MSL Rover Structural Verification and Validation via Centrifuge Testing

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Abstract—Centrifuge testing has been a tried and true method for the global structural qualification of small to medium sized test articles. During the Mars Science Laboratory (MSL) Rover structural qualification program the centrifuge test method is extended to the application of large scale Aerospace structures. With the increased test article size and dimensions, parameters otherwise considered trivial become complicated design drivers for the test hardware and implementation. These typically ignored testing provisions include facility power and structural capability, test article interface structure and enclosure, and the enclosure aerodynamics. The size of the MSL rover has been the source of many design and testing complications throughout its development. However, the solutions for these complications are paving the way for future large aerospace structures. The centrifuge testing implementation described within should serve as a guideline for implementing future centrifuge testing on similar large scale structures. [123]

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1. INTRODUCTION

The Mars Science Laboratory (MSL) Project is the third and most ambitious US led effort to land a mobile vehicle on Mars. MSL follows in the footsteps (tire tracks) of the Sojourner rover, delivered by the Mars Pathfinder mission, and the sibling Mars Exploration Rovers, Spirit and Opportunity. The MSL rover development has had the luxury in many ways of being able to use lessons and techniques learned not only in the design and development, but in the final and arguably more crucial stage of the project, Verification and Validation (V&V).

The goal of the V&V program is to ensure that the developed system meets or exceeds all the defined requirements. For structural V&V the driving requirement is that the structure be designed to survive, with adequate margin, all loading environments. In order to verify that the structure designed and built meets this requirement, a complex sequence of subsystem and system level testing is executed. For the MSL rover primary and secondary structures, targeted structural testing is completed for all structure not meeting "no test" factors of safety and all critical interfacing structures.

For the rover these critical locations can be divided up into two general categories; local and global loading. An example of local loading is the force applied to the front panel of the rover while the robotic arm is preloading and drilling into a rock sample. This Action creates localized reaction and corresponding stress state in the front panel of the rover and the immediate surrounding structure. The global loading category is best categorized by the Pathfinder and MER missions landing method referred to as the bounce and roll. For MER, the first bounce was predicted to create upwards of 28 g's. This global loading event locally creates high stresses at the primary interfaces similar to the drilling arm. However, unlike the drilling arm, the acceleration of bouncing creates a whole body loading environment where any location with concentrated mass contributes to the loading across the entire structure.

Each of the two loading categories lend themselves to different types of testing. The local loading cases can typically be simulated and tested by applying a single static load vector directly to the interfacing structure. For the Mars Rovers including the MSL rover, this has been achieved by attaching a hydraulic ram to a pull fixture and applying a static load to the interface. Applying this static load approach to global loading cases rapidly becomes complicated. In order to simulate the global loading of the structure in this fashion, a large number of coordinated static loads and vectors must be applied simultaneously to the structure. In less complicated cases, the global loading can be isolated to several critical locations allowing for single vector type pulls. In many cases this can be achieved. But as structures become more complicated, the exercise of

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[2] IEEEAC paper #1589, Version 4, Updated January 19, 2009
[3] The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

isolating the critical locations and designing a sufficient verification test becomes exponentially more difficult. It is for these cases that alternative testing means must be explored.

The MSL rover chassis is one such structure that sees a complicated global loading environment. The driving global loading environment for the MSL rover is the acceleration experienced during entry into the Martian atmosphere.

Alternative testing methods typically considered include vibe testing and centrifuge testing. Both of which have been used successfully on previous mars missions. On the previous two rover missions the global loading event of landing described above was tested using a centrifuge. It is this testing heritage and the safety and simplicity of a centrifuge test that led to the decision to again use centrifuge testing to qualify the loading, defined this time by entry.

The MSL centrifuge test article consists of the Developmental Test Model (DTM) rover chassis mounted to a flight like Descent Stage interface. The Rover chassis is populated with mass models of all the internal avionics, electronics, computers and science instruments. Externally, the rover chassis is populated with the DTM mobility assembly and selected external mass mockups representing all external appendages of appreciable mass.

2. TEST ARTICLE

To successfully qualify the structure during the centrifuge test it is desirable for the test article and boundary conditions to be as flight like as possible. The most ideal albeit unrealistic test is conducted with the actual flight vehicle assembly. In lieu of the flight vehicle, the DTM test article is used. The DTM begins as the rover chassis primary structure with no additional Items added on. The chassis primary structure is shown in figure 1. Mounted to the chassis is the DTM mobility system also shown in Figure 1. The mobility is shown in the stowed configuration where it will encounter the launch and entry loading conditions targeted for this test. These two subsystems wholly encompass the structure being targeted for qualification.

