

Orion Multi-Purpose Crew Vehicle Solving and Mitigating the Two Main Cluster Pendulum Problem

Yasmin Ali¹

National Aeronautics and Space Administration, Houston, Texas, 77058

Bruce Sommer²

Lockheed Martin Space Systems, Houston, Texas, 77058

and

Tuan Troung³, Brian Anderson⁴ and Christopher Madsen⁵

National Aeronautics and Space Administration, Houston, Texas, 77058

The Orion Multi-purpose Crew Vehicle (MPCV) Orion spacecraft will return humans from beyond earth's orbit, including Mars and will be required to land 20,000 pounds of mass safely in the ocean. The parachute system nominally lands under 3 main parachutes, but the system is designed to be fault tolerant and land under 2 main parachutes. During several of the parachute development tests, it was observed that a pendulum, or swinging, motion could develop while the Crew Module (CM) was descending under two parachutes. This pendulum effect had not been previously predicted by modeling. Landing impact analysis showed that the landing loads would double in some places across the spacecraft. The CM structural design limits would be exceeded upon landing if this pendulum motion were to occur. The Orion descent and landing team was faced with potentially millions of dollars in structural modifications and a severe mass increase. A multidisciplinary team was formed to determine root cause, model the pendulum motion, study alternate canopy planforms and assess alternate operational vehicle controls & operations providing mitigation options resulting in a reliability level deemed safe for human spaceflight. The problem and solution is a balance of risk to a known solution versus a chance to improve the landing performance for the next human-rated spacecraft.

Nomenclature

AGL	=	Above Ground Level
CC	=	Crew Cabin
CDT	=	Cluster Development Test
CFD	=	Computational Fluid Dynamics
CM	=	Crew Module
CMUS	=	Crew Module Uprighting System
CPAS	=	Capsule Parachute Assembly System
EDL	=	Entry, Descent and Landing
EDU	=	Engineering Development Unit
EFT-1	=	Exploration Flight Test-1

¹ NASA Landing & Recovery Systems Manager, MPCV Orion Crew & Service Module, 2101 NASA Parkway, Houston, TX 77058, GC, AIAA Member.

² Landing & Recovery System Landing Analysis Integration Lead, MPCV Crew Module, 2625 Bay Area Blvd, #800, Houston, TX 77058

³ Aerodynamic Subsystem Manager, Aerosciences & Flight Mechanics Division, 2101 NASA Parkway, Houston, TX 77058, EG.

⁴ Capsule Parachute Assembly System Deputy Project Manager, Aerosciences & Flight Mechanics Division, 2101 NASA Parkway, Houston, TX 77058, EG, AIAA Member.

⁵ Guidance Navigation & Control Entry Subsystem Manager, Aerosciences & Flight Mechanics Division, 2101 NASA Parkway, Houston, TX 77058, EG.

EI	=	Entry Interface
EMT	=	Entry Mode Team
FBC	=	Forward Bay Cover
GNC	=	Guidance, Navigation and Control
GPS	=	Global Positioning System
GRAM	=	Global Reference Atmosphere Model
IMU	=	Inertial Measurement Unit
KS	=	“Kitchen Sink”
L&D	=	Loads and Dynamics
L/D	=	Lift to Drag
LIPT	=	Landing Impact Performance Team
LOC	=	Loss of Crew
LOTV	=	Loss of Test Vehicle
LRS	=	Landing & Recovery System
MC	=	Monte Carlo
MPCV	=	Multi-purpose Crew Vehicle
MSL	=	Mean Sea Level
MUF	=	Model Uncertainty Factor
NED	=	North-East-Down
NFAC	=	National Full Scale Aerodynamics Complex
ODC	=	Orbiter Drag Chute
OICL	=	Over Inflation Control Line
PCDTV	=	Parachute Compartment Drop Test Vehicle
PRA	=	Probabilistic Risk Assessment
PRL	=	Permanent Reefing Line
PTV	=	Parachute Test Vehicle
RCS	=	Reaction Control System
RoD	=	Rate of Descent
RSS	=	Root Sum Squared
SS	=	Steady-State
TPS	=	Thermal Protection System

I. Discovering the Pendulum Issue

The Orion spacecraft was on its 4th Entry, Descent and Landing (EDL) architecture design, its 30th airdrop test and a year from flying its first space mission, Exploration Flight Test-1 when it was faced with a complex and costly problem. Orion’s nominal subsonic descent & landing sequence begins with the Crew Module Forward Bay Cover (FBC) jettison, followed by deployment of two drogue parachutes. At a navigated altitude around 8000 ft. Mean Sea Level (MSL), three pilot parachutes are mortar deployed individually attached to a main parachute. The mains go through a series of reefing stages to limit loads on the CM and avoid imparting severe loads on the crew members. The final touchdown orientation control includes Reaction Control System (RCS) thruster control starting around 1500 ft. MSL. Orion is a water-landing capsule with planned splash-down locations off the coast of California in the Pacific Ocean. Upon splash-down, the riser cutters sever the main parachutes from the CM followed by the Crew Module Uprighting System (CMUS) deployment. Orion nominally lands under 3 main parachutes but the system is designed to be fault tolerant and land under 2 main parachutes.

Over the course of the Capsule Parachute Assembly System (CPAS) Team Engineering Development (EDU) test campaign, they began observing a limit cycle coupled swinging or pendulum motion for a simulated single main parachute failure. The pendulum motion impacted the terminal rate of descent, horizontal velocity and attitude. For a vehicle that is structurally sized to land in a particular orientation the order of magnitude of this issue was potentially

Test	Main SS (ft - AGL)	Pendulum (ft - AGL)	Peak Swing (deg)	Observations
CDT-3-2	~5,800	Did not occur	5.9	Several wind changes throughout full open (similar to 3-12 & 3-11) but did not develop pendulum, main gliding observed in 'May pole' fashion.
CDT-3-8	5,075	575	10.8	Very steady wind direction and magnitude until inversion (heading change and decrease in wind magnitude) excites pendulum motion, still diverging at touchdown.
CDT-3-11	6,000	2,225	23.5	Significant wind heading changes did not excite pendulum, late in descent wind heading change (very low magnitude) excited pendulum motion.
CDT-3-12	7,425	5,575	24.2	Early wind event excites pendulum motion, subsequent wind shifts change amplitude of pendulum motion, but do not damp it.

Table 1. Early Observations of Pendulum Motion.

catastrophic. It was the fourth CPAS development airdrop of the two main parachute case when the team realized this was a repeatable issue that needed to be addressed. . Table 1 describes those tests, peak pendulum swing angle and the altitude if pendulum motion started to occur.

The first CPAS EDU that simulated a single Main parachute failure was Cluster Development Test (CDT) 3-2. The full open Main parachute flight lasted approximately 180 seconds. During this time, the parachute system exhibited typical flyout behavior and benign system swing of $\pm 6^\circ$. The Main parachutes exhibited one full cycle of orbiting behavior, "may pole", where the two main canopies circled around a central axis of the system, and a consistent axial oscillatory behavior, "breathing", for about 100 seconds.

CDT-3-8 was an air drop test where a single Main parachute's canopy was artificially constricted so it would purposefully not inflate. The artificially failed main was to assess how a failed 1st stage main would interact with other parachutes. The flagging main dropped approximately 230 feet below the payload when the other two parachutes reached full open. During the descent, the system exhibited typical flyout behavior, had 2 half orbits, and had two separate instances of pendulum behavior with system swing angles up to $\pm 10^\circ$. It was only after subsequent flights showing prolonged pendulum behavior that these 1 cycle swings in CDT-3-8 would be identified as possible pendulum behavior.

In July of 2013, another CPAS Drop test, CDT 3-11, the system of 2 main parachutes and payload descended down to the surface for approximately 170 seconds. One third of the way into the full open portion of the main parachute flight, the system developed a pronounced swinging motion of about 15° amplitude, and increased in amplitude up to 24° as it approached the ground. The swinging motion of the system looked like a pendulum swinging; hence, usage of the word pendulum to describe the motion. CDT-3-11 was the third full scale drop test with a 2 main parachute configuration of the CPAS EDU main parachute design, and the pendulum motion was something unusual to observers as prior tests with 2 main parachutes did not show the pronounced pendulum behavior.

Later in February 2014, CDT 3-12, descended under full open mains for approximately 230 seconds. With this flight, pendulum motion started quickly after the disreef to full open of the main parachutes, and gradually increased to an amplitude of about 24° as it neared the ground. After this flight, it became obvious that the pendulum behavior of configurations with 2 main parachutes must be more thoroughly investigated, models accounting for its motion developed, and its impacts to the vehicle and crew assessed.

The limit cycle amplitude of the pendulum motion for CDT-3-11 and CDT-3-12 was about 20° to 22° , with some swings that could get to 24° depending on wind shear.

To provide first-order system level impacts, a simple pendulum model was developed⁶. Fig. 1 depicts the terminology and definitions used in the first-order model. The model did not address the likelihood of the system transitioning into the pendulous motion. A conservative approach was taken by assuming all two main cases developed into the pendulum motion. The model defined the max pendulous swing magnitude and pendulous period. The model reproduced the effect on rate of descent by empirically tuning the pendulum model to match the test data. The model increased the two main parachute rate of descent (RoD) standard deviation from 1.6 fps to 3.3 fps. The Guidance, Navigation & Control (GNC) team took the increment to vertical and horizontal velocity and superimposed the new distribution on the existing landing conditions. The CM RCS would require 15 times the existing thrust capability and 2 times the amount of propellant to damp the pendulum motion. Pendulum motion also resulted in large changes in vehicle heading not allowing GNC to maintain the proper roll heading, thus no roll control was assumed in the model. GNC also assumed a uniform distribution for the pendulous swing plane angle for North-East-Down (NED) and the vehicle heading angle.

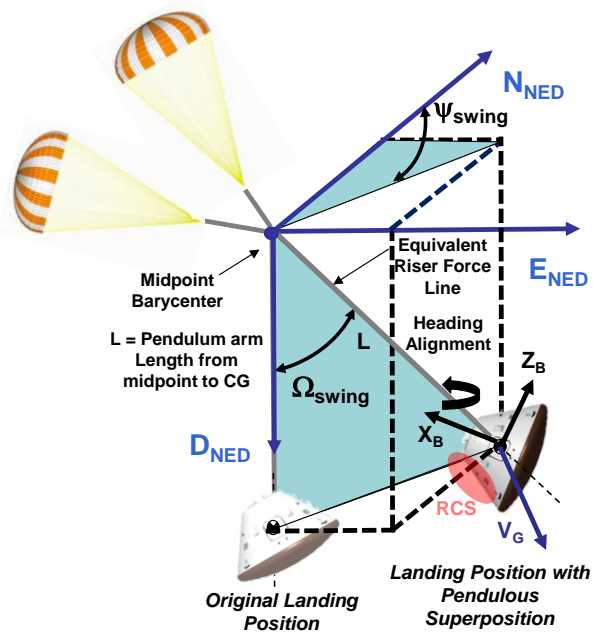


Figure 1. First Order Model Definition & Nomenclature.

