# Simulation of Launch Vehicle Dynamics on an Interstage Structure

**Richard Pantaleo**
Carnegie Mellon University
Pittsburgh, PA 15213
*rpantaleo@gmail.com*

**Jaime Bourne**
Carnegie Mellon University
Pittsburgh, PA 15213
*jimmy.w.bourne@gmail.com*

## Abstract

Flying a rover from low earth orbit to the surface of the moon requires an interstage structure. This interstage structure serves two main purposes: to contain the rocket motors used for trans lunar injection and braking, and to support the lander and rover inside the launch vehicle payload fairing. The interstage is subject to various forces imposed by the launch vehicle, and must be designed to endure these loads. This paper describes an analysis of the interstage geometry. Computer simulation is used to test the interstage structure's behavior when subjected to acceleration loads and random vibrations, and to determine its modes of vibration. The results are compared to launch vehicle guidelines and other specifications. It has been determined that the current interstage geometry constructed of 40 layers of carbon fiber provides adequate strength to support acceleration loads and meets natural frequency requirements.

## 1 Introduction

Interstage structures are commonly used in space exploration. Their main function is to support rocket motors or other means of propulsion that send space vehicles or payloads beyond earth's orbit.

During launch, the payload of the rocket, which includes the interstage, lander, and rover, is subject to various forces. Acceleration of the rocket imparts statically equivalent loads on these components. Stage separations of the launch vehicle and other transient effect impart random vibrations and dynamic forces, and the burning of rocket fuel creates high sound pressure levels. These various loads affect the design of these components, as the components must endure the loads without failing. The launch vehicle also oscillates at certain natural frequencies, and it is important that the interstage, lander and rover are designed to avoid vibration at these frequencies; otherwise they risk being destroyed during launch.

The purpose of this paper is to present analysis of an interstage geometry. The cases of acceleration loading, random vibration, and natural frequencies are investigated.

## 2 Prior Work

Lunar Prospector is a small spacecraft designed for the purpose of mapping the Moon's surface composition as well as collecting other data from the moon. The Lunar Prospector Mission parallels the mission currently under development in two aspects relevant to the topic of this report. The spacecraft is of comparable size and mass to the payload around which the research presented in this paper is reporting on. As such, the Lunar Prospector mission utilized the launch vehicle that is being considered as well as the same rocket motor for the Trans Lunar Injection stage (TLI stage).

The principal investigator of the Lunar Prospector Mission, Dr. Alan Binder writes about the entire Lunar Prospector mission from designing the spacecraft, to the end of the last mission in his book, *Lunar Prospector: Against All Odds*. In the book, Dr. Binder includes details of the Lunar Prospector TLI stage development.

Relevant to this research are the shake and drop tests performed on the TLI stage. Shake testing revealed the natural frequency modes did not meet the requirements of the launch vehicle. The structure was then modified to move the resonance outside of the harm region [7]. Drop tests were conducted to simulate stage separations.

The material used for the construction of the Lunar Prospector TLI stage was a graphite epoxy wound filament composite [6]. The composite is used for its high strength to mass ratio, which is important when trying to fit into tight mass envelope requirements as well as reducing launch vehicle costs. The Lunar Prospector TLI stage had a mass of approximately 28 kg, which provides an upper bound for the mass of the structure that will result [6]. It became apparent that some kind of carbon composite material would be used.

## 3 Interstage Components

The interstage structure is comprised of two main components: the Trans Lunar Injection (TLI) stage and the Braking Stage. These components are illustrated in Figure 1 and Figure 2, respectively. Each stage is comprised of a thin carbon fiber shell which houses a rocket motor. The TLI stage supports a STAR 37 motor, which has a mass of approximately 1140 kg. The Braking stage supports a STAR 24 rocket motor, which has a mass of approximately 240 kg. The placement of the rocket motors and the interstage structure in the launch stackup can be seen in Figure 3.

