Rigging Test Bed Enables Development of Multi-Stage Decelerator Extraction

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The Low Density Superonsic Decelerator (LDSD) project developed a Parachute Deployment System (PDS) for use on its Supersonic Flight Dynamics Tests (SFDT). The PDS involves a multi-stage pilot driven extraction of a supersonice parachute. The uncertainties and complexities of developing the design for the lines and rigging of the PDS were addressed through testing in the Rigging Test Bed (RTB). The RTB provided a facility capable of simulating a variety of extraction scenarios with full scale hardware on the ground. Through more than 100 tests conducted in the facility, a wealth of data and experience were gained that fueld the PDS development. The utility of this testing and the lessons learned are presented in this paper. The goal is to inform the development of similar systems in the future and highlight the value and flexibility this type of testing offers rapid hardware development. The RTB provided a great compliment to the analytical models greatly compressing what would have otherwise been a very lengthy analytical effort or potentially much expanded flight test campaign.

Nomenclature

DGB = Disk-Gap-Band
JPL = Jet Propulsion Laboratory
LDSD = Low Density Supersonic Decelerator
PDD = Parachute Deployment Device
PDS = Parachute Decelerator System
RTB = Rigging Test Bed
SSDS = Supersonic Disc Sail Parachute
SSRS = Supersonic Ringsail Parachute
SFDT-1 = Supersonic Flight Dynamics Test 1
SFDTV = Supersonic Flight Dynamics Test Vehicle
SIAD = Supersonic Inflatable Aerodynamic Decelerator
TPS = Thermal Protection System
V&V = Verification and Validation

I. Introduction

THE Low Density Supersonic Decelerator (LDSD) project has undertaken the task of developing a large Supersonic Parachute to provide improved capabilities for future Mars landed missions. NASA has identified the need for a new parachute system to support an increase in payload mass, target higher altitude landing sites, and improve landing accuracy. As Mars-bound spacecraft continue to get larger and the possibility of future manned missions arises the state of the art in low density supersonic parachutes must also advance. To date, all seven of the successful Mars landings have employed disk-gap-band (DGB) parachutes, which were based on a design that was developed in the 1960's and 1970's for the Viking Mars mission. While the success of the MSL parachute expands the DGB flight proven size envelope it still falls short of the necessary drag performance expected to be required by future missions. To increase the parachute diameter requires a new parachute qualification and, to that end, the LDSD project is continuing the process of developing and flight-testing these supersonic parachutes.

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Figure 1 shows an overview of the SFDT. In this test, a large helium balloon is used to hoist a 4.7 m diameter blunt body test vehicle (TV) to an altitude of over 36 km. The test vehicle is released from the balloon, spun-up for stability, and a Star-48 solid rocket motor ignites. The motor accelerates the test vehicle to speeds over Mach 4 at an altitude of 50 km. Upon burn-out the vehicle is de-spun and the primary test phase begins. Shortly thereafter, the first of the technologies, a Supersonic Inflatable Aerodynamic Decelerator (SIAD) is deployed.[2] Later in the fight, the Parachute Deployment Device (PDD) is mortar fired, inflated, and subsequently used as a pilot device to extract and deploy the large supersonic parachute from the test vehicle.[3] The parachute decelerates the vehicle to subsonic conditions and the vehicle descends to the ocean for recovery.

SFDT-1 was conducted with a balloon launch from the Pacific Missile Range Facility (PMRF) on Kauai, Hawaii. The test successfully demonstrated all aspects of the integration and test, balloon launch, balloon operation, test vehicle operation, test vehicle flight, and recovery. The parachute was successfully deployed within the desired operational envelope and succeeded in becoming fully inflated.

To achieve this successful test a multi-faceted Verification and Validation (V&V) program was developed, detaile in Ref . This paper focuses on the V&V lessons learned from the Rigging Test Bed (RTB) which was developed to conduct testing on the bridles and lines of Parachute Decelerator System (PDS). The paper also seeks to exemplify the utility of full scale testing in the development of complex new deployment systems.

