Testing using Combined Environments to Reduce Payload Mass, Cost and Mission Risk

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ABSTRACT

In today's space industry, exhaustive environmental testing is performed on payloads prior to flight to ensure that the payload can withstand the harsh environment, which it will be subjected to during launch. Some of these tests include acceleration, shock, and random vibration testing. The problem with current test methods is that a rocket launch includes a combination of acceleration, shock, and random vibration, while testing currently performed on payloads can only replicate one type of these environments at a time. By developing a capability to integrate shock, random vibration, and acceleration testing using a state-of-the-art centrifuge, it is possible to test for synergistic effects of these combined environments. A test setup has been developed, which includes a centrifuge with a modal exciter and test pod installed on its gondola. This setup will provide the capability to test payloads using both sustained and dynamic g-loads as well as simultaneous vibration loads in two independent axes. With combined environment testing, it will be possible to create a much more realistic launch environment, which will lower the overall maximum forces the payload will be subjected to. This has the potential to reduce the overall cost of a payload. The test setup and data acquisition system is described in detail, and test results is given.

INTRODUCTION

During ascent, launch vehicle systems and the spacecraft they transport experience simultaneous acceleration and vibration loads. However, today's mechanical design and launch qualification process calls for a series of discrete tests that apply individual load components separately. Therefore, if structural responses are affected by combined environments, then current methods for qualifying systems for launch cannot test these effects. A team led by American Aerospace Advisors, Inc (AAAI), including the NASTAR® Center and Drexel University, was awarded a NASA STTR (Small Business Technology Transfer) Phase I contract for "Integrated Vibration and Acceleration Testing to Reduce Payload Mass, Cost and Mission Risk". The goal of the research is to develop the capability to provide integrated acceleration, vibration, and shock testing using a state-of-the-art centrifuge (Phoenix Centrifuge) at the NASTAR Center, in order to subject payloads to the synergistic effects of combined environments. By providing more realistic load profiles, combined environment testing has the potential to significantly reduce payload and launch vehicle subsystem mass, test cost, and mission risk. Accordingly, the team proposed an environment test method that will substantially improve the quality of the load profiles used to qualify payloads for launch via a more streamlined process of performing load analysis by combining acceleration and vibration tests in a single combined environment test. The payload will respond differently when subjected to a sustained acceleration load and vibration loads at the same time, but cannot be tested with current test systems. By testing the payload in a more realistic environment, the overall project risk will be reduced.

Furthermore, today's launch qualification process is extremely expensive and time consuming. It combines sequential, discrete testing of individual load components with iterative analyses, applied first at the component level, then at the subsystem level and finally at the system level. Current methods are also vulnerable to unpredictable schedule slips. Since testing generally occurs later in programs, these schedule slips tend to be expensive, disruptive and difficult to manage. Therefore, a methodology utilizing combined environments simulation and test in combination with or instead of today's sequential process may lead to accelerated qualification schedules, lower baseline testing costs and reduced risk of schedule delays. Earlier efforts to utilize centrifuges for flight qualification included the Space Shuttle Hubble Space Telescope Servicing Mission where payload up-mass limitations created a need for additional testing using a centrifuge to reduce weight and qualify the lightened structure for flight. By testing in this way, NASA was able to substantially reduce the overall mass of the payload aboard the Space Shuttle. In addition, being able to more closely simulate the launch environment will result in reduction of required safety margins. Together with schedule and risk reduction, the reduction in requirements will translate into major cost savings. For launch vehicles, this may lead to a higher mass fraction of vehicle lift being available for payloads, increasing performance. For spacecraft, reduced mass enables a higher mass allocation to be assigned to other system elements, or, alternatively, provides for a reduced mass requirement at a given performance level, potentially reducing launch costs and increasing the number of launch opportunities available.

METHOD OF SOLUTION

The proposed solution for more closely simulating the launch environment is to test the payload onboard a centrifuge, making it possible to apply both axial acceleration loads and vibration loads simultaneously. This is depicted in Figures 1 through 3. By installing the vibration actuator inside the centrifuge, an axial acceleration can be applied to the test subject at the same time the vibration excitation is applied. This method has been used in the past including an extensive work done by Sandia National Laboratory.

Figure 1: NASTAR Center centrifuge.

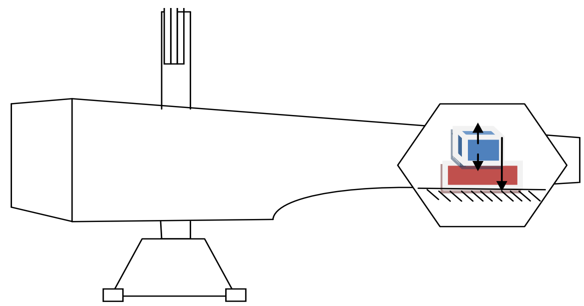

Figure 2: Depiction of internal setup for the combined-environment testing.

