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Simplifying the Structural Verification Process to Accommodate Responsive Launch

Thomas P. Sarafin and Poti G. Doukas
Instar Engineering and Consulting, Inc.
Littleton, Colorado

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Thomas P. Sarafin and Poti G. Doukas[†]
Instar Engineering and Consulting, Inc.
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Abstract

The time it takes to develop a spacecraft and prepare it for launch is often driven by integration with the launch vehicle: meetings, analyses, and tests that together ensure compatibility. Structural verification (ensuring the spacecraft can withstand launch environments) is particularly time consuming and must be greatly simplified before responsive launch will become a reality. Objectives are to eliminate the need for mission-specific coupled loads analysis (CLA), simplify and standardize the structural test program, minimize dependence on analysis, and reduce technical and schedule risk. The envisioned solution for small spacecraft is to combine three strategies: (1) tighter constraints on the physical characteristics of the spacecraft, (2) variational CLA to assess that range of characteristics, and (3) vibration isolation.

The ideas presented herein originated during DARPA's Responsive Access, Small Cargo, Affordable Launch (RASCAL) program. Unfortunately, that program was cancelled before the ideas could be implemented and demonstrated. This paper captures those ideas and expands on them.

A Major Impediment to Responsive Launch

The traditional process of structural verification for launch-vehicle payloads entails time-consuming loads analysis, stress analysis, and structural and environmental testing. This process typically takes three or more years. Even if we could reduce by an order of magnitude the time it takes to build and assemble hardware and develop software, we still would not have responsive launch unless we do one of the following: (1) Arbitrarily decide not to do the traditional analyses and tests—i.e., bury our heads in the sand and ignore the problem that drove us to that process in the first place—or (2) find a more efficient way to address that problem.

Accepting unknown risk with option (1) would be irresponsible, so we are left with the challenge of making the structural verification process more efficient. First, though, we need to understand the traditional process and why it is what it is.

Understanding the Problem and the Traditional Structural Verification Process

Each unique combination of launch vehicle (LV) and its payload(s) presents a unique structural problem: The mass and modes of vibration for the payload influence how the coupled system will respond to the time-varying forces introduced during launch. Figure 1 illustrates this problem.

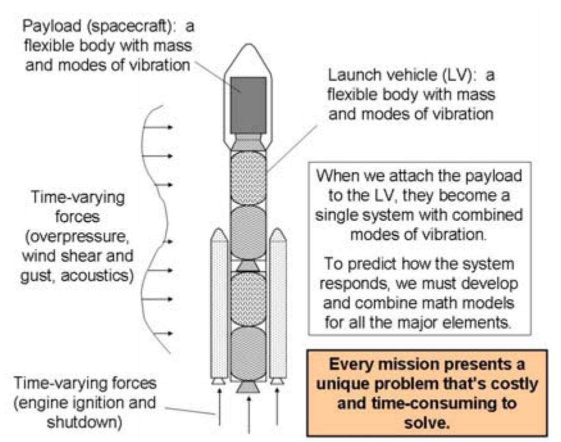


Fig. 1. Predicting Launch Loads is a Difficult, Recurring Problem.

When designing a spacecraft structure for launch environments, we typically start with quasi-static loads specified in the LV user's guide. These loads are intended to be an envelope of those that may occur during launch, as long as the payload meets the constraints on mass properties and natural frequencies defined in the user's guide. However, these loads are temporary, subject to potential increase as a result of *coupled loads analysis* (CLA), which is the response analysis done with a coupled math model created from separate math models of the payload and LV subassemblies. CLA is part of the process referred to as a "loads cycle," which is described in Fig. 2.