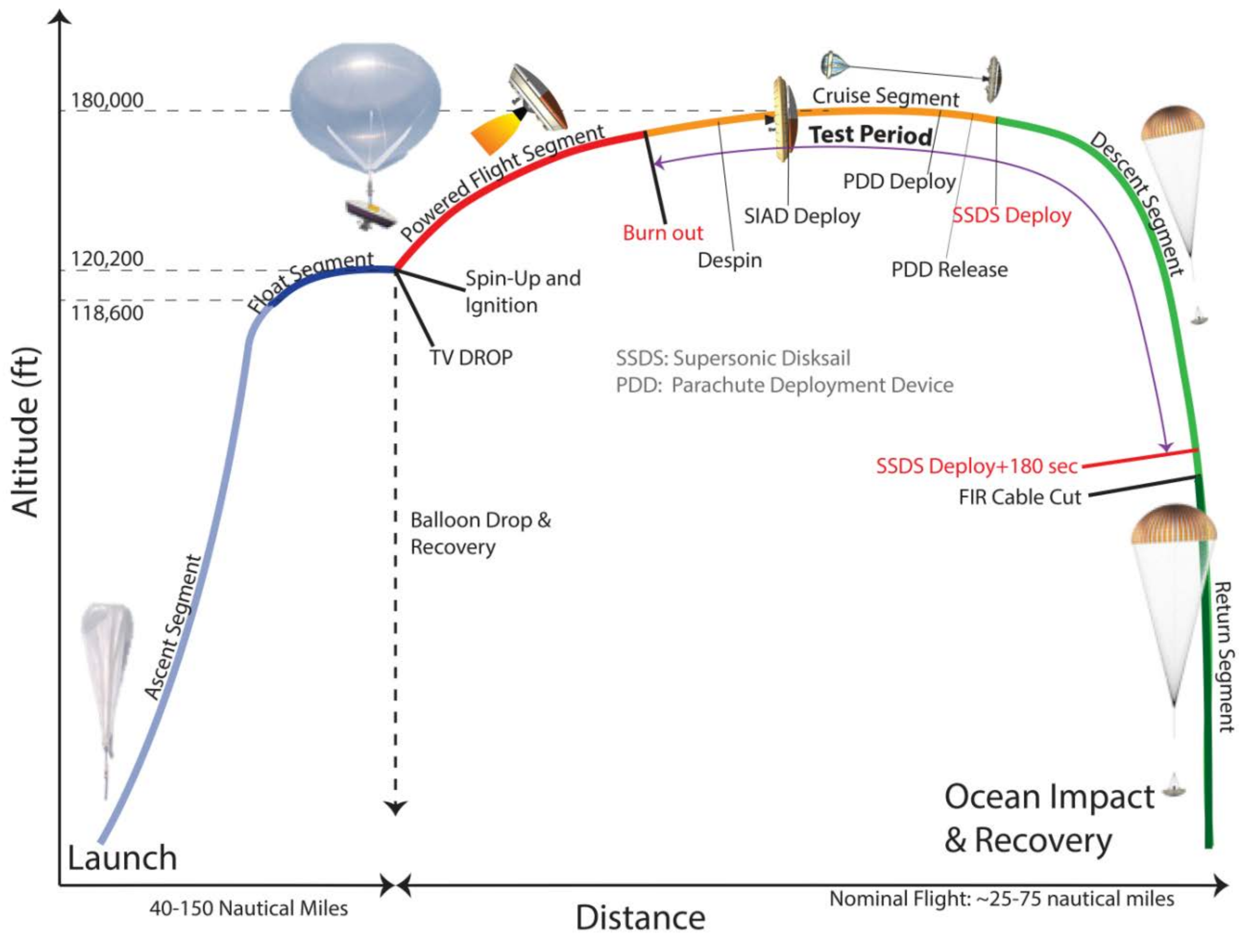

Figure 1 Overview of the LDSD Supersonic Flight Test Architecture

II. LDSD Parachute Deployment System

Parachutes on Mars vehicles are typically deployed by a mortar that is positioned on the vehicle's central axis, which deploys the parachute quickly and prevents mortar thrust loads from causing the vehicle to tumble. Velocity of the parachute relative to the vehicle starts high as it leaves the mortar and decays as it moves away. When the canopy extracts from the bag after line stretch the velocities have decreased such that friction burning doesn't occur.