The initial pendulum effects resulted in an impact condition that was well outside the Exploration Flight Test 1 (EFT-1) design environment. Nominally, Orion designs the vehicle structures to a set of landing loads in order to meet 99.86% of the Monte Carlo (MC) landing impact conditions derived by the GNC simulation. The GNC simulation uses Global Reference Atmosphere Model (GRAM) for environments. For an off-nominal case with a parachute failure, the vehicle structures is designed to meet 97.7% of the cases, which includes a structural factor of safety and model uncertainty factor. With the pendulum motion introduced and using this first-order model, the vehicle could only meet 29% of the landing impact conditions. The Loss of Test Vehicle (LOTV) risk for pendulum would equate to 1/163. The pendulum phenomenon represented a higher risk than all the EFT-1 risks combined and would violate the EFT-1 LOTV requirement. It would take a multi-disciplinary team to address this high of a risk prior to the EFT-1 Flight, later that year, and formulate a long-term plan for future crewed exploration flights.

II. Devising a Plan

Tracking the Landing Impact performance event requires a multi-disciplinary approach to successfully integrate modeling, analysis, hardware design and testing. This required close interaction across the Aerosciences, CPAS, GNC Flight Software, Loads and Dynamics (L&D), Landing and Recovery System (LRS), Crew Cabin structure, Thermal Protection System (TPS) and Systems Reliability teams.

Fig. 2 identifies the key Pendulum Mitigation discipline teams and along with their primary area of focus in mitigation

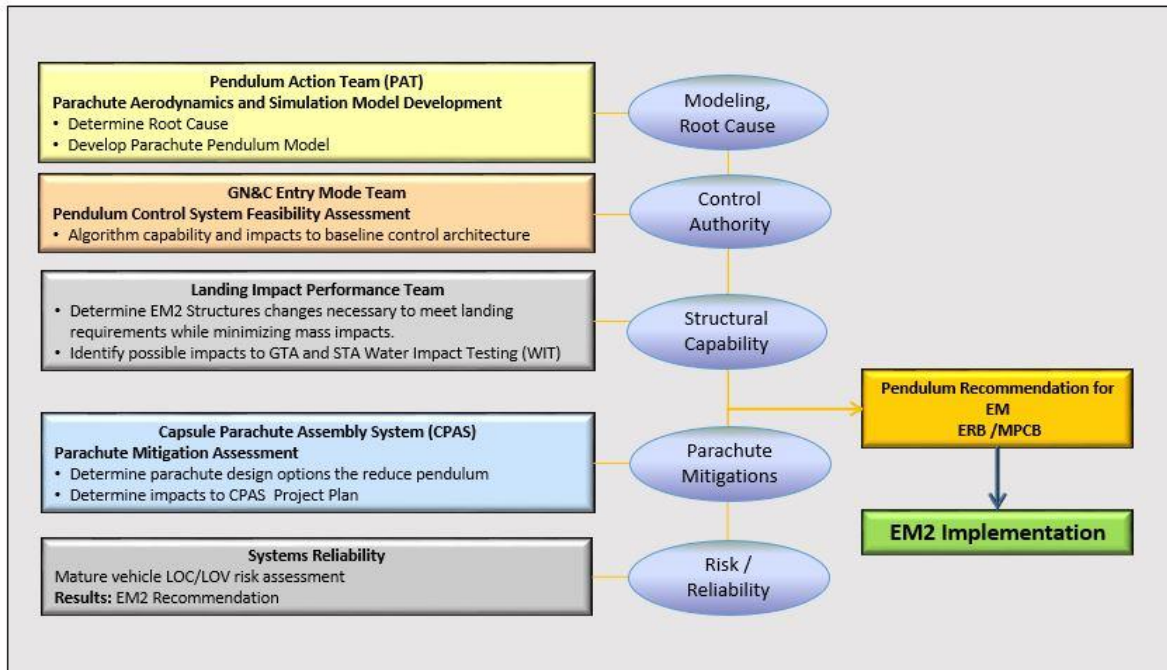


Figure 2: Integrated Pendulum Team discipline teams and primary areas of focus.

of this problem. Each discipline of the Pendulum team had a primary area of focus in helping to mitigate the pendulum phenomenon. Inputs from each of these teams played a key role in determining the final integrated solution.

The Pendulum Action Team (PAT) was comprised of the leading experts in parachute performance modeling from private industry, NASA and independent consultants. Their primary task was to determine the root cause of the pendulum phenomenon through the development of both a fault tree and the creation of a parachute simulation model that would be able to recreate the pendulum motion observed during the air drop testing. This model would be integrated into a larger vehicle level simulation that is used to quantify the overall landing performance of the vehicle from Entry Interface (EI) to splashdown.

The GN&C Entry Mode Team's (EMT) primary task was the integration of the pendulum performance models into the vehicle level simulations. An additional task was in the development of algorithms that would be able to detect the pendulum motion in flight and to improve the vehicle landing performance through either reorienting the vehicle to be at a more optimal landing impact orientation relative to the pendulum motion or by using the Reaction Control System (RCS) jets in an attempt to dampen the pendulum motion itself. In addition to the aforementioned tasks, the EMT provided multiple landing impact Monte Carlo (MC) sets in support of multiple landing impact performance studies that were used to define the primary load drivers for the vehicle or to reassess the vehicle landing performance based on model updates/refinements.

The Landing Impact Performance Team (LIPT) is composed of the Landing L&D team, the analysis team from the Crew Module LRS and the structural analysis teams from both the Crew Cabin (CC) and Thermal Protection System (TPS)/Aeroshell teams. The primary focus of the LIPT was to quantify the vehicle landing impact performance for both the CM structure as well as the astronauts themselves using the landing impact Monte Carlo data provided by the EMT. The CC and TPS teams were also tasked with quantifying what the potential design and mass impacts would be to increase the vehicle landing impact performance back to the required statistical coverage.

The Capsule Parachute Assembly System (CPAS) was given the task to characterize, through full scale and subscale testing, the stability of the baseline parachute design to aid the PAT team in their efforts to reconstruct the main parachute phase of the air drop tests. The CPAS team also investigated various main parachute canopy changes to improve stability while minimizing changes to the vehicle vertical descent rate. Initial design concepts were evaluated analytically using Computational Fluid Dynamics (CFD), wind tunnel test data, and detailed aerodynamic models with the most promising designs being down selected for multiple subscale drop tests.

The Systems Reliability team was tasked with evaluating the LOTV performance for various options as well as quantifying the amount of margin that exists in the vehicle reliability performance. If necessary, this team would

define the threshold for an acceptable level of LOTV and Loss of Crew (LOC) risk and then derive the required statistical coverage should the integrated solution not achieve the stated level of coverage noted in the baseline requirements.

III. Root Cause

The PAT performed root cause investigation and analysis, examining aerodynamic instability in parachutes, wind shifts, forebody or payload effect and trailing distance effect. The parachute aerodynamic instability in the vortex ring was the declared root cause for the pendulum motion. Two main sources of data contributed to this conclusion: (1) Historical reports from the Apollo main parachute development test program, which had the same swinging motions with 2 main parachute configurations and used the same word, pendulum, to describe the motion² and (2) CFD analysis of the flowfields around the main parachutes³ which verified the flowfield mechanisms which could drive aerodynamic stability and instability in the main parachute.

Northrup-Ventura designed, developed and tested parachutes for the Apollo capsule. Their report² describes the various main parachute canopy configurations they tried to reduce inflation loads while maintaining as much drag performance as possible. Multiple full scale drop tests were performed to assess the changes. Of particular interest are the descriptions and data of the pendulum motions these full scale drop tests had, and how the various configuration changes affected pendulum motion. The then baseline parachute design was a ringsail parachute design, of similar design to the Orion main parachute. The initial Apollo parachute design had high inflation loads and issues with consistent inflation during its reefing stages. The 2-main parachute configurations, exhibited pendulum motions up to 28° from vertical, larger than what was seen in Orion CPAS drop tests. The parametric changes performed by Northrup Ventura, which had various levels of reduction in inflation load and pendulum swing angles, provided excellent data on what could reduce pendulum motion and at what cost in drag performance, and provided corroboration and validation of results from CFD simulations of the parachutes. In the end, the qualification Apollo main parachute had a large porosity slot in the crown which was the best mix of trades for stability and drag performance for the Apollo Program.

To understand the flowfield in and around the parachutes, CFD simulations were employed³, using many different parametric variations. The Apollo report provided good details to build Apollo pre-qualification ringsail parachutes and post-qualification ringsail parachutes in CFD². For modern configurations, an Orion EDU main ringsail parachute with porosity slots and porosity windows filled in was used as the baseline. Parametric variations about that baseline were analyzed: adding the EDU porosity slot, EDU porosity windows, Apollo porosity slot, smaller and larger porosity slots, the location of porosity slots, changing the locations of 5% porosity slots at various radial locations, extra-large sails (dubbed as SuperSails), and combinations of two porosity slots.

CFD results of the Apollo main parachute configurations showed similar static stability trends to parachute configurations². This gave the team confidence that CFD was suitable for assessing why Orion parachutes were unstable.

CFD results of Orion main parachutes revealed that the baseline main parachute configuration, the EDU design with a 1.9% porosity slot in the crown and porosity windows in the 7th sail, were statically unstable out to 16 to 18 degrees angle of attack. This was evidence that a single main parachute system will likely have a coning motion. When there are 2 main parachutes, multiple modes of parachute motions can occur, including pendulum motion, flyout motion and orbiting motion.

One of the big flowfield phenomena driving the aerodynamic stability of these ringsail parachutes is the porosity on the crown.

When the size of the porosity slot at the 40% radial location is parametrically increased from 0% to 5% in 1% increments, the flow going through the porosity slot becomes strong enough to introduce a recirculation region in the leeward side of the canopy in the wake as seen in Figure 5. With the wake vortices driven away from the crown on both the windward and leeward side of the wake, with resultant smaller recirculation zones directly behind the sails, it equalizes the pressure on both sides of the canopy in the wake, and makes the canopy more aerodynamically stable. With smaller porosity slots, not enough flow goes through the canopy on the leeward side to drive the wake vortex away from the leeward crown and sails upstream of the crown. CFD results indicate that the canopy needs to have a porosity of 3% or larger to have a recirculation zone in the leeward side of the wake. If the EDU porosity slot was 50% larger or more, it would likely have a stabilizing effect on the main ringsail parachute and minimize or eliminate pendulum motion for 2 main parachute configurations. It would also incur a decrease in drag performance of 5% to 10%³. CFD showed³ that the Orion main parachutes could increase stability by introducing porosity slots closer to the skirt. While the root cause here is stating that the EDU porosity slot near the crown is too small, the static CFD results showed that porosity slots near the skirt introduce stability to the main parachute, and also likely come with a smaller decrease in drag performance as compared to porosity slot changes closer to the crown.