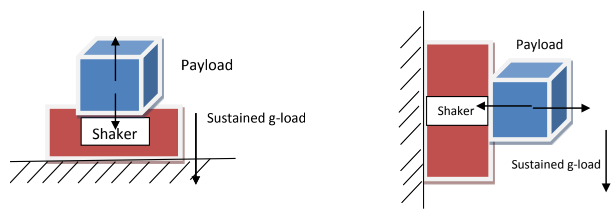

Figure 3: Variation in configuration where the payload is mounted along and perpendicular to the axial acceleration loads.

One of the main challenges in performing combined loads tests is overcoming the limitations of the equipment. The centrifuge itself has advanced in recent years to a point where the acceleration profile of a launch vehicle can be very closely simulated. As an example, the NASTAR Center's Authentic Tactical Flight Simulator-400 (ATFS-400) can provide the required high acceleration environments. It is a state-of-the-art, high performance human-rated centrifuge with a 544 Kg (1,200 lbs.) payload capacity. The ATFS-400 can deliver accelerations at up to 12 +/- 0.05 G; it has a control response time of < 100 milliseconds and high onset/offset rate capabilities (+ 8G/sec); and the cockpit module can rotate + 360 degrees in both pitch and roll. However, the shaker that is installed into a centrifuge to provide vibration loads is not adequate to operate in the increased acceleration environment. Traditional vibration tables use electromagnetic actuators where the force inducing element is actuated using magnetic field generating coils. If the acceleration is applied off-axis to the vibration load, for example perpendicular to the vibration load, the actuating element in the center is pushed towards the side of the electromagnetic assembly, resulting in shorting of the elements. This means that the increased acceleration loads must be aligned with the vibration table's direction of actuation, preventing possibility of mounting the vibration table horizontally. The only acceptable payload mounting configuration then is to affix the satellite directly on top of the shaker, without the sliding-table mechanism. Another main issue of operating a traditional shaker in this environment is that under an increased acceleration loads in the axial direction (direction of the vibration load), the center force inducing element and the payload grow heavier, reducing the overall capability of the shaker. This reduces the payload mass to a point where a massive shaker is required to test even a small payload.

One solution to this issue is to use a shaker that is driven by piezoelectric mechanism. In this design, the actuating element is fully resting on the piezoelectric exciters. This design has an advantage when applying acceleration loads in an off-axis direction. Since the actuating element is not "floating", there is no re/contact issue and the piezoelectric exciters can fully support the center actuating element. Another key advantage is that the design can generate large forces at high frequencies such that the increase in acceleration does not reduce its capability. The major drawback of this system, however, is the limitations in maximum displacement that it can generate. At lower frequencies, the vibration table must be able to generate larger displacements for a given vibration force requirements. However, since the piezoelectric material can expand only a small amount, the piezoelectric vibration system often cannot meet the required loading conditions at lower frequencies.

In order to overcome these challenges, new designs for the payload fixture have been developed and tested. The proposed design utilizes the traditional off-the-shelf vibration tables, but alleviates the effects of increased acceleration loads such that the payload mass does not drastically decrease even at high G loading conditions. In addition, one of the fixtures was designed so that the vibration loads can be applied perpendicular to the motion of the actuating element so that a two-axis loading tests can be performed. The project expands on the original design and employs extensive modeling and simulation, a larger (electro-magnetic) shaker, a CubeSat-class satellite model, increased instrumentation (~10 accelerometers), and features a series of combined environments tests with multi-axis loads.

TECHNICAL OBJECTIVES AND CHALLENGES

There were two main technical objectives for this research. The first is to characterize the effect of a combined loading on a payload. When a payload is subjected to a combined acceleration and vibration loads, the frequency response will change from that of on-the-ground tests. This means that the payload response during an actual launch cannot be exactly modeled by the traditional vibration test procedures. The objective was to show this difference in response, and characterize the trend.

The second technical objective of the research is to design, develop, and test the proposed setup in order to demonstrate the feasibility of combined loads testing. The key challenge in realizing this capability is in engineering a setup that will allow the payload to be tested using conventional shakers. Most of the commercially available shaker uses electromagnetic actuation where the center actuating element is driven by the surrounding coils that generate magnetic fields. This type of equipment is well tested and widely used in the past for vibration testing purposes. However, when operated in a high-G environment, these shakers have two major drawbacks. One issue is the increased weight of the payload when subjected to a higher acceleration. Although the mass of the payload remains the same, the weight force experienced by the shaker increases as the G-load increases, drastically limiting the maximum allowable payload size. A second issue comes from the fact that these shakers are not designed to withstand any substantial lateral acceleration. In order to apply non-parallel vibration and acceleration loads to the payload, the simplest solution would be to tilt the shaker in respect to the acceleration axis. However, this causes the actuating element within the shaker to be forced close to the surrounding coil, resulting in a short when a sufficient acceleration causes the components to touch. This limits the mounting orientation of the shaker to be aligned to the G-load direction.