[†]tom.sarafin@instarengineering.com, p.doukas@instarengineering.com

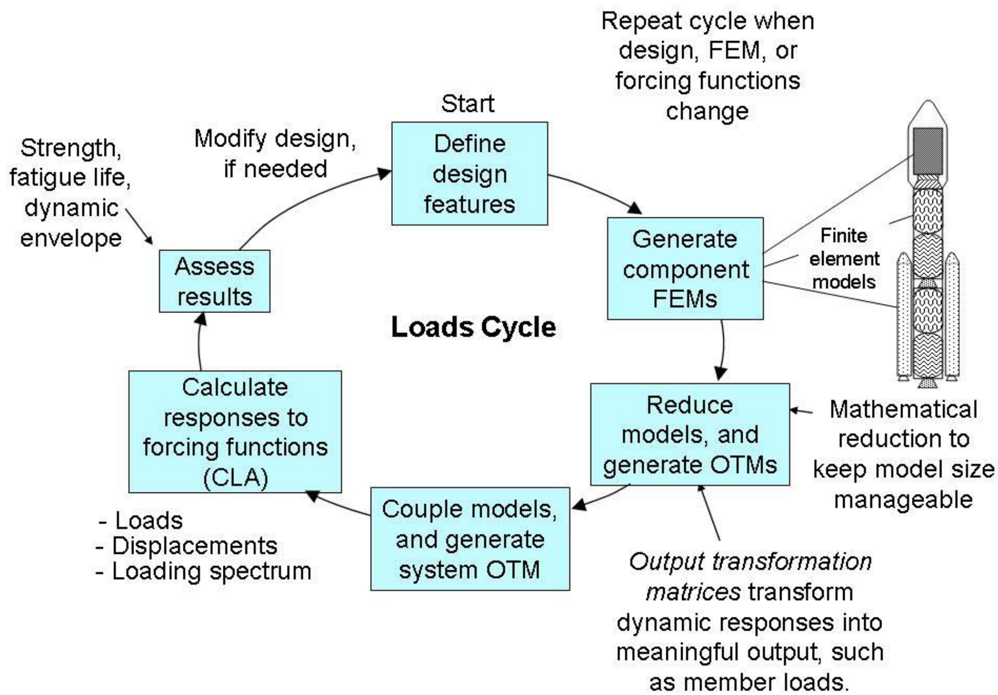


Fig. 2. Loads Cycle. The cycle starts with a design, includes preparation for and performance of coupled loads analysis (CLA), includes assessment of CLA results, and ends with inputs or potential revisions to the design. This process typically takes between three and nine months, and two or more loads cycles are common in support of a single launch.

A loads cycle normally takes between three and nine months, depending on the program. It's a labor-intensive, sequential process, and much of the time is taken up by coordination between organizations. Loads cycles often are not finished on schedule because of inefficiencies in human interaction and problems found with math models and their interfaces.

The larger the payload structure, the lower its natural frequencies tend to be, and the greater the chance of coupling with LV modes of vibration and seeing high response loads. Such coupling can increase loads not only in the payload but also in the LV itself. Thus, missions with one or more large payloads, say 2000 kg or more, tend to invest in three or more loads cycles, with progressively more accurate math models of the payload(s) as the design matures or test data are collected. Even programs with relatively small payloads, however, typically do at least two load cycles, one to support payload design and the other using test-verified math models of the payloads, just before launch.

This final loads cycle with test-verified models is called the *verification loads cycle* (VLC). Although launch organizations may agree to omit any loads cycles that would reduce risk during spacecraft design, none that we know of would consent to launch without completion of a VLC.

As noted above, the VLC uses test-verified math models. Thus, the spacecraft must be tested specifically to obtain data that will enable correlation of its math model. A *modal survey* is a test in which we excite a structure's modes of vibration at low levels to obtain data on natural frequencies, mode shapes, and damping. Such a test usually takes months to plan and perform, and additional months are needed to interpret and reduce data and to correlate the math model. To minimize schedule impact, the modal survey is usually performed before installing flight equipment, with mass simulators in place of the equipment, allowing model correlation and the VLC to take place at the same time the spacecraft is in integration and test.

Strength testing also is typical. Relatively large spacecraft structures are usually tested separately, without installed equipment, just before or just after the modal survey. Static loads testing is most common for large spacecraft structures. Smaller structures are often tested on a shaker instead.

