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Whole-Spacecraft Passive Launch Isolation

Paul S. Wilke* and Conor D. Johnson†
CSA Engineering, Inc., Palo Alto, California 94303-3843
and
Eugene R. Fosness‡
U.S. Air Force Research Laboratory, Kirtland Air Force Base, New Mexico 87117-5776

A spacecraft is subjected to very large dynamic forces from its launch vehicle during its ascent into orbit. These large forces place stringent design requirements on the spacecraft and its components to ensure that the trip to orbit will be survived. The severe launch environment accounts for much of the expense of designing, qualifying, and testing satellite components. Reduction of launch loads would allow more sensitive equipment to be included in missions, reduce risk of equipment or component failure, and possibly allow the mass of the spacecraft bus to be reduced. These benefits apply to military as well as commercial satellites. The design and testing is reported of a prototype whole-spacecraft isolation system that will replace current payload attach fittings, is passive only in nature, and provides lateral isolation to a spacecraft that is mounted on it. This isolation system is being designed for a medium launch vehicle and a 3000-kg (6600-lb) spacecraft, but the isolation technology is applicable to practically all launch vehicles and spacecraft, small and large. The isolator significantly reduces the launch loads seen by the spacecraft.

Introduction

ONE of the most severe environments that a spacecraft will be subjected to during its lifetime will occur during launch. This paper summarizes the results and status of a research effort in the area of spacecraft isolation from the launch vibration environment. The object of this effort is to reduce the launch-induced, structure-borne dynamic acceleration of the spacecraft by insertion of a vibration isolation device. The term launch loads refers to all loads from liftoff through final engine shutdown at orbit insertion. Isolation issues involving the use of passive elements and launch vehicle system-level requirements are discussed.

The U.S. Air Force Phillips Laboratory (PL) Space Vehicle Technologies Division of the Space Technology Directorate has been monitoring the development of whole-spacecraft isolation. The result of this effort has been an isolation design methodology developed from a system-level point of view. This methodology, along with models and simulations, will be used to develop new spacecraft payload attach fitting (PAF) designs that incorporate vibration isolation capability. PL is developing the technology for whole-spacecraft isolation in two phases. The first phase, discussed in this paper, is the development of passive isolation designs.[1,2] The second phase will add active control elements to develop a hybrid passive/active vibration isolation system.[3] These whole-spacecraft isolation technologies could be used to great advantage in many future launches of both government and commercial spacecraft such as the proposed constellation of satellites necessary to form global telecommunication networks.

Need for Isolation

The deployment of a spacecraft into its final orbit configuration is a highly complex operation. During the ascent of the launch vehicle, the spacecraft is subjected to many different quasistatic and dynamic loads, which vary throughout the launch. These loads change due to environmental effects such as wind gusts and buffeting, discrete events such as motor ignitions and cutoffs, and also changing structural dynamics caused by fuel depletion and stage jettisons. These transient loads can have a detrimental impact on the launch survival and life-cycle performance of the spacecraft. Undeniably, the load environment that a spacecraft endures during launch far exceeds that encountered during on-orbit operations.

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 vibroacoustic loads. A NASA study,[4] shown in Fig. 1, estimates that 45% of all first-day spacecraft failures and malfunctions are known to be attributed to damage caused by vibrations. Although the study is over 20 years old, the problem has changed little.

PAFs are used to provide an interface between the launch vehicle (LV) and spacecraft. Typical PAFs are designed to be very stiff, and subsequently they provide an efficient transmission path for both dynamic and quasistatic launch loads. The traditional approach to spacecraft design against launch vibration has been through structural stiffening or component isolation. However, this approach is costly, is time consuming, adds weight, and can lead to other liabilities once the spacecraft is in orbit. Current PAFs do not provide isolation from launch loads except on a case-by-case basis. Implementing an isolation system into the PAF is the logical place for a payload isolator. However, whole-spacecraft isolation is a substantial change in the dynamic properties of the combined system and is bound to have side effects that must be addressed. Critical to the acceptance for flight is that an isolation system must not introduce intractable new problems into either the product or the process. First flight of any whole-spacecraft isolator will occur only when both the LV and spacecraft contractors are satisfied that, at worst, a failure of the isolator will impose vibration on the spacecraft no worse than that which would occur with a standard PAF.