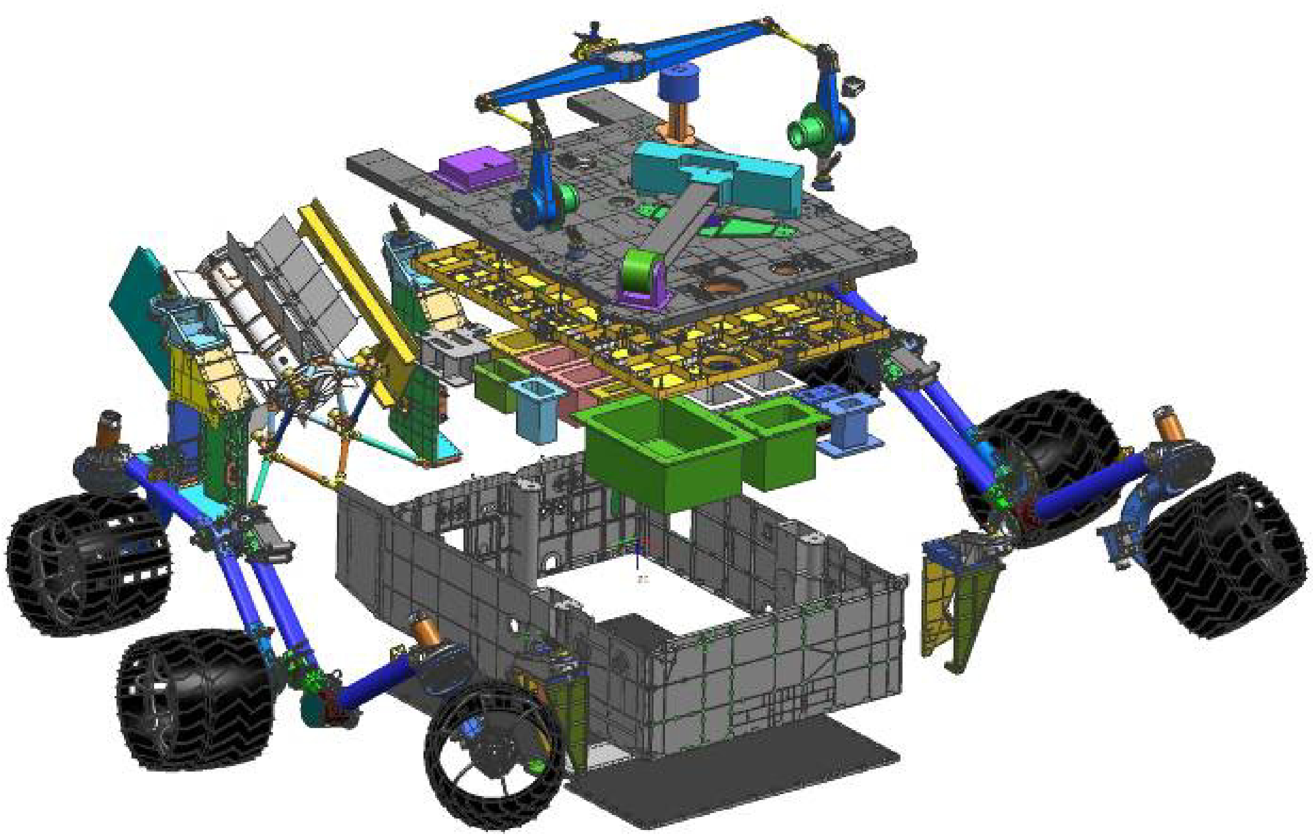

Figure 1 – Test Article Exploded View

In order to appropriately load the rover structure discussed above, the structure is populated with mass accounting for each individual appendage both internal and external to the rover. Mass mockups for each component replicate both the mass and center of mass of their respective flight components. The population of internal and external masses can be seen in Figure 1. The addition of the mass mockups brings the total rover mass to 90% the flight vehicle mass. The deficiency in mass is caused by the absences of cabling and category three hardware. Both the category three hardware and harness mass are not represented in the test article due to its relative dispersion across the structure.

