Payload Isolation System for Ground Based Stability Testing: Design and Test Validation

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A ground based test adapter was designed, built, and tested to safely support a large payload and isolate it from ground borne vibration during system level stability testing. The first six suspension modes of the adapter, with the payload attached, are less than 3.5 Hz with critical damping between 0.5% and 2.0% over a very wide operating temperature range. The adapter consists of eight coil springs, eight magnetic eddy current dampers, and four lock mechanisms, all configured between two structural aluminum rings. The rings provide an interface to the payload (emulating actual interface specifications) and to the test facility at its base. Custom springs were sized to support the payload, provide isolation, and keep the self resonances of these springs, or "surge modes," out of frequency ranges that may interact with the sensitive payload equipment. The dampers, in parallel with the springs, provide the isolation performance and the lock out mechanisms can be engaged to convert the adapter to a rigid mount. Leveling of the payload can be achieved by using height adjusters while the payload is being supported by the adapter.

I. Introduction

Performing stability tests on a payload, while installed in a thermal vacuum chamber or within a lab environment, can pose several challenges. Ground borne noise from facilities and ground support equipment can affect measurements and limit the accuracy of the payload stability testing. An isolation system is required to isolate a payload from the lab by attenuating the surrounding vibration from transmitting to the sensitive equipment on the payload. The system developed and described in this paper was designed as an isolation system that also provides the primary structural support to the payload. When in the floating configuration, the isolation system has very low frequency suspension modes in order to isolate the payload from disturbances at higher frequencies. Two large rings with eight coil compression springs and eight magnetic eddy current dampers between them are used to meet the isolation requirements. Manually operated locks are used to cage the system when not being used. Figure 1 shows the integrated system and all the major components.

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Figure 1. Payload isolation system

II. Payload Isolation System Design

The isolation system consists of four main components for interfacing to the payload at its separation plane, attaching the system to ground, locking or caging the isolation system, and for providing the required isolation and suspension performance. These four components and their functions are detailed below:

Supporting Structure – The support structure consists of an upper ring that provides an interface to the payload as well as the springs, dampers, and locks of the isolation system. The lower ring provides the interface to ground.

Springs with Integral Height Adjusters – Eight coil springs support the payload and provide the isolation frequencies of the system when under load. The height adjusters/levelers are used to adjust the floating position of the payload.

Magnetic Eddy Current Dampers – Eight magnetic eddy current dampers provide system level damping to the payload isolation system.

Lock Out Mechanisms – Four lock mechanisms are integrated into the isolation system to lock out or cage the upper ring to turn the system into a rigid adapter.

The main components of the isolation system, including the support structure, are constructed from aluminum; locks, height adjusters, and springs are primarily fabricated from steel. Where steels were used, austenitic steels were preferred for their tendency to remain ductile at cold temperatures. In general, materials and lubricants were chosen to have low outgassing properties to maintain vacuum compatibility. The isolation system is approximately 2.0 meters in diameter (78 inch), 0.6 meter in height (24 inch), and weighs nearly 430 kg (950 lbs).

A. Support Structure

The supporting structure consists of an aluminum upper ring that interfaces with the payload and an aluminum lower ring that mounts to ground. The springs, spring height adjusters, magnetic eddy current dampers, and lock mechanisms all mount between the upper and lower rings.

The upper ring was designed with an integral stiffening ring in order to provide a stiff interface to the payload. When the payload is attached to the isolation system and the system is floating, the upper ring cannot bend in a way that imparts adverse loads to the payload. The upper ring was designed to achieve the necessary interface stiffness while minimizing the parasitic mass on the isolated side.

The load path on the upper ring can consist of a payload interface with several discrete points representing specific payload release locations, or a distributed mount representing a continuous interface common to a payload clamp band release mechanism. The isolation system can accommodate either type of payload attachment. Underneath the upper ring are eight coil springs that support the payload, provide the required suspension frequencies, and transfer the load to the lower ring and ground. The lower ring is a welded structure that transfers the load to ground through four mounting feet.

B. Springs and Spring Height Adjusters

Eight coil springs support and isolate the payload. The flat and ground coil springs are custom designed and manufactured from stainless steel. The springs are designed to have a specific axial and lateral stiffness in order to meet the particular payload isolation requirements. Typically the first six suspension modes are below 3.5 Hz in order to stay clear of higher frequency payload specific operational modes. Springs are also designed with longitudinal (spring axial direction "slinky" mode) and bending surge modes to be clear of operational modes.

