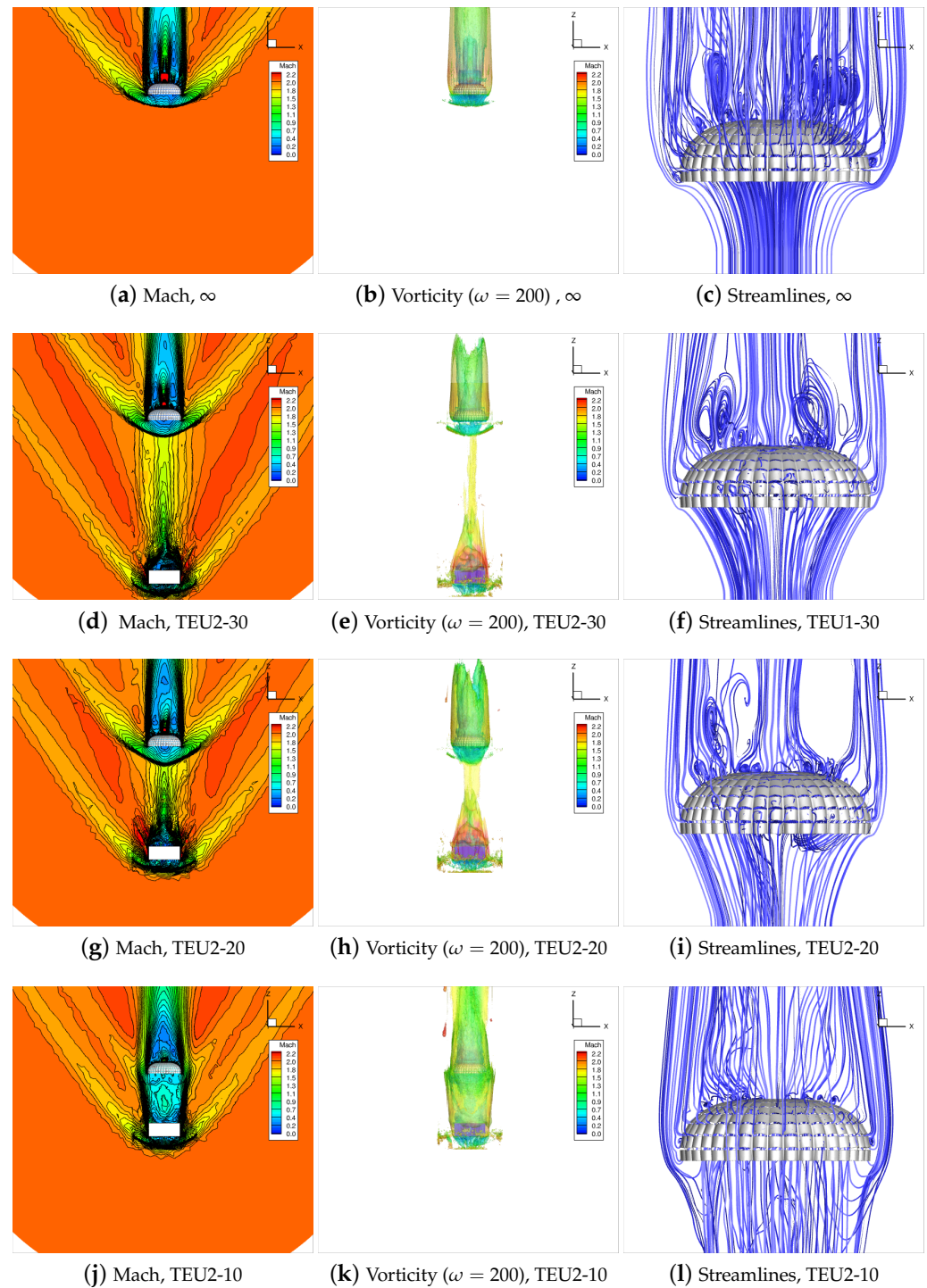


Figure 14. Mach contours, vorticity isosurfaces, and streamlines of chute in the wake of TEU2 at $M = 2.0$ and 30 km altitude.