Some programs have flown spacecraft without structurally testing them. Instead, they've used higher factors of safety in design. This approach can add significant risk because, when a structure fails, it's usually in a mode of failure that the analysis did not address. The decision to fly a structure without a test is driven by the desire to reduce cost and time, but whether this desire is truly achieved is debatable. When structural integrity is based solely on analysis, that analysis receives much greater scrutiny by supervisors and stakeholders. And the responsible engineer tends to spend much more time on the analysis in the first place. Thus, with the "no test" approach, we not only add risk, we also may incur greater cost and schedule time than would have been needed to do the test.

After flight equipment and harnesses are installed and tested, the spacecraft undergoes a series of environmental tests. Depending on vehicle size and the preference of the stakeholders, such tests may include vibration testing, shock testing, and acoustic testing. Thermal vacuum testing is common for spacecraft of all sizes and tends to be the most effective in finding defects in design and workmanship. Still, more failures in small spacecraft probably occur during random vibration testing, often the result of over-testing, which is hard to avoid. A failure during spacecraft-level vibration testing easily can delay launch.

VLC results typically are delivered to the spacecraft developer several months before launch, leaving little or no time to respond to any loads problems. Again, the larger the spacecraft, the more likely it is to uncover a problem at such a late date.

It's easy to see that the structural-verification process described above is not conducive to responsive launch. Many tasks in the process are traditionally done in parallel with other program activities, such as spacecraft integration and test (I&T), but as we find ways to reduce the time needed for I&T, we also need to compress the process of structural verification. Otherwise it will become the "long pole in the tent."

Establishing a Vision

Let's begin with the end in mind. We're looking for a process that is much faster and less prone to uncovering design defects late in the program. Thus, we want to …

- Eliminate the need for mission-specific coupled loads analysis.
- Eliminate the need for modal surveys (unless needed for on-orbit jitter concerns).
- Eliminate the need for exchanging math models between organizations.
- Eliminate the need for review and approval of structural analyses and test plans by mission stakeholders (would entail standardizing the structural test).
- Reduce the severity of vibration environments and thus reduce the chances of test failures.

Of course, we want to do all of the above without incurring significantly greater risk of mission failure.

The first thing we need to understand about the above objectives is that it is far more feasible to achieve them for small payloads than for large payloads. Thus, we should aim first at small payloads. If we are successful there, we can try to adapt the process for incrementally larger payloads. A reasonable starting point is to target payloads less than, say, 200 kg (440 lb). A detailed study would identify a true upper limit on payload size for which the envisioned approach is feasible. With a 200-kg mass limit in mind, the following sections address the above objectives individually.

Eliminating the Need for Mission-specific Coupled Loads Analysis

To eliminate the need for mission-specific CLA, we suggest doing many iterations of CLA (*variational CLA*) up front. Within those iterations, we would envelop the range of physical characteristics for payloads and thus define a set of bounding loads for design and test. Doing so is not feasible, though, unless we tighten the physical constraints on payloads.

Payloads are presently constrained by mass, center of gravity (CG), and fundamental frequency, with the actual limits depending on the launch vehicle and (at least for mass) the desired orbit. We are proposing that, for payloads wanting responsive launch, such constraints become more severe.

With the envisioned process, we would analyze the extremities of a design envelope, or "box"; then, if your payload fits inside the box, you can launch without mission-specific analysis.

Probably the most important constraint is on fundamental frequency. For payloads in the 200-kg class, some current lower limits are as follows:

- ESPA (EELV Secondary Payload Adapter): 35 Hz

- Minotaur: 12 Hz (including effects of an isolation system)
- SpaceX Falcon-1: 25 Hz