At each of the eight spring locations is an integrated spring height adjuster and leveler. The spring height adjusters and levelers can raise or lower each spring in order to achieve the correct floating attitude and ride height of the payload. This system can accommodate a payload that does not have a centrally located center of gravity (CG).

Figure 2: Spring and spring height adjuster

C. Magnetic Eddy Current Dampers

Eight magnetic eddy current dampers provide system level damping to the isolation system. The dampers use a passive magnetic damping element to provide pure viscous damping. Within the dampers a copper conductor moves with respect to a rare earth permanent magnet creating eddy currents in the conductor. The eddy currents interact with the magnetic field from the magnets creating a drag force. The all passive all metallic dampers are relatively temperature insensitive. Variation of damping with temperature is much smaller than with any other damping technique.

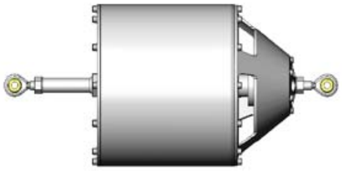

Figure 3: Damper assembly

To make this damping concept work in hardware, the conductor has to translate without friction in the magnetic field. At the vibration levels the dampers will operate in, the conductor will translate less than 0.001 inches; at these levels friction could cause the damper to act as a rigid strut transmitting the ground borne vibration through the isolation system and to the payload. Titanium flexures were designed into the dampers to translate the conductor in the magnetic field without friction or stiction.

The flexures can stroke nearly a half an inch in compression and tension before a hard stop in the dampers is contacted. The hard stop of the damper is used only to control the stroke of the dampers during any installation or removal and is not designed as a stop for the complete isolation system under the payload. The four system locks described in the next section are used to limit the stroke of the system. Below are specifications for an indeividual damper:

Property	Value	Units
Weight	6.	75lbs
Diameter	5.63	in
Rod End Size	1/4	in
Stroke	~ +/-0.5	in

Table 1: Damper characteristics

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The dampers have spherical rod ends on either end that mount into a clevis on the upper and lower rings of the isolation system. Expanding diameter pins are used on both sides of the damper to secure the dampers to the clevises.

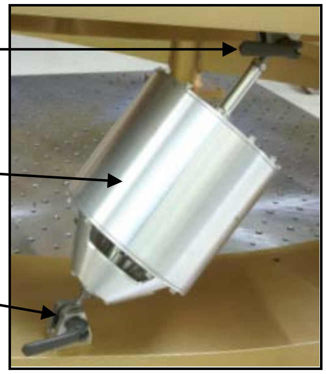


Figure 4: Damper installed in the isolation system

D. Lock Out Mechanism

Four manually operated lock out mechanisms serve two major functions. In the floating configuration, the locks provide the hard stops for large stroke excursions of the isolated mass. When not in operation, the locks cage the isolated mass turning the isolation system into a rigid payload adapter. This functionally allows the payload to be transferred to and from the isolation system without deflecting the springs.

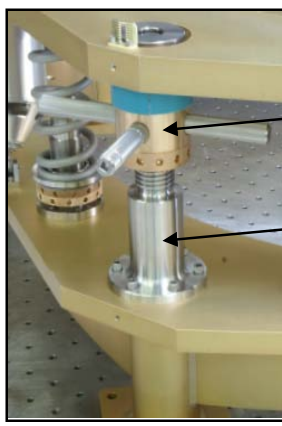


Figure 5: Lock out mechanism

The large diameter thread of the lock out post and bronze material selection of the lock out nut allows for the lock to translate easily up and down while the lock mechanism is supporting the payload. The lock out top, bolted to the top of the lock out post, is specially shaped to align the upper plate to the lock out mechanism when "grounding" or locking out the system. This interface also prevents lateral motion when the system is locked. A custom designed lock out nut provides a low friction interface between the lock mechanism and the upper plate when raising or lowering the payload. The handles are easily positioned for rotating the lock nut assembly by hand. Handles are indexed to identify position and for coordinating payload raising and lowering.