A special fixture was designed and tested to overcome these issues, and is described in detail below. A 1U CubeSat (the Drexel University DragonSat-1) was selected as the Device Under Test (DUT). Modeling and simulation of the DUT was performed using frequency analyses and random vibration simulations. To validate the simulations through test, a system was developed to deliver simultaneous acceleration and vibration loads to the satellite utilizing a state-of-the-art centrifuge. By integrating an electromagnetic shaker with the centrifuge (shown in Figures 1 and 2), the test setup provides simultaneous, sustained G and vibration loads in two independent axes.

FIXTURE DEVELOPMENT

Accordingly, two Test Fixtures were designed and fabricated for the test. One fixture was required for cases in which the vibration loads and sustained accelerations are aligned. One of the innovations of this project was the inclusion of a counterbalance system in order to most efficiently deliver the vibration loads to the DUT under sustained G loads. Without a counterweight, the DUT and armature are supported by the centering spring of the shaker. This biases the spring load such that the upward force from the coil has to overcome the G loads before the armature moves. Therefore when the armature moves downward (outward), the coil movement may be limited by the maximum travel of the armature.

A second test fixture was employed to transmit vibration loads transverse to the sustained accelerations. With no vibration forces, the centering springs in the shaker experience no load from the armature since the armature mass is part of the counter-weight. Therefore, the shaker forces can be used entirely to vibrate the armature, counter-weight, test fixture, and the satellite. This approach maximizes the effectiveness of the shaker in the high acceleration environment. Figure 4 shows a depiction of the principle behind both of these designs.

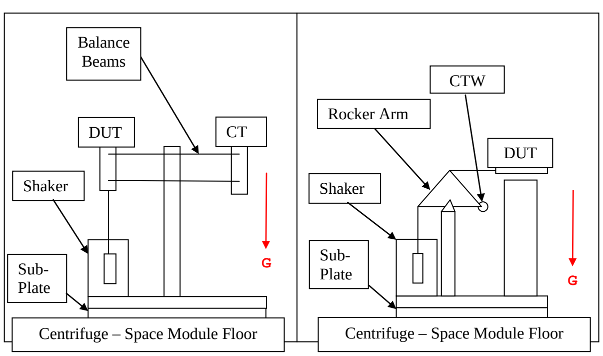

Figure 4: Parallel Fixture (left), Transverse Fixture (right). Red arrow shows direction of G load.

3.1 Parallel Fixture:

We had to find a method to separate the vibration loads from the centrifuge loads. If we constructed a balance with a mass nearly equal to the DUT on both sides of the balance point, the G-loads would balance each other and the vibrator would have to move only the moving mass independently of any G-loads. With a laboratory balance, a single beam and the weighing pans are held in place with gravity. Since we needed to vibrate the balance, a second beam was added to make a four-bar linkage. This allowed us to take all backlash out of the linkage. The moving parts then became greater than twice the DUT. Accordingly, Drexel redesigned the satellite holder and the pan (post) sections of the balance were changed to aluminum to reduce mass. Even with these changes, we reduced the frequency range to keep the loading within the limits of the vibrator.

3.2 Transverse Fixture:

We also wanted to vibrate the DUT in an axis transverse to the G-load axis. We could not rotate the vibrator's axis since it may short-circuit with that axis perpendicular to the centrifuge's axis. This required another fixture with a rocker-arm attached to the vibrator using a "stinger" and a perpendicular "stinger" attached to the DUT holder. The DUT holder was also on rail bearings to allow free motion in the vibration axis and no motion in the G-load axis. Additionally, the rocker arm was counter-balanced so that the vibrator would not have to overcome the G-loading on its armature. Figure 5 shows the actual fixture.

Figure 5: Transverse mode test fixture. Cylinder on the left is the shaker, and the square box on the right is the payload (CubeSat test pod)

4. TEST SETUP

When the NASTAR group reviewed the fixture designs, several additional needs surfaced to avoid any compromise with the existing centrifuge design or its future capabilities. First, the fixtures must be vibration isolated from the gondola to avoid imputing vibration into the structure. Second, the signal amplifier would have to be mounted inside the gondola on the fixture framing. And, third, the power to the vibrator, amplifier, and cooling vacuum had to be converted from 208V/3Ø to 110V/1Ø.