The test article is supported on three bipods in the same fashion as the flight article. The top deck of the flight chassis interfaces to three bipods integral to the descent stage structure. In order to ensure the proper loading is transferred into the rover interfaces, replica descent stage bipods were fabricated and assembled to secure the rover test article to the centrifuge interfacing structure. Figure 2 shows the bipod interface details. The support structure around the three rover/descent stage interface locations account for one of the two primary load paths within the chassis structure and is a first order target for structural qualification.

Acceleration requirements

The accelerations being tested on the centrifuge include Z axis acceleration experienced during entry and X/Y accelerations experienced during launch. The flight design load level for the entry case along the z axis is 15g. The flight design loads in the x and y axis during launch are about 2.5g. The qualifications loads require a 1.2 test factor on top of the max environmental design load bringing the applied centrifuge acceleration to 18g in the Z direction and 3g in the x and y directions. The test article as detailed above has 10% less mass than the actual flight rover. With the test vehicle being lighter than the expected flight mass, and no good method of blanketing mass across the vehicle, the testing load will be increased slightly to ensure valid qualification of the descent stage interfaces.

Increasing the g loading to qualify the interface points necessitates a thorough analysis of the increased loading seen across the rest of the vehicle. The individual mass mockups are made to match flight mass and therefore will load the supporting structure to increased test loads. Each part of the structure locally impacted must be analyzed to ensure that the increase in g acceleration loads do not over-test other locations within the chassis structure. The result of this analysis provides a balance between a slight under-test of the descent stage interfacing structure and slight over-test loads at other chassis interfaces.

During launch, the rover also experiences lateral accelerations in the X and Y directions. Early on in the test development, the decision was made to design the test fixture to accommodate interfaces for testing the X and Y axis as well. The g levels for the X and Y axis loading cases are comparatively low with respect to the 18g Z case measuring 3g each.

Loading profile

During entry, the acceleration loads applied to the chassis structure are uniform through all sections of the structure. When large centrifuges are used for acceleration loading it is typically assumed that the test article is small enough relative to the length of the centrifuge arm such that the structure experiences uniform loading across the test article. The MSL rover test article stands nearly One meter tall in the stowed configuration providing for a g variation across the structure of 1.5g in the Z loading direction. This variation within the test loading profile is also taken into account when increasing the g load described above. This analysis, balanced with the analysis required above provide the target test g levels to be registered at the approximate radial location of the rover center of mass. In order to monitor the accelerations within the test article, an added requirement on instrumentation was defined to measure

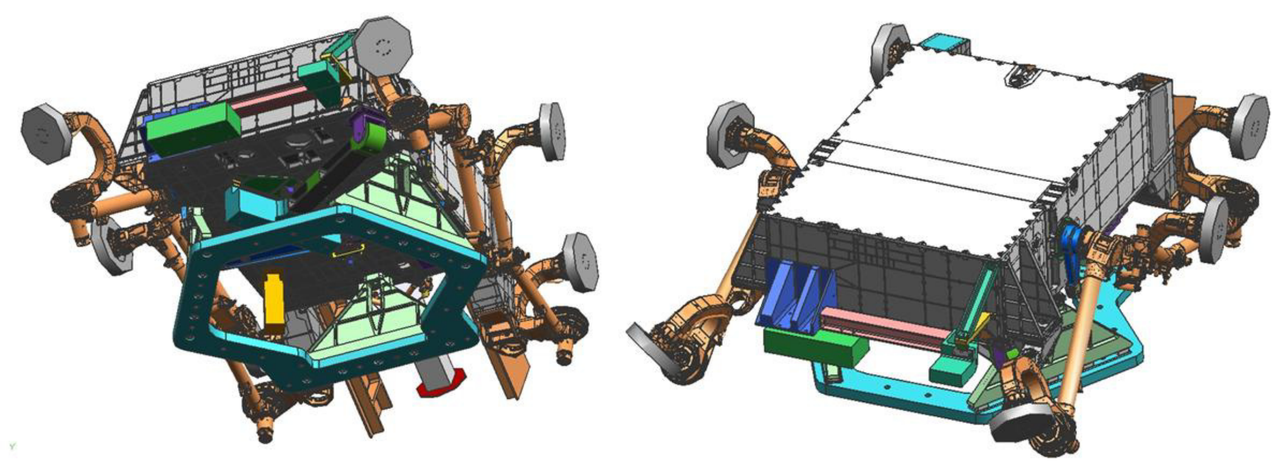

Figure 2 – Test Article Mounted on Descent Stage Interface Bipods

acceleration loads at three radial stations across the test article.