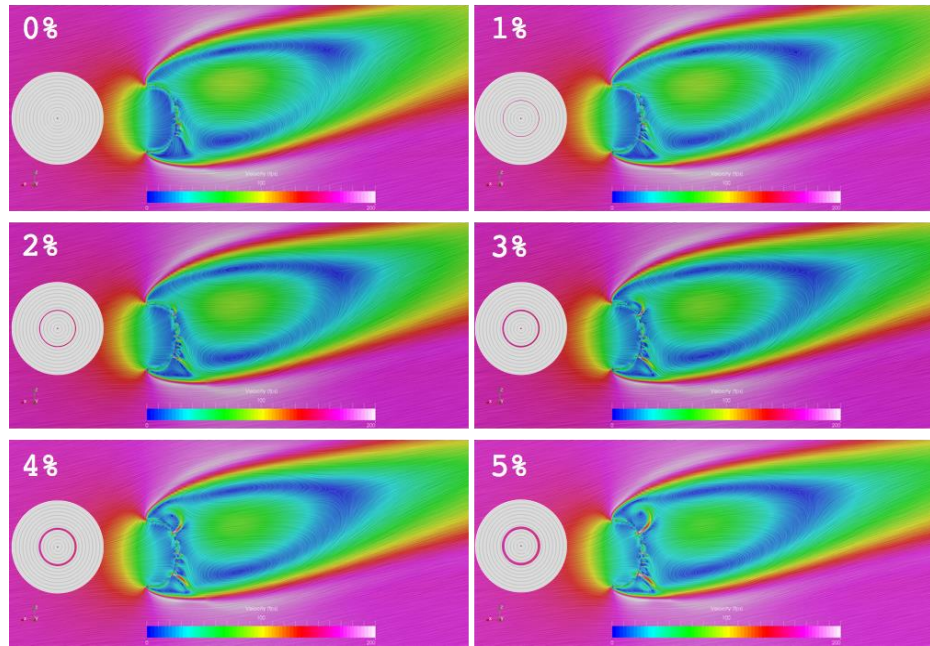


Figure 5. Flowfield pressure distribution of the porosity slot size sensitivity.

The Orion main parachutes have a suspension line length ratio of 1.4. Decreasing the suspension line length ratios to 1.0 to 1.2 may have the desired stability improvement but will also likely decrease drag performance over 10%. The idea of permanent reefing the main parachutes to about 85% drag ratio, pulls the sails near the skirt would be recommended as a mitigation. However, each of these potential design changes have impacts to nominal rate of descent for both the 2-main and 3-main configurations and also have impacts on the applicability of the previous parachute air drop test results.

The winds are classified as a contributor to the root cause. If the parachute canopies were aerodynamically stable, wind shears could induce swinging motions in the system, but they would eventually damp out. The pendulum motion requires an aerodynamically unstable canopy. In absence of wind shears, pendulum motions may not occur during the time frame of a typically descent, but with wind shears, they could start a pendulum motion as soon as the main parachutes are full open.

IV. Understanding Pendulum Swing vs. Descent Rate Loss

In order to quantify the relationship between maximum swing angle and canopy drag performance, the GNC team provided L&D with sixteen 130,000 case two parachute pendulum MCs with active RCS that incrementally increased the baseline descent up to 4.5 fps in 1.5 fps increments. The pendulum swing angles were increased from 0° to 20° in 5° increments. This data was post processed and evaluated using a mathematical boundary surface response model that is based on an interpolative method known as Kriging.

The landing impact Kriging model was developed to predict loads performance throughout the vehicle for each impact condition defined in the MC data. Fig. 6 shows a pictorial of how this process is used to evaluate the vehicle's landing performance. Each structural component has a load or stress threshold that's based on either the maximum

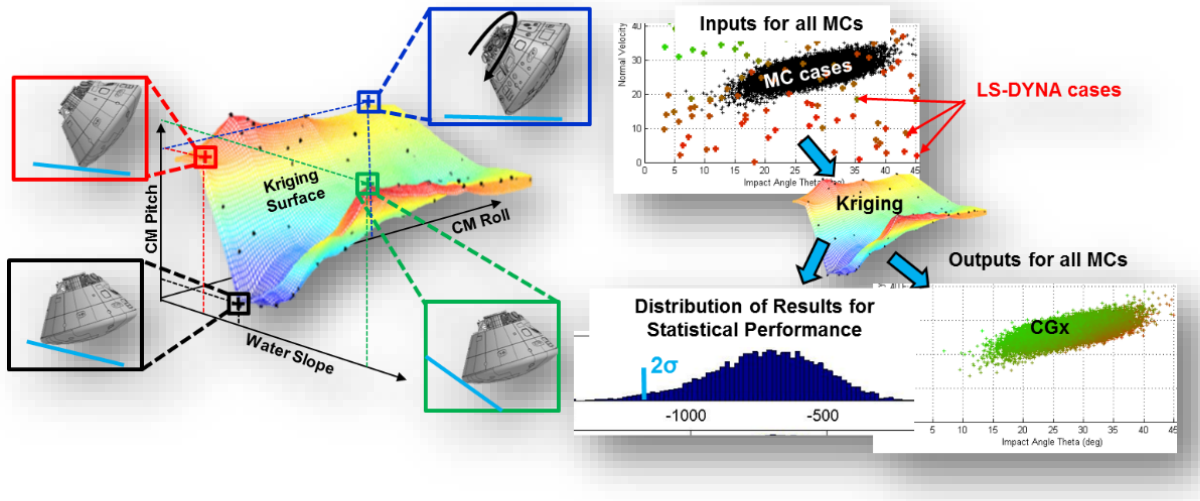


Figure 6. Process for setting landing impact load thresholds

design load or a component's capability and includes safety factor. The landing Monte Carlo data serves as an input into the Kriging Model. A case is counted as a failed case if the loads for any given threshold exceed the stated capability limit. A case is counted as a passed case if the calculated loads are lower than the defined capability threshold. The integrated vehicle landing probability of success is calculated by counting the total number of cases that pass the defined thresholds divided by the total number of cases in each MC set.

Each pendulum swing vs. descent rate increase MC set was input into the Kriging model and evaluated for changes in the resultant loads of any given structural components as well as the overall vehicle landing performance. Fig. 7 illustrates the how the statistical coverage for the vehicle, shown in the lower right table, can result in vastly different loads going into the heatshield stringers. In this case, an increase of 4.5 fps in descent rate coupled with a 10° pendulum swing resulted in 30% lower load than a 0 fps increase in descent rate with 15°'s of pendulum swing.

The results of the parametric study showed that the Main parachute mitigation options needed to focus more on reducing the pendulum swing amplitudes than maintaining the baseline vertical descent rate.

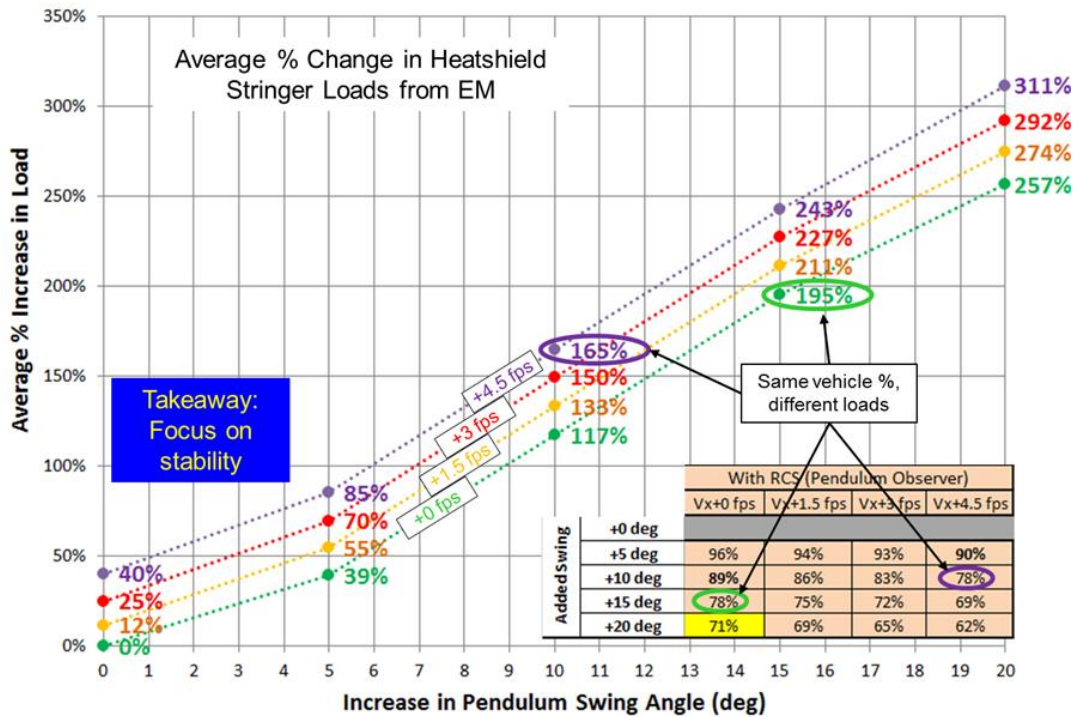


Figure 7. Load increases in the Heatshield stringers due to increases in both vertical velocity and pendulum swing angle

V. High-Level Testing Overview & Results

Because the Pendulum Action Team determined that the pendulum motion was a result of aerodynamically unstable parachutes, the CPAS team was asked to determine any design changes that would result in more aerodynamically stable parachutes. However, an opening ground rule was that the performance of the nominal, 3-main parachute system should not be drastically affected. To determine candidate design changes the team considered aerodynamic stability design updates in previous programs, such as, Orbiter drag parachute, used static CFD³ and consulted with parachute experts. Additionally, the team very heavily favored design updates that would not invalidate the previous 15 airdrop tests in the development program.

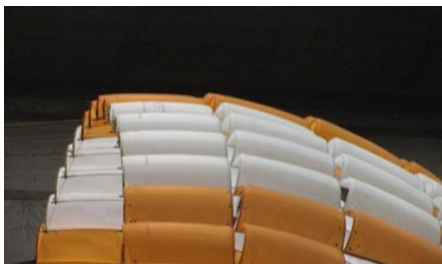


Figure 8. Sail fullness near the parachute skirt.

The primary parachute design updates considered included geometric porosity rings in sail 7, inclusion of “super sails” (sails with 35% fullness), and an OICL. Fig. 8 shows fullness in parachute sails near the skirt. Additional discussion about these design options is found in Reference¹.

While full scale testing was briefly considered to understand the potential design updates, it was decided that sub scale testing would provide the team the best opportunity to gather a large amount of data in the very tight schedule and at a lower cost. From project inception, the team had ~7 months to determine candidate design options, design and fabricate sub scale parachutes, plan any sub scale testing, execute the testing, reduce the data, and make a parachute design update recommendation. A sub-scale wind tunnel test was assumed to provide the best opportunity to study parachute design updates in a more controlled environment and obtain a large number of data points. However, to avoid blockage effects and to avoid scaling errors incurred while building much smaller parachutes, only a single parachute could be tested at a time. For this reason, the wind tunnel testing was followed by sub scale air drop testing to understand the parachute performance in a more flight-like environment, observing the interaction of the steady-state full open coupled motion between the payload and cluster of parachutes.

