2015

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AIAA

W.D. Lan, V. Kaushish, J.H. Newman, "Progress in reducing vibration levels on the Naval Postgraduate School Cube-Sat launcher," 29th Annual AIAA/USU Conference

Progress in Reducing Vibration Levels on the Naval Postgraduate School CubeSat Launcher

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ABSTRACT

The Operationally Unique Technologies Satellite (OUTSat), the Government Experimental Multi-Satellite (GEMSat), and the Unique Lightweight Technology and Research Auxiliary Satellite (ULTRASat) missions, launched in 2012, 2013, and May 2015, successfully deployed a total of 33 CubeSats from Poly-Picosatellite Orbital Deployers (P-PODs) mounted to the Naval Postgraduate School (NPS) CubeSat Launcher (NPSCuL) on the aft end of the Atlas V Centaur upper stage. An additional 13 CubeSats are scheduled to launch on the Government Rideshare Advanced Concepts Experiment (GRACE) in September 2015. Force-limited vibration testing (FLVT) has been effective on all four missions in reducing the low-frequency vibration test environment at the P-POD interface on NPSCuL; however, the CubeSats were still subjected to high-frequency amplifications from the NPSCuL structure. Implementing commercial-off-the-shelf (COTS) isolators at the base of the NPSCuL structure has recently been shown to significantly reduce the high-frequency amplifications. This paper discusses the testing and the resulting 35-85% drop in overall G_{RMS} vibration test levels, a welcome reduction in the CubeSat vibration test environment on NPSCuL. This reduction should allow more sensitive payloads to fly on future NPSCuL missions, and the implementation of low-cost, COTS isolators could possibly be useful for other small satellites and CubeSat launch applications.

INTRODUCTION

In 2007, NPS presented a paper at this conference describing the concept of clustering P-PODs in the NPSCuL (pronounced NPS "cool") to improve rideshare opportunities to deploy CubeSats in space.[1] Eight years later, NPSCuL has flown three times and is manifested on one more Atlas V mission in September 2015. The NPSCuL is capable of carrying eight P-PODs or four 6U dispensers, or a combination of the two. It consists of a five-sided aluminum structure and an Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-compatible, non-separating adapter ring. NPSCuL also includes the Splitter Auxiliary Device (SAD), an electrical interface box between the launch vehicle (LV) and the deployers. As shown in Figure 1, the fully-integrated payload is mounted to the Aft Bulkhead Carrier (ABC) on the aft end of the Atlas V Centaur stage.

Need for Reducing Vibration Levels

The CubeSats flying on the ABC missions are subjected to a relatively high random vibration environment. Given where the NPSCuL structure is located and the associated rough ride, this is affectionately referred to as "coach class to orbit."[2] The P-POD is attached to a cantilevered structure with thin plate mounting walls, both of which contribute to amplification at the P-POD-to-NPSCuL interface. The G_{RMS} levels at the P-POD interface can be as much as twice the input at the base, as illustrated by the values in Table 1. The P-POD interface G_{RMS} at the acceptance vibration test level is calculated from the maximum acceleration spectral density (ASD) values that were measured at the interface of P-PODs #1-4 during the OUTSat system-level acceptance test. The P-POD locations on NPSCuL are shown in Figure 2.

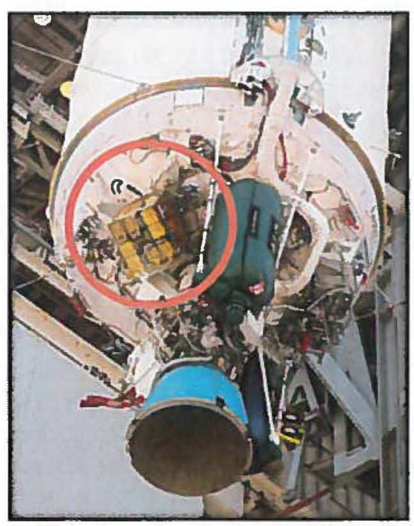

Figure 1: OUTSat Mounted to ABC

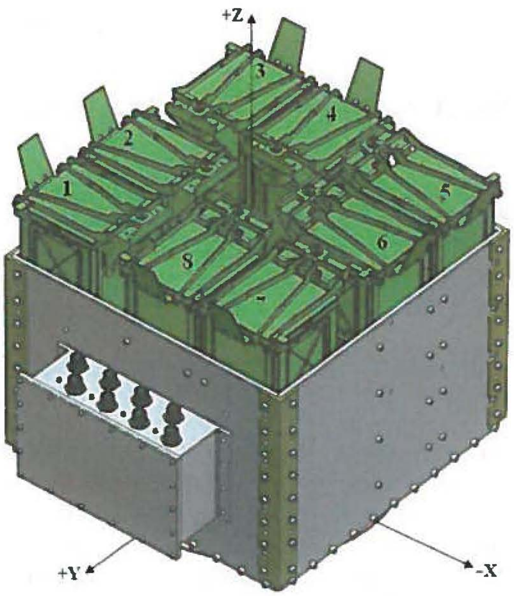

Figure 2: P-POD Locations on NPSCuL

The proto-qualification and qualification values were scaled up from the acceptance level test by 3dB and 6dB, respectively, per Test Requirements for Launch, Upper-Stage and Space Vehicles, SMC-S-016. The X-axis values are presented here as a worst-case representation of the vibration environment.