To accommodate these changes, the fixtures were split apart and recombined as a base fixture which would hold the vibrator, amplifier, and vacuum cooler; a parallel fixture sub-plate; and a transverse fixture sub-plate. The two sub-plates would bolt directly to the base. Although the base-plate area was fixed, by cantilevering supports off one end, there was space to mount the amplifier and vacuum cooler. The vibrator mounting at the front end of the plate was not changed. The change also decreased to total mass of the weldments making them easier to install in the gondola. The base plate was isolated from the gondola frame by elastomer pads under each bolt (6) with elastomer flanged sleeves and washers allowing the base to move separately from the gondola frame, yet restrained in place by the 6 bolts.

The base plate was stiffened by adding a series of channels to a 3/8" steel plate. The thickening of the base allowed the sub-plates to be shortened by a few inches which increased the resonant frequencies considerably. There was no need to remodel the revised fixtures.

Fabrication drawings could now be completed and sent out for bids. Local fabrications shop provided an acceptable bid and the fixtures were delivered to AAAI within 3 weeks and within budget.

The entire test system was assembled and its operations verified at American Aerospace Advisors, Inc., prior to transport to the NASTAR Center for centrifuge integration. The parallel and transverse Test Fixtures were first assembled during the week of October 8th. The DragonSat-1 was completed and it was installed in the Test Pod, which was then secured to the mounting plate. The system was completed by connecting the Modal Shop 2100E11 electro-dynamic shaker, the 2100E18 power amplifier, the Lab Works VL-144X Vibe Lab Pro Controller, the OROS OR35 real-time multi-analyzer, the accelerometers, and the host PC.

The test system was transported to the NASTAR Center on October 24, 2012 and integration with the Space Module was initiated. First, the common sub-plate for the Test Fixtures was secured to the floor of the Space Module, and vibration isolation pads were used to physically separate the sub-plate from the gondola floor. Physical integration with the Space Module was completed by installing the parallel Test Fixture, the DUT, shaker, accelerometers, power amplifier, and the blower, and securing each component for the high G environments to come. After reviewing the power requirements for the amplifier and the blower, a transformer was installed in the Space Module for risk mitigation to ensure that no circuits would be overloaded during the test.

The test system was completed by connecting the Lab Works controller, the real-time multi-analyzer, accelerometers, and the host PC. Multiple bench tests were then repeated in the Space Module integration lab adjacent to the centrifuge chamber in order to verify that the vibration loads and measured structural responses were consistent with the results previously acquired at AAAI. Figure 6 shows the DUT and parallel test fixture installed in the Space Module, and Figure 7 shows a close up view of the installed DUT.

Figure 6: Parallel test fixture and DUT installed in the NASTAR Space Module.

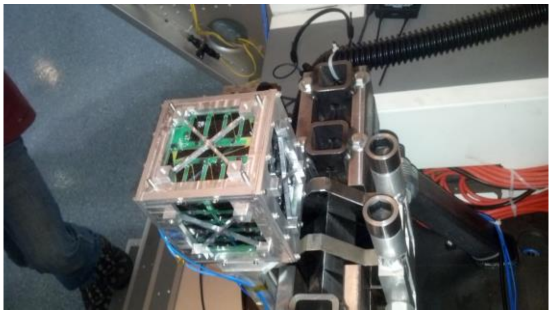

Figure 7: Close up of DUT installed on the parallel test fixture in Space Module.

Finally the Space Module was attached to the arm of the ATFS-400 centrifuge in the NASTAR Center's test bay. Signal communication between the Space Capsule and the Control Room was achieved using eight (8) circuits of 75-Ohm coaxial cables with BNC connectors. The signals passed through slip rings in the centrifuge hub. Cable runs were approximately 33 meters (100 feet) long. One circuit was dedicated to an onboard camera to maintain visual coverage of the Test Fixtures and DUT during the high G runs.

The force transducer and accelerometer leads were then connected to the BNC connections in the Space Module. Finally, the Space Module was spun to 3 and 5 Gs, and the functionality of the integrated system was verified under sustained accelerations, prior to conducting the actual test the following day.

The test used a Modal Shop 2100E11 electro-dynamic shaker. This model is capable of providing 100 lb. (440 N) of peak force excitation in a small footprint, weighing 33 pounds (15 kg). It delivers a maximum 1" stroke for solid low frequency performance and has a useful high frequency range beyond 5400 Hz.

The shaker power amplifier was a Modal Shop 2100E18 model. The amplifier was installed in the Space Module on an AAAI developed baseplate assembly.

