Update on Improving Launch Vibration Environments for CubeSats

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ABSTRACT

In the CubeSat industry, the demand for benign launch environments that can be predicted is continuously increasing, but the current knowledge of CubeSat environments leaves a lot of CubeSat developers without accurate information regarding the environments that their CubeSats will experience. Due to the severe random vibration environments experienced on launch, the industry has already taken strides to provide isolation systems that significantly reduce these levels. While these systems are very successful at reducing loads, many of them are still difficult to accurately predict for any given random vibration specification. Additionally, the demand for larger, 12U CubeSats has increased, while 12U environments have remained relatively unexplored. NLAS isolated transmissibility is compared to the baseline, and an isolated 12U dispenser transmissibility is explored. Each dispenser modeled and correlated to test data to evaluate the efficacy of analysis for each system. Additionally, methods for predicting environments for a given input specification are reviewed and compared.

INTRODUCTION

In the CubeSat industry, the demand for benign launch environments that can be predicted is continuously increasing, but the current knowledge of CubeSat environments leaves a lot of CubeSat developers without accurate information regarding the environments that their CubeSats will experience. Due to the severe random vibration environments experienced on launch, the industry has already taken strides to provide isolation systems that significantly reduce these levels. While these systems are very successful at reducing loads, many of them are still difficult to accurately predict for any given random vibration specification. Additionally, the demand for larger, 12U CubeSats has increased, while 12U environments have remained relatively unexplored. NLAS isolated transmissibility is compared to the baseline, and an isolated 12U dispenser transmissibility is explored. Each dispenser modeled and correlated to test data to evaluate the efficacy of analysis for each system. Additionally, methods for predicting environments for a given input specification are reviewed and compared.

INTERNAL ISOLATION FOR LOOSE CONSTRAINT RAIL-TYPE DISPENSERS

Cal Poly has applied an internal isolation system to its own Poly-Picosatellite Orbital Deployer (P-POD) with some success shown in “Improving Launch Vibration Environments for CubeSats” from 31st Conference on Small Satellites and “Predicting Transmissibility of Rail-Type CubeSat Deployers with Isolation” from the 68th International Astronautical Congress. The conclusion was that the internal isolation system was very effective at reducing loads to the CubeSat but it was difficult to accurately match an analytical model to the test results, specifically in the higher frequencies due to the non-linearities in the system. In order to extend this capability to 6U rail-type dispensers, the system was implemented to a Tyvak Nanosatellite Systems’ (Tyvak) Nanosatellite Launch Adapter System (NLAS) Mk.II, in order to evaluate the efficacy of the system with the larger, higher mass, 6U form factor. Even with the extra mass, with only minor modifications to the isolation system, similar results
were observed with the system when applied to the 6U application in the Tyvak NLAS Mk. II.

**NLAS Isolated Test Results**

The NLAS was hard-mounted to a test fixture and integrated with a 6U aluminum CubeSat simulator, instrumented with an accelerometer to measure the environment. The NLAS was tested to the standard NASA General Environmental Verification Standard (GEVS) acceptance random vibration levels \(3 (10 \text{ G}_\text{rms})\) in both the isolated and non-isolated configurations for comparison. The isolated 6U NLAS is shown on the Cal Poly shaker table below, in Figure 1.

The results showed significant level reductions for the CubeSat. Isolated test results inside the NLAS are shown below in Figure 2, Figure 3, and Figure 4, showing both baseline and isolated levels. The NLAS has a “free” constraint in the X- and Y- Axes with a fixed constraint in the Z-Axis.

![Figure 1: NLAS with Isolation on Cal Poly Shaker Table](image)

![Figure 2: NLAS X-Axis CubeSat Baseline and Isolated Responses from a 10 G\text{rms} GEVS Input](image)
From a 10 G_{rms} GEVS input, the CubeSat is seeing a range of 3.7-4 G_{rms}, which is a significant reduction in loads. All three axes show significant loads attenuation starting at 80 Hz and persisting throughout the entire frequency range. One high frequency CubeSat mode was observed in the Y-Axis which is unique to the dynamics of the CubeSat simulator and is not an input level to the CubeSat payloads. The isolated 6U NLAS dispenser provided 20%-70% reductions in overall loads in all configurations tested. The next step is to evaluate the efficacy of conventional analytical techniques to model this system in the NLAS, as was done previously with the P-POD.

