

Extraction-Separation Performance and Dynamic Modeling of Orion Test Vehicles with Adams Simulation: 5th Edition

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Nomenclature

<i>AoA</i>	=	<i>Angle of Attack</i>
<i>CDT</i>	=	<i>Cluster Development Test</i>
<i>CCP</i>	=	<i>Commercial Crew Program</i>
<i>COTS</i>	=	<i>Commercial off the Shelf</i>
<i>CPAS</i>	=	<i>Capsule Parachute Assembly System</i>
<i>CPSS</i>	=	<i>Cradle Platform Separation System</i>
<i>CCPAT</i>	=	<i>Commercial Crew Parachute Airdrop Team</i>
<i>DSSA</i>	=	<i>Decelerator Simulation System Application</i>
<i>EFTC</i>	=	<i>Electronic Force Transfer Coupling</i>
<i>EPJD</i>	=	<i>Extraction Parachute Jettison Device</i>
<i>FAST</i>	=	<i>Flight Analysis Simulation Tool</i>
<i>LVAD</i>	=	<i>Low Velocity Airdrop</i>
<i>MDS</i>	=	<i>Mid-Air Delivery System</i>
<i>MSL</i>	=	<i>Mean Sea Level</i>
<i>NPCQT</i>	=	<i>NASA Parachute Cluster Qualification Test</i>
<i>PCRT</i>	=	<i>Parachute Cluster Reliability Test</i>
<i>PCDTV</i>	=	<i>Parachute Compartment Drop Test Vehicle</i>
<i>PTV</i>	=	<i>Parachute Test Vehicle</i>
<i>WSTF</i>	=	<i>White Sands Test Facility</i>

The NASA parachute test team executed the last full-scale parachute drop test utilizing the parachute compartment drop test vehicle (PCDTV) mated to the Mid-Air Deployment System (MDS), at the Yuma Proving Grounds in January 2024. The last few tests, conducted for the Commercial Crew Program (CCP), took advantage of the improvements made over the last decade and a half of CPAS drop tests. This edition will focus on the simulation modeling of the PCDTV/MDS vehicle, extracted from both a C-17 and C-130 aircraft, with altitude ranges from 13,000 to 35,000 ft-Mean Sea Level (MSL).

I. Introduction

The effort undertaken by the Capsule Parachute Assembly System (CPAS) of continually improving modeling of the extraction and separation portion of drop testing was invaluable when called upon to support the Commercial Crew Parachute Airdrop Testing (CCPAT) project. Implementation began before the first test Parachute Compartment Drop Test Vehicle/Mid-Air Delivery System (PCDTV/MDS) involving the Engineering Development Unit of the Orion parachute system in September 2011. Updates continued through the last test conducted for the CCPAT project in January 2024. Early analytical efforts were successfully accomplished with a legacy simulation tool, the Decelerator Simulation System Application (DSSA) developed to support Low Velocity Air Drop (LVAD) testing. As the complexity of the CPAS drop test campaign increased, the need arose to expand beyond the limitations of DSSA and employ a simulation tool that could model the vehicle dynamic behavior

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beyond the separation event of the mated (PCDTV/MDS) test vehicle. In addition, the dynamic loading of both hardware and soft goods became critical to understanding test risk, leading to use of the Adams simulation tool.

II. Simulating the System

A. Initial Extraction and Separation Model

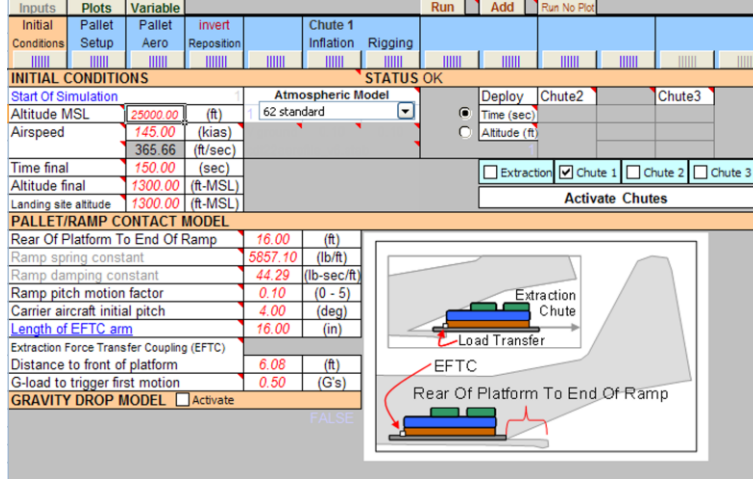


Figure 1. Example of DSSA GUI

conditions monitored in real-time by the avionics system, referred to as the smart separation algorithm³. The algorithm monitored the pitch angle, pitch rate, roll angle, a start and end time that was determined during the pre-test analysis before each drop test. Given the limitation of DSSA to simulate the separation event, an extensive sensitivity study was necessary in the months leading up to the first drop test with this vehicle (CDT-3-1). The physical criteria considered was prevention of the programmer harness lines contacting the parachute compartment as well as the fins of the PCDTV from contacting the MDS during separation, illustrated in figure 2. Separating at an undesired pitch angle and rate could have a severe effect of the PCDTV dynamics such that recovery was not possible. Early PCDTV releases tended to cause large negative pitch rates, and lower angles of attack which increased the probability of the programmer harness contacting the PCDTV and PCDTV contact with the MDS respectively. Monte Carlo results from the CDT-3-1 analysis in figure 3 show the assessment of the pitch and pitch rate criteria used to identify the time window

The initial tool utilized to predict the mated PCDTV/MDS extraction was the DSSA, a 6-degree of freedom (6-DOF) simulation¹. This simulation provided the user with a graphical user interface (GUI) on the front end as illustrated in figure 1, with a FORTRAN executable on the back end. What made this tool beneficial was the capability to model the extraction, reposition event and up to separation event². Determining when to separate the PCDTV and MDS depended on a set of