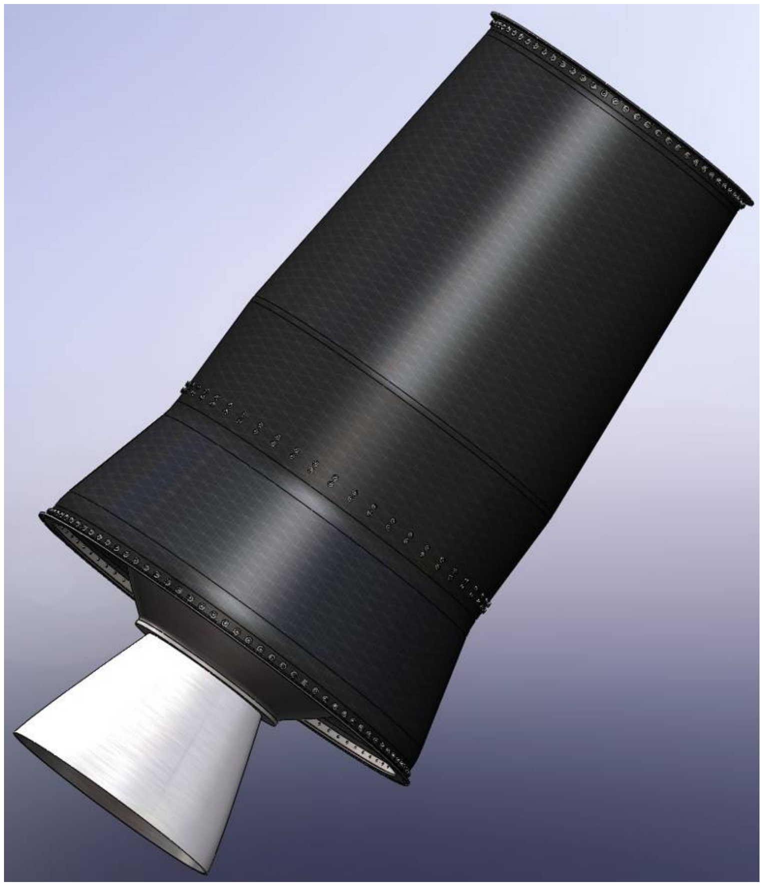

Figure 1: TLI interstage

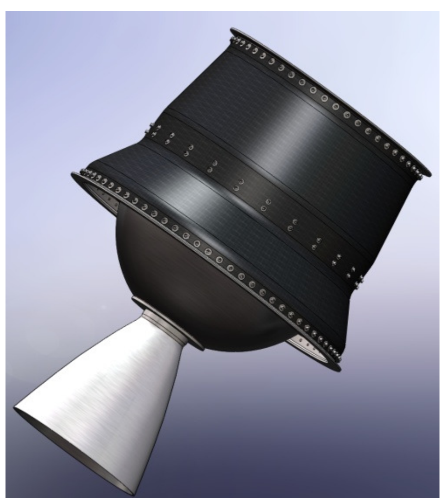

Figure 2: Braking interstage

Figure 3: The interstage stackup

### 3.1 Coordinate system definition

The origin of the model is defined at the bottom of the TLI stage, with the origin in the center of the circular base. The y direction is defined vertically from the origin. The xz plane is defined perpendicularly to the y axis. Figure 4 shows the orientation of the coordinate system with respect to the geometry of the model.