Early in the testing process a decision was needed on the sub scale parachute size to allow the team to design and fabricate the sub scale parachutes. After considering potential scaling issues due to material sizes, potential wind tunnel blockage, and payload weights in available aircraft, it was decided that 35% scale parachutes would be fabricated. However, due to the tight schedule the parachute size was selected before detailed wind tunnel blockage effects could be studied. A total of 9 sub scale parachutes were fabricated. Each had a nominal diameter of 40.6-foot reference diameter and weighed approximately 30-lbm. Fig 9 shows one of the sub scale parachutes on a packing table.

While a brief summary of the sub scale wind tunnel testing is included here, a more detailed description can be found in Reference ¹. The wind tunnel testing was carried out from January 5-16, 2015 at the National Full-Scale Aerodynamics Complex (NFAC) 80- by 120-foot wind tunnel.

The primary objectives of the wind tunnel test were to (1) gather single-canopy static & dynamic aerodynamic data for parachute configurations to understand changes to canopy stability and drag performance and (2) to down select to 2 canopy configurations for follow-on air drop testing. Understanding the relationship between pendulum swing and increased descent rate, as described in Section IV, on vehicle loads was key in helping the CPAS team down select 2 canopy configurations used for the follow-on air drop testing.

Static aerodynamic data was gathered in the wind tunnel test using instrumented tethers that were attached to the canopy vent. The tethers provided a dual-purpose in that they held the parachute in a prescribed location while also measuring parachute restoring forces. A riser load cell was also utilized to measure axial loads. Angle of attack variations were accomplished, generally, by holding the parachute vent at a fixed location while rotating the wind tunnel strut (the strut is located on a turntable in the 80x120 test section). After gathering static aerodynamic data, the tethers were released using a quick-release system and the parachute was allowed to “free-fly”. During this phase, dynamic aerodynamic data could be calculated using photogrammetry and riser load data. Figure 10 shows the overall test setup.



Figure 9. Sub scale parachute on a packing table.

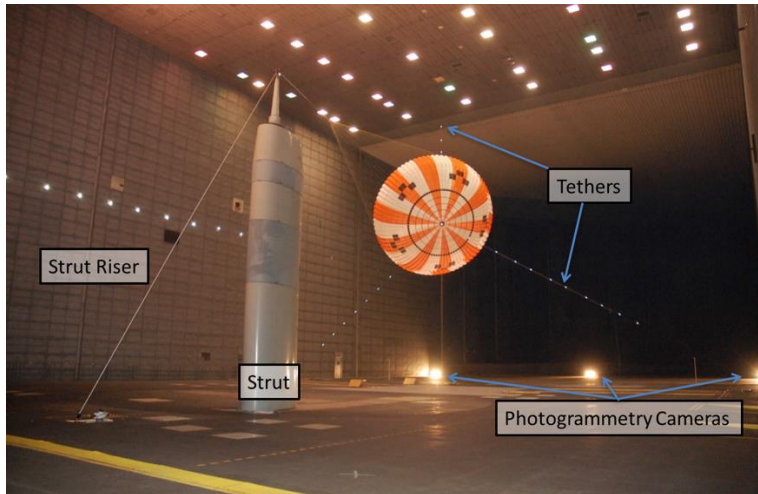


Figure 10. Wind tunnel test section setup.

drastically effect 1st and 2nd stage.

At the end of the 2-week test entry, 2 configurations were selected for sub scale air drop testing. Configuration 1 was a “super sail” configuration with 5.5% geometric porosity at sail 7. This configuration was selected because it showed the best quantitative static stability improvement with a 12% reduction in drag as compared to the EDU configuration. Configuration 2 was a “super sail” configuration with 3% geometric porosity at sail 7. This configuration was selected because it showed improved static stability as compared to the EDU parachute but had the same drag performance as the EDU. While it was desired pre-test to use dynamic aerodynamic data to aide in the down-select process, the data processing took a considerable amount of time. Instead, the dynamic behavior of the different parachute configurations were compared more qualitatively using vent tracking from photogrammetry along with video observations.

Two weeks following the conclusion of the wind tunnel testing, sub scale air drop testing was conducted over a period of two weeks in Eloy, Arizona. A short summary of the testing is included here and a more detailed review of the testing is found in Reference⁹. The test team conducted one week of testing, took a one-week break to regroup and evaluate data from the first week, and then completed the second week of testing.

A total of 37 wind tunnel runs with a total of 391 data points on 13 different parachute configurations were completed over the 10-day test entry. Configurations tested included the baseline (EDU) configuration with and without OICL, canopies with 3% and 5% geometric porosity rings at the sail 7 location, and “super sail” configurations with geometric porosity ranging from 1.4-5.5%. Fig. 11 shows a configuration with a porosity ring at sail 7. Riser load data and qualitative shape information was also gathered on some of the configurations in 1st and 2nd stage reefed configurations to ensure that the modifications at sails 6 and 7 did not

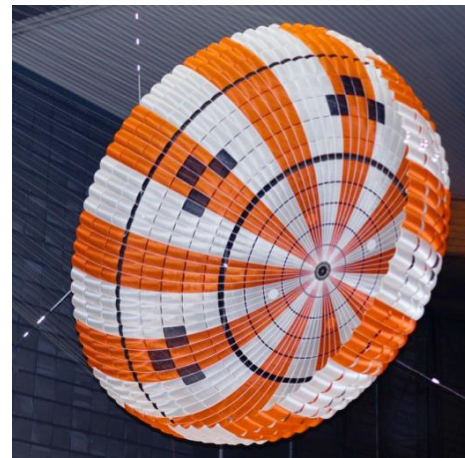


Figure 11. Sub scale parachute configuration with porosity ring at sail.

The air drop tests were carried out using a Skyvan (commonly used for sky-diving). The Skyvan generally performed the drop at 5,000-foot Mean Sea Level (MSL) (3,500-foot Above Ground Level (AGL)). .. Following extraction from aircraft, a programmer was static-line deployed as the test article exited the aircraft. The programmer then cut away and pulled the parachutes from their bags. While the parachutes had the ability to be reefed, reefing generally was not used because the objective of the testing was to explore steady state full-open performance. The test article had a Froude-number scaled mass of 830-lbm, corresponding to an equivalent scaled velocity for a 21,000-lbm full-scale vehicle. Limited testing was also performed using both lighter and heavier payloads to understand the effects of varying canopy loading on pendulum performance.

Over the course of the two-weeks of testing a total of 54 air drops were conducted. The tests included testing using a single canopy, 2-, and 3-parachute clusters. The single parachute tests were primarily meant to properly size the OICLs used during the testing. The 2-

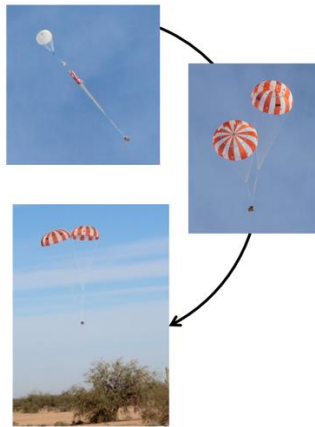


Figure 13. Parachute operations.

parachute tests were conducted to understand pendulum behavior, and the 3-parachute tests provided insight into how the different designs functioned in the nominal flight configuration. The test campaign also investigated the effects of short versus long risers on pendulum swing angle. Fig. 12 shows the packed parachutes on the aircraft and Fig. 13 shows the overall test cycle. Instrumentation sources included Inertial Measurement Unit (IMU) and GPS on-board the payload in addition to wind and atmospheric measurements for detailed post-test reconstructions. Video was captured both from the ground as well as from upward looking cameras on the payload.

The overall test results were puzzling to the team. During full scale air drop testing, 3 of the 5 2-main tests reached a full limit-cycle pendulum motion. However, during the sub-scale air drop test, only 1 of the 14 EDU-canopy tests reached a full limit-cycle. In comparison, only 4 of the 19 combined 3% and 5.5% canopies didn't reach a full limit-cycle.

Post-test data evaluations showed that the "super sail" model is statically more stable than it's EDU counterpart and had limit cycle amplitudes 6 to 8 degrees lower than EDU parachutes. However, the "super sail" model was dynamically more unstable and ramped to its limit cycle faster and would experience limit cycle motion more often. It was also determined post-test that the scaled EDU aerodynamic data did not match full scale aerodynamic data that had been obtained during full-scale air drop testing. The reason for this mismatch is unknown at the present time.

After determining that the subscale aerodynamic data did not match full scale aerodynamic data, the team recommended that no change be made to the EDU geometric porosity or riser length. It was surmised that the benefit to stability did not warrant the increase in uncertainty in modeling the main parachute performance and the potential unknowns that might take multiple full-scale air drop tests to uncover. This recommendation was accepted by the Orion Program and the pursuit of main parachute planform changes was abandoned.

IV. Modeling

A physics-based model was required to provide a more accurate assessment of the landing pendulum risk, including how often it could happen, and provide a means to address it with the RCS control system or to change the concept of operations to minimize the effect of pendulum motion. The baseline parachute model and motion simulators used simulate main parachutes as independent bodies, with a simple aerodynamics model consisting of normal/side, axial force, and pitching moment coefficients. The mass of the parachutes is modeled to be the dry mass of the materials and the mass of the air enclosed by the canopies. A stable dynamic damping in pitch term is used to damp out high frequency pitch oscillatory behavior in the simulated parachute to aid in numerical stability. Proximity effects between parachutes are not modeled, and with the chutes modeled as stable body, the baseline parachute model simulations typically end up as a stable system where 2 or 3 simulated main parachutes will overlap and occupy the same volume.



Figure 12. Packed parachutes prior to air drop testing.

The system would only have a swing angle, the system angle from vertical, if it encountered a simulated wind shear, and would damp back down to zero in a few cycles. Thus, pendulum swinging behavior was never seen in MC simulation sets.

In development of a new main parachute model, shown in Fig. 14, a few assumptions were made. The parachutes are modeled as point bodies with a virtual line, the riser, connecting the point bodies to the attach point on the payload gusset. That attach point is geometrically modeled and will impart forces, and by way of a moment arm to the payload center of gravity, torques to the payload.