Table 1: Overall X-Axis G_{RMS} Envelope of OUTSat Test Data (Worst-Case)

Level	Base G_{RMS} (Input)	P-POD Interface G_{RMS}
Acceptance (MPE +0dB)	7.6	15.1
Proto-qual (MPE +3dB)	10.7	21.4
Qual (MPE +6dB)	15.2	30.3

These levels are considered high for satellites compared to other P-POD launch interface environments that are similar to NASA General Environmental Verification Standard (GEVS) vibration levels[3]. This discourages some payloads from flying on these missions or forces the payload developers to focus more on surviving an extremely high-level vibration test instead of improving the state-of-the-art of existing technology.

PROGRESSION OF VIBRATION REDUCTION METHODS ON NPSCUL

Several methods were considered to reduce the vibration levels on NPSCuL, including changing the test set-up, the structure itself, and the test levels from the LV provider. At this time, ULA is performing a study to reduce the test levels, but updated test levels are not available; therefore, only changes to the test set-up and the NPSCuL design will be discussed.

Force-Limited Vibration Testing on NPSCuL

Force-limited vibration testing (FLVT) has been implemented on all four NPSCuL missions during the qualification and acceptance random vibration tests performed at the system level. This test set-up has been effective in reducing the resonances at the NPSCuL fundamental frequencies, resulting in a test level that is less conservative but still meets the United Launch Alliance (ULA) vibration test requirements. The FLVT set-up used for NPSCuL is shown in Figure 3. In a traditional fixed-base random vibration test, the test article would be mounted directly to the shaker adapter plate. Additionally, only the input is controlled and there is no feedback from the system under test.

However, for the FLVT set-up, force transducers are sandwiched between the shaker adapter plate and a second plate that interfaces with the test article. This allows the force transducers, which must be pre-loaded, to measure the force at the mounting interface. A force limit is then applied to the measured force, resulting in a notch at the fundamental frequencies of the test article. In this set-up, the force limit provides a form of control feedback from the test article to the acceleration input. An example of the force limit and the resulting acceleration input is shown in Figure 4 and Figure 5. The semi-empirical method[4] is used to derive the force limit because it does not require knowledge of the modal and residual masses of the source (the LV). The roll-off frequency is set at the first fundamental frequency in the axis of test, the C^2 value is estimated to be 2, and the force limit is cut-off at 500 Hz as recommended for spacecraft under 500 lbs.

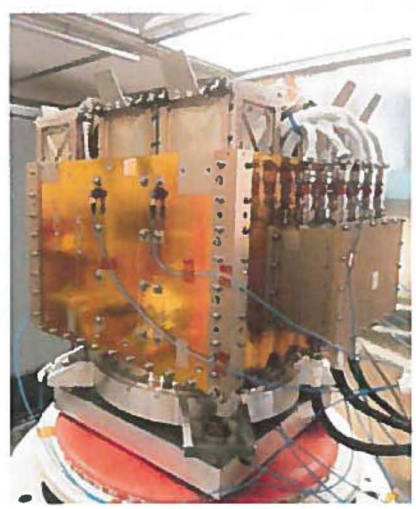

Figure 3: FLVT Setup

It is noted that there is no relief past the force-limited range; however, test data shows that there is a significant amount of energy above 500 Hz at the P-

POD interface, which is the frequency range of concern to many CubeSats. The response at the P-POD #2 interface is shown in Figure 6 as a representative case of high-frequency content that is present, even if an FLVT set-up is used.