The center-mounted motor on the SFDTV prevents use of a centrally mounted parachute mortar. This prompted selection of a modified pilot deployment where a small mortar is fired to deploy a ballute capable of extracting the SSDS without upsetting vehicle flight dynamics. Pilot deployments, however, start at zero relative velocity to the vehicle and accelerate away. This poses a challenge to the system since tension in the parachute suspension lines and triple bridle during the deployment process is principally generated by the mass flow of suspension lines coming out of the deployment bag. Slow bag velocities at the start of the parachute deployment process result in low tension in the parachute suspension lines and triple bridle. Since the SIAD is decelerating the vehicle through this extraction process, the low tension could lead to lines piling up against the back of the vehicle as they are extracted. Simply using a larger ballute to generate speed and tension in the suspension lines carries the risk of generating very large bag strip velocities which could damage the canopy. The parachute deployment system is detailed in Figure 2 below and in Ref 4.

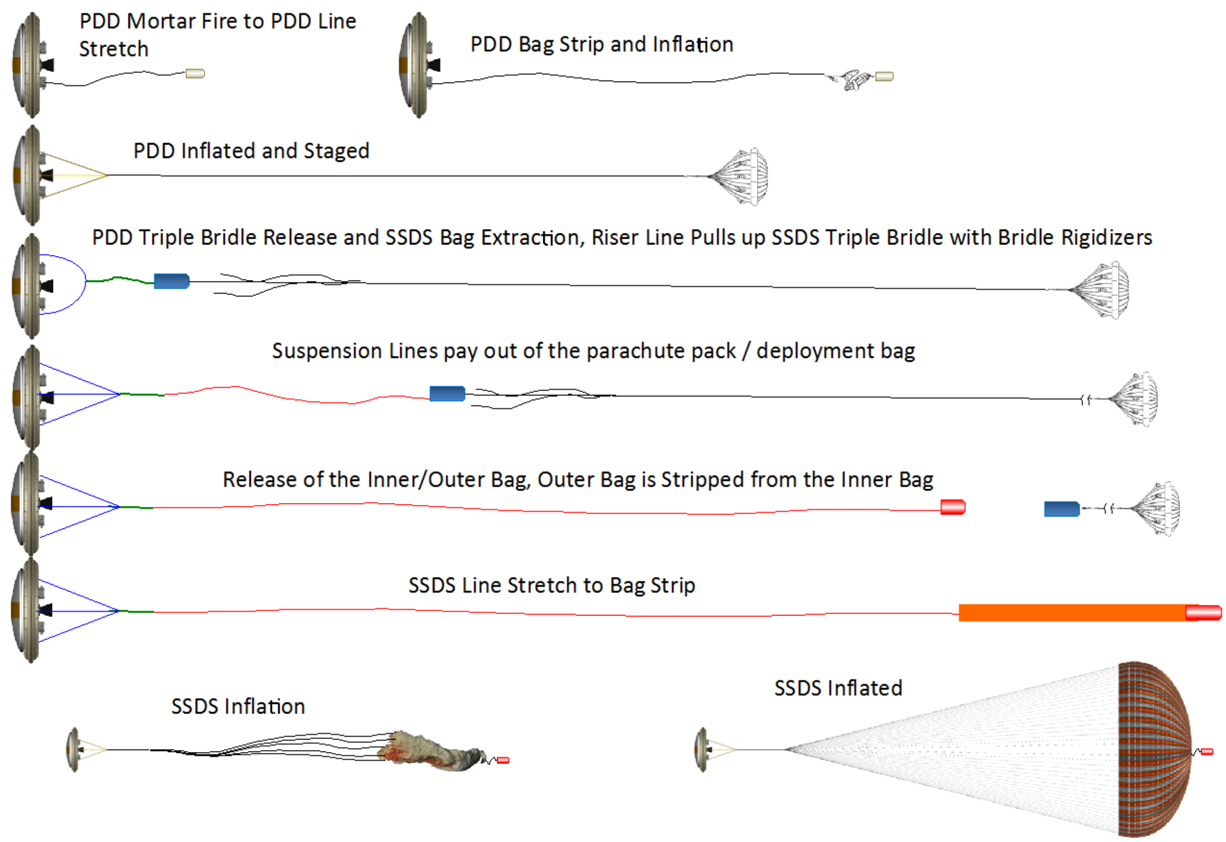

Figure 2 Parachute Deployment System Deployment Storyboard

III. Rigging Test Bed

The Rigging Test Bed (RTB) is a test venue constructed to perform verification and validation (V&V) of the extraction process for the lines and rigging of LDSD Parachute Deployment System (PDS). The test bed consists of a full scale vehicle mockup and a long pneumatic piston device capable of providing a constant force simulating the ballute drag force during the extraction events. The vehicle mockup can be oriented at different angles to simulate different relative extraction