For the X and Y axis load cases, the gradient is also present accounting for about 1 g each. Using the approach discussed for the 18 g Z axis case, the test loads are again defined at the test article CG and are monitored at three stations. Some of the hardware will see slight over test, and some will see a slight under test, but the hardware of interest located at or near the CG will see the nominal test accelerations.

Final Test Loads

Balancing the above two considerations to ensure both sufficient qualification and hardware safety, the nominal test loads are defined. The final analysis has not been completed at this papers submission. However, first round calculations increase each axis acceleration by 10% to account for the aforementioned mass deficiency without adding appreciable risk of over test.

3. TEST FACILITY

With the basic parameters of the test defined, candidate test facilities were investigated that could handle the large MSL test article. The test article mass, less any enclosure or fixture hardware is 2000lb and the testing load is 19g assuming 10% acceleration increase. In order to scope candidate facilities, the enclosure size was estimated to be between 2000 and 3000lb. The required load capability for the centrifuge facility based on these inputs is 76000 g-lb on the low end and 100000 g-lb on the high end. In addition to being able to handle the axial load on the arm, the arm would have to handle a vertical gravity load at the end of the arm. The facility must also have sufficient clearances in all directions to accommodate the test article. The final major requirement on the facility is that it has a drive motor with enough power to bring the test article up to speed and sustain the required velocity for the duration of the test.

After an exhaustive search the selected facility was National Technical Systems (NTS) located in Santa Clarita, CA. Their centrifuge facility is the same facility utilized for both the MER and Mars Pathfinder projects. The facility's designed load capability is 100,000 g-lb. The MER centrifuge test defined the highest demonstrated load of 109,000 g-lb with a modified arm. The facility recently had been modified, and as a result, showed sufficient clearance to the ground and retaining walls for the large rover test article. The drive motor for the facility is a 300hp diesel truck motor.

4. TEST ARTICLE ENCLOSURE

In order to enclose and secure the rover to the end of the centrifuge arm, a centrifuge adaptor box was (CAB) was designed. For smaller test articles, the design of the enclosure is a trivial exercise; wherein the only requirements are that it properly interfaces to both the centrifuge arm and the test article itself. For the application of a large test article as the MSL Rover, a series of design constraints come into play that otherwise do not exist. These new constraints dominate the overall design of the test article enclosure. The standard interface requirements still exist so as to ensure proper attachment. The additional design constraints levied on a large test articles are created by the performance capability of the centrifuge. The constraints include overall dimensions weight, and aerodynamic performance. These constraints dominate the Z axis test case due to the high accelerations required. The X and Y axis test cases are at such comparatively low loads that only the facility clearances and handling constraints are contributed by those load cases.

To minimize the overall size of the enclosure, the internal dimensions provide between 2 and 3 inches of clearance to the rover in all extremes. The close clearances give way to a challenging integration operation to mount the rover within the enclosure, but ensure the size and weight of the CAB is minimized. While decreasing the clearances further would be advantageous for weight efficiency, it is important to ensure that under maximum loading conditions the elastic deflections of the test article and the CAB don't constructively interfere and contact one another. The expected close approach between the CAB and the test article occurs at the wheel mass mockups where they deflect outward radially along the acceleration vector and the CAB walls deflect radially and inward towards the test article. The deflections combined for the enclosure as designed do not compromise the 3" clearance envelope provided. Given that the internal dimensions are minimized, and the structure is comprised of 6" square aluminum tubing, The enclosure outer dimensions measure to be 12 feet in length 4 feet in height, and 8 feet wide .

Strength and Weight

During the MER centrifuge test program the centrifuge was proof tested to a loading of 109,000g-lbs. The advertised capability of the facility is 100,000g-lb. The weight target for designing the test article and enclosure is 4300lbs. At this weight with a 19g test lad and a 23 g proof test load we match the centrifuge advertised and also provide an added safety factor of just over 8% against the demonstrated capacity.

With the loading envelope defined, the mass of the CAB is also defined. The weight of the Rover being tested is 2000lb, and the test load level of 19g's leaves 2300 lbs leftover for the entire CAB structure to meet the facility performance capability

Using the MER CAB design as a starting point, the initial MSL enclosure was designed to be a welded aluminum structure with the primary structure out of 6"x6" aluminum tubing. The Primary load on the structure is the main Z axis test load at 19g's but the enclosure must also interface and support the rover during the X and Y axis test cases where the Rover CG is offset significantly from the Centrifuge interface. The final loading requirements that the CAB is designed for is Handling loads.