The Combined Environments test employed a Lab Works VL-144X Vibe Lab Pro Controller, and a data acquisition system. The controller subsystem consisted of software run on a computer with a custom PCI card installed. This allows two accelerometers to be installed on the test fixture at the base, which measured the input vibrations and sent feedback to the controller to ensure that the actual vibration input from the shaker was the desired vibration input.

The data acquisition subsystem consisted of one (1) three-axis accelerometer with built-in low pass filter mounted inside the CubeSat, and one (1) single axis accelerometer mounted externally on a solar panel. In addition, one (1) single axis accelerometer was mounted on the base of the DUT. The five (5) channels from the data acquisition accelerometers were connected to an OROS OR35 real-time multi-analyzer, which was connected to the PC and recorded the data, as indicated in Figure 8.

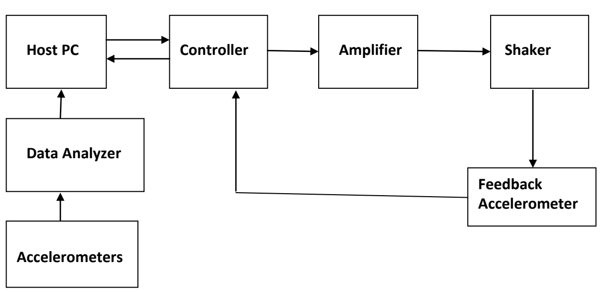

Figure 8: Closed loop connections between the PC, Controller, Amplifier, Shaker and Force Transducer.

It is important to note that the feedback accelerometer was installed at the base plate where the payload is mounted on, not at the actuating point near the shaker. This is done because what is important is the vibration loads being applied to the payload itself, not the output of the shaker. Because fixture mechanisms are placed between the shaker and the payload, the output from the shaker table does not exactly duplicate the desired input into the payload. Accordingly, placing the feedback accelerometer at the point of vibration loading (near payload) ensures that all the masses, friction, and other dynamics of the fixture is taken into account, where the shaker will generate whatever frequency and force necessary to drive the payload at the desired vibration output.

Four (4) accelerometers (with a total of 6 channels) were used in the Combined Environments test. The instruments consisted of one (1) three-axis accelerometer with built-in low pass filter (PN 356A63) and three (3) single axis accelerometers (PN 352C65). All of the accelerometers were adhesive types, and were fixed to the test assembly using Petro wax and Kapton tape.

The PN 356A63 three-axis accelerometer was chosen for two reasons. First, three axis acceleration measurements were required inside DragonSat-1 in order to fully understand the satellite's response to the excitations. Due to volumetric constraints, multiple single axes accelerometers were not an option. This led to the decision to implement a three-axis accelerometer in one central location inside the CubeSat. This specific model was also chosen due to the fact that it has a built-in low pass filter, eliminating the need for external analog filters on those channels. Also, the built-in low pass filter mitigated the possibility of inaccurate data due to crystal resonance inside the accelerometer. With a measurement range of ±500G peak from 2 to 4000Hz, this accelerometer was more than capable of making the required measurements accurately, while keeping any phasing effects to a minimum.

The single axis accelerometers were chosen because of their high sensitivity. With a sensitivity of 100mV/G, they provided high resolution data and could be used in multiple locations. One single axis accelerometer was used to measure the response of the front panel of the DUT. This provided data on the response of the front panel of the satellite due to combined environment testing. Single axis accelerometers were also mounted on the test fixture in two locations. One was placed at the base of the DUT to measure the input vibrations and a second was mounted adjacent to the stinger connection on the Test Fixtures, providing feedback to the control system.

Frequency analysis simulations aided the decisions as to where to mount the accelerometers for the test phase.

The three-axis accelerometer was mounted on the bottom center of the custom printed circuit board, which was located approximately in the center of the CubeSat. This accelerometer measured the response of the circuit board as a result of an input vibration excitation as well as combined environments. Figure 9 shows the location of this accelerometer within the CubeSat. The DUT was subjected to seven (7) combined environment profiles with the parallel mode installation and sixteen (16) profiles utilizing the transverse test fixture.

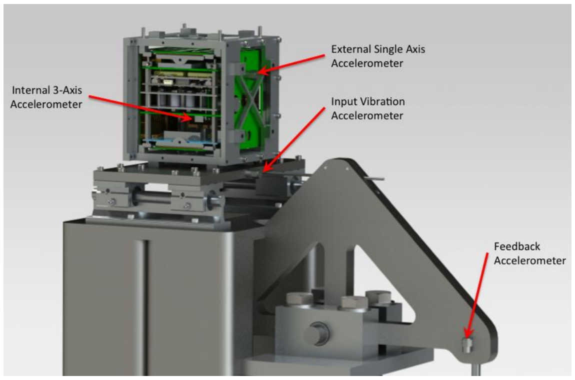

Figure 9: Internal 3-Axis Accelerometer and Single Axis Accelerometer Locations on Transverse Test Fixture.