Reduced vibration environments for future spacecraft can 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 mass and production cost savings. This also allows a larger percentage of the payload weight to be dedicated to scientific equipment. A whole-spacecraft isolation system is envisioned to replace the traditional PAFs used to physically attach a spacecraft to an LV, as shown in Fig. 2. The implementation of this technology will directly effect the following: 1) a greater survivability at launch;

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*Associate Principal Engineer, 2850 West Bayshore Road. E-mail: wilke@csaengr.com. Member AIAA.

†President, 2850 West Bayshore Road. E-mail: cjohnson@csaengr.com. Senior Member AIAA.

‡Structural Research Engineer, Phillips Research Site, VSDV, 3550 Aberdeen Avenue, SE. E-mail: fosnesse@smtpgw1.plk.af.mil.

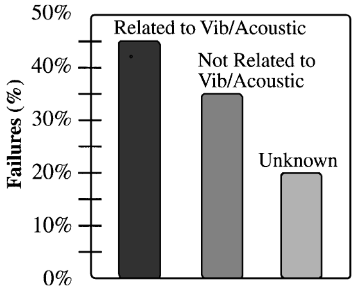

Fig. 1 Causes of space flight malfunctions.

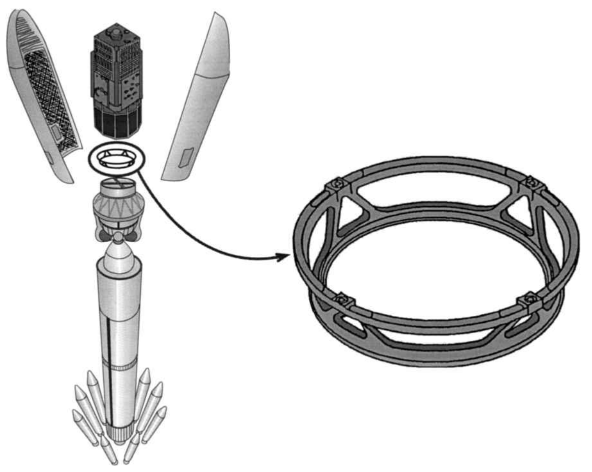

Fig. 2 Medium launch vehicle and PAFs.

2) a reduction of loads seen by the spacecraft; 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 the course of a spacecraft development program, updated coupled-loads analyses often result in increased launch loads, which necessitate unforeseen spacecraft design changes. Consequently, the spacecraft design organization is faced with unplanned hardware redesigns, schedule slips, and cost overruns. Reduction of dynamic launch loads seen by spacecraft will minimize spacecraft redesign, reduce risk, reduce spacecraft development time, reduce costs, eliminate many vibration-related failures, and increase reliability.

Isolation Design Methodology

Vibration isolation is a technique used to reduce vibration of a structure by altering the frequency content of the forces that act on that structure. Isolation of a whole spacecraft from a launch vehicle requires a unique design methodology. Figure 3 shows two connected structures being acted upon by external forces. Classic isolation design assumes that structure 2 is rigid with respect to structure 1 and that only the dynamics of structure 1 must be considered in the design process. This is not at all true for whole-spacecraft isolation design. The spacecraft (structure 1) and the LV (structure 2) are both considered to be very flexible structures, and the dynamics of one has a significant influence on the other.

Historically, the connection between the spacecraft and the LV has been made with a very stiff PAF. This is generally considered to be a hard mount and is extremely efficient at transmitting all structure-borne forces from the LV to the spacecraft over a very wide frequency band. A whole-spacecraft isolation system replaces this hard mount with a soft mount, which filters out a great deal of the frequency spectrum of the forces from the LV.

Most spacecraft are cantilevered to their launch vehicle, being attached only at the base. Whole-spacecraft isolation is a challenging problem because spacecraft typically have a very large ratio of center-of-gravity height H to attachment width W (Fig. 3). Reduction of the axial attachment stiffness will introduce low-frequency spacecraft rocking (pitch and yaw) modes and large lateral displacements at the upper end of the spacecraft. These effects are generally undesirable because they may cause guidance control system instabilities or the spacecraft may hit the fairing. However, these problems may be avoided through innovative isolator hardware design.