vectors see figures below. The extraction tests were conducted both inside a high-bay for frequent tests of individual extraction stages and outdoors using a mobile hydraulic crane for complete deployment tests from initial pack pull out to canopy extraction. These tests measured line tensions and use photogrammetry to track motion of the elements involved. The resulting data was used to verify packing and rigging as well as validate models and identify potential failure modes in order to finalize the design of the extraction system. The RTB is presented in more detail in Ref. 7.

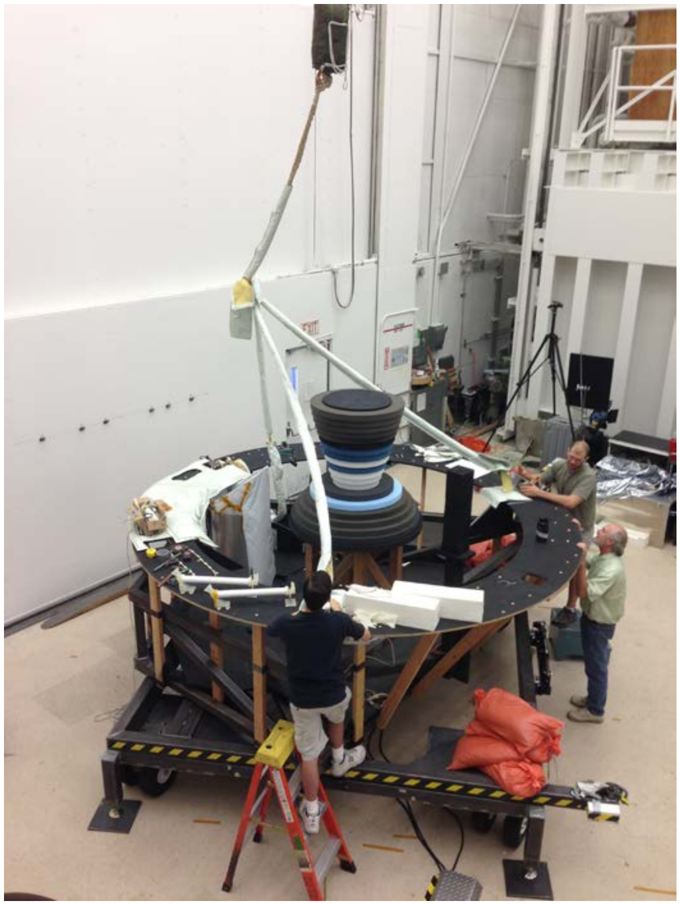

Figure 3 RTB Vehicle Mockup in Flat configuration after Bridle Deployment

Figure 4 RTB Vehicle Mockup Angled Ready for Deployment Test

Figure 5 RTB Vehilce Mockup with Prototype Vehicle TPS Installed

IV. Lessons and Value Added

Many things were learned and gained through the testing done in the RTB leading up to SFDT-1. Presented here is collection of lessons and added value which were captured from the development work done.

A. Parachute Pack Extraction

The first parachute pack for LDSD consisted of an aluminized Kevlar bag in family with former Mars parachutes deployed via mortar. The SFDTV stows the parachute in an aluminum can restrained with Kevlar cord that is cut with pull knives prior to extraction. While stowed the parachute and can are covered with thermal blankets (TPS) to protect them from the heat of the main rocket engine. The extraction is driven by the ballute drag force as it separates from the vehicle. Once the pack restraints are cut, the extraction force pulls the parachute pack out of the can through the TPS flaps covering the can by tearing closure ties which are installed after the parachute is installed.