The application of the model is only for main parachutes inflated to full open. Specifically, at the peak fly out as caused by the inflation to full open event. Initial conditions such as, altitude, velocity, vehicle attitude are handed over to the new model as initial conditions. The clock angle of the 2 main parachutes are modeled as a uniform distribution between 0° to 360°. Initial swing angles are normally distributed with a 3° 1-sigma dispersion. Since the parachutes are fabric bodies pressurized by air, and constrained by the suspension lines from body axis pitch or yaw motion, only aerodynamic forces are modeled. In effect, the parachute canopies cannot rotate about themselves due to aerodynamic moments. The parachute canopies are pitching about a system center between the payload and the canopy, due to the normal and side forces on the parachutes, i.e. the canopies are flying while being connected to a payload by way of a line, and it is not due to an aerodynamic moment that rotates the parachute canopies about a reference center. It is notionally possible for the main canopies to rotate in a rolling moment axis, along a line that goes through the riser and the vent, but to date, the main canopies have not been observed to rotate in this fashion, or not enough to be modeled. Thus, while the aerodynamic moment equations are present, all moment coefficient terms are zero.

With only forces modeled, it does not simplify the model, and it ends up a somewhat complicated aerodynamic model. At a high level, it is a standard linearized set of aerodynamic components or increments that add up to a total normal, axial, and side force coefficients, used by the motion simulator to compute forces and applied to the mass of the parachute canopies to compute how fast they go and where they go.

The three main aerodynamic components are the standard static aerodynamic coefficients, dynamic derivative force components, and a proximity increment that includes both static and dynamic dependencies. The static terms are the standard normal and axial force coefficients

that are typically published for most vehicles and objects. The side force uses the same values as the normal force coefficients, depending on the relative motion of the parachutes. The dynamic derivatives on the forces are unusual

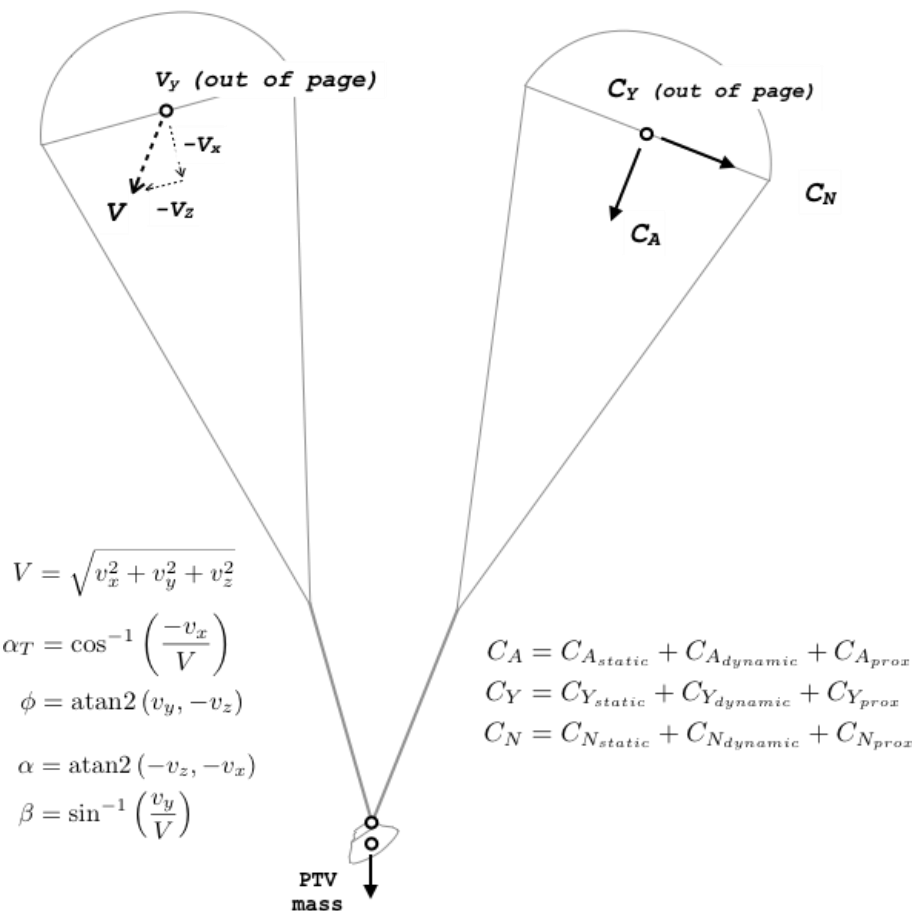


Figure 14. New Main Parachute Aero Model

and typically are not published or developed for most aircraft. For the main parachute, both axial and normal forces have dynamic terms that are dependent on the total angle of attack and the rate of change in total angle of attack. This derivative will drive how fast the system will build in pendulum swing angle from initial small values to the maximum amplitude. A similar dynamic term is applied to the axial force coefficient, wherein a rate of change in angle of attack will increase the axial force.

The last major component is the proximity effect. These terms have two driving parameters. The separation distance, which is normalized by the reference diameter of the parachute, and the rate of change in separation distance. The act of motion between chutes appears to add additional normal force which drives its flyout motion. The relative distance between the parachute centers can get close where the parachutes overlap, a collision, with their edges deforming each other. The loss of axial performance during collisions is modeled through the separation distance parameter.

Development of the aerodynamic coefficients themselves are based on aerodynamic reconstruction, or motion matching of the system during their descent while the main parachutes are fully open. This process is iterative where aerodynamic coefficients are input into a simulation, the results compared to flight data, and the aerodynamic coefficients are subsequently changed until the best match to flight results are achieved. The process for matching main parachute full open flight motion involves matching the altitude first, then the pendulum behavior next, and lastly the fly out behavior of the system.

All four flights of the drop series with the EDU parachutes were used to identify aerodynamic coefficients as they had four different characteristics of motion. Fig. 15 are the motion matches of the 4 test flights showing motion matches of varying quality. Altitude history is the easiest to match, pendulum motion matching is decent, and flyout behavior is difficult to match. There was considerable time and attention needed to derive best estimate winds, due to the imperfect knowledge of real-time winds. Best estimate winds are typically established by drop wind packs released

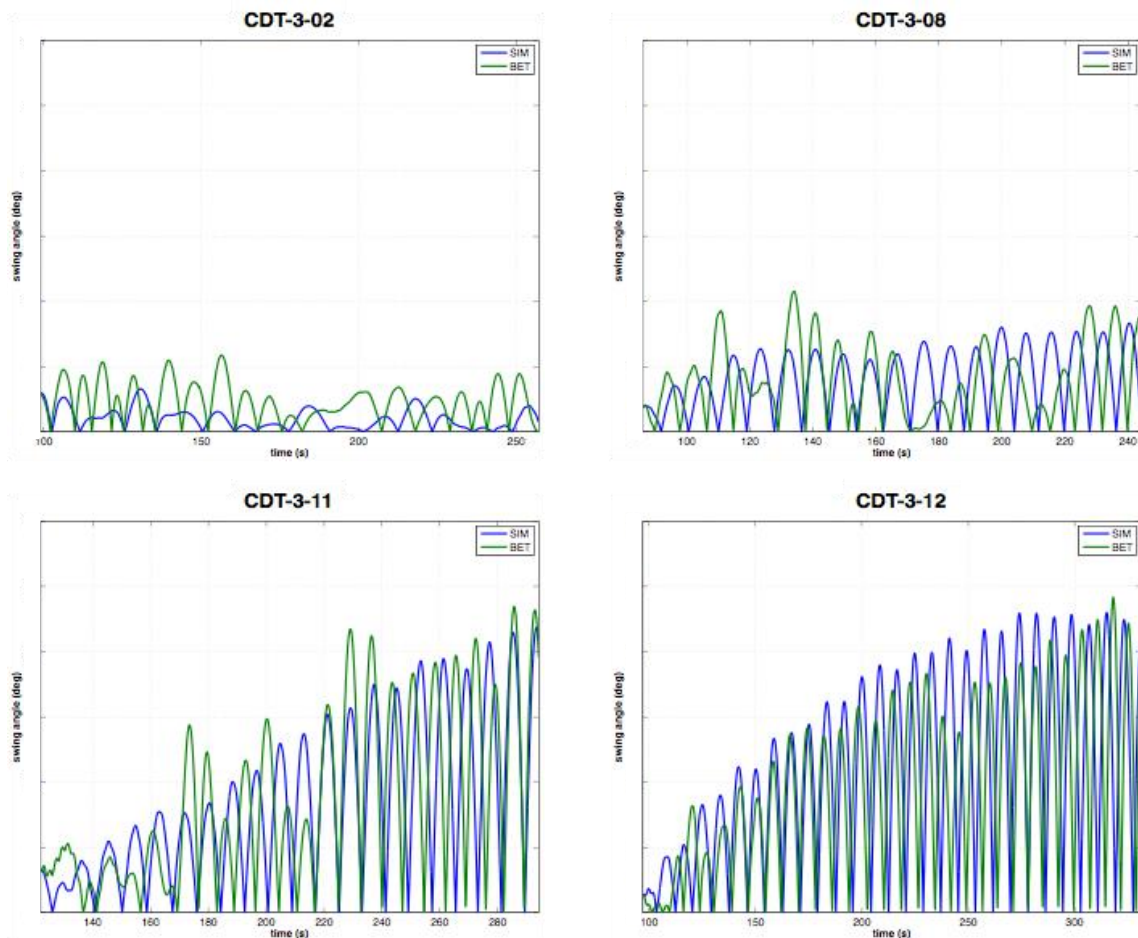


Figure 15. Test Data and Parachute Aero Hi-Fidelity Model Reconstructions.

approximately 15 minutes after the drop and within one mile from the drop location. Thus, the winds are at best an approximation of the actual winds that system saw while in flight.

As can be surmised, the system has multiple driving parameters and the state of real-time atmosphere is imperfect. The quality of the aerodynamics model is therefore considered a mid-fidelity model. The aerodynamic coefficients and math models for the main parachute aerodynamics model is documented in the MPCV 72167, Orion Aerodynamic Databook⁸.

V. Vehicle Level Mitigations

Since it was determined to abandon the pursuit of main parachute planform changes, the Pendulum Team examined and studied all possible ways to mitigate the risk of the pendulum motion. The team studied all aspects in order to prevent any major structural design modifications being required to mitigate the pendulum motion. The final set of recommended options, were known as the “Kitchen Sink” Option.

The GNC EMT assessed changes to deployment altitudes and the touchdown roll control performance. One of GNC’s critical functions during descent and landing is to trigger the parachute deployment events. All parachute deployment events use altitude as one trigger to deploy the parachutes, but they also employ smart logic to ensure they are deploying at optimal attitude and attitude rates. Drogue parachute release and main parachute deploy, for example, use vehicle rate data to time the release at minimum rate to ensure a safe deployment of the main parachutes. The second function is to actively manage vehicle roll rates and perform touchdown roll control. GNC actively controls the vehicle roll with respect to heading to ensure the vehicle is oriented properly and slices into the water. This significantly reduces landing loads for the structure and the crew. Using the newly developed two parachute pendulum model, GNC assessed changes to these two critical functions that might mitigate the impacts of pendulum motion.

