DUAL STAGE ISOLATION – A PASSIVE BI-LINEAR APPLICATION FOR LAUNCH LOAD ATTENUATION AND ON-ORBIT JITTER MITIGATION

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ABSTRACT

Traditional methods of on-orbit mechanical jitter mitigation have inherent performance limitations when subjected to spaceflight requirements. Historically, vibration isolation systems have been massive, complex, high-risk systems that provide excellent performance, but only over a limited frequency band. Through the lens of the dual-stage cryocooler vibration isolation system developed for the Astro-H (Hitomi) spacecraft, this paper addresses key challenges associated with vibration isolation and the evolutionary methods for attaining optimal performance in both launch and on-orbit regimes. This paper details functionality of the system’s key technologies and reports on advancements over traditional technologies.

1 INTRODUCTION

All imaging platforms, space-based or otherwise, are susceptible to performance degradation due to mechanical vibrational effects. Each operational environment presents its own set of unique influences and solutions. Ground based telescope jitter is generated by wind loading and seismic events. The performance of on-orbit observation platforms is influenced by spacecraft mechanisms such as cryocoolers, reaction wheels, control moment gyros, and gimbals. Pointing stability is critical for long duration observation and/or rapid scanning. Scientists and engineers have long employed a number of technologies that are used to mitigate noise pollution: vibration isolation, vibration damping, vibration cancellation, and structural stiffening. However, given the apparent dichotomy of ever more challenging on-orbit stability requirements, and the space industry’s low risk mandate, achieving a lower risk, higher performance vibration isolation system is mandatory.

The Astro-H spacecraft (named Hitomi after launch) presents an opportunity to discuss a novel approach to high performance, on-orbit vibration mitigation technology that not only provides broad band vibration attenuation, but also explores a highly effective alternative to conventional launch considerations (e.g. launch locks).

The primary instrument on Hitomi is the Soft X-Ray Spectrometer (SXS). The SXS required many stages of cooling to arrive at its operational temperature of 50mK. The instrument is sensitive to not only X-ray photons, but also any energy input. Stray energy input could increase the noise of the detector and/or cause gain variation [1]. Mechanical vibration from the cryocoolers (CC) attached to the dewar (Fig. 1) resulted in elevating the operational temperature of the SXS, reducing the science capability of the instrument. Moog isolated four of the six CCs attached to the dewar.

![Figure 1: Hitomi dewar assembly. SXS embedded internally with cryocoolers providing one stage of cooling [1].](image)

As stated, the primary function for the CC VIS was to reduce vibration induced heating of the SXS cryogenic sensor. This function will be discussed herein, as well as the jitter reduction capability which is a more prevalent need for spacecraft.

JAXA and Moog engineers collaborated on developing an entirely passive, dual stage vibration isolation system (VIS) that not only provides broadband energy reduction on-orbit, but also limited displacements and provided load attenuation during launch; a function traditionally accommodated by expensive, high risk launch locks.
Moog’s dual-stage isolation system is comprised of core technologies and is an evolution from the current state of the art.

2 ISOLATION FIGURES OF MERIT

Until the launch of Hitomi, traditional methods for on-orbit vibration isolation consisted primarily of three technologies: 1) strut isolation with viscous dampers and fluid based launch locks, 2) elastomeric mounts, 3) and metallic flexure based systems designed to survive launch. Each technology exhibits its own set of limitations which provide insight into how to design a lower risk, higher performance system.

Disaggregating launch operational and survival requirements from on-orbit operational requirements is the key to optimizing on-orbit broadband jitter attenuation. The following subsections delineate key performance metrics for vibration isolation in launch and on-orbit and how the Hitomi VIS requirements influenced these figures of merit.

2.1 Launch

With respect to the VIS, the launch environment can be described as high dynamic energy over a controlled temperature range. With that in mind, key figures of merit are:

- High broadband damping – particularly at resonances
- Broadband attenuation for random vibration loads
- Responses generally do not need orders of magnitude reduction over broad frequency bands

The need for reduction in launch loads and displacement with the Hitomi VIS was manifested in the displacements imparted to the capillary tube (CP), connecting the compressor and the cold head of each cryocooler, and the need for broadband on-orbit attenuation.