III. Payload Isolation System Analysis

All initial isolation system sizing and design was performed by analysis. A finite element (FE) model was generated and used for predicting the isolation system rigid body modes and damping, system structural secondary modes, and stability while supporting the payload. The isolation system is the direct load path between the critical payload and ground requiring additional analysis as the design progressed. This analyses included tip over studies while the isolation system is locked and floating, contact analysis between the lock out posts and the upper ring, and fastener analysis on the lock out post attachment. The figure below shows the FE model of the isolation system with the main features identified.

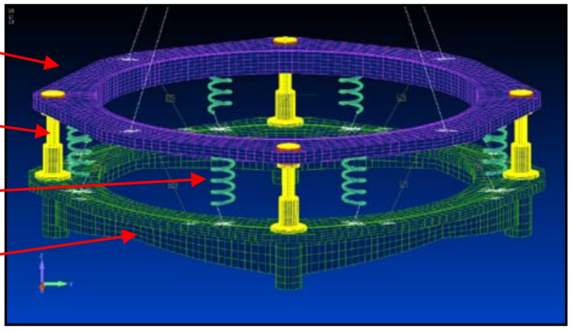


Figure 6: Payload isolation system finite element model

The final isolation system model was integrated with the actual payload model and used to predict the system level performance met the design criteria. The first six suspension modes and percent critical damping were verified. The table below details the rigid body mode frequency, mode shape, and percent critical damping for the system integrated model.

Frequency (Hz)	Mode Shape	% Crit
0.70	Rocking	0.53%
0.70	Rocking	0.54%
1.87	Torsion	1.91%
2.94	Bounce	1.90%
3.00	CG Rocking	1.36%
3.01	CG Rocking	1.45%

Table 2: Payload isolation system performance under load

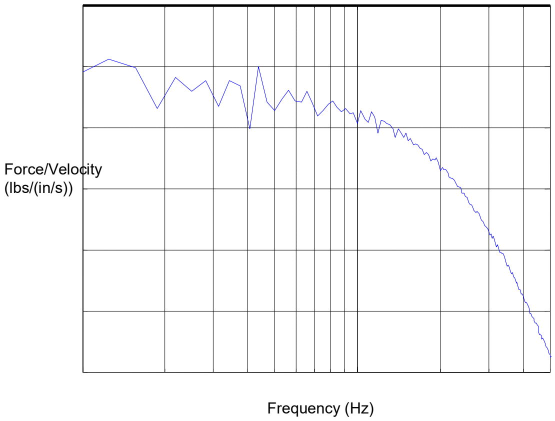
A detailed model of a spring was created in order to verify calculations on the spring axial and lateral stiffness, and spring surge modes. First and second bending modes and longitudinal "slinky" modes of the spring were all predicted to be over 140 Hz.

IV. Testing

In order to show the performance of the isolation system prior to its delivery, several tests were conducted at the component and system level. At the component level, the magnetic eddy current dampers were tested for stiffness and damping and the coil springs were tested for axial stiffness and surge mode frequencies. At the system level a float test, proof load test, and flatness test on the upper ring payload attach points were conducted. The sections below detail the main tests performed at CSA Engineering leading up to a payload mass simulator test at the isolation system end destination.

- **Magnetic Eddy Current Dampers Component Testing**

The magnetic eddy current dampers were tested in an axial direction direct complex stiffness (DCS) rig used for testing the stiffness and damping of the damper over frequency. A DCS test measures the frequency response function relating force through the test article and relative displacement across it. At the core of the dampers is the magnetic eddy current element that provides the damping as well as a flexure pair with some amount of axial stiffness (small percentage compared to the coil springs) that shows up as another stiffness element between the upper and lower rings. The figure below shows the test setup and test results (damping vs. frequency) for one of the eight dampers. The test setup consisted of two eddy current displacement sensors and a load cell for measuring force applied by a hydraulic actuator. Magnetic eddy current damping provides a robust vacuum compatible damping constant that is predictable over the frequency range of interest for this isolation system. Magnetic eddy current dampers and isolators are susceptible to inductive affects in the magnetic circuit resulting in reduced damping as the frequency increases (see Figure 7).