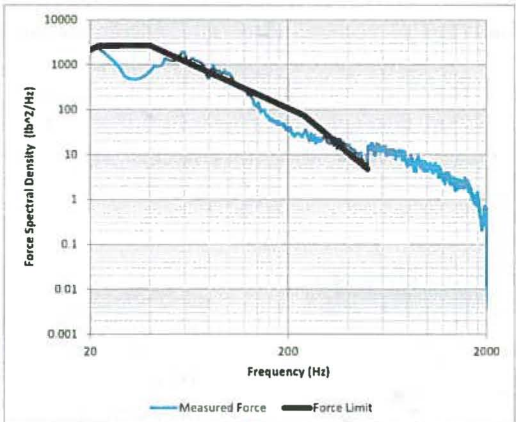

Figure 4: Force Limit

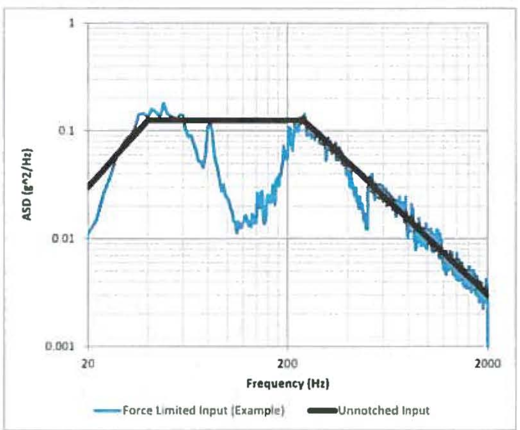

Figure 5: Resulting Notch at Fundamental Mode in Acceleration Input

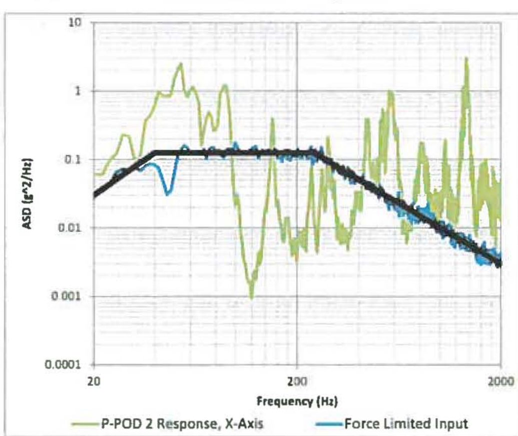

Figure 6: Response at P-POD #2 Interface (P2M2 Data from Qual Test at MPE + 0dB)

Isogrid NPSCuL Design

FLVT is not a mechanism for changing the resonant properties of the system; it is a test method that reduces the conservatism of a fixed-base test. Therefore, design changes were made to NPSCuL to modify the system properties to try to improve the vibration environment at the P-POD interface.

The main principle that drove the design modifications was that as frequency increases, displacement decreases for the same input. Lower displacement is desirable as it induces lower stresses in structural components. An attempt was made to increase the natural frequency of the NPSCuL structure by increasing the structural stiffness without increasing the overall system mass. This was achieved by doubling the NPSCuL wall thickness from ¼ inch to ½ inch, while implementing an isogrid design to ensure that the system mass did not increase. An isogrid panel is a plate or face sheet with triangular integral stiffening ribs, commonly referred to as stringers. Much of the material from a solid plate can be removed, leaving behind a lattice of intersecting ribs and a thin face-sheet, without compromising the structural integrity of the plate. Additionally, the NPSCuL baseplate and adapter ring were fused into a single, thicker part, with circular sectional cut-outs on the baseplate to reduce mass. This part was called the unibase.[5] The resulting re-designed isogrid NPSCuL structure is shown in Figure 7 and Figure 8.

The isogrid NPSCuL design was built and tested, and test results were compared with the baseline NPSCuL vibration test results. It was found that though the first fundamental frequencies of the isogrid NPSCuL design are higher than the baseline NPSCuL fundamental frequencies, FLVT is less effective on the isogrid NPSCuL structure. This is because the force roll-off associated with FLVT begins at a lower frequency when testing the baseline, less-stiff NPSCuL, allowing for a broader roll-off frequency range and deeper notches. As a result, the overall G_{RMS} levels measured at the P-POD-to-NPSCuL interface are higher for the stiffer isogrid structure, even when utilizing FLVT. This is shown in Figure 9, which contains the X-axis data taken at P-POD #2 for both the baseline and isogrid NPSCuL designs. The results of the isogrid NPSCuL testing showed that stiffening a structure may not reduce vibration test levels when utilizing FLVT. Additionally, there is no relief in amplitude at the P-POD interface, especially above 500 Hz. It was determined that either introduction of damping or utilization of vibration isolation techniques may be required to achieve better vibration environments.[5]