Considerable effort by the JAXA and Moog team went into minimizing the stress at the root of the CT by reducing displacements at the CC. JAXA focused on optimizing the length and bend profile of the CT while Moog focused on minimizing the displacement to the CC while also reducing launch loads.

The launch isolators for the VIS were placed in four locations around the CC per Fig. 2. Test articles used for stiffness verification are shown in Fig. 4.
The casted viscoelastic bumper housing with a cured contact sleeve was sized to provide a tunable stiffness/loss mechanism while the pin feature, moving with the compressor, contacted and fayed against the sleeve. See Fig. 5 for a cross-sectional view of the pin (compressor side) and isolator (dewar side).

The launch isolator sizing study was conducted using launch coupled loads analysis (CLA) inputs for the 4 compressor designs using variable bumper temperature dependent stiffness and loss plus initial gravity compensated gaps within a 96 variable combination study. Over the 5 to 25 C launch temperature range, a bumper loss threshold of 0.16 was needed and up to 0.25 performed equally and no viable solutions for gaps larger than 0.025 existed. A common bumper design variable set existed for all four compressors (gap = 0.025in, loss=0.16, and 2,215-3,000 lb/in from 25 to 5 C respectively.

Fig. 6 demonstrates the optimal launch isolator stiffness for the given design configuration and CC mass and inertia distribution. As mentioned previously, although the guise of non-linearity is present, given that the load path transitions from the on-orbit isolators to the launch isolators, modeling of the launch regime proves to exhibit linear stiffness when subjected to high energy dynamic loads. Section 3 will further define verification methods and validate the linearity of this system. Fig. 7 provides CC response due to a random base shake environment.

Both random vibration and low frequency sine vibration inputs were evaluated when designing the launch isolation system. In general, the driving load cases for CT stress, and CC center of gravity acceleration response was the sine vibration environment. JAXA provided CLA developed sine environments at the base of each compressor (Fig. 8). Moog analyzed acceleration response at the compressor CG using non-linear transient analysis (Fig. 9) across the launch temperature range of 5C to 25C. Ultimately, JAXA approved response levels even with minor exceedances to the allowable.
2.2 On-Orbit

The need for on-orbit vibration isolation is predominantly driven by line of sight jitter mitigation for observation platforms. For Hitomi, it was mechanically induced heating of the SXS cryogenic sensor. For both applications, the following figures of merit hold true:

- Provide rapid attenuation beyond the isolation frequency of 40 dB/decade or better.
- Designing isolation frequencies as low as possible allows for broad band attenuation.
- Minimize or eliminate coupling between translational modes and rotational modes.
- Minimize influence of secondary modes; also known as parasitic modes or surge modes.

The Hitomi CC vibration isolation system was designed to reduce heating of the SXS through mechanical vibration transmission from the CCs. All other hardware in the VIS was designed to accommodate loading environments and thermal conductivity requirements.

The on-orbit isolator utilizes Moog CSA’s traditional SoftRide architecture [4]. Specifically, the primary load path and main compliance element is a metallic flexure. Integrated with the flexure is a shear lap, constrained layer, VEM damping treatment (Fig. 10). This technology has flown well over 50 times in the past two decades.

On-orbit VIS will be effected by parallel stiffness paths. These shunting paths ultimately influence the ability to provide predictable modal performance and could transmitted vibration induced heat into the SXS sensor. The two shunting paths for the on-orbit VIS were the flexible thermal straps and the CT and loop heat pipe. Therefore, understanding and characterization of both stiffness and mass influences was critical in determining
on-orbit VIS performance. Ideally, the stiffness combination of all shunting paths should be one order of magnitude (or more) less than that of the isolation system. This would result in less than a 5% frequency contribution to isolation dynamics.