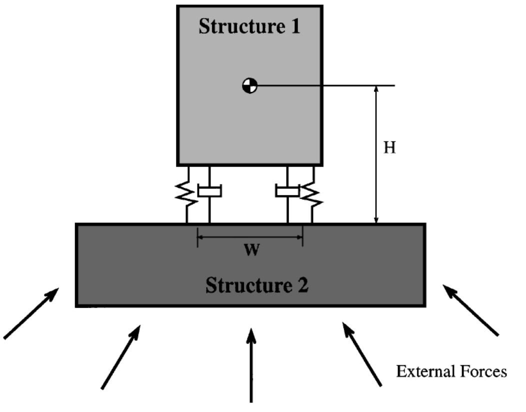

Fig. 3 Two connected structures.

LVs often have closely spaced flexible modes with frequencies starting as low as 1 Hz, and spacecraft may have modes with frequencies starting as low as 6 Hz. Isolation of a 6-Hz spacecraft from a 1-Hz LV necessitates a unique design methodology that deviates from classic isolation system design. More than ever, it is necessary to have a clear understanding of the isolation objectives and the design constraints present. Whole spacecraft isolation systems must be designed from a system-level point of view, accounting for the coupled dynamics of two very flexible bodies that will now be connected with a flexible interface as opposed to a hard mount. Indeed, the challenge is to determine exactly where to insert the new dynamics introduced by the isolation system within the sea of structural dynamics already present. The following sections discuss the methodology that was used to develop a whole-spacecraft isolation system for a medium launch vehicle.

Isolation Objectives

The specific objectives for the design of this isolation system were the following:

1) Isolate the spacecraft, as a whole, from the LV. Individual components of spacecraft have been isolated and flown, but a whole spacecraft has never been isolated.

2) Provide lateral isolation only. It was decided only to reduce lateral accelerations in this program. Axial isolation, although feasible, was deemed beyond the scope of this program. This objective is tied closely to the design constraints, discussed later.

3) Provide a 2:1 broadband rms reduction in accelerations in the 25–35-Hz range. Many spacecraft have secondary structures, such as solar arrays, antennas, etc., with modes in this range; these modes will not be excited as much if isolation is designed in this range.

4) Reduce accelerations on spacecraft secondary structure. Primary structure of spacecraft is usually designed to meet quasistatic loads and does not, in itself, generally require dynamic load reduction.

Design Constraints

There are many design constraints that pertain to whole-spacecraft isolation. Some of the typical constraints are weight, volume, and strength. However, the two most critical design constraints are as follows:

1) Structural modes below 6 Hz must not be introduced. This constraint is related to the vehicle guidance, navigation, and control systems. Structural modes below 6 Hz encroach on the controller bandwidth and may cause flight instabilities.

2) The rattle displacement (payload-to-fairing displacement) must not be increased by more than 1 in. Insertion of a whole-spacecraft isolator will introduce compliance between the LV and the spacecraft. This compliance must not significantly increase the rattle

displacements, which could cause the spacecraft to hit the fairing during launch.

System-Level Analysis

Realistic and thorough system-level mathematical models are required to properly design and analyze the system-level benefits of whole-spacecraft isolation. The correct approach to designing isolation for an LV and spacecraft system is to use finite element models of all parts of the system. This allows accurate simulation of the structural dynamics of the nonisolated system and subsequently provides a tool for simulation of various isolation hardware designs.

The LV changes significantly during its ascent, due to fuel depletion and stage jettisons. Therefore, many LV models and associated loads would be required to fully analyze any isolator design. For the purpose of designing this isolation system, two flight events were selected: liftoff and premain-engine cutoff (PREMECO). Separate finite element models were obtained for a generic medium launch vehicle, representing these two distinct periods of launch. The first is a liftoff model, matching the vehicle as it sits on the launch pad. This model was obtained in matrix form only, with 185 physical degrees of freedom (DOFs) and 49 modal DOFs, for a total of 234 DOFs. The second finite element launch vehicle model represents the PREMECO period of flight. It was also obtained in matrix form only, with 12 physical DOFs and 139 modal DOFs, for a total of 151 DOFs.

A realistic model was obtained of a NASA spacecraft that weighs approximately 3000 kg and is 4.9 m in height. This model originally consisted of a bus structure and 14 substructured equipment items totaling more than 20,000 DOFs. This model was combined into one modal-reduced spacecraft substructure having 138 physical DOFs and 148 modal DOFs for a total of 286 DOFs. This model is representative of the complicated high-modal-density dynamics present in a typical spacecraft and was, therefore, very useful in the isolation design.

