ORBCOMM Generation 2 access to LEO on the Falcon 9 using SoftRide, a case history

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ABSTRACT

The design of SpaceX's Dragon capsule includes an aft structure known as the "Trunk" which can house small payloads for co-manifested missions when re-supplying the International Space Station. One such planned mission includes the ORBCOMM Generation 2 (OG2) spacecraft. The co-manifested approach that SpaceX provides with the Falcon 9 creates affordable and responsive launch opportunities for ORBCOMM and Sierra Nevada Corporation, which built the spacecraft, but presents a unique challenge: The spacecraft were not designed for the measured Trunk environment, but were built and qualified to the environments of other potential launch vehicles. In order to be qualified for the environment, however, the spacecraft design team was faced with the challenge of either re-designing and re-qualifying or turning to using SoftRide as the launch load alleviation solution. As a result, these OG2 spacecraft have a special SoftRide designed and built to support the spacecraft in the Trunk. This paper will describe the unique obstacles faced for this mission due to this emerging launch option provided to the small satellite community by SpaceX.

STATEMENT OF THE PROBLEM

The OG2 spacecraft (shown in Figure 1) are to replace the existing fleet of ORBCOMM satellites which have been launched and in service between 1993 and 2008. The new spacecraft was designed, built, and tested long before the vehicle on which it would launch was known. This is a small spacecraft which weighs just about 160 lbs.



Figure 1 Solid model of the OG2 Spacecraft

Much like other spacecraft programs, this is commonly the case. The spacecraft are designed many years before the eventual launch and in order to design the structures robustly, an assumption must be made upon the most probable launch vehicle selection. In the case of the OG2 spacecraft, two potential vehicles were identified and their dynamic environments were accounted for when designing the structures to be stout enough. When evaluating the launch vehicle environments, random vibration levels, acoustic levels, and transient events analyzed by coupled loads all must be considered. Coupled loads analysis doesn't usually occur until the launch vehicle provider is on contract and sometimes this is too late for design modifications.

Every launch vehicle has its own characteristic dynamic content. The vehicles with liquid fueled engines have a main engine cutoff (MECO) event which acts like an axial shock impulse into the system. Other vehicles which have solid fueled motors have an event described as "thrust oscillation" or "resonant burn". This event can be best described as a sinusoidally sweeping axial input into the system as the solid fuel burns off inside the motor creating a larger resonant cavity. Liquid fueled engines don't have this problem purely due to their different design. All vehicles, regardless of fuel type, will expose the spacecraft to random vibration environments, due partly to structure borne vibrations and also acoustics within the fairing. There are several sources of random vibration energy, most notably the motor or engine thrust, the acoustic overpressures due to the thrust, as well as wind buffeting on the fairing exciting acoustic modes within.

For the OG2 spacecraft, the random environments from the two potential LV's had been enveloped to create a single requirement for the design of the satellite. This is a conservative approach in which the payload is subjected to a single combined environment in test which is far more severe than the vehicle's actual environment. This approach is typically conservative when designing a spacecraft, but in this case, the Falcon 9 Trunk environment exceeded the estimate in some frequency bands. Figure 2 is a response plot from the OG2 qualification test which shows the average of the equipment deck responses (in red) and compares it to the allowable (in blue). The red curve exceeds the blue curve in various frequency bands due to the vehicles input in black. This average curve is an indication that many components which reside on the equipment deck will have exceeded their qualification limits.



Figure 2 OG2 equipment deck responses

Once confronted with this data, there are only a few options for the mission to proceed and not fail: these components would have to be re-qualified using the higher inputs, individual component isolators would have to be developed and implemented for any secondary structure that required it, or a SoftRide system could be integrated which would isolate the entire spacecraft and inherently all of its secondary structures. The spacecraft was already assembled and awaiting launch, so removing components and requalifying them was not a simple matter. Many of the components were not designed for higher levels and most likely wouldn't survive the test. Component isolators weren't an acceptable strategy either, due to the fact that the internal volume of the bus couldn't allow for many new structures to be integrated and the extra mass due to these systems would be prohibitive to the mission.

FALCON 9 DRAGON AND TRUNK

Dragon is shaped like a traditional reentry capsule, with a nosecone that is jettisoned like a payload fairing during the climb to orbit. From forward to aft, Dragon is composed of a pressurized section, a service section, and a trunk (see Figure 3). The spacecraft is lofted to orbit aboard a Falcon 9 launch vehicle.