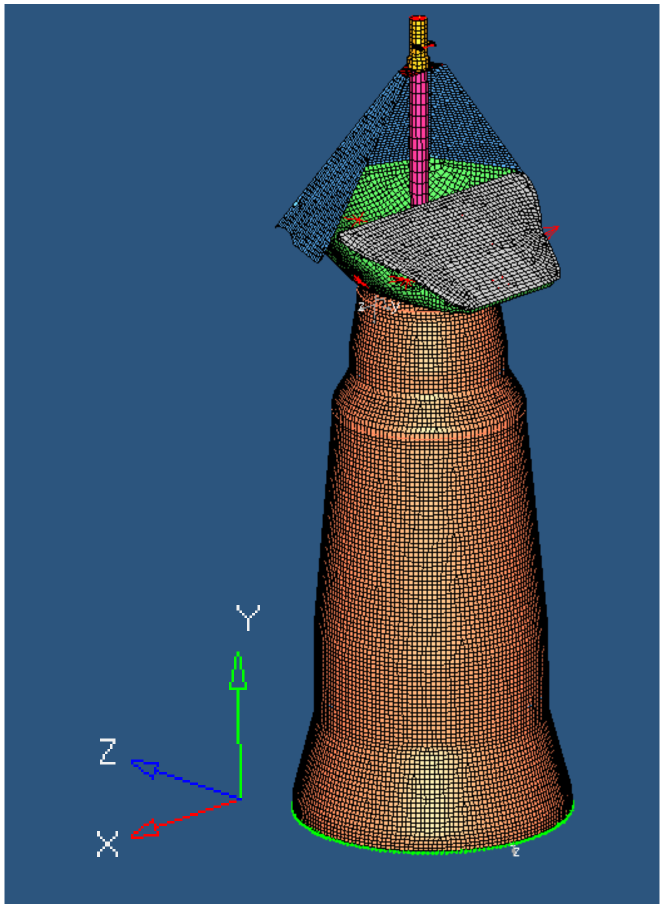


Figure 4: Coordinate system definition

## 4 Design Requirements

For lunar missions, weight of each upper stage component is critical, as every kilogram of mass adds a huge cost in fuel. A consequence of low mass requirements is low factors of safety. The factor of safety is defined as the actual strength of a structure or material divided by the required strength of the structure or material [4]. The factor of safety of a structure or material must be greater than 1 to avoid failure. Typically, factors of safety are determined based on the yield stress of the material divided by the calculated stress in the material. For structural space components, factors of safety typically range from 1.2 to 1.5 [2].

Many of the forces that the Interstage must endure are imposed during launch. Lockheed Martin has performed extensive testing with the LMLV2 launch vehicle, and has compiled relevant data into a launch handbook. This handbook specifies expected loads and other conditions present in the LMLV2 payload fairing during launch [3].

### 4.1 Acceleration loading:

The rate of acceleration of the LMLV2 is low, so the loads can be applied as static loads (i.e. the acceleration is not dynamic). Table 1 shows the expected acceleration loads the launch vehicle will endure according to the LMLV2 Handbook [3].

Table 1: LMLV2 Launch and Flight Acceleration Loads [3]

| **Flight Event** | **Axial Load, g's** | **Lateral Load, g's** |
|---|---|---|
| Launch/First Stage Ignition | -1.0/+3.0 | ± 1.5 |
| First Stage Motor Resonance | 2.0 ± 1.0 | ± 1.5 |
| Wind Gust | 2.0 | ± 2.5 |
| First Stage Maximum Acceleration | 2.0 | ± 2.0 |
| Second Stage Ignition | -1.0/+6.0 | ± 1.5 |
| Second Stage Motor Resonance | 4.0 ± 3.0 | ± 2.5 |
| Second Stage Maximum Acceleration | 8.0 | ± 2.0 |
| Third Stage Ignition | -2.0/+5.0 | ± 2.0 |
| Third Stage Maximum Acceleration | 7.0 | ± 1.0 |
| Envelope | -2.0 to 8.0 | ± 2.5 |
| 1) All loads have 99th percentile probability of nonexceedance;<br>2) Positive axial load factors act in the aftward direction at the spacecraft cg;<br>3) Axial load factors envelope spacecraft cg responses to motor ignition transients and steady-state boost accelerations<br>4) Lateral load factors are peak spacecraft cg responses to maximum nozzle deflections during all stages of boost flight;<br>5) Coupled loads analysis provides specific spacecraft dynamic response<br>6) Axial and lateral load factors should be applied simultaneously | | |

### 4.2 Natural Frequency Requirements

The LMLV2 oscillates at certain frequencies during launch. To prevent dynamic coupling between the interstage and the launch vehicle at these frequencies, the interstage must be designed such that its natural frequencies differ from those of the launch vehicle. Otherwise, the interstage risks being damaged as oscillating at its natural frequencies would impart high strain in the carbon fiber. Table 2 shows the frequency requirements of the LMLV2.