**NLAS Analysis**

The analysis took an NLAS finite element model (FEM) and integrated it with a concentrated mass to represent the CubeSat simulator. This concentrated
mass was constrained to the NLAS with spring/damper elements to model the isolator material inside the dispenser. A representation of the mesh setup is shown below in Figure 5.

![Figure 5: Concentrated Mass Representation of Integrated NLAS](image)

Isolator frequencies were correlated to test data to match the model with the measured data. The NLAS FEM model showed better correlation to test data than the P-POD. Plots comparing the FEM response to the test response are shown below in Figure 6, Figure 7, and Figure 8.

![Figure 6: NLAS FEM to Test Comparison, X-Axis](image)
In all axes the FEM model shows excellent correlation to the test data, especially at the first mode in the spacecraft response, or isolator frequency, through to 200 Hz. In the higher frequencies, there are some divergences due to the difficulty in predicting the high frequency dynamics of a system that is not fully constrained. Additionally, the CubeSat simulator mode in the Y-Axis at ~1800 Hz shown in the test data is not modeled by the FEM, because the CubeSat simulator is modeled by a concentrated mass.

One interesting observation was that in order to accurately tune the FEM response to match the test data, analysis parameters needed to be adjusted for different input levels and masses. This was also an observation of the P-POD case. Once again, this is a
result of the system containing non-linear elements that cannot be modeled in a modal response simulation. Gaps between the dispenser rails and the CubeSat cause the CubeSat to respond differently based on the displacements caused by the random vibration input. For example, a random vibration profile containing significant energy in the low frequency range will exhibit higher displacements than a profile with high energy in the higher frequency range, even if the overall level is the same. These high displacements cause repeated contact between the CubeSat and the dispenser rail, while high frequency levels, in the extreme case, may not cause any contact at all. Since these interactions are difficult to predict, a simpler, more conservative method could be used in order to provide environments to CubeSats for design purposes.

Transmissibility and Enveloping Transfer Function Synthesis

The proposed method involves taking the transfer function of a variety of different test cases, and taking the maximum transmissibility from each case at each frequency, and using that as a transfer function for a given random vibration test requirement. Transmissibility \( T \) is simply what the CubeSat is actually being subjected to with respect to the input level. This can be described by the simple equation, evaluated at a specific frequency:

\[
T = \frac{PSD_{response}}{PSD_{input}}
\]  

(1)

where \( PSD_{response} \) is the CubeSat level at a given frequency and \( PSD_{input} \) is the random vibration input level at a given frequency, both expressed in \( \text{g}^2/\text{Hz} \). A transfer function is simply the transmissibility over the entire frequency range of interest, which is commonly from 20 Hz to 2000 Hz.

Anytime the transmissibility is less than 1, levels to the CubeSat have been attenuated. Conversely, anytime the transmissibility is greater than 1, there is some amplification to the levels to the CubeSat. Transmissibility greater than one is expected in the low frequency range whenever isolation is applied, because the principal of isolation is introducing a damped, low frequency mode to the system, that facilitates significantly reduced levels across most of the frequency range, resulting in less overall level to the CubeSat.

The goal with enveloping the transmissibility across a variety of different test cases with both different overall levels, and different frequency content, is to evaluate the worst-case transmissibility of the dispenser to the CubeSat, and apply that to a given input specification. The transfer function is applied by multiplying it by the input specification as follows:

\[
PSD_{response,\text{predicted}} = TF_{env} \times PSD_{input \ spec}
\]

(2)

where \( PSD_{response,\text{predicted}} \) is the predicted CubeSat level, \( TF_{env} \) is the enveloping transfer function over the entire frequency range, and \( PSD_{input \ spec} \) is the random vibration input specified by the launch vehicle/integrator. Being as the transfer function is an envelope, including the transmissibility from multiple environments, it is expected that there is a degree of conservatism that provides assurance that the CubeSat will not experience a structural anomaly during testing.