The substructuring facility of the Universal Analytics, Inc., version of NASTRAN was used to simplify the system-level analyses. The launch vehicle models were each stored in the database as separate substructures, as was the spacecraft. The only changing component in each analysis was the PAF, which was also substructured. The assembly of a system-level model involved combining the spacecraft substructure, the current PAF iteration substructure, and the desired LV substructure into a single system. Then this system was analyzed using either frequency response or transient response solutions. This process is shown in Fig. 4. Direct solutions were quite feasible, as opposed to modal solutions, because the substructuring significantly reduced the solution matrix sizes.

Selection of an isolation system design was an iterative procedure, in which each concept was analyzed in a dynamic system model to assess its performance characteristics. Because the main isolation target was the PREMECO stage of flight, this model and PREMECO loads were used for preliminary evaluation of isolation designs. Initially, the isolation system was modeled as a set of springs and dampers between the LV and the spacecraft. This modeling technique allowed rapid trade studies to be performed with several variables such as lateral stiffness, axial stiffness, and damping. Full finite element models of the isolating PAF (IPAF) were used once the design progressed.

The most useful analysis method for the isolation trade studies was frequency response analysis. Using this method, transfer functions were generated between main-engine force inputs and spacecraft acceleration outputs. Comparison of these transfer functions between nonisolating PAFs and IPAFs provided considerable insight into the isolation performance. Figure 5 shows the isolation performance for the final IPAF design in this program. Figure 5 shows that the acceleration response will be greatly reduced in the 25–35-Hz frequency range. The amount of broadband attenuation may be indicated by a single number called the rms ratio. This ratio is simply the ratio of the rms of the isolated acceleration power spectral density (PSD) to the rms of the nonisolated acceleration PSD when subjected to uniform white noise input. For the final design, the rms ratio is 0.39 over the 0–40-Hz frequency band, and it is 0.17 over the 20–40-Hz frequency band. These results exceed the program goal of a rms ratio of 0.50.

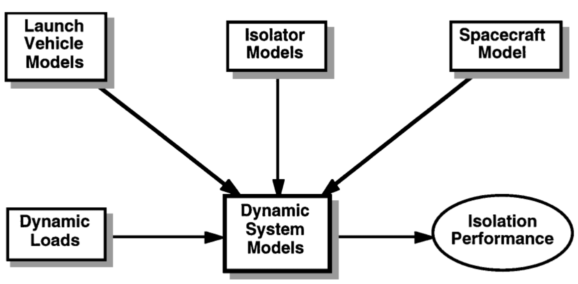

Fig. 4 System-level dynamic analysis.

Table 1 Summary of isolation performance

Location	Direction	Maximum overall[a] acceleration change, %	PREMECO acceleration change, %	rms ratio[b]
Top of	X (lateral)	−30	−33	0.39
spacecraft	Y (lateral)	−31	−33	0.37
	Z (axial)	−9	−69	0.77
Component	X (lateral)	−41	−46	0.37
on top of	Y (lateral)	−29	−30	0.38
spacecraft	Z (axial)	−14	−70	0.42

[a]Maximum liftoff, transonic, and max Q.
[b]Isolated rms acceleration divided by the nonisolated rms acceleration (0–40 Hz).

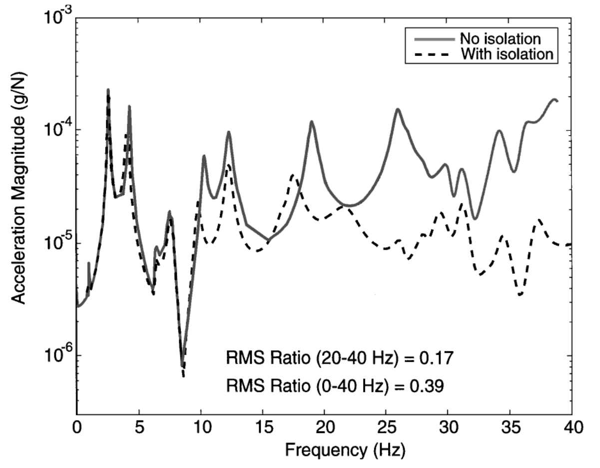

Fig. 5 Transfer function showing lateral isolation.