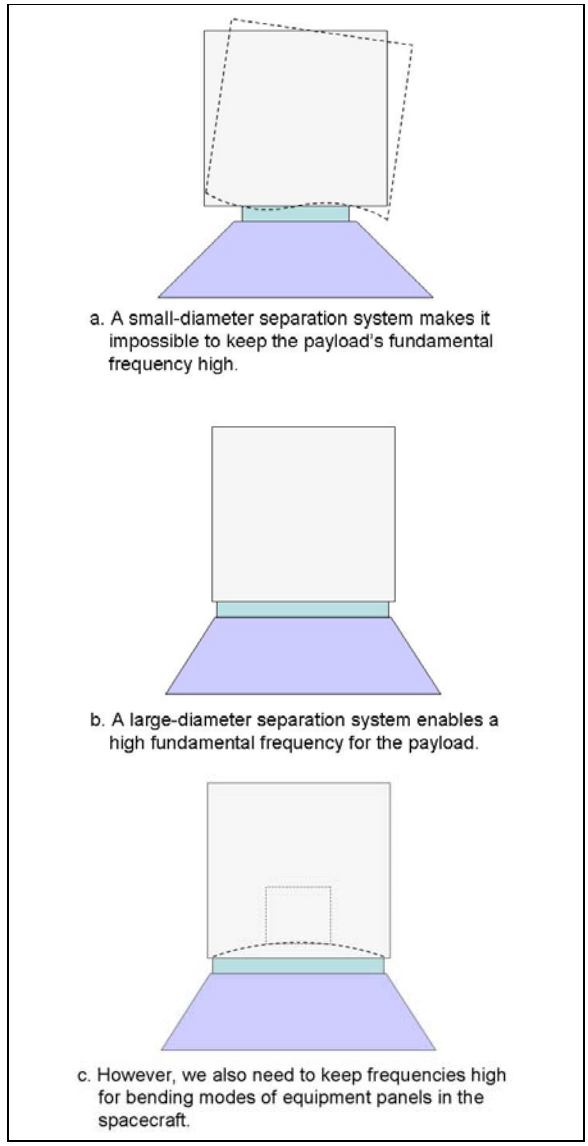
There are two reasons that an LV organization may impose such constraints: (1) reducing risk of high response loads from coupling with the LV and (2) preventing potential loss of vehicle control as a result of low-frequency vibration confusing the control system. If the former is the case, the constraints may reduce risk of high loads, but they don't eliminate them; hence the need for CLA.

Raising the lower limit for a payload's fundamental frequency makes it more feasible to eliminate the need for payload-specific CLA. The high-mass modes of an LV are usually well below 50 Hz. Likewise, transient forces, such as those from engine ignition or a gust of wind, tend not to excite modes above 50 Hz or so. (Above 50 Hz, random vibration, which is typically not addressed in CLA, usually becomes the driver.) Therefore, keeping the payload above 50 Hz or so would lead to minimal likelihood of coupling with the LV.

The lowest natural frequency for payloads in the 200-kg class is typically for a lateral mode in which the spacecraft rocks about its mounting base. Most of the strain energy for such a mode is in bending of the spacecraft's base plate. If we make the cross-sectional dimensions of the spacecraft about the same as the diameter of the separation system (Fig. 3), it is not difficult to keep the fundamental frequency well above 50 Hz. To support the process we propose for enabling responsive launch, LV's should be designed to provide bolt circles and separation systems that have a diameter about the same as that of primary structure for their expected payloads.

As an example, SpaceX's Falcon-1 provides a payload interface with a 38.81" (0.9858 m)-diameter bolt circle for payloads the 700-lb (318-kg) class. Most 700-lb spacecraft will not have a cross-sectional diameter much larger than 38.81". It's not too hard to design a 700-lb spacecraft whose fundamental frequency is above 50 Hz when mounted on such a large footprint. On the other hand, ESPA provides a 15"-diameter bolt circle for payloads up to 400 lb. Most 400-lb payloads will have a cross-sectional width of approximately the 24" that the ESPA payload envelope permits. With so much of a dimensional disparity, it would be nearly impossible to keep the fundamental frequency above 50 Hz.

A study would tell us the appropriate frequency cutoff for a given LV, but 50 Hz is a reasonable assumption for now. We would have to identify appropriate lower limits for a payload's fundamental frequencies in both the lateral and axial (thrust axis) directions. Identifying appropriate frequency cutoffs would require the cooperation of the LV organization beyond the information typically provided in the user's guide.



a. A small-diameter separation system makes it impossible to keep the payload's fundamental frequency high.

b. A large-diameter separation system enables a high fundamental frequency for the payload.

c. However, we also need to keep frequencies high for bending modes of equipment panels in the spacecraft.