As part of the validation component of the project and also to predict canopy suitability for the operational application, a freestream Mach sweep through the trans-sonic region was conducted. The data for the rigid 8.53 m ring-slot canopy decelerator show an increase in C_{Davg} (Figure 15), with a steep rise near $M = 1$. These data correlate very well with the drag variation of Disk–Gap Band (DGB) parachutes reported in Ewing et al. [12]. For the DGB tests, different forebodies were seen to have a significant magnitude affect in the resulting parachute C_D due to the variation in wake deficit associated with each shape. However, in all cases there was a sharp rise and subsequent leveling of C_D as the Mach

number increased from less than 1 to 2. It is worth noting that this qualitative agreement only represents a preliminary validation reference, as many other factors associated with the parachute design also affect C_D , including length of suspension lines, fabric permeability, Reynolds number, relative elasticity, and canopy stiffness.

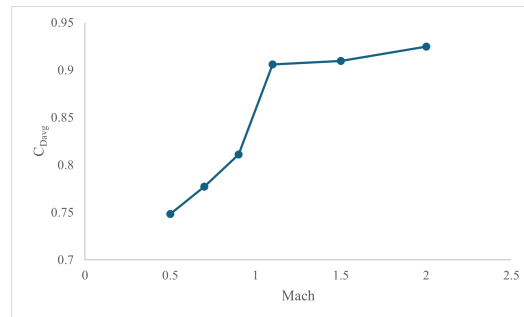


Figure 15. Rigid ring-slot model C_{Davg} Mach dependence at altitude 30 km.

Finally, the last two datasets provide a preview of future dynamic stability analysis. Figure 16 verifies the instability amplitudes associated with increasing Mach number.

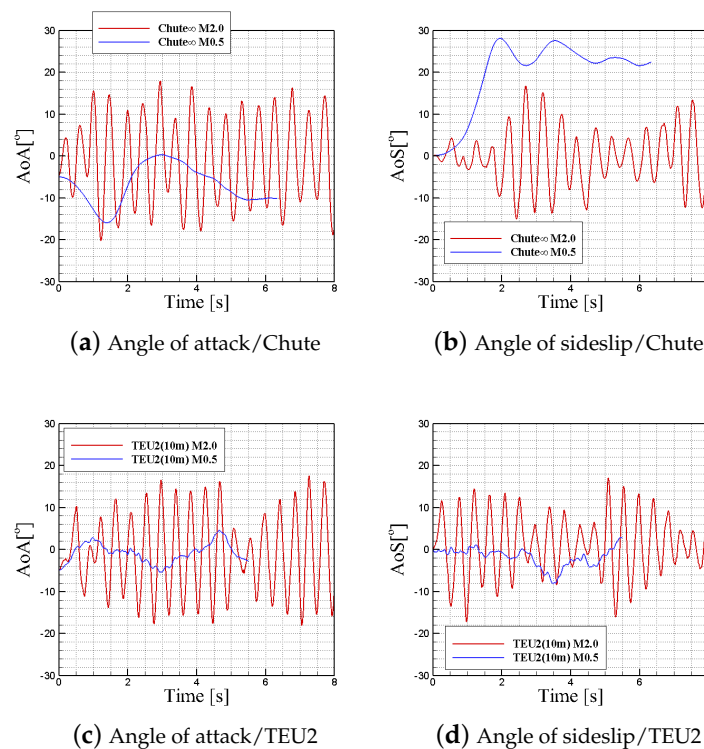


Figure 16. Angle of attack and sideslip angle time histories of chutes responding in freestream and in the presence of TEU2(10m) at $M = 2$ and $M = 0.5$. The chutes have a ball constraint at the moment reference point.