The first example of this utilized test data from both GEVS acceptance random vibration levels as well as Atlas V Aft Bulkhead Carrier (ABC) proto-flight levels. The resulting enveloping transfer function prediction is shown below in Figure 9, compared with test data and the input specification.
There is some overshoot from the prediction, notably in the 50-300 Hz range. The resulting prediction cannot be assumed to be a perfectly accurate prediction that a high fidelity FEM with accurately defined boundary conditions would provide. The benefit of this method is that it is much simpler and faster to implement, requiring only the use of a simple Excel spreadsheet, or similar program. Including additional input profiles to the transfer function specification produces a more robust system of prediction, but may also introduce additional conservatism in the resulting levels. A solution lies in using enveloping profiles with reasonable similarity. For instance, using an input profile with significant low frequency levels to predict for an environment with benign low frequency levels would be counterproductive to this effort. The higher displacement loading caused by the low frequency levels will produce some high transmissibility across certain frequency ranges that are not a realistic expectation with an input specification that lacks these high displacements.

The internal isolation system provided by the 6U Dispenser was successful at reducing environments experienced by the CubeSat, but some of the inherent non-linear elements with rail-type dispensers prevent the system from being perfectly predictable. FEMs can be correlated to test data with specific tuning for each case, but a robust FEM that can predict environments for any input spec and any CubeSat configuration is still currently out of reach. However, synthesizing a transfer function based on test levels from a variety of input specs is a simple way to predict the environment in the isolated 6U NLAS without requiring the use of complex analytical tools. This tool is ideal for CubeSat programs where funds are limited, and full FEMs are not attainable. The next step in providing benign launch environments to as many CubeSats as possible includes expanding this isolation capability to the 12U form factor.

12U INTERNAL ISOLATION

There was an initial thought to apply Cal Poly’s rail isolation model to the 12U, but because of the dramatic increase in mass, the constrained layer design was simply not practical. Fortunately, another 12U dispenser with internal isolation exists, also made by Tyvak, but this dispenser applies the isolation in a different way.

**Tyvak 12U Dispenser**

The Tyvak 12U dispenser, instead of utilizing a constrained layer of isolator material within the rail, uses a mechanism to cradle the CubeSat without any gaps, and then isolate the entire assembly. A representation of the isolation system is shown below in Figure 10.
This system provides the same advantages as the system on the NLAS and the P-POD, as well as being classified as a rail-type dispenser, but it also removes the gap between the CubeSat and the dispenser. Removing this non-linear element from the system should, theoretically, make high fidelity accurate FEMs more simple to create. This system was also tested to the same levels of the 6U NLAS. The 12U dispenser was hardmounted on its base plate to the shaker table. The 12U dispenser is shown on the Cal Poly shake table below, in Error! Reference source not found.. The resulting CubeSat responses are shown, in red, below in Figure 12 and Figure 13.
The X/Y-Axis levels are the same as the dispenser is symmetrical in these axes. The 12U dispenser exhibited large reductions, bringing overall level down to 1.1 G rms and 1.5 G rms from a 10 G rms input level in the X/Y-Axis and Z-Axis, respectively. This is accomplished by providing a lower isolator mode, which results in the majority of the frequency range being attenuated to a benign level. The Tyvak 12U dispenser reduced overall levels by between 77% and 93% in all cases. It is clear that this system is extremely effective at knocking down CubeSat loads, but the next step is to evaluate the ability to predict CubeSat environments using finite element methods and the transfer function method previously described in the 6U section.