Drogue release and main parachute deployment is triggered using a smart drogue release algorithm. The release is based on two criteria, altitude and minimum attitude rate (RSS of pitch and yaw rate). After an altitude minimum is met the drogue parachutes are

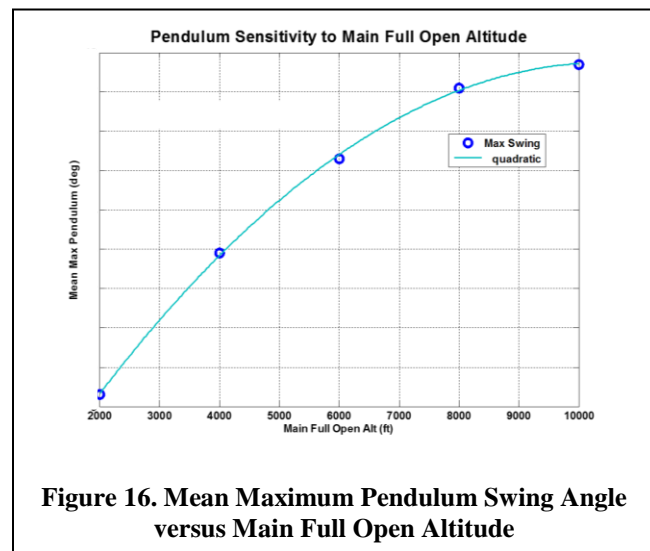


Figure 16. Mean Maximum Pendulum Swing Angle versus Main Full Open Altitude

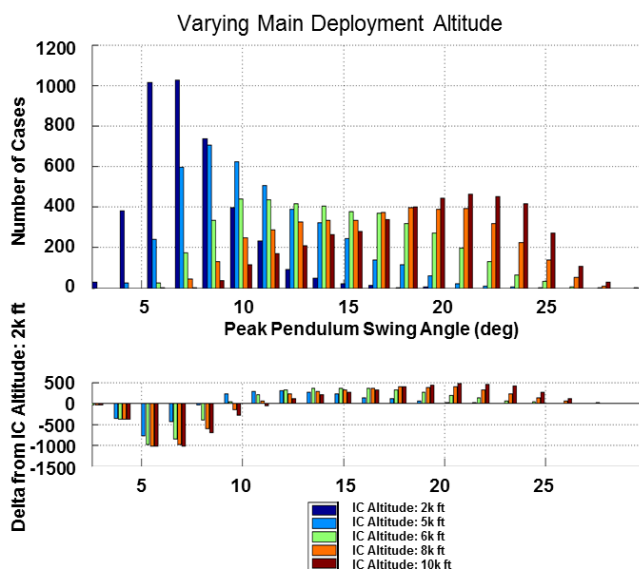


Figure 17. Peak Pendulum Swing Angle Distribution for Varying Main Deployment Altitudes.

released when the RSS of pitch and yaw rate are at a minimum. If smart drogue release hasn’t found a minimum rate condition by a required threshold, the main deployment altitude floor, the drogues are released immediately. Based on the fact that CPAS 2-main parachute drop tests showed pendulum motion for both the Parachute Test Vehicle (PTV), capsule shaped test article, and the Parachute Compartment Drop Test Vehicle (PCDTV), dart test article, attitude of the vehicle during main deployment was not deemed a contributing factor in developing pendulum dynamics. Because of the test architecture, main deployment on CPAS drop tests occurs considerably higher than the nominal planned deployment on Orion. CPAS drop test data did show evidence that it could take some time prior to the start of pendulum dynamics. Using the 2-Main parachute

pendulum model and GRAM a Monte Carlo was run varying the deployment altitude. The results, shown in Fig. 16, show that the mean maximum pendulum swing angle decreases as a function of main parachute deployment altitude. Fig. 17 shows the same Monte Carlo cases, but plots the distribution of the maximum pendulum swing angle for each Monte Carlo case. This shows that the worst case maximum swing angle in a Monte Carlo set doesn't necessarily reduce, but that the number of cases that develop into a pendulum limit cycle and achieve a large pendulum swing angle decreases as main deployment altitude is lowered.

Using this trend, GNC assessed how low the Orion main parachute deployment altitude could be reduced. GNC requires a minimum altitude to perform touchdown roll control. This value also accounts for navigated altitude errors. Using a 3,000 case MC set for a 2 main parachute deployment, GNC assessed the maximum altitude loss from pilot mortar fire to main parachute full open. The data is shown in

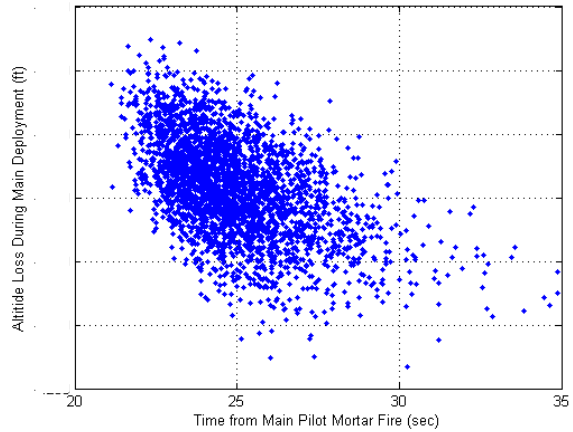


Figure 18. Altitude Loss During a 2 Main Parachute Deployment.

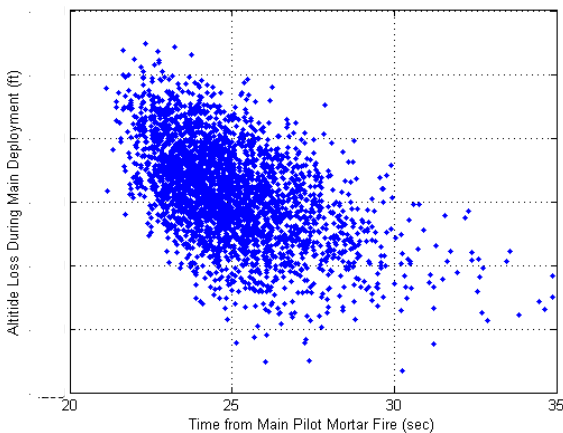


Figure . 18. The maximum altitude loss and the minimum altitude to perform touchdown roll control were combined to set the minimum deployment altitude. The baseline main deployment floor was reduced by 2000 ft and the team recommended lowering the nominal main deployment altitude.

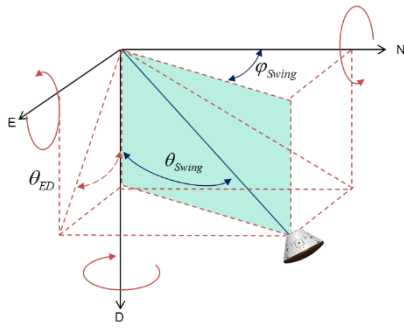


Figure 19: Pendulum Coordinate System and Key Parameters

observation in GNC's Touchdown Pointing Flight Software consists of three parts: 2D pendulum observer used in estimating states in the North-Down plane, 2D pendulum observer used in estimating states in the East-Down plane, and generation of 3-dimensional states using the 2-dimensional observations. 2-dimensional pendulum state observation is based upon a classic control theory, Luenberger Observer. The pendulum mode is modeled as a two-dimensional simple gravity pendulum. The main parachute cluster is considered to be the origin of the system and is represented as a moving attach point. The vehicle is considered to be a suspended point mass. Swing angle is defined as the angle between the line drawn between the point mass and the attach point and the downwards axis. Forces included in the model are those due to gravity (g), assumed to be downwards, as well as forces due to RCS firings (F_{RCS}). The 2-D pendulum model is depicted in Fig. 20. The observer state implementation uses a linear pendulum motion model and the only input is navigation derived velocity in the North-East-Down frame. The key advantages of this approach⁴ include: low order filter and state propagation, minimal lag, quick reaction to changes in steady-state wind, dynamic tracking of pendulum frequencies, and ability to derive pendulum energy level.

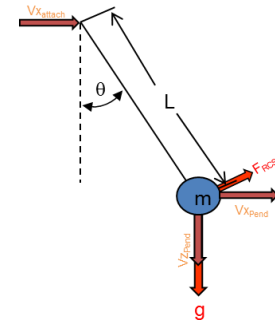


Figure 20. Two-Dimensional Pendulum Model

With the pendulum observer design in place, GNC assessed control options available using knowledge of the pendulum motion. Preventing or reducing pendulum motion is the most desirable solution as it removes the dynamics that result in increased off-attitude landing and increased landing loads. Pendulum damping uses the CM RCS during the pendulum swing to counteract the pendulum velocity. Fig. 21 is a diagram of how pendulum damping works. The pendulum observer provides the pendulum energy estimate and swing plane orientation. There were two control damping options assessed: passive and active damping. Passive damping uses CM RCS to damp pendulum motion when vehicle alignment naturally occurs. The baseline touchdown roll control algorithm is still active. Active damping rotates the vehicle to align with the pendulum plane and then fires the CM RCS to damp the pendulum motion. The concept of operations assessed was to perform active damping from main full open to the start of touchdown roll control at 1,500 ft. During touchdown roll control, passive damping is implemented. Passive damping can only occur when the pendulum swing plane is in line with the wind.

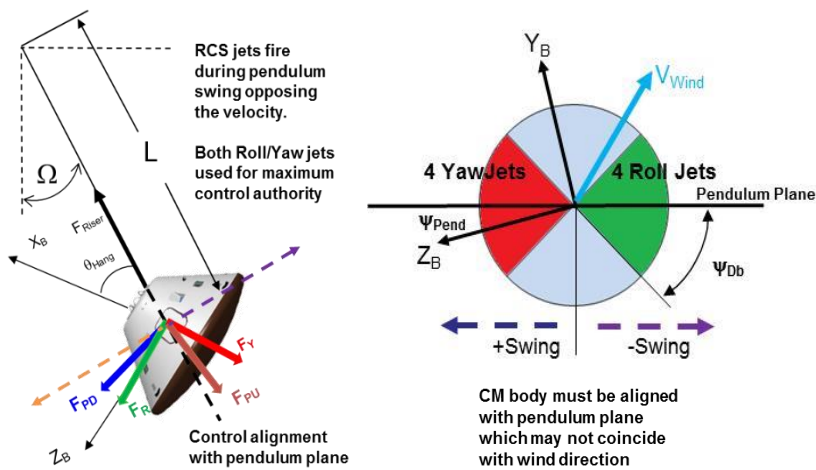


Figure 21. Pendulum Damping Diagram.

The threshold set to activate damping only when the observer senses pendulum energy above 8 degrees. This was used to preclude damping during nominal 3 parachute operations and also to reduce propellant usage. All yaw and roll jets

were used to damp pendulum motion as quickly as possible. While the pitch down jets are the most effective thrusters available, they are unavailable for use after FBC jettison due to concerns about loads applied to the thrusters during FBC jettison and drogue mortar fire. GNC Monte Carlo assessments showed pendulum damping could reduce maximum pendulum swing angle and improve landing impact performance, unfortunately the propellant usage was prohibitive. GNC also expressed concerns due to reliance on system complexity and reliance on simulation models. These factors resulted in the team not recommending pendulum damping as a mitigation⁴.