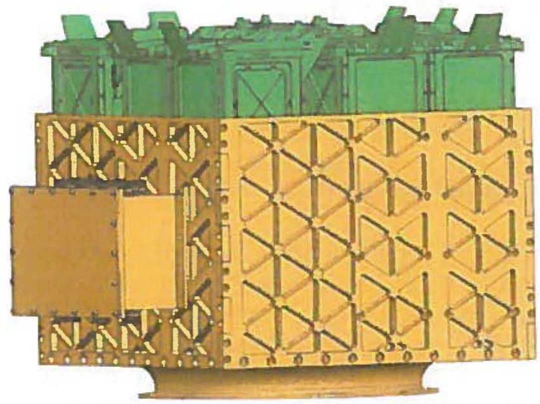

Figure 7: Isogrid NPSCuL Design

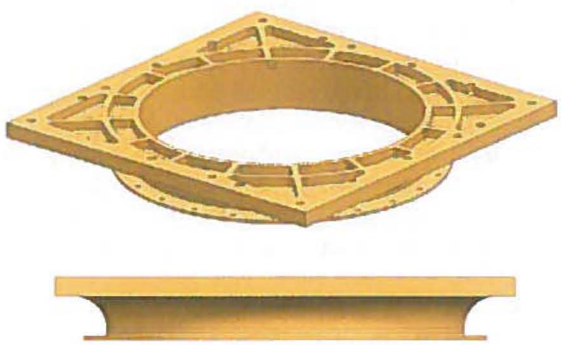

Figure 8: Unibase

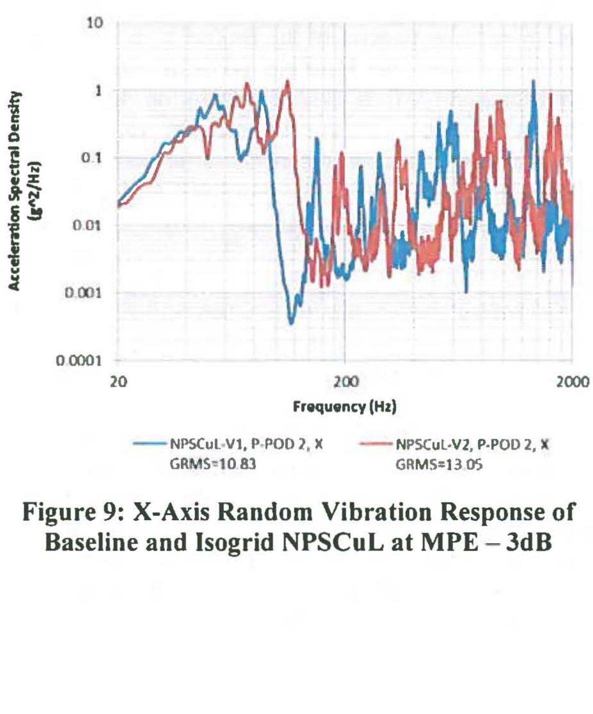

Figure 9: X-Axis Random Vibration Response of Baseline and Isogrid NPSCuL at MPE – 3dB

ISOLATORS ON NPSCUL

Because increasing the stiffness of NPSCuL was not beneficial, isolators were implemented at the ring-to-baseplate joint to reduce the stiffness. Eight COTS isolators were incorporated between the adapter ring and the baseplate; the adapter ring was modified to maintain ESPA compatibility and accommodate the isolators. The modified adapter ring only uses eight of the 24 fasteners on the 15" ESPA standard LV interface, but fastener analysis showed that this is still adequate for positive structural margins. The modified baseline NPSCuL design with isolators is shown in Figure 10.

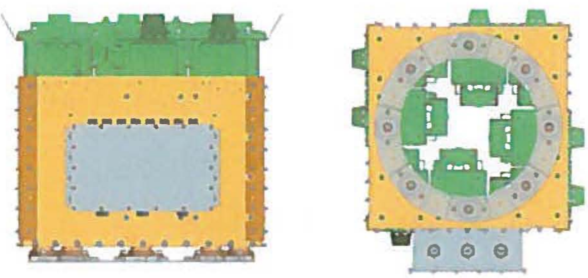

Figure 10: Side and Bottom Views of NPSCuL with Isolators

Isolator Installation Configurations

The LORD low-profile, conical, broad-temperature-range (BTR), silicone isolators (part number AM-009-14) were initially chosen due to their minimal height profile and broad operating temperature range.[6] However, in presenting this design change to ULA, it was discovered that this particular isolator is generally recommended for use in compression only. Since NPSCuL adapter ring is mounted to the ABC plate on the aft end of the Centaur, the isolators will be statically loaded in tension. In applications similar to the ABC where the isolators are not statically loaded in compression, alternative isolators that are fail-safe and all-attitude must be used. Therefore, the work performed with the LORD isolators is presented as proof-of-concept test results.

