Whole-Spacecraft Isolation Development Efforts At The USAF Phillips Laboratory

Eugene R. Fosness, Keith K. Denoyer, Alok Das, and David B. Founds

U.S. Air Force Phillips Laboratory
PL/VTVD
3550 Aberdeen Ave. SE
Kirtland AFB, NM 87117-5776
(505) 846-8252
fosnesse@plk.af.mil

Abstract. One of the most severe environments that a satellite experiences during its lifetime will occur during launch. The traditional approach to spacecraft design against launch vibration has been through structural stiffening or component isolation. This approach is costly, time consuming, and adds significant weight. The USAF Phillips Laboratory is actively investigating an alternative approach, which involves isolation of the whole spacecraft from the launch vehicle effects. This is in contrast to other efforts which have utilized isolation of secondary components of the spacecraft only. The objective of the current effort is to reduce the launch-induced structural-borne dynamic acceleration of the satellite by insertion of an isolator between the spacecraft and the launch vehicle. This paper summarizes the status of several programs being managed by the USAF Phillips Laboratory in the area of whole-spacecraft isolation. These programs are targeted towards isolation for small to medium class launch vehicles, but are applicable to all sizes of launch vehicles. This paper presents key results from several of these programs, perceived benefits of whole-spacecraft isolation, and planned activities for flight demonstration of a whole-spacecraft isolation system.

Introduction

Launch dynamics are a major design driver in the structural design of a spacecraft. The vibrations that occur in a spacecraft during launch are both structure-borne and acoustic in nature. It is well established that a significant number of spacecraft malfunctions occur during launch, and that they are often due to vibro-acoustic loads. Excerpts from a NASA study\(^1\) shown in Figure 1, estimate that 45 percent of all first-day spacecraft failures and malfunctions are known to be attributed to damage caused by vibrations. While the study is over twenty years old, the problem has changed little. Spacecraft are typically ground tested to detect failures using random vibration and acoustic testing to simulate the launch environment. However, the NASA

![Figure 1: Causes of Space Flight Malfunctions](image-url)
study indicates that ground tests are not 100% effective in detecting potential failures. The study states that ground tests are found to be between 80 to 90 percent effective. The load path for structure-borne vibrations from the Launch Vehicle (LV) to the spacecraft is through the spacecraft adapter. The focus of this paper is to provide information on current Phillips Laboratory (PL) programs that involve technologies encompassing launch vibration isolation. The PL is developing the technology for payload isolation in two phases. The first phase and the focus of this paper is the development of passive isolation designs. The second phase will add active control elements to develop a hybrid vibration isolation system. It is anticipated that the technologies currently under development will reduce costs and the number of failures. This will be especially important for launching large numbers of similar spacecraft such as those envisioned for proposed satellite constellations necessary to form global telecommunication networks. Similar benefits for other applications are anticipated as well.

**Motivation/Payoff**

Spacecraft adapters or Payload Attach Fittings (PAF) are used to provide an interface between the LV and payload. Typical adapters, are designed to be very stiff. Therefore, they provide an efficient transmission path for both dynamic and quasi-static launch loads. The traditional approach to spacecraft design against launch vibration has been to stiffen structural components or by providing isolation to spacecraft components on a case-by-case basis. While often effective, this approach is costly, time consuming, adds weight, and can lead to other liabilities once the spacecraft is in orbit. An alternative approach discussed in this paper is to integrate an isolation system directly into the PAF. It is envisioned that a whole-spacecraft isolation system will replace the traditional PAF used to physically attach a spacecraft to a LV as shown in Figure 2. By integrating an isolation system into the PAF, the whole spacecraft can be effectively isolated from launch loads. Since the isolation system is no longer spacecraft specific, the same basic isolation design may be used for a variety of payloads to be launched from a common LV. This substantially reduces the recurring development cost for this type of isolation system. Despite the obvious benefits, whole-spacecraft isolation can change the dynamic properties of the combined payload/LV system. This must be properly addressed to avoid unwanted side effects introduced by the isolation system. It is critical for flight acceptance that an isolation system not introduce intractable new problems into either the product or integration process. Therefore, the design must be simple, relatively easily analyzed, and have a failure mode which results in spacecraft vibration levels no greater than those that would occur with a standard PAF. Reduced vibration environments for future spacecraft will have a direct impact on the overall cost of spacecraft design, testing, and operation. Several subsystems, such as solar arrays and other flexible structures can be made lighter and use less expensive materials, resulting in both a mass and production cost savings. This also allows a larger percentage of the payload weight to be dedicated to scientific equipment. The implementation of this technology will directly effect the following: 1) greater survivability at launch; 2) a reduction of LV loads; 3) a minimization of dynamic-related spacecraft failures; 4) a reduction of cost, size, and weight of some spacecraft; 5) a lowering of certain test requirements; 6) the allowance for “tuning” of the isolator instead of spacecraft requalification; and 7) a reduction of the number of analysis load cycles.
In 1993, the PL awarded CSA Engineering a Phase I SBIR to determine the feasibility of a payload isolation system. A system analysis was performed to insure that interactions between the LV and the dynamics of the isolator and spacecraft were taken into account during the design process. Axial vibration isolation was the main target of the Phase I effort.