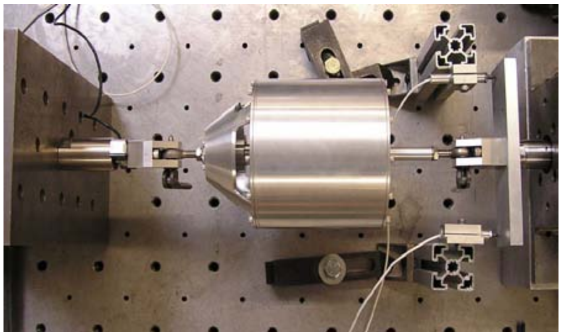


Figure 7: Damper component level testing (damping shown on the left)

- **Custom Coil Springs Component Testing**

Springs were tested at CSA Engineering for both axial stiffness and surge mode frequencies. In order to accommodate the wide manufacturing tolerances common to large wire diameter spring fabrication, additional springs were ordered. All of the springs were tested and the springs with the closest stiffness to the as-designed were selected for the isolation system. Variability that cannot be dealt with by spring selection can be handled with the spring height adjusters. The table below lists the springs used in the final assembly of the isolation system and their percent stiffness variation from the nominal spring design.

S/N	% from nominal K
1	-0.01%
3	0.82%
4	0.04%
5	0.94%
6	1.17%
7	0.91%
8	0.93%
9	0.42%

Table 3: Spring rate from the nominal spring design

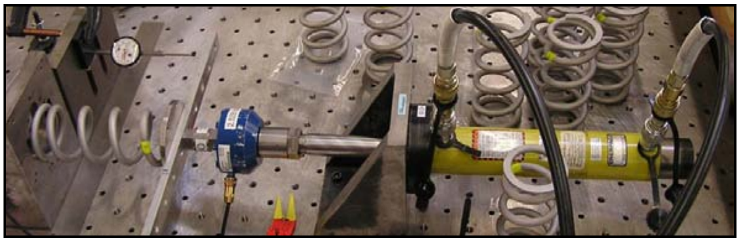


Figure 8: Spring stiffness testing

- **System Level Float Testing**

In order to characterize the system level performance of the payload isolation system rigid body modes, a mass simulator was mounted on the system. The mass simulator attached to the isolation system at four locations of the upper ring emulating the actual four payload attach points. A bolt at each of the four locations attached the payload to the isolation system upper ring providing a rigid connection between the two. Tap testing was performed with the payload in the floating position in order to characterize the first six suspension modes of the system (the test set up is shown in Figure 9).

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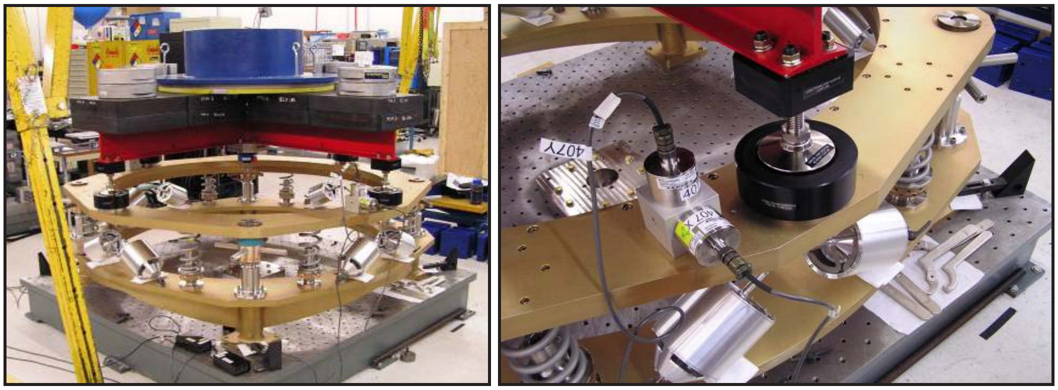

Figure 9: Payload isolation system with CSA mass simulator installed

The simulator used for the float testing was designed to have the same weight as the actual payload but it was not required to match all of the payload mass properties. By having the same weight as the actual payload the float test was used to verify that the bounce mode frequency and damping were consistent with the predicted analysis results. The secondary objective of the float test was to verify the operation of the isolation system including the spring height adjusters, lock out mechanisms, and magnetic eddy current dampers. While in the test configuration tap tests were also conducted in an attempt to identify the test configuration rocking and sway modes.

The figures below show results from two tap tests that were used to identify three of the first six suspension modes of the system while loaded with the mass simulator. The first plot shows the bounce (vertical or axial direction) frequency test results and the second plot shows the rocking direction test results. Sway and rocking mode influence can be noticed in each test result. All tests were performed with and without the dampers installed as shown in the test data. Significant damping is achieved with the dampers integrated into the system.