Fig. 3. Increasing the Diameter of the Separation Ring Helps Increase the Fundamental Frequency of the Payload.

Once determined, the frequency cutoffs become the lower bounds for the variational CLA that would be used to establish a loads envelope for payload design and test. Natural frequencies above the lower bounds are further removed from the major modes of the LV, which implies less likelihood of modal coupling. Therefore, it is likely that the variational CLA would not have to account for payload fundamental frequencies above the lower limit.

The up-front CLA would have to account for variations in mass, CG, and mass moments of inertia. Existing constraints on mass and CG for a given LV probably would suffice; we simply would have to assess the extremities of the envelope. Constraints on moments of inertia would not be necessary; they would derive from mass and envelope constraints.

Eliminating the Need for Modal Surveys and Exchanging Math Models

If the payload satisfies the constraints described above, and thus does not require CLA, there would be no need to perform a modal survey—at least not for launch concerns. The spacecraft developer still may want to do a modal survey and develop a test-verified math model for internal use if on-orbit jitter is a concern.

For the same reason that a modal survey would not be required for launch loads analysis, neither would transmittal of math models by the payload developer to the LV organization.

Eliminating the Need for Document Review and Approval

The best way to eliminate the need for mission stakeholders to review and approve structural analysis reports is to decouple the verification from the analysis: Require a test.

The best way to eliminate the need for stakeholders to review and approve test plans is to standardize the required test. In other words, remove the role of analysis from the test.

Standardizing the Structural Test

Given that, with the envisioned process, there would be no mission-specific CLA and no delivery of analysis reports to the LV organization, verification for launch readiness would be solely by test. For relatively small payloads, the required test program would be intentionally simple, as defined below. Spacecraft developers may choose to supplement this test program in order to reduce risk of test failure at the spacecraft level.

Most small payloads do not respond much to acoustics, making acoustic testing unnecessary. Assuming this is the case, the envisioned structural test program would be with an electrodynamic shaker. In each of three orthogonal axes, the following tests would be done at the full spacecraft level:

- Low-level sine sweep (0.1 g peak) to verify that the fundamental frequency is above the required minimum.
- Sine-burst test at 1.1 times limit load to verify strength for the payload's primary structure.
- Random vibration test to verify integrity of secondary structures, spacecraft equipment, and electrical interfaces.

From the standpoint of the LV organization, there would be no need for shock testing of the payload, as shock seldom causes catastrophic structural failure. Shock can cause electronics and small items such as valves to fail, which may lead to the spacecraft being unable to perform its mission. Thus, whether shock testing is done would be up to the spacecraft developer. To reduce risk of shock-induced failure during launch, the selected separation system should impart low shock to the payload and dissipate shock from other sources. A vibration-isolation system, discussed below, may be of great help here.

The test program defined above is not different than the approach many small-satellite programs use. The difference we are proposing is that the tests be standardized in a way that removes options that affect test adequacy while also eliminating the need for pre- and post-test analyses.

On the surface, a sine-burst test appears to be a simple test. Let's say the fundamental frequency of our spacecraft is 50 Hz and the limit quasi-static acceleration is 10 g. If we want to do a strength test to, say, 1.1 times limit load, we introduce a sinusoidal acceleration of 11 g at 15 Hz or so in a short burst, gradually ramping up to full level and then ramping down. Because the input frequency is so much lower than the spacecraft's fundamental frequency, the spacecraft moves nearly as a rigid body with the shaker, with very little dynamic amplification. As a result, the spacecraft experiences near-uniform acceleration of 11 g.

However, a key complication is that the specified quasi-static loads for a spacecraft typically are not uni-axial. In other words, a typical specified load case is something like, "+/-8 g's in the X direction acting simultaneously with +/-5 g's in the Y direction." Given such a load case, what sine-burst test would we do for a strength test? Let's ignore the test factor (1.1 in the above discussion) while we address this question. There are several possible solutions, all of which are being used, depending on the organization.