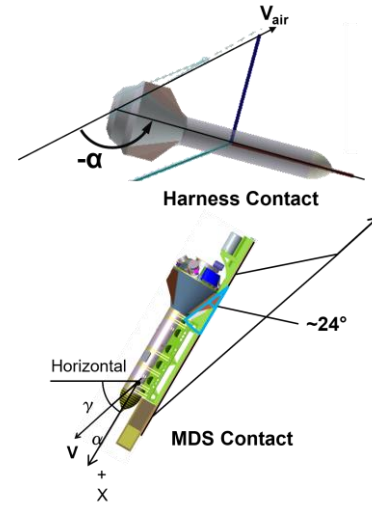


Figure 2. PCDTV/MDS CAD models

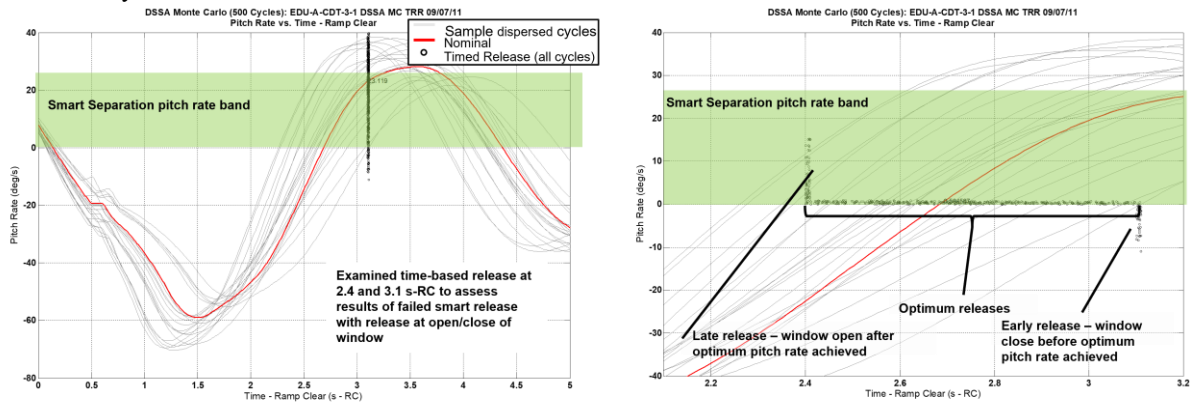


Figure 3. CDT-3-1 DSSA Monte Carlo results of the mated PCDTV/MDS pitch and pitch rate

As the test program for this vehicle evolved, a higher fidelity prediction of the reposition loads became necessary. For example, instead of modeling individual harness lines, DSSA used an elastic parachute riser that terminates at the confluence location. The forward and aft harness line loads were post-processed using the confluence location and pitch of the platform. A 62/38 port-to-starboard load split was assumed as the applied load input. The applied load was then used to provide a margin of safety for the test hardware, which lead to increased risk acceptance, as complexity of the drop tests increased, shown in table 1. The need for improved prediction of the reposition harness line loads was evident during execution of CDT-3-6. This test was the first to use two parachutes

Table 1. CDT-3-12 margin of safety summary for the reposition event using loads determined by DSSA

Reposition	Max Load* (lbs)	Load Share	Applied Load (lbs)	Design Factor	Working Load Limit (lbs)	MOS	D-TCR MOS
Deployment Line (8 Ply Kevlar)	50,685	1.00	50,685	3.23	49,508	-0.02	-0.04
Deployment Line (8 Ply Kevlar) <i>FOS reduced to 1.95</i>	50,685	1.00	50,685	3.15	50,778	0.00	<i>FOS reduced to 1.91</i>
4:2 Confluence Top Pin	50,685	1.00	50,685	2.00	42,000	-0.17	-0.18
4:2 Confluence Top Pin <i>FOS reduced to 1.65</i>	50,685	1.00	50,685	1.65	50,909	0.00	<i>FOS reduced to 1.62</i>
4:2 Confluence Single Bottom Pin**	50,685	0.62	31,424	2.00	52,500	0.67	0.63
Forward Harness (6 Ply Kevlar)	50,685	0.62	31,424	2.90	41,360	0.31	0.29
Aft Harness (6 Ply Kevlar)	29,904	0.62	18,540	2.90	41,360	1.23	1.17
1 Front Single Event Fitting**	50,685	0.62	31,424	2.00	34,400	0.09	0.07
1 Aft Single Event Fitting**	29,904	0.62	18,540	2.00	25,000	0.34	0.31

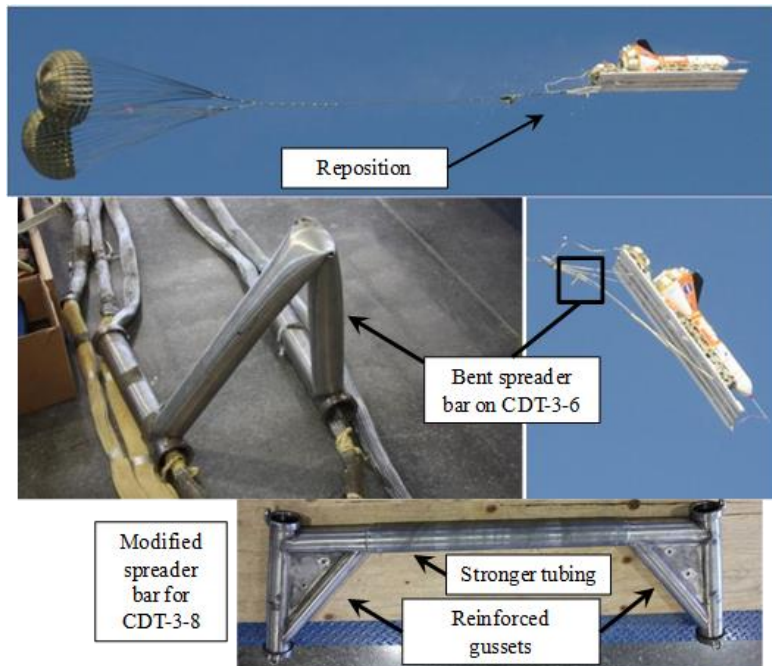


Figure 4. Bent MDS spreader bar due to two extraction parachutes

update the model developed using the Adams simulation tool⁵.