A thorough coupled-loads analysis was done to evaluate the final design for many other load cases. Table 1 shows the maximum overall accelerations with and without isolation. These acceleration values were the peak values from all load cases analyzed. The IPAF has reduced the peak lateral accelerations by as much as 46%. The system-level analysis shows that the IPAF provides excellent lateral vibration isolation for the spacecraft.

Component-Level Analysis

The isolation system consists of both stiffness components and damping components. The system-level analysis was used to arrive at the optimum values for stiffness and damping of this isolator. Then, using these requirements, the isolator stiffness and damping elements were designed. This process consisted of both hardware design and component-level analyses, using detailed finite element models to size and verify the design.

Hardware Design and Fabrication

One purpose for building hardware in this program was so that it could be tested and the resulting data be used for tuning the mathematical models. High confidence in the IPAF mathematical model gives high confidence in the full system-level, coupled-loads analysis results.

The final design for the IPAF structure and its full-scale hardware implementation are shown in Fig. 6. This design is intended to be a

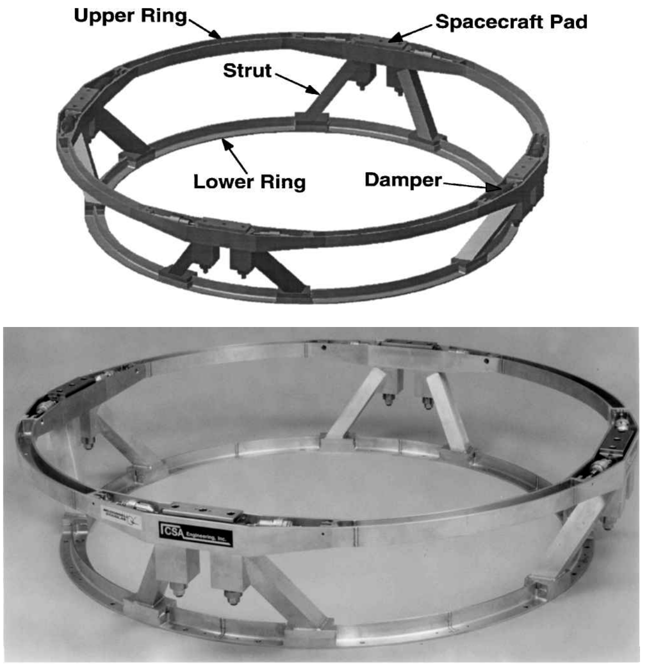

Fig. 6 Passive Isolation for Payloads (PIP) IPAF: solid model and full-scale hardware (1.75-m diam).

slip-in replacement for the existing hard-mount PAF. Care was taken to match the same basic dimensions and bolt patterns. The lower ring bolts to the upper stage of the launch vehicle. The spacecraft bolts at four locations to the spacecraft pads. The load path from the spacecraft to the launch vehicle goes through the spacecraft pads into a flexure system (not shown), then into the upper end of the struts, then down to the lower ring, and finally into the launch vehicle. Space is left between the upper ends of the strut pairs to accommodate a pyrotechnic nut at each spacecraft mounting location.

The original hard-mount PAF, which has flown many times, is fabricated from a monolithic piece of aluminum. The resulting structure has no welds and is extremely costly to manufacture. To avoid prohibitive costs in this program, the full-scale hardware for the IPAF was made from several pieces welded together. Both the lower ring and the upper ring were made from eight machined pieces welded together. The struts were bolted to the upper and lower rings. This fabrication technique was a perfectly reasonable approach for building a nonflight version of this IPAF. A flight version of the IPAF would not have any welds or bolted strut joints.

Hardware Tests

Several tests were performed to measure the stiffness and damping of the hardware for the purpose of test verifying the mathematical models.

The damping element, which is a version of Honeywell's D-strut, behaves like a viscous dashpot and was tested to measure its damping constant. Direct complex stiffness testing resulted in force/velocity transfer functions such as that shown in Fig. 7. This shows the magnitude of the force/velocity transfer function for a damping strut, which was subjected to a medium stroke and 50-Hz bandwidth test. The measured damping constant is independent of frequency, for all practical purposes, and meets the requirements for the system.

The isolator stiffness elements, which consist of a system of flexures, were tested for both their axial and lateral stiffness values. The isolation performance, at the system level, is crucially dependent on the stiffness of these flexures. Table 2 shows a comparison of the stiffnesses from both the test and the finite element model of the flexures. This shows excellent correlation between the model and the test data, indicating that the flexures behave in test exactly as they were designed to.