Table 2: LMLV2 Natural Frequency Requirements [3]

| Mode | Requirement (Hz) |
|---|---|
| Axial[1] | >30 |
| Axial[2] | ≠ 45 to 70 |
| Lateral[3] | >12 |
| 1) Axial mode frequency requirements avoid dynamic coupling between spacecraft and booster ignition-forcing functions<br>2) Minimizing spacecraft structure resonances in this range will reduce dynamic coupling with launch vehicle solid motor resonances<br>3) Lateral mode requirements avoid dynamic coupling between spacecraft and first bending mode of the launch vehicle | |

**4.3 Random Vibrations**

Transient effects of launch of the LMLV2 propagate random vibration throughout the vehicle superstructure [3]. Lockheed Martin has developed a graph of the spectral densities of these random vibrations at frequencies ranging from 20 Hz to 2000 Hz [3], which can be seen in Figure 5.

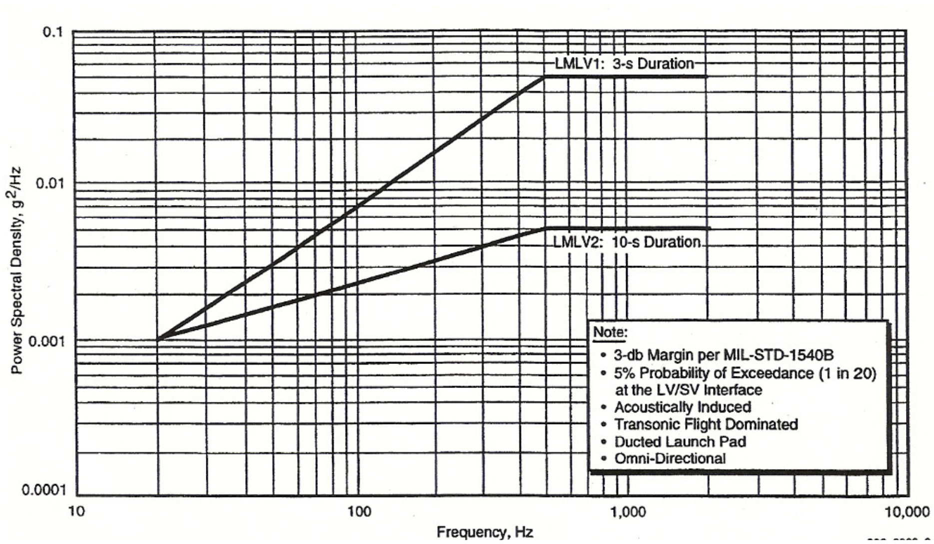


Figure 5: LMLV2 Random Vibration Environment [3]

### 4.4 Material Choice and Factor of Safety

Carbon fiber composite materials offer the advantage of high strength to mass ratio. Composite materials, by definition are comprised of multiple materials. The use of multiple materials combines the strengths of the materials to make a new material with the properties of both. For example, the composite material modeled in this research is carbon fibers pre-impregnated with resin epoxy. The carbon fibers have high tensile strength only in one axis. Resin epoxy is strong in shear. The combination of the two results in a material that has both the tensile strength of the carbon fibers and the shear strength of the resin. The carbon fiber composite material allows for relatively rigid structures to be manufactured with little mass compared to a similar structures made of traditional space material such as aluminum or titanium.

The interstage will use M55J carbon fiber, which is manufactured by Toray Carbon Fibers America, Inc. This carbon fiber has a tensile strength of 1.86 GPa [5]. The analysis of the interstage will provide data regarding the maximum stresses developed by different loading scenarios. These maximum stresses will be compared to the tensile strength of the carbon fiber by calculating the factor of safety. The particular factor of safety that the interstage is being designed for is 1.4. The choice of this factor of safety is discussed in detail in Section 6 of this report.

The loads that will be applied in the analysis are maximum expected loads. The factor of safety accounts for uncertainties such as design procedures, material properties, and manufacturing procedures [1].

## 5 Analysis method

Performing physical testing of the interstage would provide very accurate results, but the cost in money and time, especially if much iteration is needed, is prohibitive. This problem can be solved by leveraging the power of modern computers and software to perform preliminary analysis of the interstage. Using finite element analysis (FEA) software, testing can be simulated for a broad variety of scenarios. The FEA approach is used to perform analysis on the interstage.

### 5.1 Hyperworks

Created by Altair Engineering, Inc., Hyperworks is a finite element based engineering analysis software. It is well suited to analysis of carbon fiber components.