The first cut at the structure design yielded a result that was significantly heavier than the defined allowable. The mass overage is easily traced to the strength knockdown factor for welded aluminum structures, and design conservatism inherent in ground support equipment.

The initial approach for the design was that the entire structure, less the three DS interface bipods, was constructed of Aluminum Alloy to afford maximum strength properties in the tubing. At the welded locations, the strength properties would be reduced likely to an untreated condition given the amount of heat input expected for the specified welds. The welded locations, not surprisingly proved to be too weak after welding and required significant reinforcement to prevent failure. The weight of the reinforcement destroyed the defined mass budget.

With the first approach proving to be too heavy given the strength requirements two parallel paths were pursued: Constructing the structure from steel; getting creative with the aluminum conditions and treatments.

Using steel proved to be attractive because there is no appreciable knockdown factor for welding low carbon steels. Although this is the case, we found that using a low carbon steel did not provide the strength required without again blowing the mass budget. Higher carbon steels were investigated, but the wall thicknesses required and the amount of heat introduced during welding knocks down the strength and creates a more brittle joint; both of which requires design additions (added mass).

The second path proved to be more lucrative and provides us with a material and process plan for the final product. The material used is an Aluminum Alloy for the piece parts of the enclosure. However, instead of having the Aluminum in a stock treated condition, the entirety of the pre-welded material will start in a lower strength condition. By welding the material in the lower strength condition and then subjecting it to a series of treatments, a 20% increase in strength is achieved over the pre welded material.

With this material scheme, the weight of the structure was optimized and decreased to 2300lbs falling just inside the advertised performance envelope of the centrifuge.

Aerodynamics

Aerodynamics typically plays a small role with centrifuge testing in general. The primary consideration for small test items is simply to ensure a smooth non-turbulent ride for the test article. When the size of the test article begins to increase the aerodynamic considerations become more significant. In the case of a test fixture the size of the CAB, the aerodynamics of the test fixture play a significant role. Given that the test centrifuge arm radius is slightly over 7.5 m, the linear velocity of the test article and enclosure must be about 36 m/s.

Drag— The drag force created at this velocity is significant with a bluff body test enclosure. This drag force applied on the end of the 7.5m arm forces a requirement that the drive motor has a continuous output capability of 500 hp. The test facility motor has an advertised hp output at the shaft of 300 hp. To define a drag requirement for the CAB a 50hp de-rating was assumed to account for losses through the transmission and an additional 50hp de-rating is taken to account for arm drag and other unidentified power sinks. These de-ratings are intentionally conservative because the available drive power for the facility is a fixed value, and the power sinks have never truly been identified for the facility. The actual magnitude and quantity of power sinks was not an issue in the past because no test articles have required the full power capacity of the motor.

The MER centrifuge test required a fairing to decrease drag. Through some testing and analysis, the MER team found that a Cd of .5 was achievable with minimal aerodynamic design effort. Applying this Cd of .5 to the planform area defined by the CAB dimensions; the required constant horsepower output is 130hp. This power requirement gives us margin against the conservative power availability estimates, and also has built in safety due to the fact that the aerodynamics of the design can be refined providing a lower drag coefficient.

Lift— Given the above requirement to reduce drag using added fairings to the CAB, the lifting characteristics of the design must also be analyzed. The lift vector generated along the radial axis is of primary concern. The overall estimated length of the CAB with fairings is 6m. With 6m at the end of the 7.5m centrifuge arm, the wind has a relative angle of attack to the test fixture of 10 degrees. This inherent angle of attack has the potential to cause a significant radial lifting load. The lift load adds to the interface strength requirements on the fixture.

Lift in the out of plane direction must also be addressed. If the vertical lift of the CAB with fairings is sufficient enough to deflect the end of the centrifuge arm vertically, the X and Y axis of the rover will begin to see the acceleration loads during the Z test case. If the deflection angle reaches 10 degrees, there is a risk of over-testing the hardware in the other directions. It can be shown however, that the stiffness of the centrifuge arm in addition to the inertial force of the test article constrain the deflection angle to <1 degree.

Stability—The stability of the test fixture is also a primary consideration dealing with the aerodynamics. The size and weight of the test article at the end of the centrifuge arm invokes a large inertial constraint. This constraint lowers the natural resonance of the centrifuge arm in both torsion and bending. The possibility for an aero elastic flutter type reaction, albeit unlikely, has to be ruled out. For the Centrifuge in question the stiffness in both bending and torsion is extremely high and even with the inertial constraint, the frequencies are much higher than would make this unstable condition likely to occur. The centrifuge arm also has many structural reinforcements in the form of cross braces and truss cable that increase stiffness and structural damping. For these reasons this instability was decidedly not a threat for our particular test setup, but, is worth noting as a possible problem for future testing programs.