Company A decides to do an 8-g sine burst in the X axis and a 5-g sine burst in the Y axis. This approach is clearly inadequate. If the two accelerations can indeed occur at the same time during launch, testing individually in each axis would not adequately stress the structure.

Company B computes the vector sum of acceleration by taking the root sum of the squares (RSS), arriving at 9.4 g's. They decide to do the sine-burst test at 9.4 g's in each axis. Although this approach is better than the one taken by Company A, it still may not be an adequate test for strength. As an example, consider a square bolt pattern supporting an electronics box, with a bolt at each corner of the pattern. The bolt pattern is in the X-Y plane and is symmetrical about the X and Y axes. Acceleration of the box in the X axis causes a moment about the Y axis acting on the bolt pattern, and vice-versa (plus or minus). In this case, a combined load case of 8-g X and 5-g Y would cause a greater tensile load in one of the bolts than would a uni-axial case of 9.4 g's in either the X axis or the Y axis.

Company C recognizes the shortcomings in Company B's approach and decides the only way a test to 9.4 g's would be an adequate strength test is if the 9.4 g's were applied in the directions of the RSS'd load vectors. (More than one direction applies because the possible sign combinations of X and Y loading.) Thus, Company C decides to build a special fixture to rotate the spacecraft relative to the shaker's axis.

Company D recognizes that Company C's approach, while technically correct, complicates the test, driving cost and schedule as a result of the special fixture and additional setup time. Company D decides to keep the spacecraft's axes aligned with the shaker's axes, as is typically done for random vibration, and to increase the acceleration in each axis as needed to ensure the critical regions of the primary structure would be adequately tested. In the case of the square bolt pattern, to ensure at least one bolt sees as much tension in a uni-axial test as it would see for the specified multi-axis load case, the test would have to be done at 8 + 5 = 13 g's.

For responsive launch, we don't want the decision on how to convert the specified quasi-static loads into a sine-burst test to be an issue. Issues take time to resolve. Instead, we want to simplify and standardize the process. Thus, the design loads should be specified as single-axis load cases, the same way the loads will be introduced in a sine-burst test. The envelope of loads resulting from the variational CLA (discussed above) should be converted into equivalent single-axis load cases, e.g., "Case 1: 8-g X; Case 2: 8-g Y; Case 3: 10-g Z." Such load cases are "equivalent" in that, as a set, they are sure to stress each area of the structure at least a severely as did the variational CLA. With the right assumptions, it is possible to derive such load cases without knowing the actual details of a spacecraft's structural design.

The equivalent single-axis accelerations may be excessive for most payloads in order to be sufficient for all payloads. We can reduce this unwanted, weight-penalizing conservatism by planning ahead during the variational CLA so we can recover useful response loads. For example, summation of moment at the spacecraft's mounting interface about axes that are 45 degrees apart, calculated time consistently in the CLA, would be more useful than X, Y, and Z accelerations at the tip of the spacecraft. Still, we should allow the option of less-penalizing, multi-axis load cases for payloads that can't withstand the specified single-axis loads.

Another aspect of testing on a shaker that is often controversial and thus entails considerable outside review is notching of a base-driven vibration test environment. If the vibration levels are not reduced ("notched") at the spacecraft's fundamental frequency, the primary structure probably will be severely over-stressed, with much higher response loads than would occur during launch. Notching is intended to make the test more realistic, given limited energy in the vibrating LV. Justifying the extent of notching, however, often requires spacecraft-unique analysis. Of course, any spacecraft-unique analysis entails time to perform and time to review and approve by mission stakeholders.

Two ways of avoiding the need for analysis related to notching come to mind: (1) standardizing the notching process as part of the test standard and (2) not allowing notching. The latter approach would simplify things the most, but it would be feasible only if we either can meet requirements with an over-designed structure or do something to reduce the spacecraft's response to the un-notched environment. Adding a vibration-isolation system to the payload mounting interface may be the solution to that problem. Isolation is discussed in a later section of this paper. Here we will discuss the option of standardizing the notching process.