To analyze the interstage, a surface geometry is imported into Hyperworks. A finite element mesh is then applied to the surface geometry. Material properties and composite layups are defined using the software, and then these properties and layups are applied to the mesh. Additional surface models can be imported, like the lander and rover, and meshes and properties can be applied. Components in the model that do not require structural analysis, such as the STAR motors or rover computer, are represented as point masses. These point masses are positioned with respect to the center of gravity of the component they represent, and then are rigidly fixed to the mesh of the model. Rigid connections are also created to connect meshed components together, such as the interstage and lander. Loading and constraint conditions are then specified, and then the Hyperworks Optistruct solver performs the FEA. A results file is generated, which contains a variety of material data such as shear stress and natural frequencies.

### 5.2 ANSYS

While Hyperworks is a powerful computer aided engineering tool, it is limited in the analyses it is able to perform, which are static in nature. Random vibration simulations are dynamic, and this necessitates the use of a more powerful solving program. ANSYS, another FEA software created by ANSYS, Inc, for this task.

## 5.3 Test plan

The method for testing the interstage structure is presented below.

### 5.3.1 Acceleration Loading Testing

The acceleration load cases that will be performed are specified in Table 3. A total of 8 load cases will be explored using the Hyperworks Optistruct solver. These load cases cover the envelope conditions of launch (i.e., maximum expected forces in axial and lateral directions), and use different load combinations in the x and z directions to represent axial loading cases. The maximum von Mises stress from each run will be compared to the yield stress of the he material to determine a factor of safety.

Table 3: Acceleration loading cases

| Load Step | Load in x (g) | Load in y (g) | Load in z (g) |
|---|---|---|---|
| 1 | 2.5 | -8 | 0 |
| 2 | -2.5 | -8 | 0 |
| 3 | 0 | -8 | 2.5 |
| 4 | 1.77 | -8 | 1.77 |
| 5 | -1.77 | -8 | 1.77 |
| 6 | 2.5 | 2 | 0 |
| 7 | -2.5 | 2 | 0 |
| 8 | 0 | 2 | 2.5 |

### 5.3.2 Random vibration testing

The random vibration test will be performed at the frequencies and power spectral densities specified in Table 4. Hyperworks will be used to set up the geometry, mesh, loads, and constraints, and then the resulting Hyperworks model will be ported to ANSYS for solving. The ANSYS solver will determine the maximum von Mises stress in the stack up, and this stress will be compared to the material yield stress to determine a factor of safety.

Table 4: Random vibration analysis test conditions

| Frequency, Hz | Power Spectral Density, $g^2$/Hz | Frequency, Hz | Power Spectral Density, $g^2$/Hz |
|---|---|---|---|
| 20 | 0.001 | 300 | 0.004 |
| 30 | 0.0011 | 400 | 0.0045 |
| 40 | 0.0013 | 500 | 0.005 |
| 50 | 0.0017 | 600 | 0.005 |
| 60 | 0.0019 | 700 | 0.005 |
| 70 | 0.002 | 800 | 0.005 |
| 80 | 0.0021 | 900 | 0.005 |
| 90 | 0.0022 | 1000 | 0.005 |
| 100 | 0.0023 | 2000 | 0.005 |
| 200 | 0.0031 | | |

### 5.3.3 Natural frequency testing

The natural frequency of the Interstage stack up will be determined through analysis using both the Hyperworks Optistruct solver and ANSYS solver. Having results from two separate solving packages will be useful to determine the accuracy of the model.

## 5.4 Interstage finite element models

To perform the above analyses, different finite element models will be used. For the acceleration loading case and Optistruct solution of the natural frequencies, a model including the TLI stage, braking stage, and rover surfaces will be used. The lander surface model is not included because the current geometry does not meet stiffness requirements, so it is represented as a point mass in the model and rigidly attached to the top of the braking stage. The STAR 37 and STAR 24 motors are also represented as point masses and rigidly fixed to the interstage structure at locations respective to their centers of gravity. The TLI and braking stages are meshed with an element size of 1.8 cm.