The test began with the parallel test fixture installation, and the DUT was accelerated to 3 and 5 Gs. At each elevated G condition, the DUT was subjected to a low-level sine sweep profile in order to characterize the resonance characteristics. The sine sweep profile extended from 20 to 400 Hz at 0.2 G level. Then, the sine sweeps were repeated in order to acquire measurements to assess data consistency/repeatability. In addition, sine sweeps were performed with the centrifuge at idle condition (1.4 Gs) in order to establish tare measurements. The peak magnitude of the low level sweeps was also 0.2 Gs. These profiles were repeated after each high G run in order to verify that the installation was not compromised.

After these cases were completed, the parallel test fixture was removed from the Space Module and replaced with the transverse test fixture. In this mode, vibration loads were transmitted perpendicular to the sustained acceleration vector. As indicated in Table 3, the sustained acceleration levels during this portion of the test were 3, 5, 7, and 9 Gs. At each G level, two low-level sine sweeps were performed, followed by a random vibration.

Due to the limitations of the Test Fixtures, the spectral density of the random vibration profile was reduced, as shown in Figure 10. While maintaining the same slope of GSFC-Std-7000, the actual test levels were decreased. This does not impact the results obtained because the objective of the test was to evaluate the frequency response, which was achieved with the reduced-level testing.

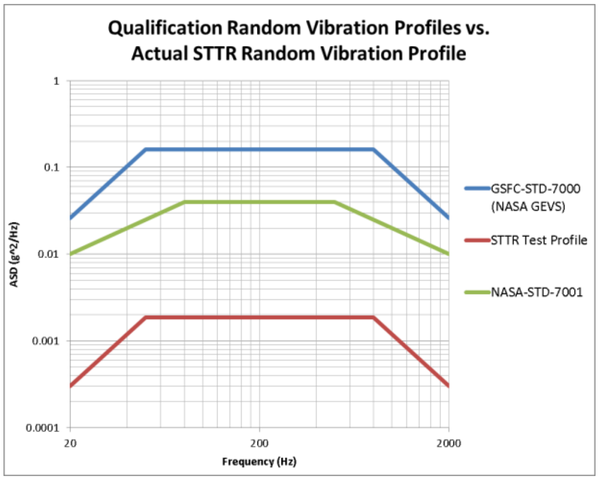

Figure 10: Random vibration test profiles.

As was the case with the parallel testing, low-level sine sweeps were performed before and after each high G test to determine whether the test system characteristics had been altered.

5. RESULTS AND DISCUSSION

Two phases of testing were conducted. The first test consists of performing mission profile tests on the ground, before the vibration testing setup was integrated into the centrifuge. This was done to verify and ensure that the fixture functions as designed and the desired vibration input can be transferred to the payload. The second set of tests consisted of a full combined loading testing. The fixtures were integrated into the gondola alternatively, as described above, then tested to verify that the proposed designs can provide both parallel-axis and perpendicular-axis vibration excitation while being subjected to high-G loading conditions.

Extensive bench tests were then performed in the 1G environment to verify that the desired vibration loads were delivered through the Test Fixtures to the DUT, and that the data acquisition system was recording the structural responses. This 1G verification of the test system was an essential prerequisite to testing in the high acceleration environment. Upon a successful set of tests on the ground for both Parallel and Transverse fixtures, they were mounted on the gondola, and were tested together with the centrifuge. Figure 11 shows a picture of the system mounted on the gondola.

Figure 11: Picture of the test fixture installed onto the centrifuge, including the DUT (CubeSat satellite)

A series of tests were performed to verify the functionality of the fixtures. An accelerometer was placed on the base plate where the DUT is mounted that measured the input vibration into the DUT from the shaker. Figure 12 shows the collected test data for the Transverse fixture and Figure 13 shows the data obtained from repeated test runs from the Parallel fixture. For all the test runs, a sine sweep was performed from 20 Hz to 400 Hz, at 0.2 G level.

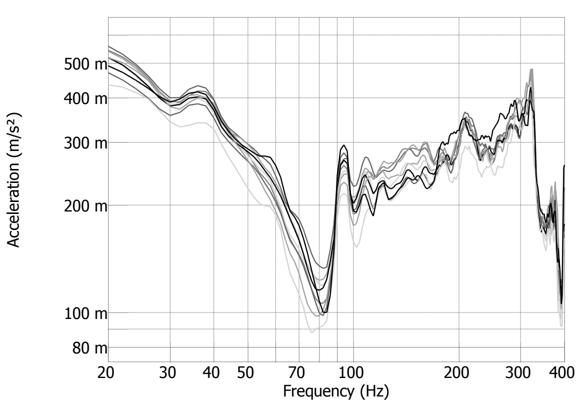

FIGURE 12: VIBRATION INPUT INTO THE DUT FOR THE TRANSVERSE FIXTURE.