B. New Extraction and Separation Model

MSC/Adams (formerly Automatic Dynamic Analysis of Mechanical Systems)⁵ is a Commercial Off-the-Shelf (COTS) multi-body 6-DOF simulator originally employed by CPAS to simulate the mated Parachute Test Vehicle/Cradle Platform Separation System (PTV/CPSS) extraction from the aircraft and subsequent PTV/CPSS separation⁶. Building upon the work that went into that test vehicle, the model that was developed in support of

to extract the mated vehicle from a C-130. Simulation results showed that the additional drag area from the second parachute resulted in a faster extraction and pitch plane dynamics, and nearly doubled the reaction loads on the MDS. Although structural analysis showed acceptable margins, the effect of additional load was not considered on the “spreader bar,” a solid tube that ensures the forward harness slings do not snag on the Electronic Force Transfer Coupling (EFTC) link assembly during reposition. The spreader bar yielded under the additional load, as seen in Figure 4. The test was not negatively affected, and the spreader bar was modified successfully and flown on the subsequent test, CDT-3-8.

Since DSSA lacked the capability to model a vehicle separation maneuver, a different simulation was needed for that phase of flight. It was not until the last drop test of this series, CDT-3-17, that resources were available to revive and

CDT-3-1, was revived with updates and expanded using the knowledge and testing obtained by the CPAS project up to that point. Figure 5 depicts the analysis conducted using Adams, demonstrating that for the planned time window of the smart separation event, the resulting PCDTV AoA indicated no instances of contact of the PCDTV with the MDS would occur.

III. Model Refinement

A. Smart separation and PCDTV stability

The smart separation logic² is emulated in the Adams simulation model, and allows for modification of the parameters based on given test conditions (airspeed, number of extraction parachutes, etc.)

The simulation commands PCDTV/MDS separation (using separate aerodynamic databases), with no further interaction between bodies. This is due to the negligible frictional and aerodynamic interactions between the two



Figure 6. Mated vehicle extraction through programmer line stretch

Separation of the PCDTV from the MDS was not optimal for the first two tests. Neither test commanded separation at the desired conditions (pitch and pitch-rate) as the command was delayed until the expiration of the time window. The first test, CDT-3-1, experienced an incorrect activation of the avionics system, which nominally

occurs at vehicle ramp clear from the aircraft. Due to an incorrectly sized lanyard, depicted in figure 7, the activation occurred roughly 0.25 seconds prior to ramp clear; therefore, the smart separation window was biased early by the same amount of time. The post-test analysis, in figure 8, shows that the vehicle dynamics were approaching smart separation conditions when the timer expired. CDT-3-2 also separated on window close time due to the unaccounted effects of aircraft wake on the extraction parachute, which also induced a pitch rate during extraction. The non-optimal PCDTV release resulted in a high angle of attack at programmer deployment illustrated in figure 9. Although the separation event was not as expected, the programmer parachutes quickly damped the PCDTV motion, leading to a

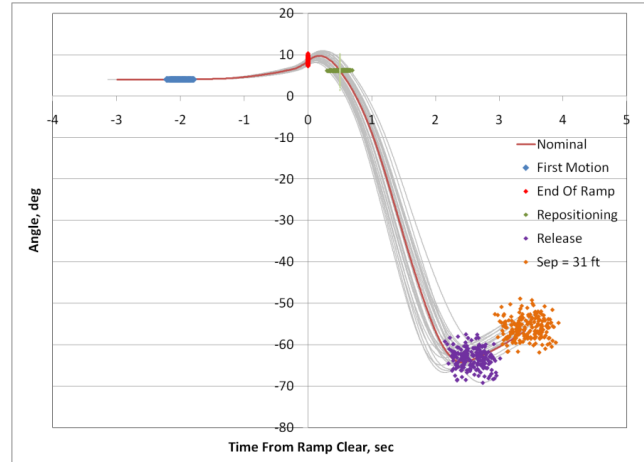


Figure 5. Angle of attack results for CDT-3-1 using Adams

bodies as compared to the instantaneous tendency to separate. The state of each body post-separation is handed off as initial conditions to the Flight Analysis Simulation Tool (FAST) for the remainder of the test trajectory. The difference between DSSA and Adams, is the PCDTV was modeled after separation until programmer deployment line stretch as shown in figure 6. While the time frame was around one second, it became clear the vehicle state was not the same as assumed at separation.

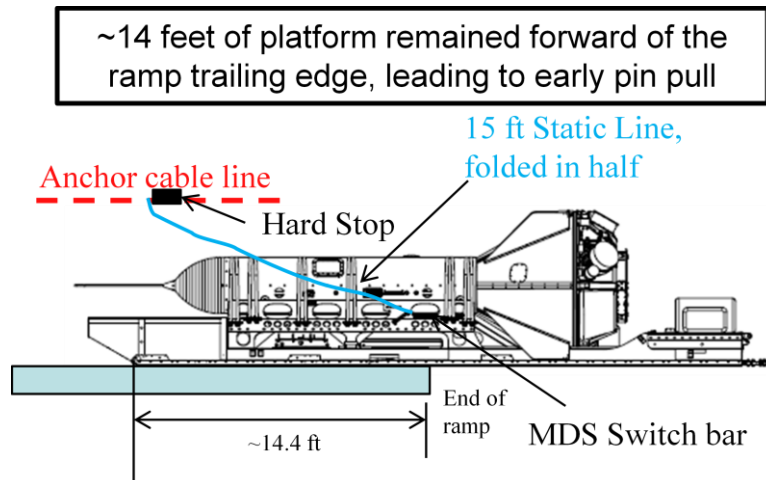


Figure 7. Avionics activation lanyard placement

successful test. The wake effect was mitigated for subsequent tests by biasing the extraction parachute aerodynamics. Confidence in the smart separation algorithm was gained on CDT-3-1 and CDT-3-2 since the algorithm functioned as designed on both tests. As a result, the time criteria of the window were expanded to account for system and environmental unknowns that are not modeled. All subsequent tests were successful and

separated on attitude/rate conditions instead of on time, resulting in benign release conditions.