Fairing Design— To streamline the test article such that it meets the .5 maximum Cd requirement an elongated stern fairing is required. With a long enough stern fairing and the natural geometry of the front of the CAB, it likely that a Cd less than .5 is achieved. By simple comparison to objects with known drag profiles it is easy to see that the Cd should be much lower than .5, but it is unclear how the CAB structure performs at 10 degrees angle of attack to the free stream. In addition to the raw Cd, an additional induced Cd is added as a function of the lift magnitude. For these reasons a series of bow and stern fairing shapes were designed to interface to a rapid prototyped structure for the purpose of wind tunnel testing.

Testing— In order to properly characterize the lift and drag performance for the fairing candidates, scale models were rapid prototyped for wind tunnel testing. The wind tunnel testing was scaled to test at centrifuge like Reynolds numbers on the order of 10^6. Two stern fairing geometries were tested with one being 25% longer than the other. Three bow fairings were tested to compare rounded vs pointed and symmetric vs asymmetric geometries.

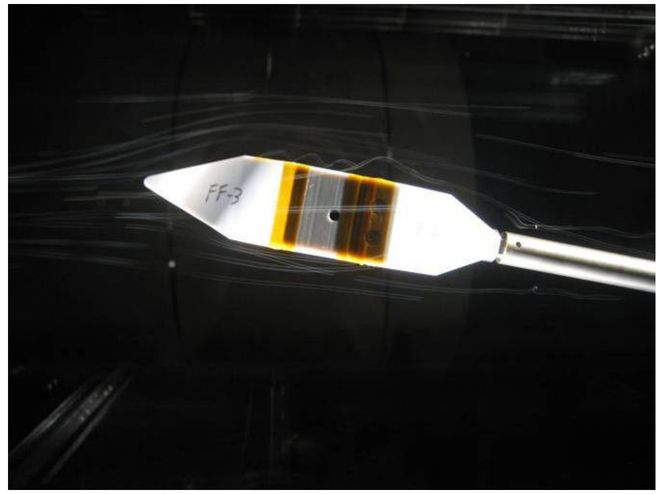

Figure 3– Candidate fairing configuration with Helium Bubble flow visualization.

The wind tunnel models were tested at 0 and 10 degrees angle of attack to account for the relative wind vector discussed prior.

The results show that the elongated stern fairing provided a 33% drop in Cd with each bow fairing when compared to its shorter counterpart. The variation in drag between the bow fairing design was less significant than the stern fairings, but the symmetric and rounded fairing had 10% lower Cd than the pointed asymmetric alternative. The lift coefficient for the longer stern fairing also is on average 13% greater than its shorter counterpart at the induced angle of attack. The lift coefficient data for the different bow fairings did not show a clear dominating trend as the drag data did. The asymmetric fairings had slightly higher Cl's, but only in the 3-6% range.

Figure 3 shows flow visualization testing with the short stern fairing and symmetric bow fairing installed.

This data combined with a study in manufacturability led to the final fairing design shown in figure 4. The forward fairing is slightly shorter than that of the tested items, but is symmetric so as to minimize the generated lift. The rear fairing is a 1:1 scale up of the best tested rear fairing. Based on the test data collected. The final shown configuration is expected to have a Cd at or nearly 0.15 giving us further margin against the centrifuge power output capacity. Selecting the lowest drag fairing configuration comes at the price of also selecting the configuration on the higher end of the Cl's tested. The expected lift coefficient at the effective 10 degree angle of attack based on the test data is roughly 0.2.

The Lifting behavior of the test article with fairings installed increases the radial force by 1%. This additional load is accounted for in the design by ensuring large interface capability and margins against the expected radial loads.