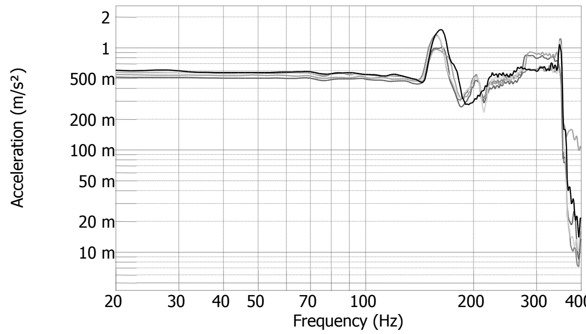

FIGURE 13: VIBRATION INPUT INTO THE DUT FOR THE PARALLEL FIXTURE.

As can be seen from Figures 12 and 13, the input signal is consistent and repeatable, indicating that the fixture is functioning correctly as designed, successfully implementing the counterbalance system, as well as the mechanism that redirects the vibration excitation. The sharp drop shown is from a resonance in the fixture at the locations of the knife-edge assembly. Some audible vibration was noticed towards the cutoff freuqency of 400 Hz, and some wear can be seen in the assembly when the fixtures were taken apart for inspection after the testing was conducted. The mechanism can be improved in the future to eliminate any de-contact issues.

The data shown in Figures 14 and 15 are from multiple test runs conducted throughout the overall system testing. Accordingly, the data consists of measurements before and after each high-G testing of the fixture. From the consistency of the data, it also verifies that higher G loading conditions do not negatively affect the structural integrity of the fixtures.

Figure 16 shows that a component on the satellite payload has shifted during testing. This is a very interesting result due to the fact that the shifting of the side panel was not displayed during repeated ground shake tests. Throughout the multiple on-ground characterization shake tests, no changes in the frequency response were noted. However, when combined with a constant acceleration load, the physical changes in the satellite were identified. This is significant because it provides an excellent example of how the current on-ground testing does not accurately capture the response of the payload during the actual launch environment (combined-loading environment).

Figure 17 shows the change in the response frequency of the payload when subjected to combined loads. “Idle condition” lines show sine sweep response before and after the high G loading. The plot shows that the response frequencies match, indicating that there was no physical change to the payload. However, under 9Gs, the same sine sweep results in a significant shift in the response frequency. This shows that a combined environment testing is required to accurately simulate the actual launch environments.

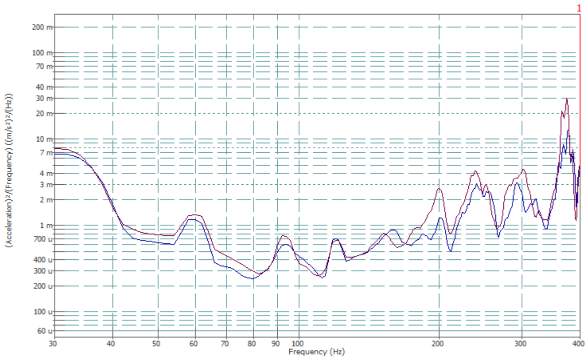

FIGURE 14: Y AXIS SINE SWEEP RESPONSE AT CENTRIFUGE IDLE (1.4G) BEFORE 3G, AFTER 9G TEST.

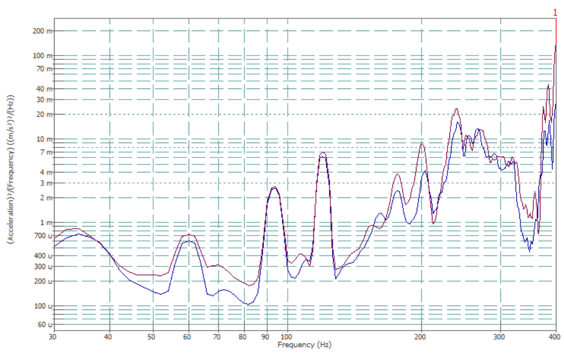

FIGURE 15: X AXIS SINE SWEEP RESPONSE AT CENTRIFUGE IDLE (1.4G) BEFORE 3G, AFTER 9G TEST.