The successful demonstration of smart separation, through incremental testing, allowed for using fewer and/or more tightly reefed programmers to allow the PCDTV to accelerate to higher airspeeds

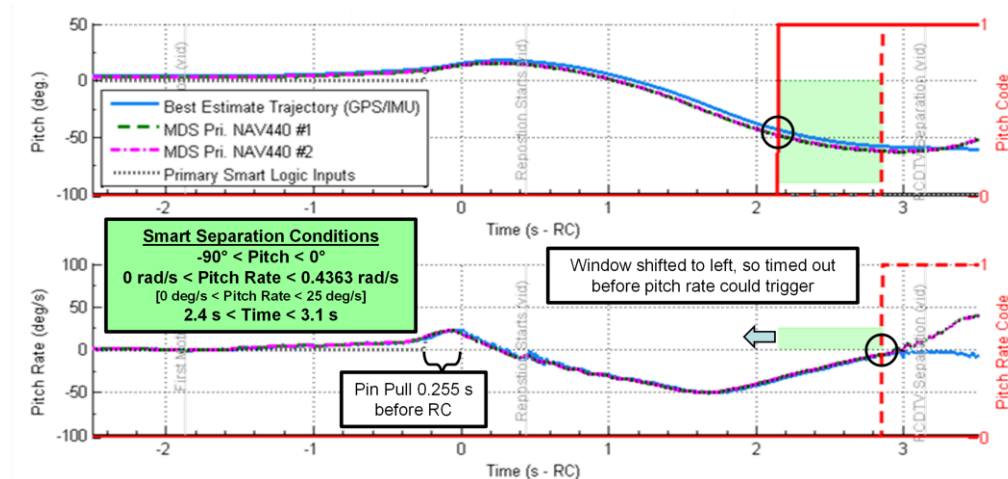


Figure 8. Smart separation system time-out prior to entering window

for test parachute deployment. This in turn allowed the deployment of the Drogue parachutes at higher dynamic pressures.



Figure 9. CDT-3-2 smart separation time-out leading to off-nominal separation

B. NAV Bias

Each successful drop test with the PCDTV/MDS test vehicle was an opportunity for continuous learning for model refinement. Figure 10 shows the CDT-3-17 nominal pre-test prediction from Adams (grey) is a good match with the test data (blue). The MDS, using the Crossbow NAV440⁷ readings (dashed orange) enter the smart separation window (green), commanding separation. Using the day-of-test data as input parameters allowed for a satisfactory Adams reconstruction (black). Also observed is that the pitch angle measurement on the MDS (green

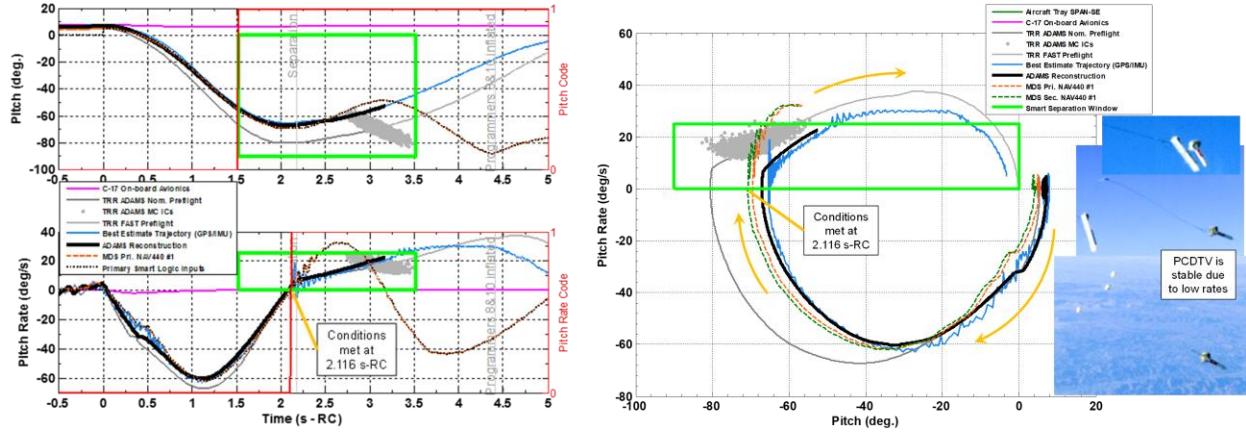


Figure 10. CDT-3-17 smart separation data vs. time (left) and phase plane (right)

and orange dash) is slightly lower than the “truth” SPAN-SE pitch reading. This was determined to be due to the

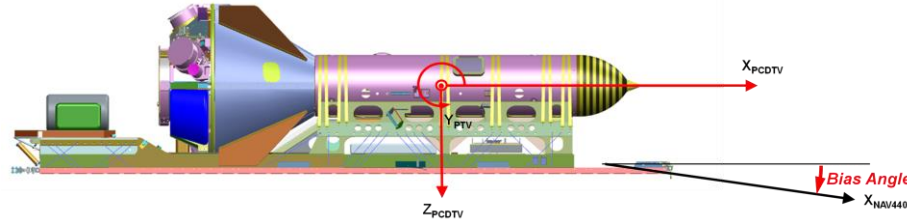


Figure 11. Definition of NAV440 bias angle on the PCDTV/MDS

NAV440 installation on the cantilevered front end of the MDS, resulting in a bias angle where the x-axis points slightly below the mated vehicle centerline, as illustrated in figure 11. This discovery led to an examination of all PCDTV drop tests and determination

that there was a measurement bias that could affect separation window optimization. Therefore, a NAV440 bias angle distribution was constructed for Monte Carlo studies, as shown in figure 12. The Adams simulation was updated to alter the pitch state value by the randomized bias when evaluating the trigger criteria, which resulted in lowering the pitch portion of the smart separation window from -90 degrees to -110 degrees, as shown in figure 13, for the pre-test prediction of CQT-4-7.