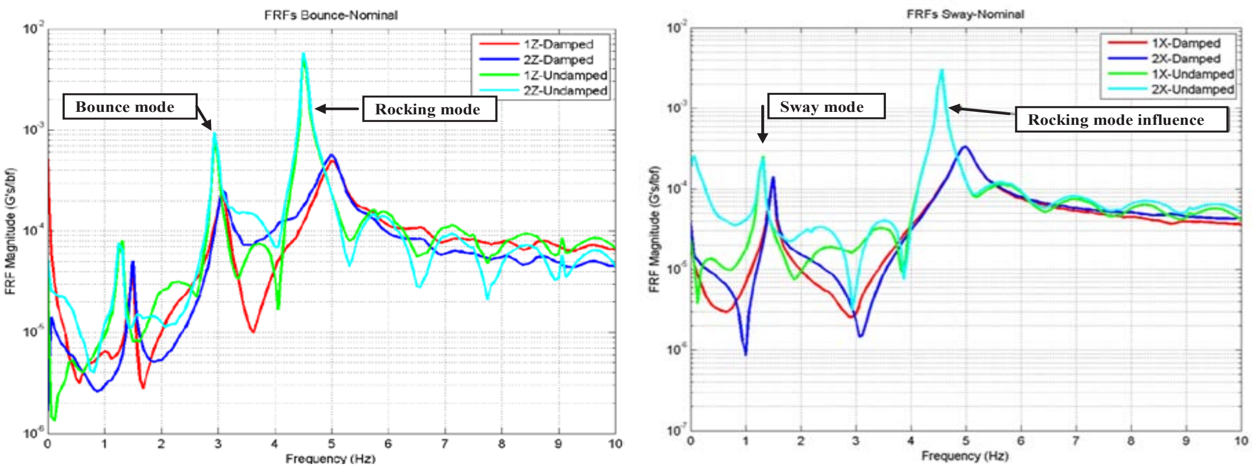

Figure 10: Float test results with and without dampers installed

Mode	Predicted Freq (Hz)	Predicted Damping (Zeta)	Tested Freq (Hz)	Tested Damping (Zeta)
CG Rocking (Sway)	N/A	N/A	1.48	1.79%
Bounce	2.94	1.90%	3.07	1.82%
Rocking	N/A	N/A	4.96	3.23%

Table 4: Float test frequency and damping

- **Proof Load Test**

The strength of the isolation system was verified by a proof load test in the axial direction to 2x the working load limit. In order to easily apply the load to the system the mass simulator used for float testing and a hydraulic cylinder were used. The hydraulic cylinder, mounted between a rigid steel test base plate and the steel I-beam test fixture, applied a downward force on the steel I-beam test fixture at the center of the isolation system. The I-beam and mass simulator attached to the upper ring of the isolation system at the four payload mounting pads consistent with the float test mounting configuration described in the previous section. The proof load test was performed when the system was in the locked configuration. When the test load was applied the load transferred from the upper ring, through the four lock out mechanisms to the lower ring. The complete load was applied for a duration of five minutes.