The ANSYS finite element model includes only the TLI stage and braking stage. The lander is not included for the same prior reasons. The rover surface model is not included due to issues with connecting it to the braking stage. The ANSYS solver does not assume a connection between the TLI stage and braking stage like the Optistruct solver, so these connections must be added by hand in the preprocessing of the model. Creating these connections generated errors during earlier ANSYS runs, so reducing their number would simplify the model and make troubleshooting easier. For this reason, the rover was not included. The STAR motors, lander, and rover are represented as point masses in this model, with each being located with respect to its center of gravity and each being rigidly connected to the interstage. The TLI and braking stages are meshed with an element size of 3 cm. The 3 cm size was chosen due to computer hardware limits, which required a greatly increased solving time for smaller mesh sizes.

For both finite element models, 40 layers of simulated M55J carbon fiber are applied to the mesh. Each layer has its fibers oriented with the Y direction for the model's coordinate system. The mass of the interstage with 40 layers of carbon fiber is 29 kg. The base circular base of the TLI stage is also constrained so that it will not move in any direction.

# 6 Metrics

Several resources are employed to validate the results of the analyses. These resources include the requirements specified by the LMLV2 Launch Vehicle handbook and United States Defense Standards (MIL-STD and MIL-SPEC).

MIL-HDBK-304A provides the required factor of safety for unmanned space vehicles. Both yield failure and ultimate failure factors are specified. Since the interstage is made of carbon fiber, which exhibits no yield failure, the ultimate failure criteria is used. The ultimate factor of safety is specified as 1.4 [1].

The factor of safety will be computed from the static loading and random vibration analysis results. If a factor of safety is less than 1.4, the interstage structure and layup will be considered a failure. If the factors of safety are higher than 1.4, the interstage will be considered successful.

For the natural frequency tests, the results will be compared to the LMLV2 requirements handbook. If a natural frequency of the interstage falls within the natural frequency bounds of the LMLV2, the interstage structure and layup will be considered a failure. The natural frequency results from the Optistruct and ANSYS results will be compared. If the results are not similar, they may imply that one solution is incorrect.

# 7 Results

## 7.1 Static loading

The results of the static loading test can be seen in Table 5. The maximum stress in the interstage occurs during the third load step, and gives the interstage a factor of safety of 4.6. This result shows that an interstage structure with 40 layers of M55J carbon fiber is adequate to support the forces created by acceleration.

Table 5: Static loading stress results

| Load case | Max Stress (MPa) | Factor of Safety |
|---|---|---|
| 1 | 338 | 5.5 |
| 2 | 338 | 5.5 |
| 3 | 408 | 4.6 |
| 4 | 406 | 4.6 |
| 5 | 405 | 4.6 |
| 6 | 147 | 12.7 |
| 7 | 147 | 12.7 |
| 8 | 129 | 14.4 |

This acceleration loading model used only a mesh of 1.8 cm. To validate this model, a mesh independence study may be performed. To perform a mesh independence study, a model is run through multiples of the same loading case using an increasingly smaller mesh size for each subsequent run. The maximum stress results from each run are then plotted on with respect to the number of finite element nodes. A best fit line is created among the plotted points. If the line appears to converge, then it can be assumed that the resulting stress is accurate. However, if the line increases linearly or grows exponentially, then there may be a stress concentration, which will require a refined mesh (different type of element, extremely fine mesh) in the location of high stress.

Besides mesh size, another source of error in this model could be representing additional components as point masses with rigid connections. The behavior of these point masses and rigid connections are idealized and do not account for the deformations that would occur in the actual system, but it is unlikely that they would have a major impact on the overall result. A final source of error would be user error in constructing the finite model, defining material properties, etc. Having others examine the model would be another proper means of validation.

### 7.2 Random Vibrations

The result of the random vibration test can be seen in Table 6. A factor of safety of 9.5 would imply that an interstage with 40 layers of M55J carbon fiber is more than adequate to withstand the random vibrations of the LMLV2. Figure 6 shows a stress plot developed from the result.