A generic medium LV model, a 2,722 kg pseudo-spacecraft model, and transient loads for the liftoff flight event were obtained from McDonnell Douglas Aerospace (MDA). The PAF that was used in the analysis is shown in Figure 2. The transient liftoff loads consisted of pad reaction forces, main engine thrust, and the solid booster thrust loads. The baseline case consisted of the unmodified PAF (67 Hz axial modal frequency). The results of the analysis are shown in Figures 3 and 4. Based of these results, the following assessments were made for the system under study (Note...
that these are all based on a large spacecraft and do not necessarily apply to smaller a spacecraft): 1) high axial dynamic loads occur at low frequencies (<15 Hz); 2) isolators with axial break frequencies <8 Hz are too soft and consume too much rattlespace; 3) isolation modes are in the middle of system modes; 4) high-g steady state loads on a soft isolator cause excessive clearance reduction and have unrealistic stroke requirements; 5) there are no quasi-static loads in the lateral direction; 6) clearance reduction of a <20 Hz axial isolator was too great; 7) cannot isolate against the high axial steady-state loads; and 8) need hybrid active/passive system to isolate axial disturbances.

The analysis indicates that incorporating axial isolation into the PAF introduces axial compliance, which tends to allow low-frequency pitch and yaw rigid body rotation (rocking) of the spacecraft. Axial passive isolation was not feasible because of geometric restrictions such as excessively large rattlespace requirements and static sag due to the large quasi-static loads. The axial constraint required that an isolation system be designed between system frequencies, which also makes it hard to meet the isolation criteria. To avoid dynamic coupling, the isolation system must be designed with axial frequencies above 35 Hz and lateral frequencies above 15 Hz, which again limits the level of passive isolation to be achieved. In order to accommodate the static sag, the isolator must be designed for accelerations that exceed 6 g’s. Based on the results of the analysis, it was believed that low frequency passive axial isolation was not feasible under current LV constraints for a large spacecraft on a medium LV. This is mainly applicable for large a spacecraft with small footprints and a high CG. Smaller spacecraft are more amenable to axial passive isolation. Final studies in the Phase I SBIR indicated that lateral isolation is both feasible and useful to protect secondary spacecraft structures. These secondary spacecraft structures typically have modes at frequencies in the 25-35 Hz range.

**Delta II Phase II**

In 1994, CSA Engineering was awarded a Phase II SBIR to design an isolator that provides lateral isolation to spacecraft without excessive lateral rocking. The goal of the Phase II SBIR was to develop a passive lateral isolator that would replace an existing PAF for a medium LV. The isolator would be designed to reduce the structure-borne lateral dynamic vibrations by a factor of 2 RMS and satisfy all requirements imposed on current PAF. A launch loading condition, known to cause the most severe lateral loads, was identified for use in design and analysis trades studies for an isolating PAF. This loading condition, common to most launch vehicles, is typically caused by a main-engine resonance which couples with an axial mode of the LV. As fuel is depleted, the axial mode tunes to the engine resonance. This excited axial mode couples laterally to the spacecraft as an almost purely sinusoidal lateral excitation to the spacecraft base. Several trade studies were performed on parameters to optimize the isolator’s performance. A unique isolating PAF was designed that allows lateral isolation but retains axial stiffness. Based on the analysis results, the isolator would have a lateral break frequency of 15 Hz. The performance of the isolating PAF is shown in Figure 5. For the frequency range of interest for the spacecraft (20-40 Hz), the analysis indicates that a factor of 7 reduction in broadband RMS lateral vibration is obtainable using a passive isolator design.
The isolating PAF was designed to replace the 6915 PAF (Figure 2) for the Delta II. The 6915 PAF is fabricated from a monolithic piece of aluminum. The isolating PAF was constructed as a weldment of several aluminum pieces. This full-scale hardware shown in Figure 6 was fabricated for ground verification tests of the isolation technology. The upper and lower rings were each fabricated from eight separate pieces. The isolating PAF uses a system of flexures and dampers. These flexures and dampers connect the spacecraft pads to the PAF. The spacecraft then bolts to the four spacecraft pads. The upper and lower rings and the struts were made from aluminum. The initial goal of the program was to have at most a 2.27 kg weight penalty from adding the isolation components. The 6915 PAF weighs 85.7 kg and the designed isolating PAF weighs 102.5 kg, which is a 16.8 kg increase over the baseline 6915 PAF. However, construction practices and materials that were used in fabricating this isolating PAF prototype would not be used for an actual flight unit. A study looking at optimizing the weight of this isolator indicated that this isolating PAF could be designed to within a 2.27 to 4.54 kg weight penalty.