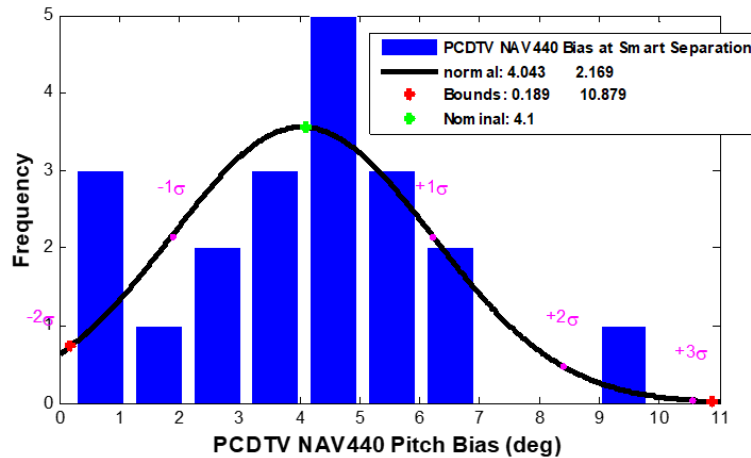


Figure 12. PCDTV/MDS NAV440 bias angle distribution

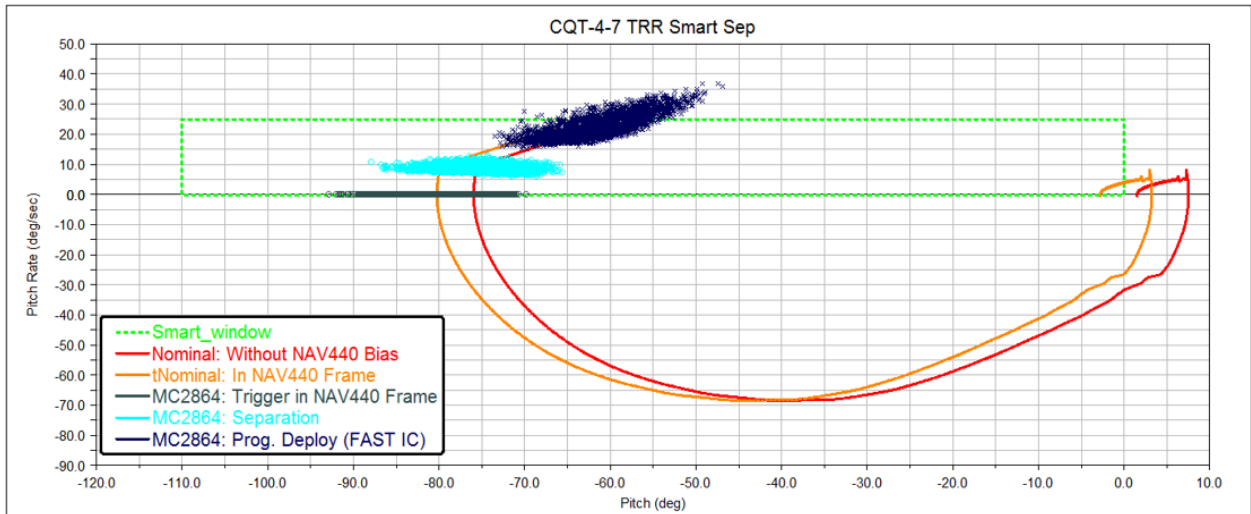


Figure 13. CQT-4-7 Monte Carlo results of the pitch plane phase including the NAV440 bias

C. Model confidence

Of the six PCDTV drop tests conducted prior to the transition to Adams, CDT-3-12 was the closest in configuration to what was planned for CDT-3-17. Figure 14 illustrates results of the reconstruction of the extraction/separation phase of flight for the CDT-3-12 (left), providing the data driven, pre-test analysis for CDT-3-17(right). A good match in the pitch plane dynamic behavior, along with the model improvements, and Monte Carlo dispersion parameters identified during testing up until this point in time, provided confidence in using this simulation tool.

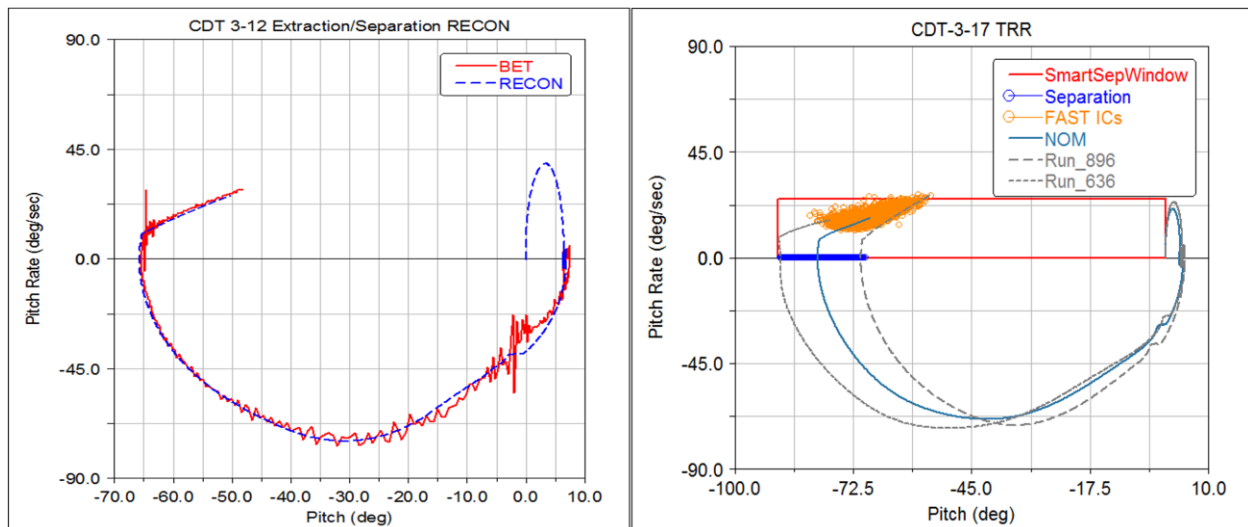


Figure 14. CDT-3-12 Reconstruction (left) and CDT-3-17 Monte Carlo result (right)