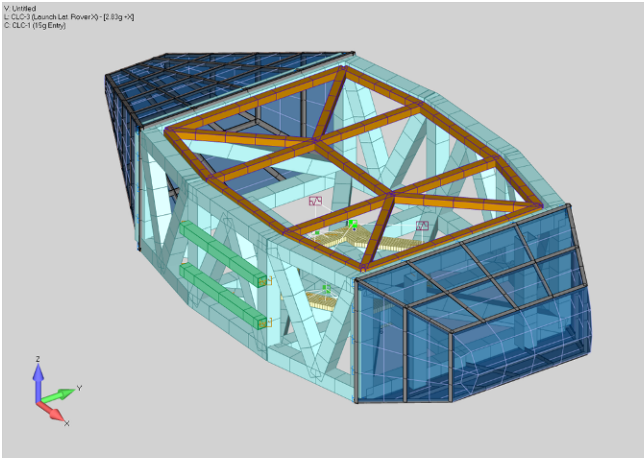

Figure 4– Final bow and stern fairing geometries

For the X and Y axis testing, the linear velocities are so low, that the drag does not encroach on the Power capability of the centrifuge. Fairings are not required for these two test orientations.

5. Instrumentation and Data Acquisition

Instrumentation

The first purpose of the test instrumentation is to ensure the safety of the hardware. The secondary purpose of the instrumentation is to collect information about the structural behavior to ensure model predictions correlate. The third purpose of the instrumentation is to control the test levels. A combination of instrumentation is installed with the rover test article and in the CAB to satisfy these three functions.

Force Transducers— In order to measure the force input to the rover at the three descent stage interface points, a series of 5 load cells are inserted into the bipod support load path. The Load cells measure axial load and 2 axis of shear. To calculate the net load input into the rover test article the output signals on each bipod from each similar axis are summed prior to reporting to the data acquisition computer. Each of the bipods report 3 channels of resolved 3 axis force data. The force data collected ensures adequate qualification of the interface locations and is also monitored real-time as a secondary manual feedback control.

Strain Gages— The strain and stress measurements made on the rover structure comes by way strain gages installed at the critically loaded locations. 15 channels of gages provide sufficient test data. The most critical channels are monitored in real time during the test for hardware safety considerations, and the rest are logged for post test analysis.

Accelerometers— Nine accelerometers are mounted in the CAB enclosure. They are mounted in three stations radially about the rover to monitor the testing loads on each testing axis. The most critical accelerometer is mounted at the radial position of the rover CG. The CG accelerometer station serves as the primary control feedback for the centrifuge velocity.

Data Acquisition

The data acquisition design for a moving test platform presented some challenges. At the hub of the centrifuge a large slip ring exists to provide power to anything mounted on the moving portion of the centrifuge. The slip ring also provides 100 channels to pass data to the control room. The problem inherent with a slip ring interface is that they are electrically noisy, and require that instrumentation signals, particularly those of the type used on this test, be pre-conditioned and amplified prior to transmission to the control room data collection. In order to eliminate the need for centrifuge mounted signal pre-conditioner, the data acquisition system rides on the rotating part of the centrifuge for the test. The data Acquisition crate is mounted at the centrifuge hub where it will experience minimal g-loading and have ready access to power via the slip ring. The data acquisition suite mounted at the hub includes a data logging computer and a wireless router. The wireless router transmits real-time test data from a few selected critical channels (including the control accelerometers) to the Control Room. Inside the control room a labview GUI is set up for the test conductor to monitor. The Remote computer receiving the wireless signal also logs the test data, but is limited to lower number of channels at a lower data rate. The data logging computer at the centrifuge hub logs all the data collected for the entire test duration to ensure seamless data in the event of wireless signal loss.

Cabling— To streamline test setup and cabling the CAB enclosure has an interface bulkhead where all the Test article instrumentation is routed. The bulkhead splits the difference between the three interfaces to the centrifuge to provide access close to the end of the arm for all three test axis. One large cable bundle runs the length of the arm from the hub mounted data acquisition box to the test article interface. Upon installation of the test fixture the cable will be plugged into the CAB based connector bulkhead.

6. Test Implementation

In comparison to preparation, implementation is relatively simple. The implementation of the test has two distinct parts. Proof testing and final testing.

Proof testing

In order to ensure the safety of the rover test article, the entire setup must be proof tested fully assembled to a load level higher than the test load in each of the three testing axis. In order to provide this load simulation, a Mass model is built that simulates the rover mass and interfaces to the