A series of tests were conducted in the rigging test bed to verify that the restraints were suitable for the accelerations of the powered flight and opened cleanly under the predicted extraction forces. The closure of TPS over the parachute can was also evaluated to ensure that the parachute could successfully emerge.

Verifying the restraint force was accomplished through a static pull test using the overhead crane in the high bay. Once installed, the pack was pulled on with a wireless load cell in line to confirm the restraints held agains the design load.

Verification of release for extraction was accomplished through a series of extraction tests where the vehicle mockup was held in different orientations relative to the vector of the extraction force and a set of predicted extraction forces was applied. The first extraction test which was conducted at a vector straight out of the can uncovered that testing at ambient surface air density created excessive suction force on the pack during extraction when using flight test like hardware. The pack did emerge from the can on the first test, but much slower than predicted. As a result the vehicle mockup was modified to include large vent holes in the plate supporting the base of the parachute to equalize the pressure. Small gaps in the can had been incorporated for the flight test design which were evaluated for air density at altitude. These features were part of the mockup but had not been re-evaluated for the increase in density at surface level.

Subsequent tests conducted with the vehicle angled to the extraction force vector uncovered unexpected jamming of the pack in the can. This discovery was one of the most valuable trouble spots uncovered through testing. Prior to testing the expectation was that extraction forces that ranged from twice the pack weight and up would easily pull the pack free from the vehicle.

Two sources friction were identified. The first was heel-to-toe jamming caused by the sudden jerk when the extraction force was applied at an angle to the can which could wedge the pack in place. The second was the aluminized Kevlar surface of the pack rubbing on the aluminum surface of the parachute can causing drag.

A campaign of quasi-static friction tests were conducted where the overhead crane was used to lift the pack while the vehicle was angled to different inclines and the extraction force measured. The application of force was gradual to avoid the snatch loading and any potential heel-toe jamming. In addition to the aluminum surfaces, Teflon sheets were introduced to see if they improved the extraction forces. It was found that there was a greater sensitivity to the surface finishes at higher angles of extraction. The result was modifications made to both the parachute pack and can. The pack was modified so that it's outer layer was a Teflon fabric. The interior of the can received a dry lube treatment that was impregnated with Teflon.

Following these modifications it was found that the pack would emerge under the expected range of angles and extraction forces inspite of the sudden jerk from the extraction load which could not be mitigated. From these results an empirical model was constructed and incorporated into analytic simulations of the test flight.

TPS flaps protecting the can were still in development for much of testing and only able to be included in the final handful of tests. The architecture had four triangular flaps that would fold over opening of the can and overlap each other slightly on the edges. These edges were to be "laced" shut by running a single piece of fiberglass thread down each seam going back and forth as one "laces" their shoes and then secured with a single knot. It was discovered that if the extraction force was on the lower end of the expected range that the load sharing of the lacing architecture was sufficient to stall the pack and prevent it from tearing the knots. An alternate approach of tying each seam with two discreet knots was developed in the test bed.

All subsequent tests in the testbed were successful and the force data collected during the extractions were used to verify the empirical friction model that had been created earlier in the development. The surface material changes and the TPS tie architecture identified through the testing effort were implemented on SFDT-1.

B. Parachute Triple Bridle Local Stress Risers

Composite tubes are attached to the parachute bridle legs to provide stiffness once the bridles are stood up to ensure they don't collapse against the decelerating test vehicle as the rest of the lines and parachute are extracted from the parachute pack. To stow, bridle legs 1 and 2 (see Figure 3) are laid down and bent to follow the curved shape of the aft deck of the vehicle. To achieve this shape 4 stow-posts are provided which act as two contact points on each end of the rods to bend them into shape. In Figure 4, the pair of red and blue posts at each end of the rod hold it in its shape. Restraint ties are then placed distributed along the length of the bridles to hold the bridles to the deck. These restraints are designed to be strong enough to resist flight test accelerations but still break under loads generated as the parachute pack is extracted from the vehicle.