D. Reposition Loads

The line loads acquired from drop tests not only contributed to the modeling of the mated vehicle dynamic behavior but also improved predicting the reposition event loads. Knowledge gained during the static and dynamic line pull testing campaign conducted at Holloway Houston Inc⁸, allowed force-deflection curves to be developed and implemented into this model, to predict

individual (dynamic) loads at each line in the reposition event load train as illustrated in figure 15. The load is driven by the extraction parachutes into the extraction line which is connected to the EFTC. At the predefined time, the EFTC would release, allowing it to engage the 3ft reposition deployment line which would then pull the confluence from a stowed location on the MDS. The forward harness legs are loaded next then finally the aft harness legs as the mated vehicle begins to pitch down as a result. To confirm that the model behaved as expected, load pins were added to the four harness attach locations on the underside of the MDS as well as an accelerometer mounted onto the confluence, attaching the reposition deployment to the four harness lines

Results are plotted from the CQT-4-1 reconstruction in figure 16. The predicted load(gray), measurement from the load pin(red), and reconstructed load(blue). The peak reposition deployment line load was checked, by comparing the reconstructed value to the resultant load estimated from the confluence accelerometer (red dash) and MDS loads load pin data(magenta, navy, green, and steel blue dash). This estimate was compared with the reconstructed value from Adams (solid blue), and came within 3%, which provided greater confidence in the margin of safety determination of the test hardware as shown in table 2.

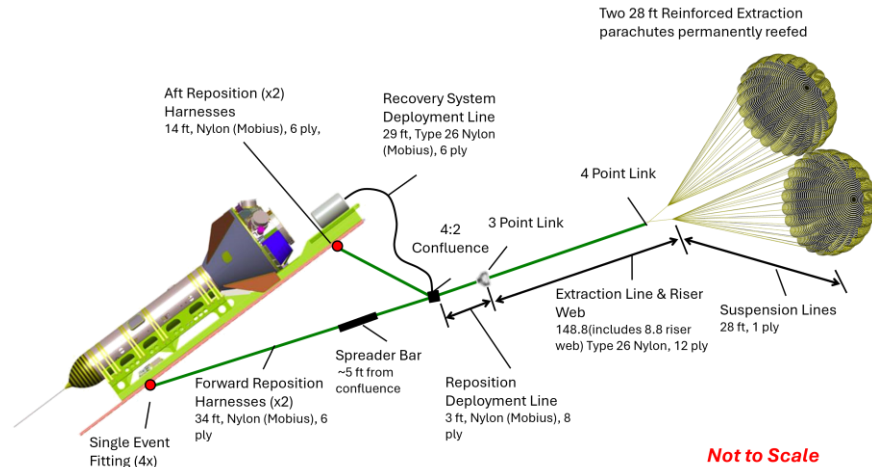


Figure 15. PCDTV/MDS load train for the reposition event

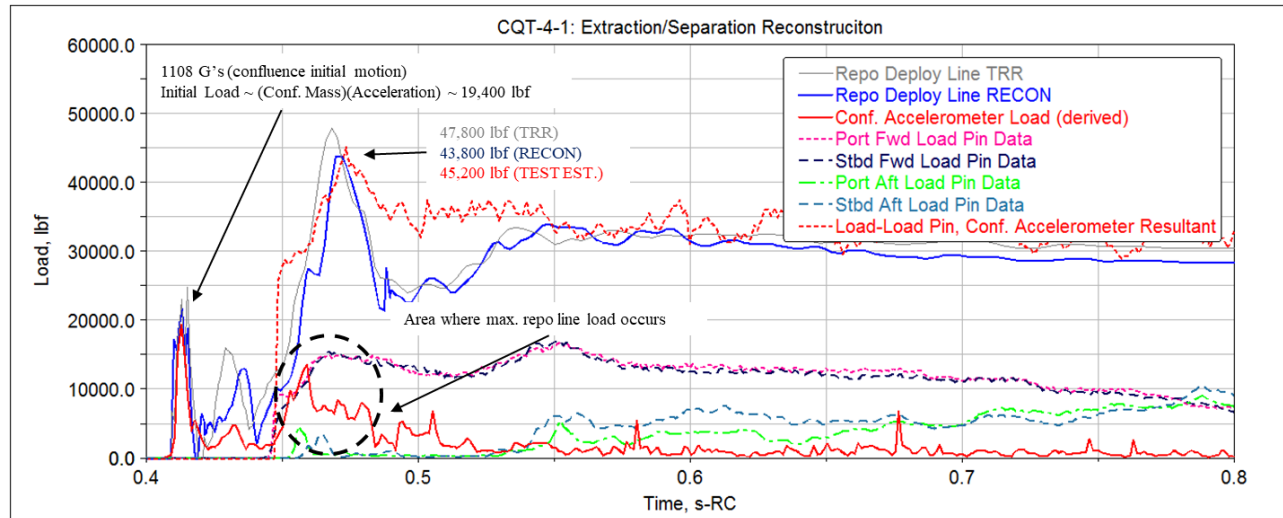


Figure 16. CQT-4-1 Reposition deployment line load reconstruction

Table 2. CQT-4-7 margin of safety summary for the reposition event using loads determined by Adams