The LORD COTS isolators were constrained using two different methods. In the first method, shown in Figure 11, the fastener that bolts the supporting unit to the isolator was also threaded into the support member. For NPSCuL, the supported unit is the baseplate, and the supporting member is the adapter ring. This constrained the elastomer in compression, tension, and shear, with little reduction in joint stiffness at each isolator location; however, the overall joint stiffness at this interface is lower than the baseline NPSCuL due to the reduction in both the number of fasteners and the contact surface area between the baseplate and the adapter ring. In the event that an all-attitude isolator cannot be used in a static tension application, this constraint method is a possible alternative if reduced isolation performance is acceptable.

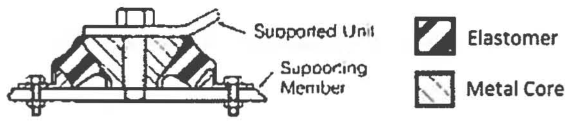

Figure 11: Isolator Installation Method #1 (Constrained)[6]

In the second method, shown in Figure 12, the fastener was not threaded into the supporting member (adapter ring), thus allowing the elastomer to deflect as intended by the vendor. This results in a significant reduction in the overall joint stiffness compared to Method 1. The center of gravity (CG) of NPSCuL is lowered by 0.9" in both methods due to the design change to accommodate the isolators on NPSCuL.

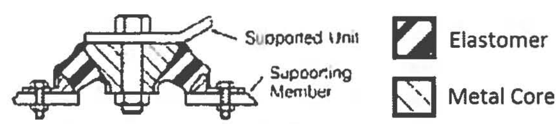

Figure 12: Isolator Installation Method #2 (Typical)[6]

Test Set-Up

The configurations listed in Table 2 were integrated with eight P-POD mass models (P2M2s) and a SAD engineering development unit (EDU), as shown in Figure 13. Isolators were incorporated into both the baseline and isogrid NPSCuL designs for comparison; however, due to the replacement of the unibase with a separated ring and baseplate on the isogrid structure, the isolated responses are very similar between the baseline and modified isogrid NPSCuL designs (Configurations #2 and #4). Additionally, the baseline NPSCuL with isolators resulted in lower P-POD responses; therefore, the results from the isogrid NPSCuL with isolators will not be presented here.

Each configuration was subjected to a fixed-base 0.5 G sine sweep from 20 to 2000 Hz in each orthogonal axis. Random vibration tests were also performed in each axis to the ABC[7] maximum predicted environment (MPE) of 7.6 G_{RMS}; the ASD values for these levels are shown in Table 3. The random vibration tests were performed with and without force-limiting to determine whether or not FLVT is still necessary for the isolated spacecraft.

Table 2: Isolated NPSCuL Test Configurations

Configuration	NPSCuL Structure	Isolator Installation Method
1	Baseline	N/A
2a	Baseline	1
2b	Baseline	2
3	Isogrid	N/A
4a	Isogrid	1
4b	Isogrid	2

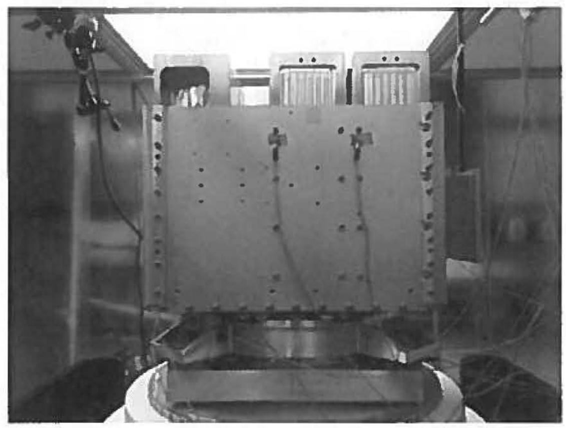

Figure 13: Isolated Baseline NPSCuL Test-Setup

Table 3: ABC Vibration Requirement[7]

Frequency (Hz)	Random Vibration (G^2/Hz)
20	0.03
40	0.125
240	0.125
2000	0.003

NPSCUL DYNAMIC PROPERTIES WITH ISOLATORS

The apparent masses of the isolated NPSCuL, measured during the sine sweeps, were compared to those of the baseline NPSCuL to assess the changes in dynamic properties due to the isolators.

Constrained Configuration Dynamic Properties

The apparent mass plots of Configuration 1 and 2a, shown in Figure 14, indicate that the isolators are not effective in the lateral directions (X and Y) when constrained. The first fundamental frequency in both axes dropped by approximately 15 Hz, but there is no signification reduction in overall amplitude. These changes are attributed to the reduction in overall joint stiffness at the ring-to-baseplate interface, not the properties of the isolators. There is a reduction in both the apparent mass amplitude in the Z-axis and the fundamental frequency, which indicates that there is a reduction in overall joint stiffness and the isolator properties in this direction.