The first step in notching is to determine a target response level. For example, let's say we are planning to shake the spacecraft laterally, in the mounting plane. The load we are most concerned about usually is the overall moment at the mounting interface. If we can measure this moment during test, we can devise a notch to ensure the 3-sigma moment does not exceed a defined target moment. The trick is not in measuring the moment (we can do so with force gages or by other methods) or in controlling the environment to hit the target moment (shakers can be controlled with a process called "force limiting"), but in defining an appropriate target moment in the first place, one that will ensure an adequate test while also protecting the hardware from unrealistic loading.

The Jet Propulsion Laboratory has done considerable research on force limiting as a method of notching and has devised analytical processes for establishing an appropriate force (or moment) limit, based on relative impedance of the spacecraft and its mounting structure during launch. However, from our experience, many potential practitioners do not understand these methods and thus do not use them.

In support of responsive launch, it would be far easier and less controversial if the engineering community would agree on one thing: Random vibration during launch, which is mainly the result of lightweight panels and shells responding to acoustics, does not have enough energy to cause overall acceleration of a 200-kg spacecraft that exceeds the acceleration caused by steady-state and transient loads, which are assessed with CLA. If we could get such agreement, the force (or moment) limit used in notching a random vibration test would simply be the limit quasi-static loads generated to envelop the variational CLA (or some percentage of those loads). Some programs already are taking this approach.

With this approach, notching would be permitted only to limit the overall force or moment at the base of the spacecraft. Many programs presently notch to reduce other responses, such as the peak acceleration of a mounted electronics box on a support panel. Establishing appropriate notching targets for such responses is time-consuming and subject to risk.[*1] It's not conducive to responsive launch. Therefore, we suggest that such notching not be permitted when responsive launch is the priority. Instead, spacecraft developers should design and test components and structural panels for the full response levels expected during spacecraft testing. Of course, such loads may well be far more severe than the launch loads, but it may be an acceptable price for responsive launch. Many programs presently design equipment and mounting panels for conservative loads based on one of several mass-acceleration curves that have been generated with the intent of enveloping vibration loads without having to do configuration-specific vibration analysis.

Reducing the Severity of Vibration Environments

Despite the above comments, test failure during vibration testing is a significant risk to responsive launch. Many small-spacecraft programs are delayed because of such failures. Effective use of vibration isolation can significantly reduce this risk.

Mounting spacecraft on isolation systems is not a new idea. The Minotaur LV offers an isolation system as an option, and the system has proven effective at reducing the effects of transient loading and base-driven random vibration. We believe such a system can make launch more responsive as part of the overall vision described herein.

Because of the stated objective of keeping the spacecraft's natural frequencies well above those of the LV's major modes of vibration, the benefits of an isolation system would be reduced response to base-driven random vibration and shock more so than reduced response to transients. The greatest benefits related to random vibration would be in test as opposed to launch, given the additional objective, as stated above, of not permitting notching at secondary modal frequencies.

As an example, let's say we were to put a 50-Hz spacecraft on an isolation system tuned to create a highly damped 20-Hz mode of the spacecraft rocking or bouncing as a rigid body. (The actual target frequency would depend on the modes of the LV.) Random vibration energy is very low near 20 Hz, so the fundamental mode of the spacecraft moving on the spring of the isolation system would see very little response. Notching probably would not be necessary. The spacecraft's own modes of vibration would be isolated to some extent from the shaker and thus would respond less to the vibration environment.

To accommodate a wide range of payload mass properties, several designs of isolation systems probably would be necessary. Each design would be compatible with a subset of payload mass properties.

Use of such an isolation system is compatible with the objective of eliminating the need for mission-specific CLA. It actually may make that objective easier to realize because isolation would make

[*] After a 1997 launch aboard a Pegasus XL, no contact could be made with the Space Test Experiments Platform #4 (STEP-4) spacecraft. The failure investigation report concluded that the most likely cause of failure was low-frequency vibration that exceeded the spacecraft test levels. The test environment had been reduced to limit the response of an equipment panel that had a mode similar to that shown in Fig. 3c. Unfortunately the frequency at which the test environment was reduced was the frequency of a major mode of vibration in Pegasus during captive carry.

dynamic response less sensitive to the payload's design variables.