![Figure 5: Predicted Whole-spacecraft Isolation Performance (Delta II)](image)

![Figure 6: Isolating Payload Attach Fitting Components and Hardware](image)


Delta II (Passive/Active Axial)

In 1996, MDA was awarded a contract to design, fabricate, and test a flight-qualifiable passive/active (hybrid) launch isolation system for a Delta II LV. The team consisted of MDA, Honeywell Satellite Systems, CSA Engineering, and Space Systems/Loral. The goal of this program was to develop a hybrid axial isolator that would complement the lateral isolation system developed in the Phase II CSA SBIR. The isolator would be designed to reduce the structure-borne axial dynamic vibrations by a factor of 5 RMS and satisfy all requirements imposed on current PAF. Isolating PAF struts (Figure 7) were designed, fabricated, and tested to demonstrate a strut capable of providing the performance required. The isolation system design involved using metallic crossbars with hydraulic-pneumatic struts with a hydraulic cross-link feature that stiffens under rotation to meet rocking restrictions.

Figure 7: Isolating Strut

Minuteman Launch Vehicle

During the 1950’s, the Minuteman LV was developed by Boeing to launch U.S. warheads. These Minuteman LVs that once supported nuclear warheads are now in the process of being converted for military/experiments applications. The Air Force currently has several programs to use existing ICBM assets to support ballistic, sounding rocket, and space missions. The Multi-Service Launch System “MSLS” program is responsible for converting Minuteman LV for sub-orbital missions. The Orbital/Suborbital program (OSP) is responsible for converting Minuteman LV for orbital missions. The Minuteman, because it is a small LV that was designed for warheads for quick strike capabilities, provides an extremely rough ride to orbit. The Minuteman LV has peak axial accelerations that can reach 10 to 15 g’s quasistatic and 15 to 20 g’s dynamic. Currently, the Air Force has over 400 Minuteman LV’s in its inventory. Lockheed/Martin Marietta (Denver) is the prime contractor for the MSLS LV program.

In November 1995 CSA performed analysis to determine the feasibility of inserting a passive isolation system into a Minuteman LV to reduce structure-borne vibrations. CSA acquired Minuteman LV models and other information from Lockheed Martin in order to perform a LV isolation feasibility study. These models included NASTRAN-format finite element models, load cycles for three flight events, and a satellite model. A dynamic analysis with the inserted isolator was performed for three flight events. The three events were: (1) liftoff, (2) stage 1 burnout/stage 2 ignition, and (3) stage 3 termination. A time history plot of the satellite acceleration for each of the events is shown in Figures 8, 9, and 10. For the liftoff event, the peak axial acceleration was reduced from 8.2 g’s to 2.5 g’s. The peak lateral acceleration for the stage 1 burnout/stage 2 ignition was reduced from 6.8 g’s to 2.2 g’s. The peak axial acceleration for the stage 3 termination was reduced from 17 g’s to 5 g’s. The analysis indicated that it is feasible to reduce the dynamic axial and lateral vibrations for the Minuteman LV with a passive isolation system by a factor of three. Currently, the Minuteman does not provide a PAF. To use these LV for payloads, a PAF will have to be
integrated and designed into the existing system. The results of this study suggest that designing this PAF to incorporate isolation will have significant benefits.

Based on the results of the preliminary MSLS whole-spacecraft isolation study, OSP plans to insert an isolation system into their program. CSA Engineering will design, fabricate and test an isolation system for the first OSP launch scheduled for September 1999, with flights scheduled for every 18 months thereafter. The isolation system will be passive and provide both axial and lateral isolation. The goal of this effort is a factor of three reduction in the peak dynamic acceleration at the spacecraft. The payload capability for OSP for low earth orbit is between approximately 360 kg, depending on the configuration, altitude and inclination.