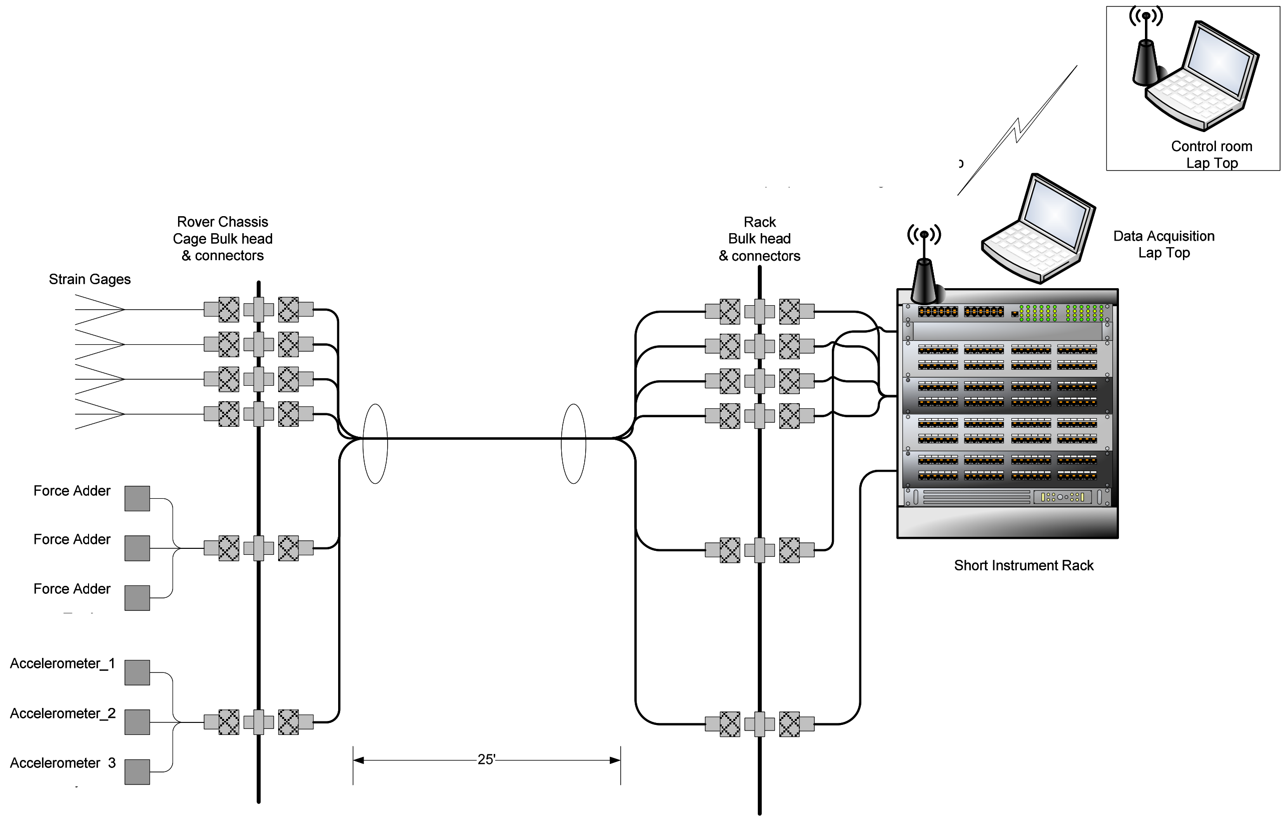

Figure 5 – Test Data Acquisition Representative Schematic

cab enclosure in an identical fashion. The proof test is essentially a dry run for the actual test and provides an opportunity to practice handling and integrating the Large CAB fixture.

Test execution

Having dry run and updated all the handling and operational procedures during the proof testing runs, the final test execution should go without incident.

For the MSL centrifuge test, one axis will be tested on each of three days with one day in between for data analysis and article reconfiguration. The design of the CAB structure and fairings is such that reconfigurations of the test article within the CAB are not required. The only necessary configuration changes are the mounting orientations to the centrifuge arm. These reconfigurations are complicated by the size of the test article, but are manageable with the appropriate transportation and rigging equipment.

7. CONCLUSIONS

In the past, centrifuge testing has been demonstrated as a very simple and safe method for structurally qualifying small to medium sized test articles for global loading environments.

As the size of the test article grows, a multitude of performance variables otherwise considered to be “in the noise” emerge as primary test and hardware design drivers. The successful design of the MSL centrifuge test fixture described and the future successful implementation of the testing shows that the usefulness of centrifuge testing on small articles can in fact be applied to very large aerospace structures. The upfront preparation work is significant as described, but the safety and simplicity of centrifuge testing make it a powerful tool in the engineering quiver and as demonstrated, need not be held exclusively for small sized test hardware.

The MSL Rover Centrifuge test schedule has been delayed with the official launch delay of MSL. Final test results and data are not available for presentation within.

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9. Biography

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