Another strategy investigated was alternate heading control. An alternative to removing pendulum motion is to reorient the vehicle to reduce the probability of a low angle impact at touchdown. As shown in Fig. 22, impact angle, θ , varies during a single cycle of pendulum swing. The range of impact angles is largest when the vehicle is aligned with the pendulum swing plane and has the highest probability of impact at the center of the heat shield. Alternatively, when the vehicle is aligned perpendicular to the swing plane the range of impact angles is reduced and has the lowest probability of impact at the heat shield center.

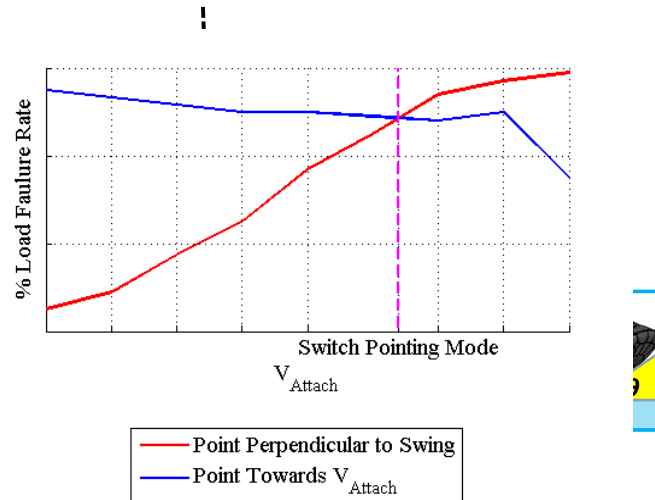
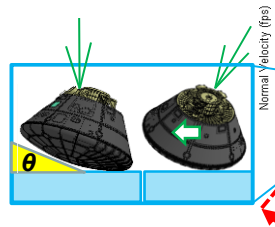


Figure 23: Wind Velocity Switching Threshold.

Figure 22: Pendulum Impact Angle Scenarios

The black dots in the figure are MC results without alternate heading, the red dots are with alternate heading implemented. When GNC detects large pendulum energy and the wind velocity is low enough, the vehicle is pointed perpendicular to the swing plane. When orienting the vehicle to be perpendicular to the swing plane there are two directions that can be selected. The pointing direction is chosen to minimize the angle between the perpendicular pointing angle and the wind velocity direction. A MC sensitivity study was conducted to determine when to employ alternate heading. One set pointed in the direction of the velocity and the other set pointed perpendicular to the pendulum swing angle. Load failures were assessed to determine the optimal switching point from perpendicular to the swing plane to the wind. Fig. 23 illustrates the cross-over velocity threshold.

In addition, the team explored an increase to the hang angle beyond the current requirement, since landing at higher impact angles decreases the overall landing loads. There are currently two ways to achieve a higher hang angles on Orion. Option 1 would be to move the main parachute attachment location out further radially which would result in higher hang angles. Option 2 would utilize vehicle's ballast to shift the Crew Module's center of gravity at landing to achieve a higher hang angle.

Option 1, shifting the Main Parachute attachment location, was not a viable option since the current attachment location is already located at the furthest point radially given the current vehicle architecture. Shifting the Main Parachute attachment location further outboard would violate the FBC static and dynamic jettison envelopes. Changing the outer mold line of the FBC to accommodate and update to the attachment location was not a viable option.

For Option 2, it must be understood that the vehicles hang angle is not independently controlled. Instead, it is dependent on the desired Lift to Drag (L/D) ratio required for reentry landing events. It is also important to note that the hang angle has a secondary relationship to the L/D chosen flight path angle. A higher L/D would result in a higher hang angle.

A thorough assessment was performed by the mass properties team to evaluate the baseline L/D design/requirement envelope vs. the known mass properties for the matured baseline vehicle. This assessment would quantify the level of risk associated with not maintaining the appropriate margin in L/D given the ballast mass allocations imposed on the vehicle. The results of this analysis showed the max achievable hang angle could improve landing impact

performance, but to maintain the L/D 100% of the time it would require a substantial increase in ballast mass, which was not acceptable. However, the mass properties team was willing to back off the current minimum hang angle and increase it, which would increase the low end nominal hang angle and allow the targeted L/D be achievable while staying within the baseline ballast mass allocation 100% of the time.

Another potential option to mitigate the effects of increased pendulum swing would be to reinforce key structural components until you achieve the desired vehicle capability that would protect both the integrity of the Crew Cabin structure as well as the crew. Initial EFT-1 Pendulum loads assessments showed loads increases that were more than double those of the current baseline loads assuming no benefit from the RCS.

A final mitigation option, was adding a Permanent Reefing Line (PRL) to the skirt of the main parachute, which would prevent the projected diameter from reaching the ‘natural’ full open diameter. The Shuttle Program⁷ explored this as an option to improve Orbiter drag parachute stability, but eventually chose to change the geometric porosity because it was more effective from a drag loss perspective. A PRL will affect the terminal performance for all nominal and off-nominal landings,

by increasing the descent rate, vehicle applied torque, fly-out angle and pendulum swing amplitude. In review of historical test data for stability trends, Fig. 24, Apollo had one drop test where suspension line length ratio (Ls/Do)

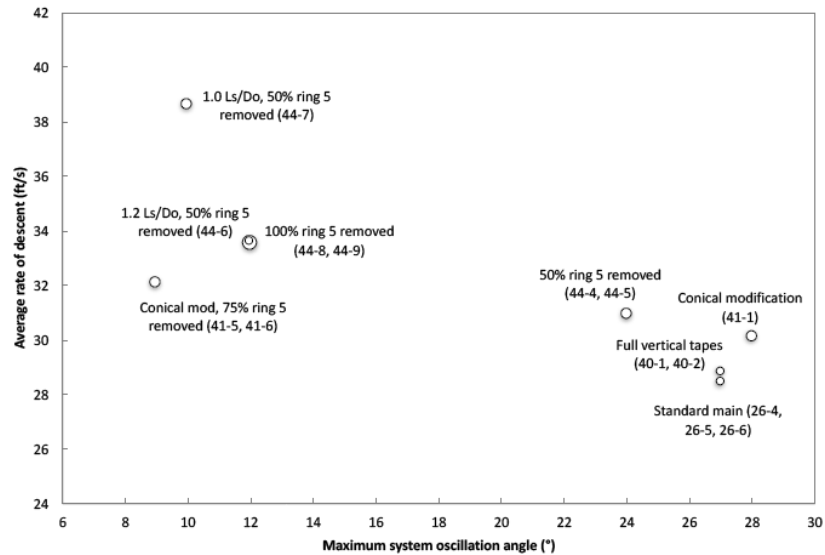


Figure 24. Historical test data for parachute stability trends².

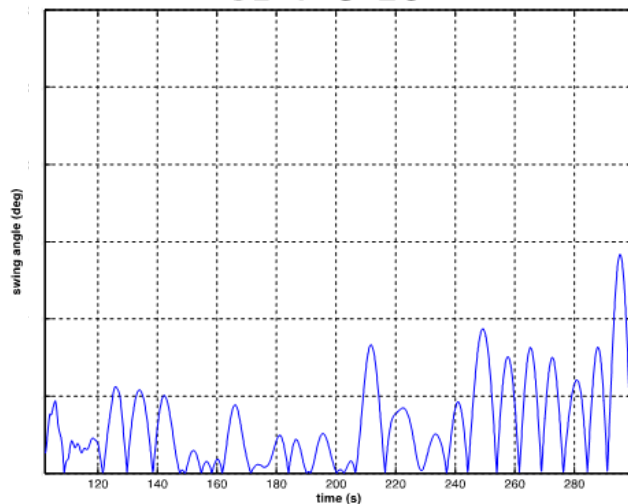


Figure 25. CDT 3-16 amplitude of swing angle during main terminal descent.

parachute model memo parameters. For both tests, the average drag area yielded 81.4%. On CDT 3-16, the main steady state phase was dominated by ‘maypole’ motion followed by late pendulum. The mean RoD increased by 4.18 ft/s. As shown in Fig. 25, the amplitude of the pendulum was smaller than seen previously, but it is uncertain whether limit cycle was achieved. The peak amplitude observed was similar to the peak amplitude on CDT3-15, which included

the short riser and OICL. On CDT 3-17, the RoD increased by 2.77 ft/s, but the distribution appeared to be more bimodal. Both flights exhibited a reduction in canopy ‘breathing’ and the fly-out time histories were within existing models. Based on these two test flight, there was insufficient test data to prove or disapprove PRL benefits to Pendulum. The team would need to resize the PRL, to increase drag and then prove on several tests in order to generate a new validated database of main steady-state data. Within the team there were debates, if PRL would result in more consistent main parachute behavior which is important for both nominal and contingency cases.

VI. Integrated Solution

While all of the viable mitigation options would improve the vehicle landing impact performance individually, it was still unknown how the landing performance would improve when they were combined as an integrated system. Each viable mitigation was incorporated into an integrated vehicle simulation along with the latest 2-main parachute aero model. These combined options became known as the “Kitchen Sink” options since the team was throwing everything at this problem to quantify what the impact would be to vehicle landing performance without making changes to either the Main parachute planform or the primary structure.

The GN&C team again provided a unique 130,000 case MC set for each individual mitigation option shown in Fig 26. Two Kitchen Sink (KS) options were derived by combining all of the viable individual options. For KS1, PRL mitigation option was

not considered in this assessment. KS1’s performance was based on combining the Pendulum Observer with the 90° to Pendulum swing, the Lower Deployment Altitude and the higher hang angle. KS2 contained the same mitigations options as KS1 but added in the estimated performance improvement for the PRL. Fig. 26 shows the increased landing capability for each individual option and the two proposed Kitchen Sink integrated solutions. Each mitigation option assumes that the Pendulum Observer has

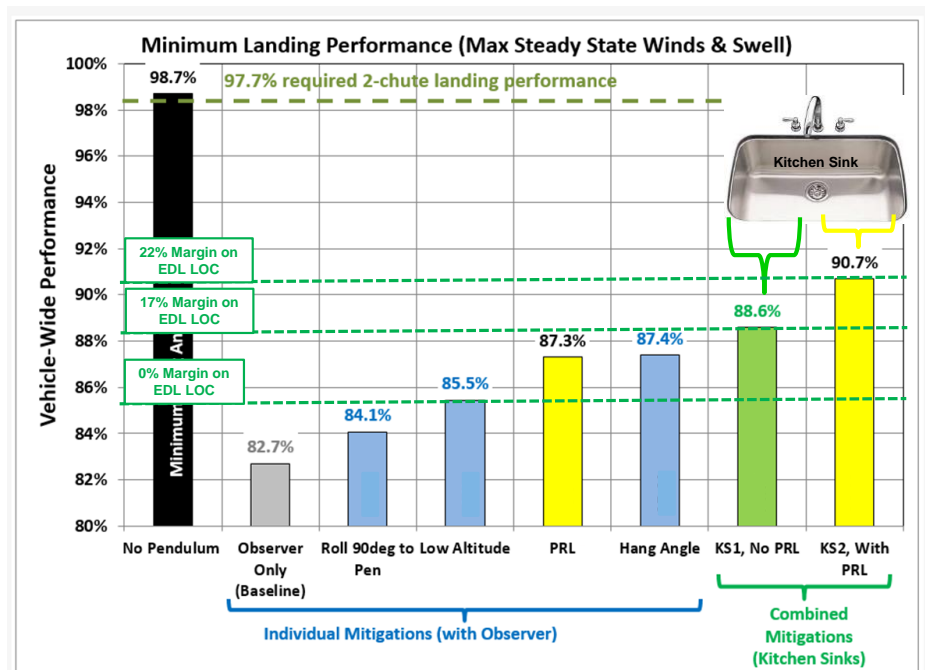


Figure 26: Minimum Landing Performance for all Pendulum Mitigation Options

been implemented into the flight software as part of the new baseline. The KS1 and KS2 options improved the overall landing performance from 82.7%, noted with just the Pendulum Observer, to 88.6% and 90.7% which was still lower than the stated two parachute landing performance requirement of 97.7%.