Realizing the Vision

The key enabler to the envisioned simplified process for structural verification is the ability to do rapid iterations of variational CLA. It's easy to see that what we propose would entail CLA for a large number of combinations of payload characteristics. With traditional CLA software and processes, analyzing such a large set of variables is not practical. Assessing sensitivity of a model change requires making the change at the FEM level, prior to mathematical reduction and coupling. Thus, a significant portion of the process shown in Fig. 2 must be repeated for each iteration.

However, the enabling technology for the envisioned structural verification process does exist. At least one company has succeeded in streamlining the process to make rapid iterations with CLA feasible. The *ASD/Enigma* software developed by Applied Structural Dynamics, Inc., uses a "multi-body" approach to greatly improve the efficiency of CLA and to enable rapid iterations with varying model parameters. A case study[2] with this software included 114 full CLAs for the Space Shuttle (six manifest configurations times 19 stiffness variations), each with twelve liftoff and 7 landing forcing functions. The study was completed with a single work station in one calendar week and 40 engineering hours. Other companies also have made significant improvements to the CLA process in recent years.

The key point here is that the technology for variational CLA exists. Other technologies, such as vibration-isolation systems for full spacecraft, also have been developed and demonstrated. These technologies have yet to be combined and implemented the way we are suggesting.

The Next Step: A Detailed Study

We have established a vision and described a process for streamlining the structural verification process and removing it as an impediment to responsive space. To make the vision a reality, a detailed study is needed to answer the following questions:

- Would spacecraft developers be able to live with the resulting constraints on mass properties and natural frequencies?
- How harsh would the enveloping payload design and test loads be for a given launch vehicle?
- How effective would an isolation system be in reducing the effects of random vibration and shock while still supporting the other objectives and satisfying all necessary constraints?
- For how heavy a spacecraft is the process feasible?
- What are the impediments, if any, that may prevent this process from being implemented, and how do we address them?

To answer such questions, the study would entail a "dry run" of the full process for a selected launch vehicle, including identification of appropriate payload constraints, conceptual design of an isolation system, variational CLA with and without the isolation system, definition of enveloping quasi-static loads for design and test, and random vibration response analysis.

Summary

Responsive launch will not become a reality until we simplify and standardize the structural verification process. We have the tools to address launch environments up front for a range of physical characteristics for payloads. For relatively small payloads, it is feasible to establish practical constraints on those characteristics that would allow launch without a dedicated coupled loads analysis.

Standardizing the structural test program for small spacecraft also is feasible. Benefits include less time required for test planning and data reduction. In addition, verification would have little, if any, dependence on analysis and its accompanying assumptions.

Finally, the use of an effective vibration-isolation system would reduce the severity of payload vibration, particularly during ground testing. As a result, there would be less risk of test failure and associated launch delay.

While the intent is to enable responsive launch by imposing constraints on payload development, we recognize that freedom from such constraints may be of higher priority than responsive launch to some programs. Thus, we suggest that the constraints be offered as an option; any program may opt instead for the traditional three-year development process.

A detailed study is required to iron out and demonstrate the process we propose, and to answer several key questions.

Again, the enabling technologies exist for achieving the established vision. The keys to implementation are effective mechanical systems engineering, adequate funding for an effective study, and cooperation from one or more launch-vehicle programs.

[1] "AFI 51-503, Space Accident Investigation Report for Space Test Experiments Platform Mission 4 (STEP-4)," 29 June, 1998. Air Force Materiel Command.

[2] "Variational Coupled Loads Analyses: Reducing Risk in Development of Space-Flight Hardware." A. Majed, K. Partin, E. Henkel, and T. Sarafin. Journal of Spacecraft and Rockets, Volume 42, Number 1, Jan-Feb 2005.