Typical Installation Configuration Dynamic Properties

The apparent mass plots of Configuration 1 and 2b, shown in Figure 14 and Figure 15, indicate that installing the isolators in the vendor-recommended configuration produces results that are typical of a box-like structure on base-mounted isolators. There are two distinct modes in each lateral axis, and there is no amplification of the higher order modes. The apparent masses at the fundamental frequencies are lower in all axes, which indicate a lower response at the P-POD interface.

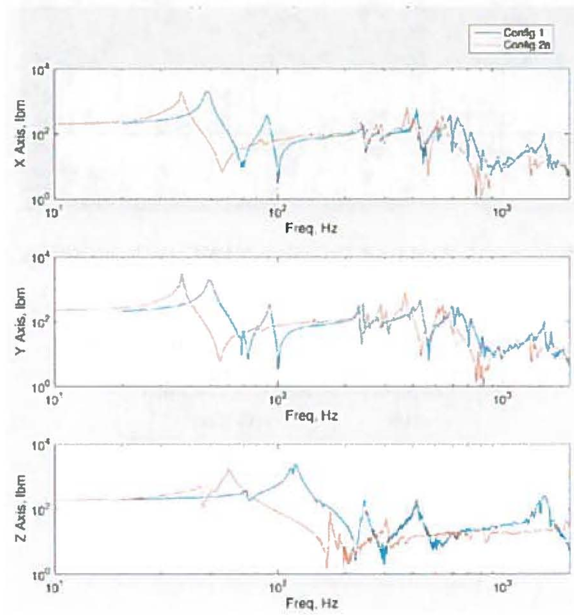

Figure 14: Measured Apparent Mass, Config. 2a

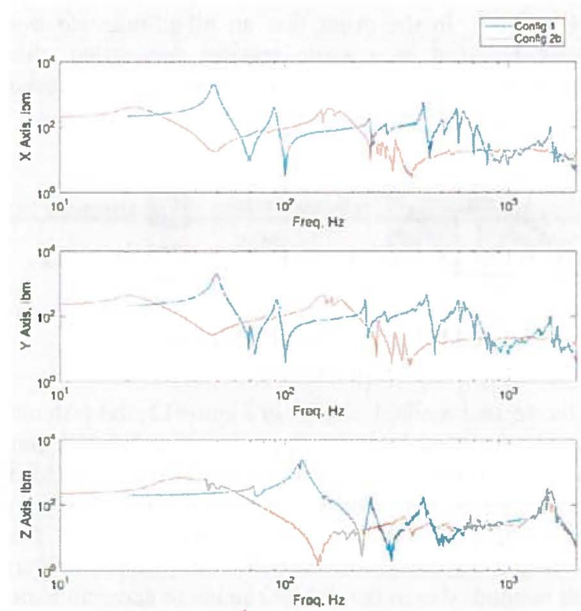

Figure 15: Measured Apparent Mass, Config. 2b

FEM Correlation

The fundamental frequencies of each configuration were also compared to the finite element model (FEM) properties for mode correlation purposes. The baseline NPSCuL FEM, which has been used for loads and strength analyses on the four ABC missions thus far, is shown in Figure 18. It is a thin-shell and beam model, and the P-PODs, SAD, and harness mass properties are represented as concentrated mass elements. The adapter ring and the joint stiffness between the ring and the baseplate were modified to model both isolator configurations.

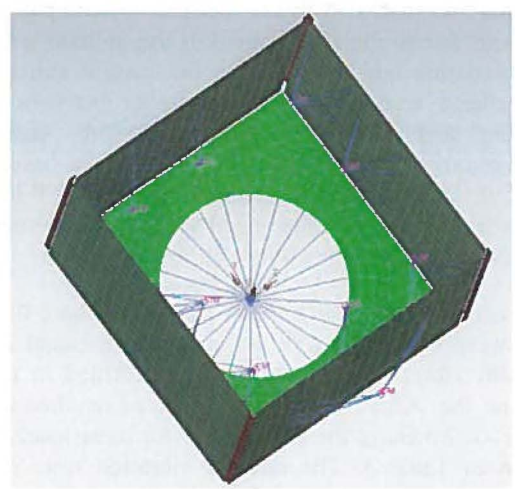

Figure 16: NPSCuL FEM

The fundamental frequencies predicted by the FEM and those measured during test are shown in Table 4 through Table 6. Correlation past 80 Hz was not expected due to the element type and size used in the model; however, this is acceptable for loads and strength analysis for both NPSCuL and the launch vehicle coupled loads analyses (CLAs).