**Tyvak 12U Analysis**

The Tyvak 12U dispenser was modeled in the same way as the isolated 6U NLAS. The model consisted of the dispenser FEM, with a concentrated mass constrained to the four corners with spring/damper elements. Isolator frequencies were correlated to test data to match the model with the measured data. The 12U FEM model needed minimal tuning across different configuration, showing that the constraint is more predictable. Similar to the 6U, the high frequency dynamics did not correlate as well due to the use of a concentrated mass to represent the CubeSat simulator. Plots comparing the FEM response to the test response are shown below in Figure 14 and Figure 15.
Correlation to test data is excellent from 20 Hz to 800 Hz in the X/Y-Axis and 20 Hz to 300 Hz in the Z-Axis. At higher frequencies, the same divergence is present, similar to the 6U NLAS analysis.

The result of the minimal tuning required for the 12U dispenser FEM is that analytical predictions for untested random vibration specifications will provide higher accuracy levels for CubeSat developers. Any developer that has a full FEM of their CubeSat could be integrated into the dispenser FEM to run a full system level analysis to determine the loads on each component. Future work would include demonstrating this capability in order to determine the degree of accuracy of the 12U isolation FEM. Alternatively, the same transfer function envelope mention described in the 6U section also applies to the 12U dispenser.

**Tyvak 12U Enveloping Transfer Function Synthesis**

Transfer functions for the 12U were determined in the same way as the 6U, with test data from both NASA GEVS and the Atlas V ABC levels. The resulting enveloping transfer function prediction is shown below in Figure 16, compared with test data and the input specification.
Once again the enveloping transfer function exhibits a small degree of conservatism, but still provides a realistic prediction for CubeSat developers. In the absence of high fidelity FEMs, this method can be used to estimate CubeSat loads without the added complexity of creating the associated FEMs. This is particularly useful for programs that do not have the resources to produce such models. Similar to the 6U dispenser, this enveloping transfer function can be made more robust by including transfer functions from additional input profiles.

The internal isolation system provided by the Tyvak 12U Dispenser improved upon the success of the 6U internal isolation implementation at reducing environments experienced by the CubeSat. Additionally, the primary non-linear element of typical rail-type dispensers, the interface gaps, was removed. FEMs can be correlated to test data with only minimal tuning, making the FEM, theoretically, more accurate at predicting loads for a given input specification. Synthesizing a transfer function based on test levels from a variety of input specs is a simple way to predict the environment in the isolated Tyvak 12U dispenser, as it was for the 6U NLAS. It follows that this transfer function method could theoretically be used with any CubeSat dispenser.

CONCLUSION

Launch environments for CubeSats have traditionally been severe, and developers have had to prepare for the worst. As CubeSat have become more complex and are conducting high profile science and commercial missions, it follows that mission assurance be an important factor in any CubeSat program. There are now multiple avenues to implement isolation, including mounting CubeSat dispensers on isolators such as Moog’s ShockWave™ isolator, or using a dispenser with isolation integrated into the dispenser’s payload constraint. Certain CubeSat programs are only interested in dramatically reduced levels, and do not plan to do complex analysis or create spacecraft FEMs. For these customers, the use of an enveloping transfer function created for the respective CubeSat dispenser that they are flying with is a simple way to determine realistic levels that the CubeSat will experience.

CubeSat programs that require the highest degree of accuracy may elect to generate a high fidelity FEM of the spacecraft. This spacecraft model can be integrated into the FEM of the CubeSat dispenser for a system level analysis to determine the accurate response of the CubeSat and all of its components. For any given input specification, it may be beneficial to conduct a characterization test to tune the dispenser model to the appropriate level. This is especially true of the 6U NLAS, but is not as much of a concern for the Tyvak 12U dispenser based on the analysis previously conducted.

The FEM method is the most accurate, but also the most resource intensive. The transfer function method is a good compromise of accuracy and resources required, and provides a much more realistic design load compared to the loads that many CubeSats are using. This method is more feasible for some CubeSat programs, which expands access to predictable launch loads to additional developers.

References