Figure 3 Dragon capsule with trunk

The trunk section, which is located below the heat shield and physically connects the Dragon to the Falcon 9 upper stage, can host unpressurized payloads. It allows pass-through to the Dragon capsule itself, as well as payload deployment. The trunk supports the capsule during ascent and remains attached to Dragon until shortly before reentry. For payloads hosted in the trunk section, the trunk contains a carrier designed to support ISS cargo and flight releasable attach mechanisms (FRAMs), but can be customized to suit mission needs. Depending on the desired length, the trunk can accommodate a total volume of 14 m³ to 34 m³.

Stand-alone payloads that require only deployment can be accommodated inside the trunk of Dragon as well. On the December 2010 mission after separation of the Dragon spacecraft from the launch vehicle, six 3U P-PODs containing eight small satellites were deployed from the trunk of Falcon 9 Flight 2. These included the US Army's first satellite in 50 years! In this single launch, SpaceX became the world's top provider of CubeSat flights. Furthermore, demonstrating a commitment to responsiveness, SpaceX integrated all six P-PODs, representing five different customers, within a 24-hour period at the SpaceX launch complex at Cape Canaveral Air Force Station. One of these P-PODs was contracted only six months prior to launch.

The trunk can accommodate larger payloads, with deployment occurring any time during the Dragon mission. SpaceX has performed studies that indicate EELV Secondary Payload Adapter (ESPA) class payloads can be launched in Dragon missions as well; an ESPA or similar adapter can be mounted to the upper stage, underneath the Dragon inside of the trunk volume. This potential uniquely leverages the restart capability of the Falcon 9 upper stage to take ESPA-class payloads to orbits different than that of the Dragon.

SOFTRIDE

Whole-spacecraft vibration and shock isolation systems (SoftRide) have been developed and flown to attenuate dynamic loads for many U.S. launch vehicles. These systems support the entire spacecraft and isolate it from the vibration loads imparted from the launch vehicle (see Figure 4). Implementing a whole-spacecraft isolation system can provide many benefits for the mission, not just spacecraft design and launch. Using SoftRide during payload vibration testing will reduce the risk of experiencing a test failure, thereby decreasing delays due to repair and re-test. Including SoftRide in the spacecraft's shipping container further protects against component failure due to shock and vibration loads from transport and handling. This will facilitate smooth spacecraft integration onto the LV.



Figure 4 SoftRide integrated onto a payload adapter cone

ORBCOMM and Sierra Nevada decided that the best option for the OG2 mission was to implement a SoftRide system. This option would have been the most efficient in order to keep the launch schedule. Sierra Nevada Corporation (SNC) made contact with Moog CSA at the end of July, 2011. In order to preserve the launch schedule, the SoftRide would have to be delivered to SNC by the end of September. The Falcon 9 mission was slated for November 2011 and SNC required the SoftRide for random vibration testing at its facility during the first week of October. The implication was that the entire system would have to be designed, built, tested, and delivered within eight weeks.

For Moog CSA to meet this very aggressive schedule the design effort could take no more than two weeks and would have to culminate in the Critical Design Review (CDR) during the third week of August. A typical clean sheet SoftRide design effort takes anywhere from four to six months. The longer design efforts have occurred on missions for which SoftRide had never flown on the launch vehicle due to consideration of all flight dynamics with the SoftRide system in place. Since Moog CSA had no flight heritage on the Falcon 9 (F9), a two week design period was extremely fast-paced.

The SoftRide design effort was limited to tuning the system for the random environment and ensuring that the strength of the system could withstand the quasistatic load factors provided by SNC. Given the Falcon 9 environment, this was all conducted with base-shake analysis at the base of a truss structure which would support the OG2 spacecraft (Figure 5).



Figure 5 OG2 Spacecraft and truss inside Dragon's trunk

Early in the design process, Moog CSA brainstormed different implementations of the SoftRide system in this configuration. Since SoftRide can be inserted at any existing joint, an obvious selection was having one set at each of the spacecraft's four attach points, one in each corner. Another choice was to connect both spacecraft to a single interface adapter plate and isolate the entire adapter. This would keep the SoftRide design simple, but would increase the mass due to the extra plate. Within each configuration, two styles of SoftRide were selected as well. The first is the UniFlex type of isolator which is very stiff in-plane and primarily offers isolation in the axial direction. The second is the OmniFlex which is soft in all three translational directions and offers isolation performance in each (see Figure 6).



Figure 6 OmniFlex type of SoftRide

The OG2 spacecraft was designed with four separation nuts at each corner (see Figure 7). Due to this, and after performing all of the trades, the SoftRide in each corner was selected as the path forward. Each system would have two OmniFlex style isolators at each corner as shown in Figure 8. Due to the design of the spacecraft interface on the truss, the SoftRide required two adapter plates: one aft of the OmniFlexes in order to fit into the existing bolt patterns on the truss side and one on the forward side to pick up the separation nut (colored red in Figure 7) and push off spring (colored blue).