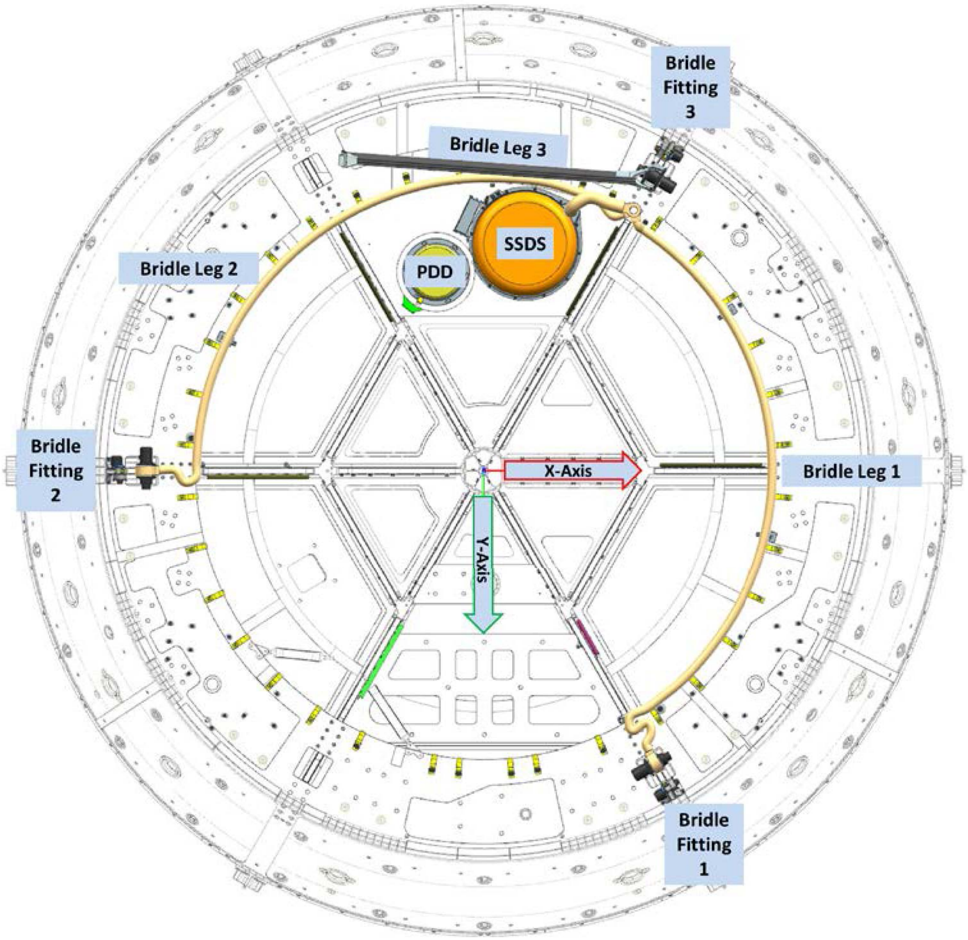

Figure 6 SFDTV Parachute Bridle Layout

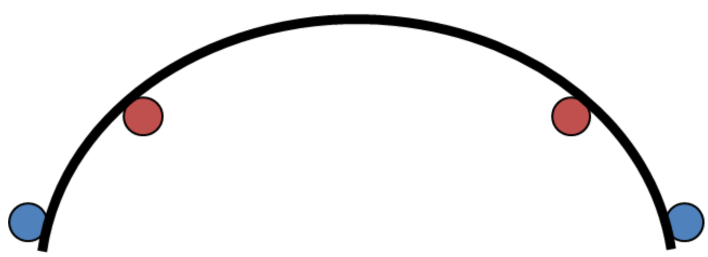

Figure 7 Stow Post Diagram for Bridle Stiffeners

The development of the final architecture with 4 stiffening rods in each these two legs required lots of iterative testing since adequate analytic models could not be developed or validated within the scope of the project. Initial implementations started with 2 rods per leg, increasing to 3, and then to 4 through over 40 developmental deployments. One issue identified early on in the testing was the ability for the restraint ties and posts to create stress risers in stowed rods which could cause the rods to break as they were released from the deck. In high speed video it was seen that placing restraint ties directly at stow post locations held the rods in place long enough for them to be bent around and snapped against the stow posts.