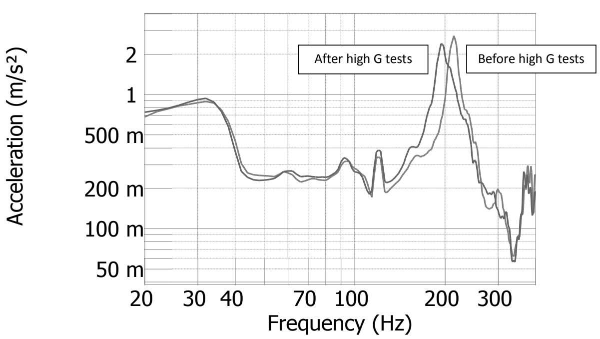

FIGURE 16: SIDE PANEL SINE SWEEP RESPONSE AT THE START AND END OF THE TESTING (BEFORE 3G, AFTER 9G) UNDER IDLE (1.4G) CONDITION.

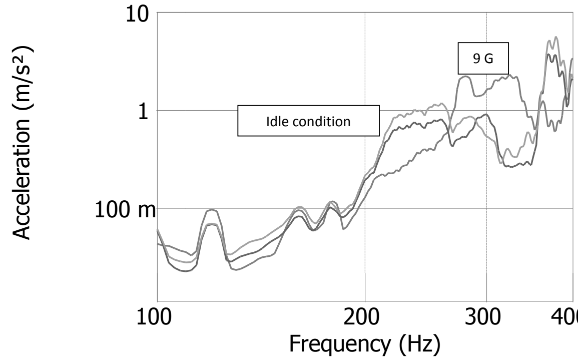

FIGURE 17: Z AXIS SINE SWEEP RESPONSE AT 9G FOR TRANSVERSE TEST FIXTURE. GREEN LINES REPRESENT TARE SWEEPS AT 1.4G.

6. CONCLUSION

All planned test runs were successfully completed. The main objectives of capturing the nonlinear behavior at a higher G load conditions was achieved, as well as introducing the capability of using a traditional shaker in an increased-acceleration environments. The combined environments test results revealed that the natural frequency of the payload can shift under higher G loading conditions and the payload exhibited a different response to vibration excitation under higher G loading conditions.

The significance of these results is that the combined loading test is critical in identifying the "hidden" nonlinear responses of the spacecraft under actual launch conditions where the random vibration is superimposed on top of a sustained G load. Theory indicates that a structure under sustained G loads will have an increased spring constant under non-linear conditions, changing the response frequencies. The test result demonstrates that this is indeed the case when testing satellites under combined loads, which cannot be accounted for in traditional sequential vibration tests as called for by current test standards.

This research has shown that the combined environments testing can be performed on actual satellites by using a CubeSat as the test payload. The application of simultaneous acceleration and vibration loads can cause, at higher Gs, nonlinear structural responses markedly different from those seen when load components are applied separately. Therefore, combined loads can cause natural frequencies to shift, mode shapes to change resulting in changed responses to random vibration, and cause physical shifting or ‘settling’ of parts during actual launch can only be tested under a combined-loading condition.

Many vehicles experience simultaneous acceleration and vibration loads during their missions and are therefore susceptible to nonlinear structural responses that can only be evaluated by combined environments testing. This novel approach to testing may allow payloads and vehicle subsystems to be tested in a more realistic setting prior to operations in the real world, and may lead to higher performance systems, as well as result in reduced cost.

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REFERENCES

1. VanGoethem, D., R. Jepsen, and E. Romero. "Vibrafuge: Re-Entry and launch Test Simulation in a combined Linear Acceleration and Vibration Environment." Proc 44th AIAA 1318 (2006).
2. Yue-gang, Wang, et al. "Modeling and simulation of centrifuge facility-vibration shaker system virtual mocking based on flexible centrifuge arm." Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), 2012 IEEE International Conference on. IEEE, 2012.
3. Jepsen, Richard Alan, and Edward F. Romero. "Testing in a Combined Vibration and Acceleration Environment." IMAC XXIII, Orlando, FL (2005).
4. Rogers, J. D., et al. “VIBRAFUGE---Combined vibration and centrifuge testing.” No. SAND-89-1656C; CONF-891152--5. Sandia National Labs, Albuquerque, NM (USA), 1989.
5. Doggett, J., and F. R. E. D. Cericola. “VIBRAFUGE: A combined environment testing facility---vibration testing on a centrifuge.” No. SAND-89-1881C; CONF-8909168-1. Sandia National Labs, Albuquerque, NM (USA), 1989.
6. Rogers, J. D. "Testing in combined dynamic environments." Journal of the IES36.6 (1993): 19-25.
7. Harper, Abigail, et al. “General Environmental Verification Standard, for GSFC flight programs and projects. (GSFC-STD-7000)” (2005).
8. Ryschkewitsch, M.G., et al. “Payload Vibroacoustic Test Criteria”, NASA-STD-7001A, 2011.