Table 6: Random vibration stress result

| Max Stress (MPa) | Factor of Safety |
|---|---|
| 195 | 9.5 |

There are some concerns with the validity of this result. Throughout the modeling process, there was difficulty in producing a result from ANSYS. Porting the finite element model, created in Hyperworks, to ANSYS was often unsuccessful. Several weeks of iteration were required before a successful Hyperworks to ANSYS transition was made. Therefore, the confidence in the ANSYS results is low because the model is still imperfect. Given the very high factor of safety, it is likely that the interstage will withstand the random vibration despite possible errors in the model, but the model still needs to be validated. Consultation with ANSYS experts would be a proper means of determining if the model is valid. Also, a mesh independence study could also be performed.

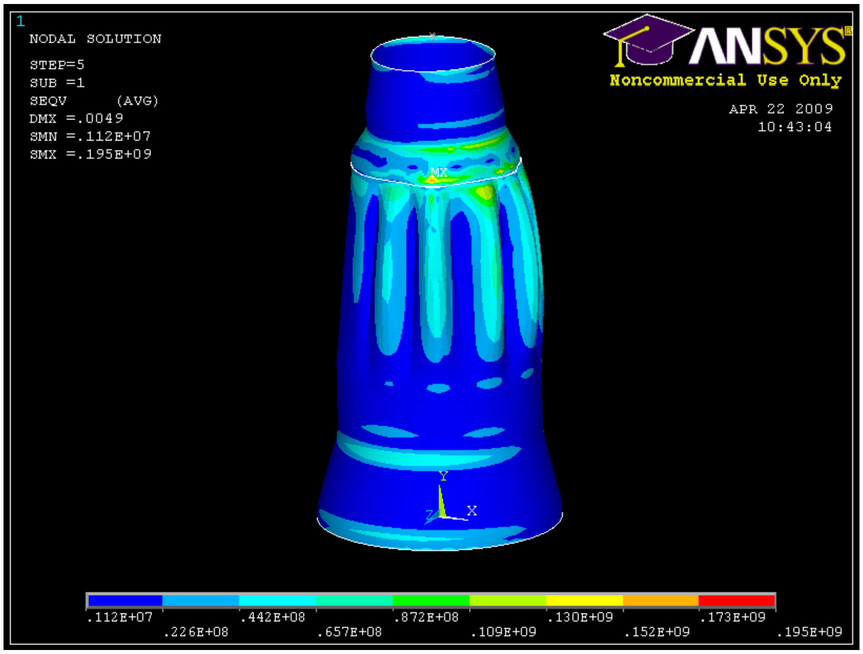


Figure 6: Stress plot of random vibration result

### 7.3 Natural frequencies

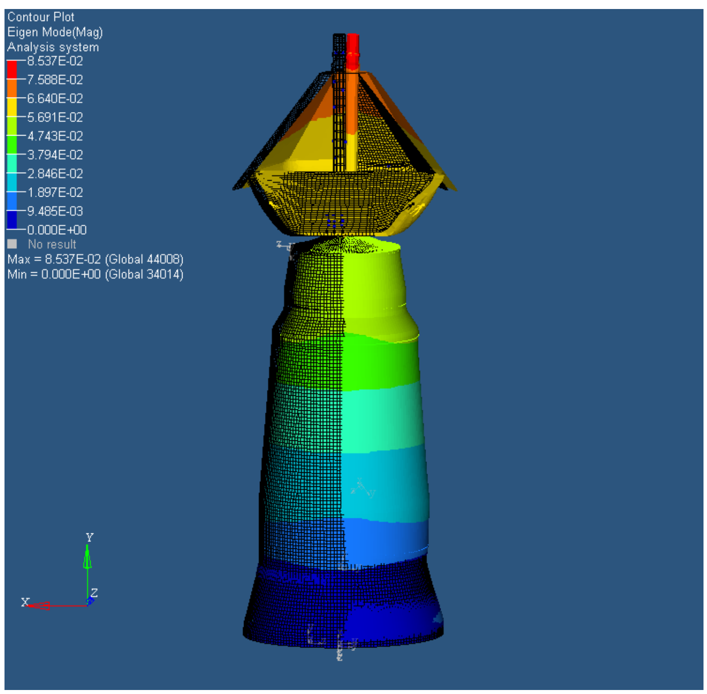


Figure 7: Displacement plot of Optistruct result, 1st lateral mode of vibration

Figure 7 shows the displacement that results from the first mode of vibration of the interstage. Table 7 shows the natural frequency results from both Hyperworks and ANSYS. The Hyperworks results show that the 40 layer carbon fiber interstage model meets all of the natural frequency requirements. The ANSYS results, however, show that the model fails the requirements because it has an axial mode at 63.8 Hz, which does not meet the LMLV2 requirements.