As the design developed, requiring heavier bridles and more stiffener rods, the ties had to be adjusted. The strength of the tie material was increased to accommodate the acceleration loading on the heavier bridles and the locations adjusted to prevent this stress rising effect at stow posts and between adjacent ties placed too close together.

Due to the offset nature of the extraction of the parachute, bridle leg 1 always goes through more bending as it is peeled up from the vehicle deck. This caused by the concentrated mass of bridle legs 2 and 3 being almost on top of each other on the opposite side of the vehicle. In the final configuration it was found that even removing restraint ties from leg 1, the bending around the final inboard stow post was breaking the rods in the leg on every deployment. The solution was to use the offending stow post for installation of the bridle leg and installation of the restraint ties. Then this stow post was removed before flight, allowing the bridle leg to leave the vehicle deck without breaking.

C. TPS Inertia

TPS was required on the bridle legs to protect them from the heat of the test vehicle's main rocket motor as well as the spin motors. Initially the design for the TPS were sleeves of Kevlar which fitted over the bridles. As the vehicle design progressed the thermal environment became better understood and gradually increasing requirements were imposed on the TPS. The Kevlar was deemed insufficient protection, but did remain as a structural component for holding the parachute bridle legs to their stiffening rods.

Combinations of fiberglass fabrics and insulating felts were explored. As the mass of more layers was added to the bridles their inertia also increased. When the bridles are lifted from the deck by the extraction forces they are imparted with a fair amount of speed and tend to "fly past" their stood up state only to recoil back and settle out. The added inertia of the increasing TPS increased the stress on the rods during the recoil event causing them to break. This lead to increasing the number rods to provide load sharing while keeping the individual rod diameters the same so they could still safely be bent into the curve of the vehicle deck for stowing. The result was the 4 rods used for stiffeners in each legs 1 and 2 which were previously mentioned.

The final TPS design for the vehicle structures consisted of a fluffy aluminae mat material encased in coated fiberglass fabric. When this approach was taken to create sleeves that fit over the bridles the result was very bulky. Even with 4 stiffening rods sharing the load, testing showed the added inertia broke the rods on the recoil event. This conclusion was confirmed by conducting tests with the TPS removed which were successful.

Since the rods were already densely packed around the bridles it didn't appear viable to insert more than 4 per leg. The result was to change the TPS architecture to a clamshell design which encased the bridles while they were on vehicle deck. During stand-up the bridles would break ties allowing the clamshell to open and the bridles to emerge. Final testing with this design showed inertia to still be a limiting factor. Some flaps needed to be reduced in size to reduce the energy it took to flip them out of the way. Excessively large flaps were found to cause the extraction to stall since they took up too much energy to move out of the way at the start leaving not enough energy to finish the stand up process.

D. 3rd Leg Hinge Development

The 3rd leg of the triple bridle is stowed on the vehicle folded in half so it can stretch from its bridle fitting and return back to the SSDS parachute can adjacent to its fitting (see Figure 3). To achieve this while including the necessary stiffeners a hinge is incorporated in the middle of the bridle leg. The initial implementation of this hinge incorporated a ratcheting feature (see Figure 5). The intent was for the hinge to open through the stand up process and not fold shut again after the extraction was done. It was thought the ratchet would be the best solution for this deployment since it would be able to maintain the furthest extension achieved without backtracking if there were any temporary slackness through the deployment. In development testing it was quickly found that the loads generated on the ratchet teeth were too high and even with a second interation to reinforce them the ratchets would fail.

Figure 8
Ratcheting concept for 3rd Leg Hinge

Figure 9
Latching concept for 3rd Leg Hinge

Subsequent design iterations utilized a single latching clasp that could be made much larger to better accommodate the latching forces (see Figure 6). Initial tests showed that the latch survived the tests, but consistently failed to latch up and prevent the 3rd leg from folding back on itself. Scrutiny of the high speed video showed that the inertia of a concentrated mass at the midspan of the leg, caused by the dense metal hinge itself, was creating unforeseen dynamics. The hinge would be accelerated upward from the vehicle deck during stand up along with the rest of the lines but also be imparted with a significant tangential velocity in a clockwise direction around the vehicle. During stand up the leg would swing wildly twisting on itself from the momentum of the hinge.