Figure 17 captures the damping of the motion when the suspension lines are modeled. The lines are permitted to stretch such they can accommodate unequal loading depending on the angle of attack of the canopy. This is an important modeling capability to implement in future simulations, as is the addition of canopy fabric material properties.

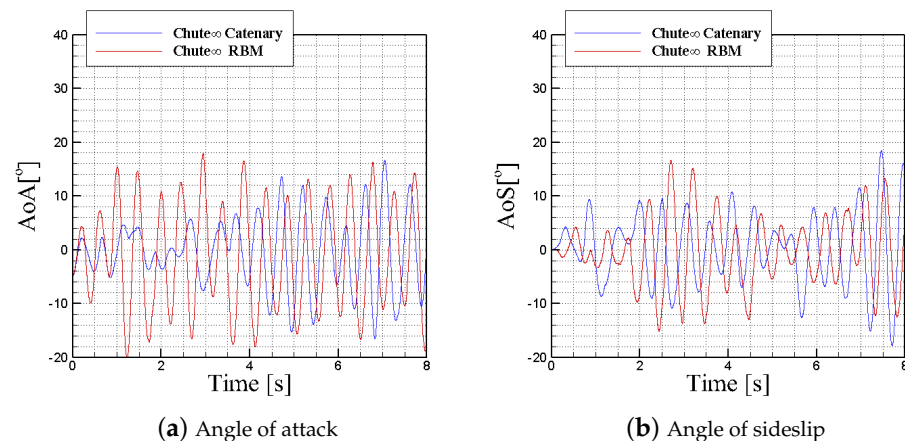


Figure 17. Angle of attack and sideslip angle time histories of chutes responding in freestream at $M = 2$ with and without cables. The chutes have a ball constraint at the moment reference point.

5. Conclusions

An initial study of a payload–parachute system consisting of a standard TEU shipping container and an 8.53 m rigid ring–slot parachute demonstrates significant deviations from traditional analyses of streamlined and capsule-shaped payloads. In particular, the bluff-body shape of the TEU strongly influences the C_{Davg} , especially as the payload–parachute distance for the simulations reached 10 m. This deviates slightly from the accepted payload–parachute distance scaling. Future work will further refine this functional dependence. In addition, the effect of a rigid canopy on the variation of the C_{Davg} with Mach number demonstrated a monotonically increasing trend, as opposed to the monotonically decreasing trend associated with fabric parachute drop test and wind tunnel results. Finally, the interaction of the payload fixed in space and the wake with the ring–slot model showed very little adverse effect on the stability of the canopy. Future work will address full coupling of the payload to allow for multi-body 6-DoF dynamics.

Author Contributions: Methodology, M.G.; Investigation, M.G., K.B. and A.J.; Writing—original draft, K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by US Air Force Academy, grant number FA7000-20-2-0014, FA7000-22-2-0004.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: This article has been approved for public release with unlimited distribution; Distribution Unlimited; PA Number USAFA-DF-2024-812. Mehdi Ghoreyshi’s and Adam Jirasek’s sponsorships are through the US Air Force Academy under agreement numbers FA7000-20-2-0014 and FA7000-22-2-0004, respectively. Material presented in this article is a product of the HPCMP CREATETM-AV project sponsored by the U.S. Department of Defense HPC Modernization Program Office. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the organizations involved with this research or of the U.S. Government.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

c	chute reference length
C_D	drag coefficient
C_L	lift coefficient
C_M	pitching moment
C_{M_α}	pitch–moment curve slope
C_p	pressure coefficient
CG	center of gravity
D_O	chute diameter as calculated from its total wetted surface area
D_P	chute projected diameter
M	Mach number
Re	Reynolds number, $\rho \cdot V_\infty / \mu$
V_∞	freestream velocity
α	parachute angle of attack, deg
λ_g	parachute geometric porosity
ρ	air density, m/kg^3

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