Table 7: Natural frequency modes

| | **Hyperworks** | | | **ANSYS** | | |
|---|---|---|---|---|---|---|
| Mode 1 | 24.8 Hz | Lateral | ✓ | 18.7 Hz | Lateral | ✓ |
| Mode 2 | 24.9 Hz | Lateral | ✓ | 20.8 Hz | Lateral | ✓ |
| Mode 3 | 34.3 Hz | Lateral | ✓ | 30.3 Hz | Lateral | ✓ |
| Mode 4 | 34.4 Hz | Lateral | ✓ | 36.8 Hz | Lateral | ✓ |
| Mode 5 | 52.5 Hz | Lateral | ✓ | 39.5 Hz | Lateral | ✓ |
| Mode 6 | 59.3 Hz | Lateral | ✓ | 63.8 Hz | Axial | X |
| Mode 7 | 81.6 Hz | Axial | ✓ | 94.7 Hz | Lateral | ✓ |
| Mode 8 | 105 Hz | Lateral+axial | ✓ | 110 Hz | Lateral+axial | ✓ |
| Mode 9 | 108 Hz | Axial | ✓ | 114 Hz | Lateral+axial | ✓ |
| Mode 10 | 112 Hz | Axial | ✓ | 117 Hz | Lateral+axial | ✓ |

In this scenario, the ANSYS result is again assumed to be incorrect. Throughout the analysis process, the results coming from the Hyperworks were consistent while the ANSYS results often varied. The problem with the ANSYS model is attributed to the rigid connection that joins the braking and TLI stages together. Though the TLI and braking stages are modeled and as separate geometries with independent carbon fiber layups, Hyperworks assumes that a connection exists between the two stages. However, ANSYS does not assume this connection, so it must be defined in the model. In ANSYS, many test iterations were performed using different styles and numbers of rigid connections for joining the two stages. Most resulted in very low first and second modes of vibration, often below 10 Hz. Successive iterations were able to get the frequencies to the above values seen in Table 6. Yet, the ANSYS model is believed to be flawed and requires further refinement. Given the consistent results of the Hyperworks model, it can be concluded that the interstage is capable of meeting the natural frequency requirements of the LMLV2.

For validation of the Hyperworks model, a mesh independence study could be performed, though the natural frequency results would be analyzed as opposed to maximum stress. Like the other models, errors can be attributed to mesh size, representation of components as point masses, and errors in model construction. Once the ANSYS model is repaired, a mesh independence study can be performed and compared to the Hyperworks results.

## 8 Conclusions

This paper demonstrates that the current interstage geometry designed by Astrobotic Technology, Inc. is capable of withstanding the acceleration loads imparted by the Lockheed Martin Launch Vehicle 2. 40 layers of M55J carbon fiber also gives the interstage adequate strength to withstand acceleration loading.

The interstage is likely to withstand random vibrations of the launch vehicle, though further validation of the finite element model is needed. The interstage meets the natural frequency requirements assuming that the ANSYS model is flawed. Natural frequency requirements appear to be the driving design factor, as was the case with the Lunar Prospector TLI stage [7].

The resulting factors of safety determined from simulation are much higher than the required 1.4, which suggests that the interstage can be optimized by both changing the geometry and carbon fiber layup. Optimization will reduce the mass of the interstage, which is currently 29 kg.

## 9 Future Work

Before moving forward with additional testing, the ANSYS model of the interstage must be refined and validated, possibly with assistance from ANSYS experts. Mesh independence studies for both the Hyperworks and ANSYS models are recommended, though not required. Further simulations must be performed considering other loading conditions as specified in the LMLV2. Acoustic loading and shock loading analyses must be performed.

There should also be some means to verify the accuracy of simulation results, and verification can be done though physical testing. Compressive, tensile, and flexure tests can be performed on a 40 layer M55J carbon fiber sample to determine failure properties. These results can be compared to simulation results to determine the validity of the finite element models.

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