Figure 7 A single OG2 connection to the truss



Figure 8 OG2 connector with SoftRide

The SoftRide assembly consisting of the two OmniFlexes and the forward and aft adapter plates added a total of 26 lbs. to the system weight per spacecraft. This added mass is well within the capabilities of the F9 vehicle. The OG2 spacecraft have been pushed forward about 4.5 inches from nominal configuration. This fits well into the available volume within the Dragon's trunk.

SYSTEM'S ANALYSIS

Moog CSA performed a random vibration analysis in which the payload was exposed to the F9 environment. The two critical locations which were monitored were referred to as the equipment deck and the payload deck. A single DOF response for each of these locations is shown in Figure 9. A comparison is made in this plot between the hard-mounted spacecraft (i.e. the configuration in which the OG2 is mounted directly to the truss) and the isolated configuration.



Figure 9 Comparison of equipment deck responses

The isolated response peaks at about 22 Hz and has higher response than the hard-mounted configuration between 20 Hz and 30.5 Hz, this is by design. The amplification at this frequency is due to the tuning of the SoftRide system to have a "bounce" mode at 22 Hz. This is intentionally designed into a passive isolation system in order to reap the benefits of having much less vibration energy transmit itself across the system at higher frequencies. As can be seen by the plot, there is a much more benign environment on the spacecraft above 30.5 Hz. This "roll off" in high frequency response is beneficial to sensitive electronics and other components on the spacecraft.

TESTING

For the program to be successful, testing at the component level and also at the integrated system was necessary. The component tests conducted by Moog CSA consisted of verification of the strength of the isolation system. This is imperative since the SoftRide assembly is directly in the load path between the launch vehicle and the spacecraft. Any failure in any of the assemblies could have been detrimental to the mission. Moog CSA also performed dynamic characterization of the isolation system. This test reveals the complex stiffness and damping characteristics of the assembly. This information is necessary to analytically predict and gauge the isolation performance when integrated with the spacecraft.

Sierra Nevada Corporation was responsible for the dynamic system test which consisted of applying the Falcon 9 random environment to the payload stack.

Component Testing

Strength of the assembly was verified by a multi-axis static load application (Figure 10). In this test, three actuators applied 125% of the maximum predicted environment to the SoftRide assembly. Sierra Nevada had asked that Moog CSA assume a quasi-static environment of 15 g's applied simultaneously to the OG2 payload. SNC felt that this enveloped the F9 environment as well as could qualify the SoftRide for other OG2 missions since there are a total of eighteen which need to be launched on yet-to-be-determined launch vehicles.



Figure 10 Multi-axis static loading of a SoftRide assembly

A complex stiffness test characterizes the stiffness and damping of the isolator as a function of frequency. These are important characteristics of viscoelastic material (VEM) based isolators due to the fact that VEM is frequency and temperature dependent.



Figure 11 Representative stiffness of the OmniFlex as a function of frequency



Figure 12 Representative loss of an OmniFlex as a function of frequency

The stiffness of the isolator at the nominal design temperature of 20°C and at 22 Hz is approximately 5300 lb/in as shown in Figure 11. The loss factor at the same nominal design points is approximately 7% as seen in Figure 12. These data match well with the finite element model predictions

System Testing

Sierra Nevada conducted a ground vibration test of the OG2 spacecraft on the SoftRide isolators (Figure 13).



Figure 13 Testing of the OG2 Spacecraft on SoftRide

A sample of the dynamic response from a single axis test is shown in Figure 14. The acceleration PSD shows that the equipment deck response with the SoftRide is much lower beyond approximately 30 Hz just as the analysis predicted.



Figure 14 OG2 random vibration test results with and without SoftRide

CONCLUDING REMARKS

The Falcon 9 launch vehicle has the excess capability to launch small satellites during routine missions to the ISS within its Dragon capsule. This could be a regularly scheduled opportunity for the small satellite community to share launch costs since the F9 could be resupplying the ISS on a recurring basis. The Dragon spacecraft recently mated with the International Space Station and flawlessly returned to earth. This mission not only transported cargo to the ISS, but successfully brought back items as well (see Figure 15).



Figure 15 Dragon spacecraft approaching the ISS on May 25th, 2012

For the upcoming OG2 mission, SpaceX, Sierra Nevada, and ORBCOMM included a SoftRide system in order to ensure the functionality of the spacecraft when exposed to the higher-than-expected F9 dynamic environment.