Table 4: Configuration 1 Frequencies

Mode	Description	FEM (Hz)	Test (Hz)
1	Rocking, X	50.5	48.5
2	Rocking, Y	50.9	49.7
3	Axial, Z	90.3	117.0

Table 5: Configuration 2a Frequencies

Mode	Description	FEM (Hz)	Test (Hz)
1	Rocking, Y	37.6	32.2
2	Rocking, X	38.4	37.7
3	Axial, Z	82.4	97.1

Table 6: Configuration 2b Frequencies

Mode	Description	FEM (Hz)	Test (Hz)
1	Rocking, Y	23.7	19.8
2	Rocking, X	24.0	20.4
3	Axial, Z	49.0	56.3
4	Rocking/Bending, X	78.0	77.8
5	Rocking/Bending, Y	79.2	81.5
6	Shear/Rocking, Y	114.7	144.0
7	Shear/Rocking, X	117.8	154.0

RESULTS

Random Vibration Performance Summary

The isolators provide a significant reduction in the P-POD environment on NPSCuL. The overall G_{RMS} is reduced by up to 85%; this results in a qualification test level that is lower than the current acceptance level, as shown in Table 7. The proto-qualification and qualification test levels are projected from the random vibration tests performed with the isolators, in which the ABC MPE was used. The G_{RMS} measured during the Configuration 2a testing showed that the effect of lowering the CG and reducing the joint stiffness only reduces the P-POD vibration environment by 30%; therefore, the majority of the reduction is due to the isolators.

Table 7: Overall X-Axis G_{RMS} Envelope, Isolated NPSCuL (Worst-Case)

Level	Base G_{RMS} (Input)	P-POD Interface G_{RMS}, Config 1	P-POD Interface G_{RMS}, Config 2b
Acceptance (MPE +0dB)	7.6	15.9	6.2
Proto-qual (MPE +3dB)	10.7	22.5	8.8
Qual (MPE +6dB)	15.2	31.8	12.4

The P-POD responses shown in Figure 17 and Figure 18 are consistent with the properties seen in the apparent mass plots; there is not much reduction in the Configuration 2a response, but there is a noticeable reduction in amplitude in the Configuration 2b response.

The high frequency content, defined as above 500 Hz, drops by up to 93%, indicating that the isolators provide relief at frequencies of concern to the CubeSats; the G_{RMS} content in this frequency range is shown in Table 8.

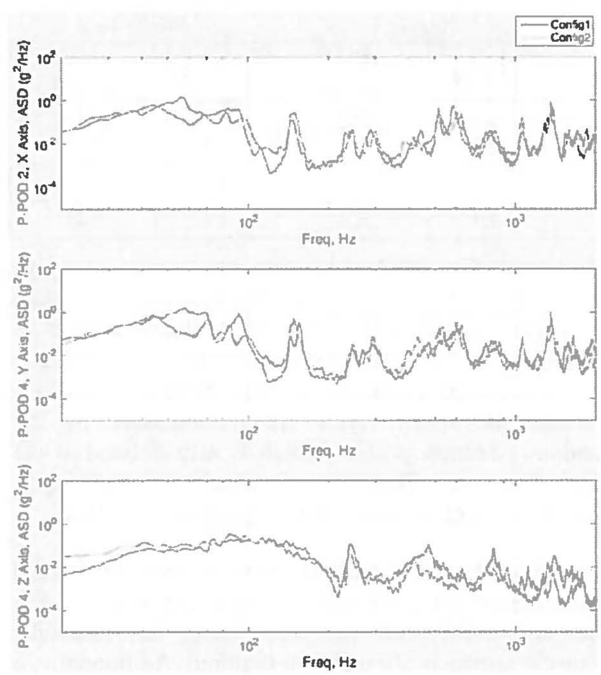

Figure 17: P-POD Response Comparison, Config. 2a

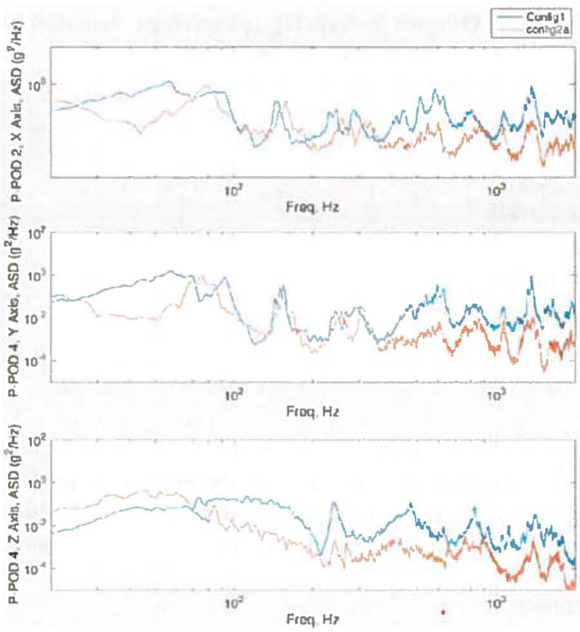

Figure 18: P-POD Response Comparison, Config. 2b

Table 8: High-Frequency G_{RMS} At P-POD Interace, Isolated NPSCuL

Axis	Config 1		Config 2b	
	Overall G_{RMS}	High-Frequency G_{RMS}	Overall G_{RMS}	High-Frequency G_{RMS}
X	15.9	7.7	6.2	0.60
Y	16.7	7.5	5.5	0.49
Z	8.4	2.3	4.4	0.17