The solution was to provide a path for this tangential velocity to be reacted out and allow the bridle leg to straighten and latch up. To achieve this the 3rd leg was implemented with a stiff composite tube approximately 2 inches in diameter running from its bridle fitting to its hinge at the midspan. The bridle in this span was routed through the center of the tube. The tube itself was bonded to a special hinge fitting at the bridle fitting and to one half of the hinge at the midspan. This provided a rigid link that was able to react the tangential loads and allow the hinge to latch up.

The remaining upper portion of the bridle leg was stiffend by a collection of smaller rods which were also bonded to the hinge. This approach was similar to legs 1 and 2 discussed earlier. Again as the TPS developed, reinforcing measures were needed on the 3rd leg by adding additional rods to the upper portion of the leg and there was a light weighting effort to reduce the loads and inertia in the assembly overall.

To achieve this 5 iterations of the hinge were explored and used in multiple tests. The quick retest cycle of the rigging test bed was complemented by dedicated out-of-house CNC shops which could rapidly produce accurate metal parts from digital CAD files.

E. PDD Bridles

RTB was designed with a focus on the parachute bridle architecture. One of the most helpful side campaigns was the development of the architecture for stowing the bridles of the Parachute Deployment Device (PDD). The mortar fired ballute of the PDD provides the extraction force which drives the extraction of the parachute. The ballute has its own bridles which similarly needed to be stowed on the vehicle, protected from the thermal environment of the rocket motors, and rapidly deployed. However the line tensions involved are much smaller than those driving the SSDS deployment. The force device developed for RTB could not be operated at these low forces and instead a system of elastics was developed.

Surgical tubing was purchased and assembled into elastic cords. Different diameters and rubbers provided different spring forces which were characterized using a load cell and the overhead crane to measure the force and stretch for each. This provided a set of calibrated elastic cords.

To conduct a PDD bridle extraction test, a cord of the desired strength was selected and attached between the crane and the bridles. With the bridle end restrained by a release device, the crane would be used to stretch the elastic cord out to the desired stroke and then the test could be actuated by the release device allowing the elastic cord to pull up the bridles. These tests were used to iterate through the strength of break-ties used to restrain the bridles to the vehicle deck and witness the dynamics to observe any potential snags or hang-ups.

F. Practice Makes Perfect

Operating the test bed required frequent repetition of the processes of configuring the parachute system for a flight test. The benefit of the developmental testing was that many of these processes evolved organically over time. The abundance of photos and videos taken through the testing also provided clear documentation of the processes and enabled conclusions to be drawn about how effective they were and how they affected the deployment.

The great output of this effort was a trained group of personell ready to seamlessly transition into installing test articles on the flight test vehicle with a printed procedure complete with photos, tips, and tricks to instruct new team members.

G. Aiding Vehicle Development

Once the test bed was built it was a convenient venue for testing other elements at full scale as well. One of the major efforts conducted in the RTB was the development of the vehicle's TPS blankets. The full scale mockup was useful in creating templates for blanket and heat shield production and subsequently doing fit checks on prototypes. These prototypes could also be included in rigging tests to evaluate interactions between the bridle extraction and the TPS which was very valuable.

H. Data Acquisition Practice

The SFDTV is equipped with various cameras to record test results in flight. The mockup in the RTB was used to place identical cameras in the flight test locations and record video of the developmental deployments. This provided valuable feed back to the data team and helped them calibrate their cameras before the first flight test.

Additionaly the testing done in RTB enabled cameras to be placed around the setup in places where a camera couldn't be positioned in flight. This enabled capturing deployment phenomena from many angles. After the data from SFDT-1 was recovered it was possible to see similarities in the flight videos and the developmental ones taken in the test bed. The additional camera angles made possible in RTB enabled better conclusions to be made about the behaviours seen in flight.

V. Conclusion

The value of testing is clearly seen in the results produced by the Rigging Test Bed. It is the intent that the lessons and utility of the tests captured in this paper can be leveraged in the development of other complex systems relying on textiles and softgoods. Most importantly that this testing can be done at a much greater pace and at less expense than flight drop tests to reduce the risks and size such campaigns.

Acknowledgments

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