Taurus Launch Vehicle

In 1997, CSA Engineering performed two studies investigating the feasibility of a whole-spacecraft isolation system for two different payloads on a Taurus LV. The isolation system was designed to be passive and provide axial isolation. The models and other information required to perform the whole-spacecraft isolation feasibility study were provided by Orbital Sciences Corporation (OSC). These models included NASTRAN-format finite element models, load cycles for three flight events, and satellite models. A dynamic analysis with the inserted isolator was performed for the resonant burn and buffet flight events. The two payloads weight were 377 and 669 kg respectively. The results of each of the analysis are discussed below.
For the 377 kg payload, a normalized bar chart for the resonant burn flight event is shown in Figure 11. Each bar on the chart represents points or components on the spacecraft. The vertical axis represents the ratio for analysis involving isolation to non-isolated. For example, a factor of 4 reduction in the dynamic loads would be 0.25 or a factor of 5 reduction would be 0.20. There were several spacecraft components that had high axial accelerations, the analysis indicate that the isolation system would reduce the peaks by a factor of 4 to 5.

For the 669 kg payload, dynamic load reductions at the spacecraft were similar to those obtained for the 377 kg payload. Component isolation hardware was designed, fabricated, and tested. The results of the component tests matched closely to what was predicted. To demonstrate the performance of the isolation system, system level ground tests were performed. OSC provided a 377 kg satellite mass simulator for the system level ground testing. The results of the ground testing also closely matched predicted results. The weight of the isolation system was approximately 5.5 kg.

**Evolved Expendable LV (EELV)**

The Space and Missile Center (SMC) Space Test Program (STP) office at Kirtland AFB has the payload for the first EELV flight scheduled to be launched in 2001. The STP mission is to provide cost effective ways to flight test new space systems technologies, concepts, and designs. The STP contacted the PL in April 97 about inserting a passive isolation system into their EELV flight. Ground testing of the whole-spacecraft isolation system is scheduled to begin in 1999. The STP expects to use multiple payloads with a total weight between 1,362 to 2,270 kg. It is uncertain at this time if the isolation system will be axial, lateral, or a combined axial/lateral. This will be determined from subsequent analysis.

![Ratio of Isolated / Baseline Acceleration for Payload Response Points](image)

*Figure 11: Taurus Launch Vehicle/Satellite (635 kg) Analysis Results*
Conclusions

The PL has aggressively pursued a series of programs to develop and insert whole-spacecraft isolation technology. The near-term goal of this program has been to advance the state-of-the-practice in isolation technology rather than the state-of-the-art. Spacecraft have been launched for decades without the benefits of even rudimentary isolation from LV loads. The primary goal has been to design an isolation system that will be accepted and used by the aerospace community. Having a team with a heritage in the aerospace industry was identified as essential to insure that the spacecraft isolation system design represents the point of view of both LV and spacecraft manufacturers. This insures that objectionable features are identified early in the design process, with substantial input from the eventual customers. Analysis and testing have demonstrated that the additional benefits (weight savings, reliability, etc.) that a whole-spacecraft isolation system provides to the spacecraft far outweigh the weight penalty of the isolator. Also, it is expected that additional weight savings will be achieved due to lower spacecraft design loads and that these savings will outweigh the isolation system weight penalty. It is expected that the successful implementation of these programs will have an impact on all future military and commercial spacecraft programs by decreasing the launch loads for which spacecraft systems must currently be designed to withstand.

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Appendix I - References


Biography

Eugene R. Fosness
Gene Fosness received a B.S. in Civil Engineering from North Dakota State University in 1981 and his M.S. from the University of New Mexico in 1991. He is currently employed as a Research Structural Engineer at the U.S. Air Force Phillips Laboratory.

Keith K. Denoyer
Keith Denoyer received a B.S. in Mechanical Engineering from the University of Michigan in 1990, a M.S. in Mechanical Engineering from Stanford University in 1992, and a Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1996. He is currently employed as a Research Aerospace
Engineer at the U.S. Air Force Phillips Laboratory.

Alok Das
Alok Das got his PhD from VPI&SU in 1982. He is currently the Technical Director of the Space Vehicle Technologies Division at the U.S. Air Force Phillips Laboratory.

David Founds
David Founds is the Branch Chief of the Dynamic Systems Branch of the Space Vehicle Technologies Division at the U.S. Air Force Phillips Laboratory.