A modal test was performed on the complete assembled structure to verify that the finite element model is accurate and correctly predicts the behavior of the IPAF. This test was designed to simply extract the first few modes of the structure for use in tuning and validating the model. The measures of comparison between the test and analysis results were a frequency comparison and a mode shape cross-orthogonality matrix. The frequency comparison is shown in Table 3. It can be seen that the frequencies for the first several modes match within about 5%, indicating good correlation.

The mode shapes were compared by calculating the cross-orthogonality matrix between test and analysis mode shapes. An analytical reduced mass matrix was calculated, using Guyan reduction in NASTRAN, and was used in the cross-orthogonality calculation. All data were imported into MATLAB for this process. The cross-orthogonality matrix is shown in Table 4. This matrix indicates that there is excellent correlation between the finite element model and the hardware.

Table 2 Comparison of the stiffnesses of the flexure system

Stiffness direction	Test stiffness, kg/cm	Model stiffness, kg/cm	Difference, %
Lateral	2,775	2,782	+0.3
Axial, tension	298,223	296,437	−0.6
Axial, compression	360,368	359,118	−0.3

Table 3 Frequency comparison between test and analysis

Frequency, Hz		Difference,
Test	Analysis	%
20.65	19.56	−5.3
33.75	32.21	−4.6
37.38	37.78	1.1
77.06	81.78	6.1
83.50	75.70	−9.3

Table 4 Modal test and analysis cross-orthogonality matrix

Test	Analysis				
frequency, Hz	19.56	32.21	37.78	81.78	75.70
20.65	**0.993**	0.012	0.085	0.000	0.023
33.75	0.006	**0.995**	0.030	0.078	0.003
37.38	0.083	0.046	**0.991**	0.002	0.073
77.06	0.015	0.048	0.014	**0.970**	0.020
83.50	0.107	0.007	0.202	0.003	**0.844**

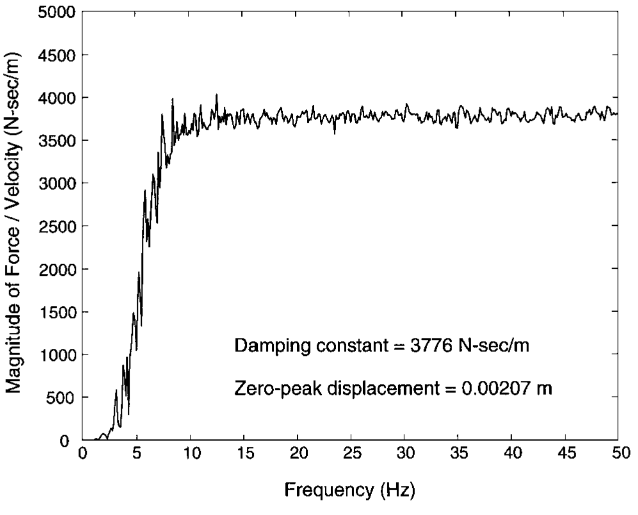

Fig. 7 Results from medium-stroke test of PIP D-strut.

Summary

There is a need to reduce launch loads on spacecraft so that spacecraft and their instruments can be designed with more concentration on orbital performance rather than launch survival. A softer ride to orbit will allow more sensitive equipment to be included in missions, reduce risk of equipment or component failure, and possibly allow the mass of the spacecraft bus to be reduced. These benefits apply to military as well as commercial satellites.

The approach taken in this work is to incorporate an isolation system into the PAF, which is the structure that connects the spacecraft to the launch vehicle. The isolation system was to provide lateral isolation in the 25–35-Hz range, an important dynamic range for secondary equipment.

Whole-spacecraft isolation is a challenging problem requiring a great deal of system-level and detail design engineering. Using realistic models of an LV and spacecraft, coupled-loads analyses were performed for several flight events to determine the optimum isolation parameters. Once these parameters were determined, detailed design analysis was used to develop hardware that would produce the desired results. Full-scale prototype hardware (1.75 m in diameter) was fabricated and tested to verify the analytical models. The IPAF was a one-for-one replacement for the original. At the conclusion of the design phase, complete (all cases) coupled-loads analyses were also performed to verify the performance of the isolation system. This program brings technology to the launch community that may significantly reduce launch vibration problems and reduce risk of spacecraft component failure.

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I. E. Vas
Associate Editor