The CT and loop heat pipe is well characterized and adjustable to accommodate stiffness. The thermal straps provided a different set of challenges. The graphite fiber thermal straps (GFTS) yielded non-linear stiffness with load, frequency, and temperature. This was due to use of encapsulation compounds. Test verification of stiffness is discussed in [3]. A co-linear comparison of GFTS and isolation system is best described in the CC local Z-axis (Fig. 12). The GFTSs accounted for less than 10 N/mm stiffness in the system Z-axis while the on-orbit VIS stiffness was approximately 220 N/mm. While the stiffness ratio is below 10%, stiffness contribution from the GFTS needed to be included in system modeling for accurate predictions. Given the non-linearity of stiffness, the GFTS were tested at various temperatures and loads to evaluate stiffness influence to the on-orbit VIS [3].

Strength margins for the on-orbit VIS are calculated by a combination of sag and displacement due to compliance in the launch isolators. Discussion on this interaction is provided in Section 3.

While neither mass nor strength were driving parameters for the Hitomi CC VIS design, these elements are noted due to their influence.

3 MODELING AND PREDICTION METHODS

Development of the dual-stage, bi-linear technology posed significant challenges in predicting how the launch and on-orbit VISs interacted with one another, how loads are transferred between isolators, predicting maximum loading events due to CLA results, and determining reaction loading into mounting locations.

Moog’s suite of tools included use of Nastran linear and non-linear (SOL 601 / Adina) codes, as well as a unique, modal space Matlab algorithm that enabled transient based modeling of the loads propagating through the system. The following section describes the use of this code in predicting the behavior of the Hitomi CC VIS.

3.1 Customized Algorithm for Bi-Linear Simulation

Non-linear or bi-linear behavior of dual stage isolators under non-stationary launch loading environments drove development of customized analysis algorithms which coupled Matlab manipulation of output from Nastran linear solutions.

Moog developed the Matlab Simulink dynamic simulation tool in order to efficiently predict maximum responses during random vibration and varying amplitude sine vibration loading events. The non-linear code is an analytical flexible body time domain (required for non-linear) simulation that enabled predictions of response forces, accelerations, and displacements due to the engagement of launch locks after an initial stroke through the pin to isolator gap.

Fig. 13 provides a case specific flow diagram on the usage of the Matlab algorithm. In this scenario mode vectors and frequencies were calculated from a detailed finite element model (FEM), generated in FEMAP. The algorithm than exercised the model with input transient environments generated from CLA results to recover displacements and rotations in key locations. Also, the code directly exported launch isolation impact forces Those displacements and rotations were then applied back to the FEM for strength margin calculations. This approach provides many advantages to strictly using traditional non-linear codes for strength margins.
First, compiling the model once as opposed to for every loads iteration enabled efficient trade studies by varying non-compiled parameters. For instance, optimal gap sizing (as discussed earlier) for the launch isolators was an iterative complex process which involved assessment of deflection limits and geometric non-linear effects.

Second, definition of key parameters (launch isolator gap size) within Simulink, as opposed to Nastran non-linear applications proved more efficient when directly defined within the model.

Lastly, compiling a modal model (vector and frequency) is much more run time efficient than running non-linear analysis within Nastran, using restarts or super elements.

4 TEST VERIFICATION
The test verification for the Hitomi CC VIS was exhaustive. The VIS was tested in on-orbit configuration, launch configuration, and at temperature. All compliant subcomponents were also tested (launch and on-orbit isolators and thermal straps). A test-like-you-fly approach was used in order to ensure performance across all operational regimes.

As discussed in [3], the verification test sequence for the VIS needed to account for the following performance parameters:


2. The inherent multi-dimensionality of the system.
3. The multiple compressor configurations relative to the G field and the quasi-static launch accelerations.
4. Temperature sensitivity
5. Out of band dynamics (i.e. fixture modes, mass simulator internal resonances) that could lead to non-substantive conclusions about isolator performance.