The need for shock and acoustic testing was re-evaluated due to the significant reduction in the P-POD vibration environment. The ABC shock profile is defined at the ABC-to-NPSCuL interface[6], and there is a no-shock-test rationale for the NPSCuL missions because the shock levels are encompassed by the random vibration profile, which is also defined at the same interface. There is no change in the input; therefore, shock testing is still not required by ULA.

Similarly, the ABC acoustic analysis was performed assuming the ABC acoustic environment[6] is defined at the ABC-to-NPSCuL interface. Using this rationale, acoustic testing is also still not required. Additionally, a study performed by JPL[8] showed that if the area/mass ratio of an object is less than 150 in^2/lb, the random vibration environment usually encompasses the acoustic profile. The area/mass ratio of an NPSCuL wall with two P-PODs is approximately 8 in^2/lb, which also indicates that acoustic testing is not required. However, this rationale is still under review by ULA.

Combined Effects of FLVT and Isolation

The overall G_{RMS} measured in each axis during the random vibration tests without force limiting is shown in Figure 19, and with force limiting in Figure 20. The isolation system alone is effective in reducing G_{RMS}, but the test conservatism is further reduced using FLVT. The combination of using FLVT and isolators on NPSCuL is necessary to provide relief across the entire test frequency range.

Benefits to the Small Satellite Community

Isolation systems for larger satellites (i.e. greater than 500 lbs) exist, but are often mission specific and are not cost-effective for small spacecraft that are usually auxiliary payloads. Using COTS isolators reduces the cost to less than $2,000 for a system that costs upwards of $200,000 for similar, custom isolation performance.[9,10] The proposed isolation system is not specific to the ESPA interface, and can be easily adapted to different spacecraft interfaces and masses.

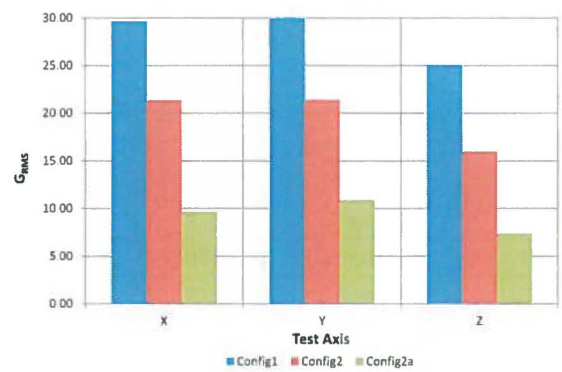

Figure 19: Overall G_{RMS}, ABC Input without FLVT

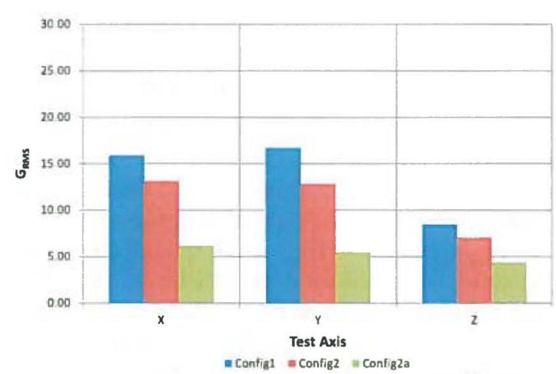

Figure 20: Overall G_{RMS}, ABC Input with FLVT

CONCLUSION AND PATH FORWARD

The combination of incorporating isolators on NPSCuL and implementing FLVT is an effective and low-cost solution for providing a "first class ride" to space for CubeSats and small spacecraft. Although the LORD AM-009-14 is only recommended for use in static compression load cases, it demonstrated the proof of concept. Since many payloads are mounted in tension and shear, a fail-safe and all-attitude COTS isolator (Barry Cupmount NC-1035-T4) with similar dynamic properties as the LORD AM-00-14 has been found and will be tested to demonstrate that this solution is suitable for all static load directions.

Acknowledgements

The authors would like to acknowledge the NRO Office of Space Launch and the CubeSat Program Office for sponsoring this work, and the ULA team for their support and guidance.

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