Reposition	Max Load (lbf)	Load Share	Applied Load (lbf)	Total Design Factor	Working Load Limit (lbf)	Margin Result	Percent of Cases with Negative MOS
Reposition Deployment Line (8 Ply Nylon Mobius)	40,848	1.0	40,848	1.68	42,148	0.03	0.00%
3 Point Link	40,848	1.0	40,848	NA	60,000	0.46	0.00%
4:2 Confluence Upper Pin (2)	40,848	1.0	40,848	2.00	42,150	0.03	0.00%
4:2 Confluence Lower Pin (4)	17,131	1.0	17,131	2.00	42,150	1.46	0.00%
Forward Harness (6 Ply Nylon Mobius)	17,131	1.0	17,131	2.90	31,020	0.81	0.00%
Aft Harness (6 Ply Nylon Mobius)	17,131	1.0	17,131	2.00	34,400	1.00	0.00%
1 Forward Single Event Fitting	13,429	1.0	13,429	2.90	31,020	1.30	0.00%
1 Aft Single Event Fitting	13,429	1.0	13,429	2.00	25,000	0.86	0.00%

IV. Commercial Crew Airdrop Testing

The CPAS extraction modeling experience was invaluable for the CCPAT PCDTV drop test campaign. This included new on-board data measurements, leading to improved modeling of the carrier aircraft pitch profile. All tests were extracted from either a C-130 or C-17 aircraft, while both were capable, the pitch rate induced on the test payload at ramp clear was not equal. Consideration of initial deck angle, altitude, true airspeed, aircraft response during extraction, and the length of the extraction line all contribute to when and how the mated vehicle enters the smart separation window⁹.

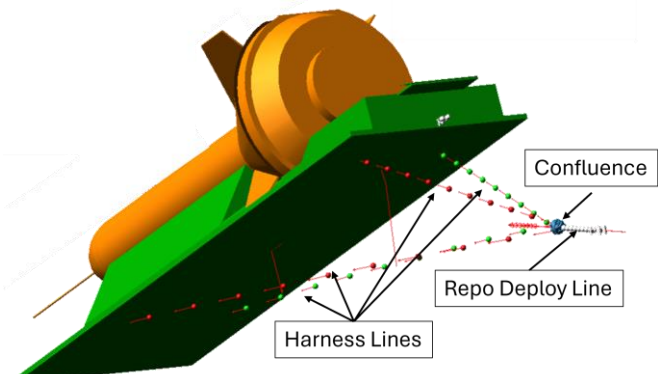


Figure 17. Model of the reposition deployment event in Adams

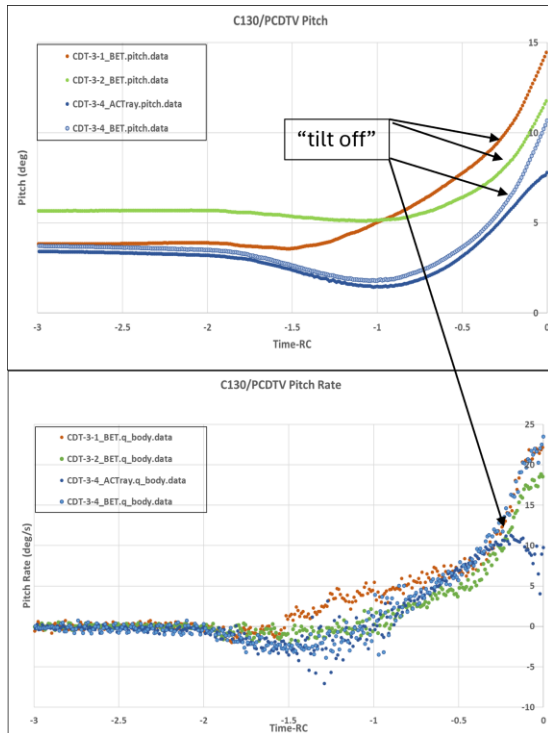


Figure 18. Mated vehicle pitch dynamics as tested

reaches the end of the ramp.

The first three tests, designated Parachute Cluster Reliability Test, the CCPAT team conducted (PCRT-01, PCRT-02, PCRT-03), employed the C-17 aircraft and benefitted from knowledge in extracting from that aircraft as well as the NAV bias and load modeling efforts previously discussed. The last two tests, designated NASA Parachute Cluster Qualification Test (NPCQT-01, NPCQT-02) were extracted from the NASA owned C-130, based out of the Wallops Flight Facility. Although most of the CPAS tests of the PCDTV were extracted from a C-130, modeling the ramp behavior in Adams was focused on C-17 aircraft. Review of the pitch and pitch rate data from previous tests was required to be confident in the pre-test analysis. Figure 18 shows pitch and pitch rate data gathered from aircraft and test vehicle instrumentation. The observation was made that MDS seemed to tilt off the ramp about 0.25 seconds before ramp clear, however, the model in Adams did not produce the same result. The original implementation employed a table look up of pitch rate tables which work reasonably well for the low pitch and pitch rate response achieved from the C-17⁹. The ramp model was modified to be able to emulate the pitch and pitch rate of the test article rather than the aircraft. This was accomplished by implementing a pitch rate function that is applied at about 1 second from ramp clear. An initial pitch constant is set such that the desired angle is achieved when the mated vehicle