With these considerations in mind JAXA and Moog arrived at the test plan presented in [3]. The following sections provide a brief summary of launch and on-orbit focused verification tests that validated the predicted performance of the system.

Direct Complex Stiffness Test
Moog traditionally tests all VIS hardware at both the component level and system or subsystem level. Component level testing, such as Direct Complex Stiffness (DCS) testing ensures that the key compliance elements are directly measured to ensure predicted performance is verified.

Moog uses a straight forward test configuration (Fig. 15) in which a broad band random wave form is imparted on a single, or multiple test articles. Displacement across the test article(s) is measured by non-contact probes (e.g. eddy current probes or laser probes) and reaction force is measured through the test article(s). Obtaining force, displacement, and phase allows for calculation of the test article(s) stiffness over varied temperatures and frequencies. DCS of the launch isolators, on-orbit isolators, and the thermal straps were all acquired and used for system level analysis.
Transmissibility Testing

Transmissibility testing is key to jitter attenuation verification for all vibration isolation systems. As discussed in the previous section, testing needed to be performed across the on-orbit operational environment. Moog developed a custom dynamometer to measure transmitted loads from the CC to the dewar. The test article was mounted onto a stiff plate which, in turn, was mounted to tri-axial load cells at each corner (Fig. 18). Electrodynamic shakers imparted controlled wave forms on the test article about the origin of input force. The input and output definition for this test is in Fig. 16. The entire test environment was controlled via the thermal enclosure. Transmissibility performance was as expected (Fig 19). It should be noted that, while the test article observed in Fig. 17 includes the thermal straps, the transmissibility shown in Fig. 19 is without thermal straps.

Launch Verification Testing

Launch verification testing consisted of sine sweep profiles (performed at Moog CSA) and 6-DOF testing using time consistent inputs from CLA. JAXA and Moog CSA performed these tests using a hexapod with broadband control. Not only was the 6-DOF correlated transient waveforms a challenge to implement, the test article also needed to have a static load applied at defined vectoring to simulate the launch quasi-static acceleration. The matrix of tests was 126 test long and was designed to evaluate deviations in each suspected CLA variable.
5 LESSONS LEARNED
The following list provides a brief summary of lessons learned through development of the Hitomi dual-stage cryocooler vibration isolation system:

Design
- Due to physical design space constraints, performance was limited in some DOFs. Integrating vibration isolation technology into system architecture early in program schedule enables a more holistic design approach, and optimal performance for dual-stage vibration isolation systems.
- All shunting path stiffness should be accounted for (e.g. thermal straps and CT). These shunting paths will always contribute / hinder the performance of the VIS.
- Code development for non-linear systems enabled efficient analysis techniques that capture most of the internal and external effects due to the bi-linear system.

Test
- Test-like-you-fly was exhaustive and time consuming. However, given the bi-linear nature of this system, all deviations from predictions needed to be correctly accounted for.

Programmatic
- Clearly defined program plans require broad understanding of analysis, test, design, and review campaigns that don’t often follow linear program models.

6 SUMMARY
Implementation of a dual-stage, passive, vibration isolation system offers a number of key advantages over traditional space based vibration isolation systems. The solution offers an alternative approach that, in many instances, is optimal when compared to launch locks. In the case of Hitomi, it provided broadband mechanical vibration filtering to reduce the heating impact to the SXS. In imaging systems it could provide jitter reduction while minimizing parasitic mode effects. The architecture is compact and reliable. However, modeling the system and performing test-as-you-fly qualification and acceptance proved challenging and time consuming. Ultimately, when spacecraft providers view release mechanisms as high risk to the mission, yet optimized vibration isolation is mandatory, a dual-stage passive isolation system is an attractive solution to a challenging problem.

7 ACKNOWLEDGEMENTS
The authors thank the Hitomi and Moog team members for supporting and pursuing the dual-stage vibration isolation system technology development. The authors appreciate the considerable cooperation of TAI members for GFTS development.

8 REFERENCES