A final structural evaluation was performed to determine if further reinforcement of the vehicle had become a viable mitigation option to achieve the statistical level of coverage noted in the current requirements. The results of this evaluation showed that improving KS1’s landing performance levels to meet the current two parachute requirement was still not viable given the magnitude of the loads increase relative to the baseline design loads. Revised mass impacts to both the Crew Cabin structure and the Heat Shield for the KS1 option were estimated to be over 1500 lbs. Other items of concern were the potential impacts to the manufacturing processes and geometric limitations that would limit the ability to further reinforce the critical regions of the vehicle. Achieving a 97.7% level of statistical coverage was not viable.

It should be noted that the flight crew’s (Astronauts) ability to withstand these severe landing conditions was monitored throughout this assessment. The initial results of the crew loads assessment showed that a crew member

would be able to withstand the loads imparted to them up to and beyond the current requirement of 97.7%. This is due to the fact that the majority of the loads increase due to pendulum is driven through the vehicle's x-axis (normal to the crew's chest) and not through the spine. Therefore, the crew's landing performance/health was not a driving factor in the overall mitigation plan.

. While it is important to meet the requirements, the team was also assessing and evaluating the overall reliability of the system due to the pendulum motion. The Orion Systems Reliability team's system wide performance analysis uses the same statistical landing performance data as what is used to define the vehicle's landing performance with one notable exception. Reliability is not so much concerned with the vehicle's landing performance relative to the design requirements, which includes all of the various multipliers used to account for uncertainty in the loads and the factors of safety used to calculate the margins of safety of any given component. System Reliability's primary focus is determining the threshold for ultimate or catastrophic failure where the ultimate failure of any given structural component could lead to either LOTV or LOC. The Orion Probabilistic Risk Assessment (PRA) is intended to capture a realistic risk prediction for the weighted average range of mission scenarios. Therefore, it is imperative that the top LOC risk drivers are normalized by removing conservatism from the prediction where possible, ensuring Orion benefits from the risk informed design process.

During the course of the Pendulum mitigation assessment, an EDL margin threshold was established to aid in the development of an acceptable Two Main Parachute Landing performance threshold. The target margin for the EDL epoch was set at 20% to cover for any adverse changes in Orion's mission performance for other hazards. To determine the LOC threshold, the statistical data used to evaluate the vehicle's landing impact performance pass/fail criteria thresholds were increased by 1.4 to account for the ultimate factor of safety used to size the primary structural elements of Orion. The model uncertainty factor (MUF) of 1.15, that is used to account for the uncertainty in the structural landing models, was still included in the landing statistics but was uniformly distributed 1.0 +/- 0.15 to each resultant landing impact load/stress. The updated pass/fail statistics for a two Main Parachute landing are included in a larger Entry Descent and Landing (EDL) model used to evaluate the vehicle's reliability performance for all environments (entry through landing). Fig. 28 shows notional the results of the updated reliability assessment imposed on top of the bar chart that shows the minimum landing performance for each mitigation option and the two kitchen sink options. Integrated solution KS1 has a vehicle LOC margin of 17% while KS2 has 22% LOC margin.

Both the KS1 and the KS2 options would drop the landing impact event from being the top program risk down to either the fourth or fifth. Fig. 28 shows where these two options fall on a notional program risk Pareto. The Orion Engineering Review Board (ERB) concurred that the LOC margin for the KS1 or KS2 was at an acceptable level of risk for LOC. The recommendation of the ERB was to proceed forward with the KS1 option which had no active pendulum damping. Active damping was thought to be a higher risk to achieve with diminished benefits due to the complexity of the modification, the immaturity of the

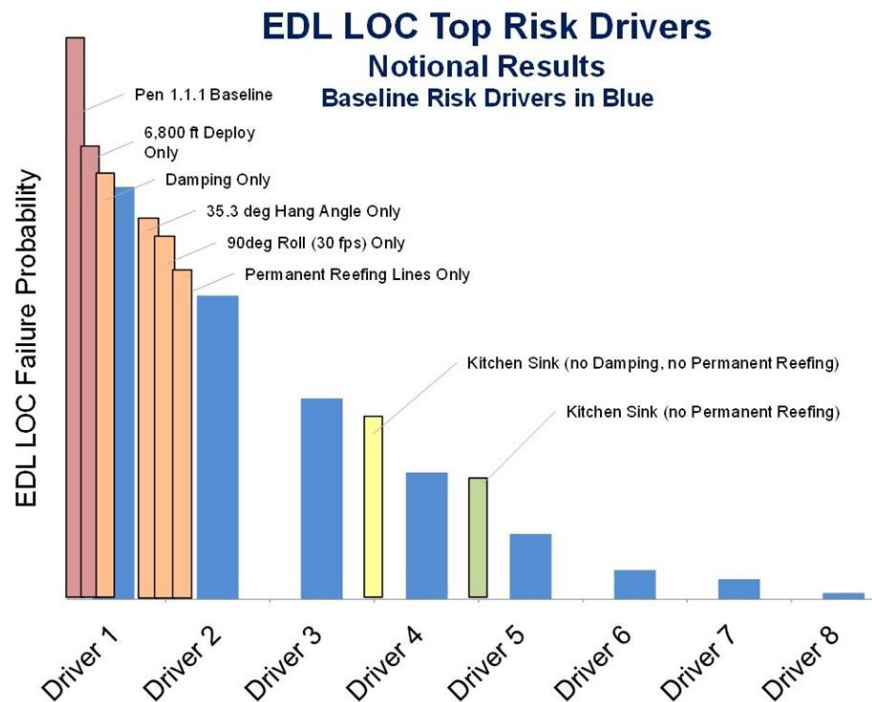


Figure 28: Notional EDL LOC risk Pareto from baseline landing loads to noted pendulum mitigation options

pendulum parachute model used in the landing MC simulations, and the increased RCS propellant usage.

VII. Conclusion

When trying to mitigate a complex system level problem, it is often very difficult to determine when the mitigations are enough and it is time to put the pencils down and move on. The toughest decision the Orion Program made was the decision to not implement the PRL. The Program did not agree that incorporating the PRL into the Main Parachute architecture was worth the loss in drag that would occur on every nominal landing even though ‘the nominal landing’ performance showed margin to the requirements. There was insufficient data and analysis to prove or disapprove PRL benefits to pendulum after a single test. The additional tests to validate main descent performance with PRL was deemed not worth the cost and schedule impact to the CPAS Qualification Test Program. In the end, the final decision came down to the low likelihood of losing a Main Parachute vs. sacrificing the nominal performance to benefit an off-nominal event. The Program accepted the risk that the baseline EDU system will likely never meet the 2-Main Parachute Landing Performance criteria requirement of 97.7% coverage. For the first unmanned Exploration Mission-1, the landing performance requirement was reduced from 97.7% down to 90%. The EM-2 landing performance requirement was not changed and would be readdressed at the Delta Critical Design Review for EM-2.

Since the Orion Program decision, the Aerosciences team refined the two main cluster aerodynamics model for the main parachutes. Early iterations of the model did a good job in matching pendulum motions, but adequate to poor job in matching flyout and orbiting (or maypole) motions observed in the 4 EDU drop tests. Refinements to the aerodynamic model matched flyout motions better enabled wind shears to start orbiting (maypole) motions. The changes resulted in smaller maximum amplitude pendulum motions.

Since the Aerodatabase enhancements, the current best estimate for 2-Main Parachute landing impact performance is closer to-achieving the 97.7% EM-2 requirement and is no longer considered a major contributor to LOC/LOTV. The team reflected on if any of the previous decisions would be reversed based on the recent results. The team concluded that the decisions and mitigations implemented improved overall landing performance. The key in solving this massive issue was promoting a multi-disciplinary team based on their abilities and desire to contribute to the end goal. Team creativity leading to engineering ingenuity squeezed margin out of the design. The problem was challenging but in the complexity of it all, there were many lessons learned. The team forged on, not necessarily ‘solving the issue’ as much as achieving an acceptable level of risk.

References

- ¹Anderson, Brian. "Sub-scale Orion Parachute Test Results From the National Full-Scale Aerodynamics Complex 80-by 120-ft Wind Tunnel" *24th Aerodynamic Decelerator Systems Conference*. AIAA, 2017.
- ²Belknap, S and K Goar. "Summary Analysis Report of Drop Tests Performed During the Apollo Main Parachute Improvement." *NVR-3722*. 1964.
- ³Greathouse, James and Alan Schwing. "Study of Geometric Porosity and Drag using Computational Fluid Dynamics for Rigid Parachute Shapes." *23rd Aerodynamic Decelerator Conference*. AIAA, 2015-2131.
- ⁴Kane, M and R Wacker. "Orion GN&C Detection and Mitigation of Parachute Pedulosity." *2016 American Astronautical Society Guidance and Control Conference*. AAS 16-115.
- ⁵Knacke, Theo. *Parachute Recovery Systems Design Manual*. China Lake: Para Publishing, 1992.
- ⁶Ray, Eric S., Machin, Ricardo A. "Pendulum Motion in Main Parachute Clusters." *23rd Aerodynamic Decelerator Systems Conference*. AIAA, 2015-2138.
- ⁷SAND93-2544. "Orbiter Drag Chute Stability Test in the NASA/Ames 80x120 Foot Wind Tunnel." Albuquerque: Sandia National Laboratories, February 1994.
- ⁸Troung, Tuan. *MPCV 72167 Orion MPCV Aerodynamic Databook*. Johnson Space Center, 2017.
- ⁹Daum, Jared and Mollman, Catherine. "Design and Drop Testing of the Capsule Parachute Assembly System Sub-Scale Main Parachute." *24th Aerodynamic Decelerator Systems Conference*. AIAA, 2017