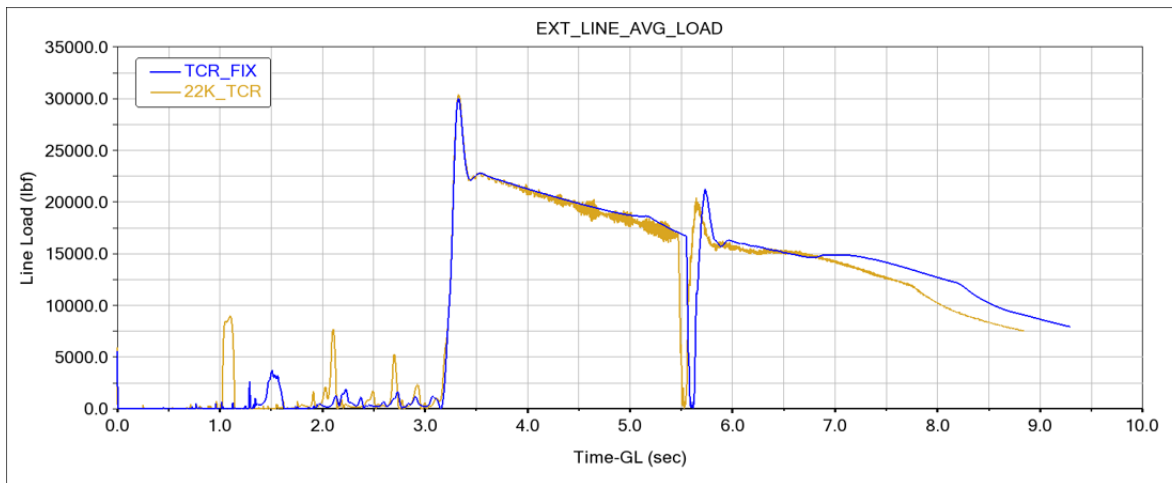


Figure 19. Extraction line load co-plotted to illustrate model damping update for NPCQT-01

The extraction parachute is modeled as a point mass which uses an inflation model with parameters derived from drop and tow tests, with the addition of an aerodynamic force applied to the extraction bag. This extraction drag force, as implemented, supported extraction from a C-17 utilizing a surface area consistent with a 19ft diameter conical ribbon tow chute. Since extraction parachute deployment, from a C-130, did not involve use of a tow chute, an adjustment was necessary to prevent the force on the extraction line from prematurely triggering the lock release event in the simulation and start motion of the payload. This force is applied to the extraction line, which consists of ten-point masses shown in figure 17 with element-to-element forces, a spring damper model for the axial direction and damping applied to the normal and lateral axis. Prior modeling only considered point to point damping, along the axial direction. Without damping applied to the normal and lateral direction of the point masses, the motion of the point masses became unstable resulting in unrealistic peak loads in the presence of dispersions, and increased processing time. This required manual removal of individual Monte Carlo runs. Reduction of the extraction line from 140ft (C-17) to 60ft (C-130) resulted in longer processing time due to a noisy line load, seen in figure 19 (gold line), which also had an undesirable effect on the ramp motion.

The decision to use a test vehicle that became a work horse⁴ during the EDU and Qualification drop test campaign of the CPAS project, significantly reduced the time and labor involved in designing a new test vehicle and assembling a team to execute at a high level. While this placed the CCPAT project in a great position, there remained opportunities for continuous learning and model refinement as discussed throughout this paper and identified in table 3.

Table 3 Extraction/Separation summary of the PCDTV drop tests

Project	Generation	Test Designation	Date	Aircraft	Ext. Chute Config.	Planned Altitude	Planned Airspeed	Simulatoin	Notes
		(ft-MSL)	(Knots)						
CPAS	EDU	CDT-3-1	21 Sep. 2011	L382G (stretch C-130)	1 x 28ft	25000	145 +/-5	DSSA	Incorrect size lanyard resulted in an early activate of the smart separation algorithm leading to window time out.
		CDT-3-2	20 Dec. 2011						Time window was shorten based on pre-flight analysis. Due to unaccounted effects from the aircraft wake, smart separation occurred at the end of time window. Future predictions increased time window to account for unknowns.
		CDT-3-4	17 Apr. 2012	C-130A	2 x 28ft				
		CDT-3-6	28 Aug. 2012						First test with two extraction parachutes. Extraction speed was faster than predicted, effecting the pitch plane dynamics.
		CDT-3-8	12 Feb. 2013						
		CDT-3-12	26 Feb. 2014						
	Qualification	CDT-3-17	13 Jan. 2016	C-17A	2 x 28 ft (reefed)	35000	190 +/-5	Adams	First use of Adams for pre-flight analysis, providing better initial conditions of the PCDTV due to modeling the dynamics of separation through programmer line stretch.
		CQT-4-1	30 Sep. 2016			30000	170 +/-5		Added instrumentation to measured harness line loads and confluence acceleration to determine rdposition deployment line load.
		CQT-4-7	12 Jul. 2018			35000	190 +/-5		Updated Monte Carlo distributions to account for NAV440 bias in pitch angle determination.
CCPAT	Reliability	PCRT-1	22 Feb. 2018		1 x 28ft	25000	145 +/-5		
		PCRT-2	20 Feb. 2019		2 x 28 ft (reefed)	35000	190 +/-5		
		PCRT-3	26 Jun. 2019						
	Qualification	NPCQT-1	15 Nov. 2022	C-130A	1 x 28ft	22000	145 +/-5		Updated the ramp model to better predict the pitch and pitch rate dyanmics at ramp clear. Modified model damping of the extraction line and aerodynamic drag of extraction chute deployment without a tow chute.
		NPCQT-2	9 Jan. 2024			13000			

Following the success of the last CCPAT drop test, NPCQT-02, the PCDTV and MDS were transferred into NASA custody on 12 October 2023 and placed in storage at the White Sands Test Facility (WSTF) alongside the same named vehicles used during the CPAS test campaign seen in figure 20.



Figure 20. PCDTV/MDS used during the CPAS (left) and CCPAT (right) test campaigns stored at WSTF

V. Conclusion

The six plus years of experience and knowledge gathered from the PCDTV/MDS test vehicle during CPAS drop testing provided the foundation needed for similar testing conducted for the CCPAT project. Initially to ensure a clean extraction and successful separation, continuing to better load predictions and refinement of the aircraft ramp model to further enhance the Adams simulation for future drop testing.

Acknowledgments

The authors of this paper would like to acknowledge all members, current and past, that contributed to the development and improvement of the extraction and separation modeling used during the CPAS and CCPAT drop testing campaigns. The effort resulted in five technical papers and spanned more than thirteen years ensuring each test was set up for success.

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