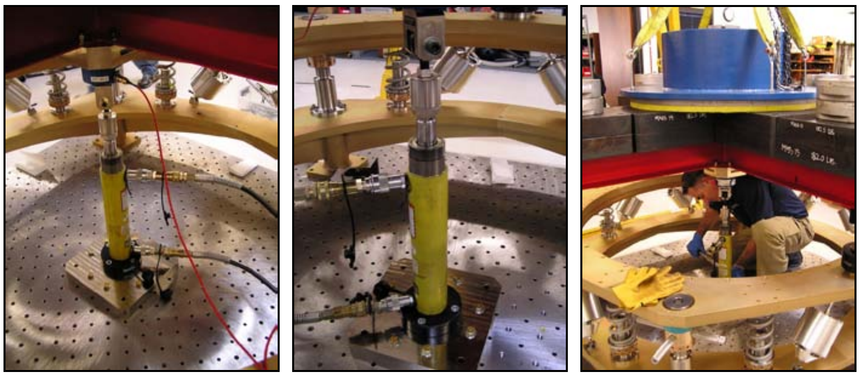

Figure 11: Proof load testing

- **System Level Testing at the Customers Facility**

A mass simulator was used to verify the as-built rigid body modes of the isolation system. The mass simulator was a good representation of the payload mass and CG, but was not an inertial simulator. The isolation system was shimmed and bolted to a steel counterweight for stability. The assembly was then shimmed to the lab floor to eliminate any rocking. A forced displacement modal verification was performed and the first six modes were found to be less than 3.25 Hz. The first 2 rocking modes were verified to be 0.70 Hz as predicted. The CG rocking modes were measured to be 3.25 Hz as opposed to the 3.0 Hz prediction. This small variation is partially attributable to the inertial differences between the mass simulator and the payload. The accuracy of the finite element model predictions allowed optimized isolation system performance while avoiding modal coupling with the local payload modes.

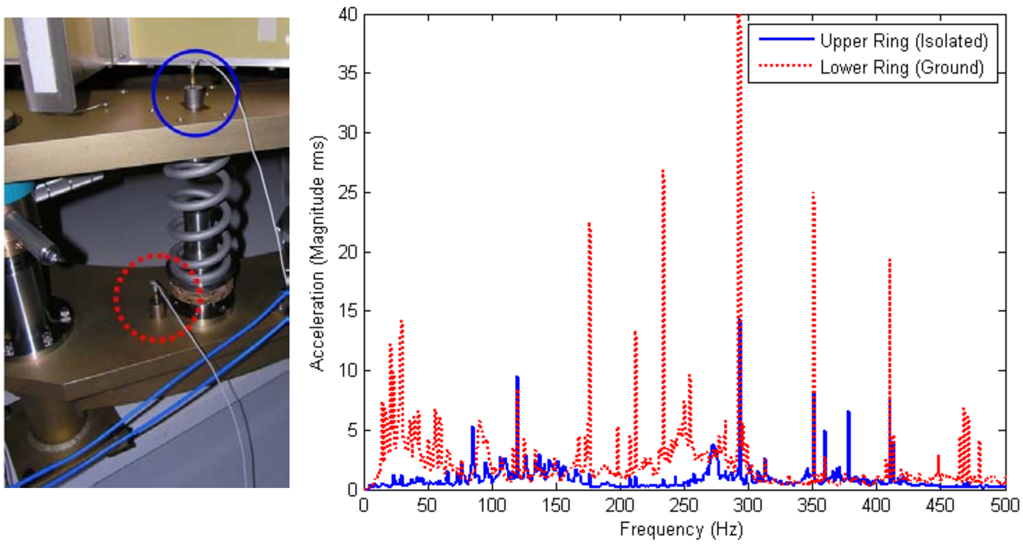

Figure 12: Ground Borne Noise Attenuation

The isolation system was used in the lab environment for payload stability testing. Background noise data was recorded with the isolation system in the floating configuration and every attempt was made to create a “quiet” lab environment. Seismic accelerometers were placed on the lower and upper rings of the isolation stand. The accelerometer on the lower ring monitored the axial component of the ground borne vibration, while the accelerometer on the upper ring represented the axial direction on the isolated side. Figure 12 is a plot of the rms acceleration at a given frequency. It is a PSD multiplied by a 1 Hz frequency bandwidth centered at 1 Hz intervals. Inspection of Figure 12 shows that the ground borne noise signal is composed of several tones, as opposed to a broadband noise. The isolation system was effective at attenuating the peaks by factors of up to 40.

Further inspection of Figure 12 reveals that there are a finite number of disturbances that are not well attenuated, or exist on the upper ring without a corresponding peak on the lower ring. This is an indication that the payload was also being excited acoustically. Although this effect was seen at a limited subset of tones, if these frequencies were of particular interest, the assembly could be placed in a vacuum chamber to eliminate the acoustic noise source.

V. Conclusion

In order to perform payload level stability testing in a lab environment or in a thermal vacuum chamber a vibration isolation system is required. The low frequency isolation system will attenuate ground borne noise from corrupting sensitive equipment performance data. This paper discussed an isolation stand or payload isolation system that was developed, designed, and fabricated to support and isolate a heavy payload. The vibration isolation system can operate in a thermal vacuum chamber at a temperature range of -50 deg C to +70 deg C. When not isolating, the system can be locked out to provide a rigid mount to ground. The first six suspension modes of the adapter, with the payload attached, were less than 3.5 Hz with critical damping between 0.5% and 2.0%. Three systems of similar performance have been delivered to several aerospace companies.