Vibration Testing of Small Satellites

This series of papers provides a tutorial along with guidelines and recommendations for vibration testing of small satellites. Our aim with these papers is to help you (a) ensure the test meets its objectives in demonstrating flight worthiness and (b) avoid test failures, whether associated with a design deficiency or with excessive loading during test. Addressed are sine-burst testing, random vibration testing, and low-level diagnostic sine sweeps. Although much of the guidance provided in this series applies to CubeSats, the series is primarily aimed at satellites in the 50 – 500 lb (23 – 230 kg) range. Most of the guidance applies to larger satellites as well if they will be tested on a shaker.

The plan is for this series to include seven parts, each of which will be released when completed:

1.	Introduction to Vibration Testing	(released April 11, 2014; last revised July 19, 2017)
2.	Test Configuration, Fixtures, and Instrumentation	(released April 11, 2014; last revised July 19, 2017)
3.	Low-level Sine-Sweep Testing	(released May 13, 2015; last revised July 19, 2017)
4.	Sine-Burst Testing	(released April 28, 2017; last revised July 19, 2017)
5.	Random Vibration Testing	(released April 7, 2016; last revised July 19, 2017)
6.	Notching and Force Limiting	(released May 13, 2015; last revised July 19, 2017)
7.	Designing a Small Satellite to Pass the Vibration Test	(yet to be released)

The most recent versions of these papers are available for free download at

http://instarengineering.com/vibration_testing_of_small_satellites.html.

Part 1: Introduction to Vibration Testing

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Most satellites weighing less than about 500 lb (227 kg of mass) are tested on electrodynamic shakers in each of three orthogonal directions, as shown in Fig. 1-1. Some larger spacecraft are tested on shakers as well, depending on stakeholder preference.

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Part 1 of this series explores some important aspects of testing in general and vibration testing on a shaker in particular.

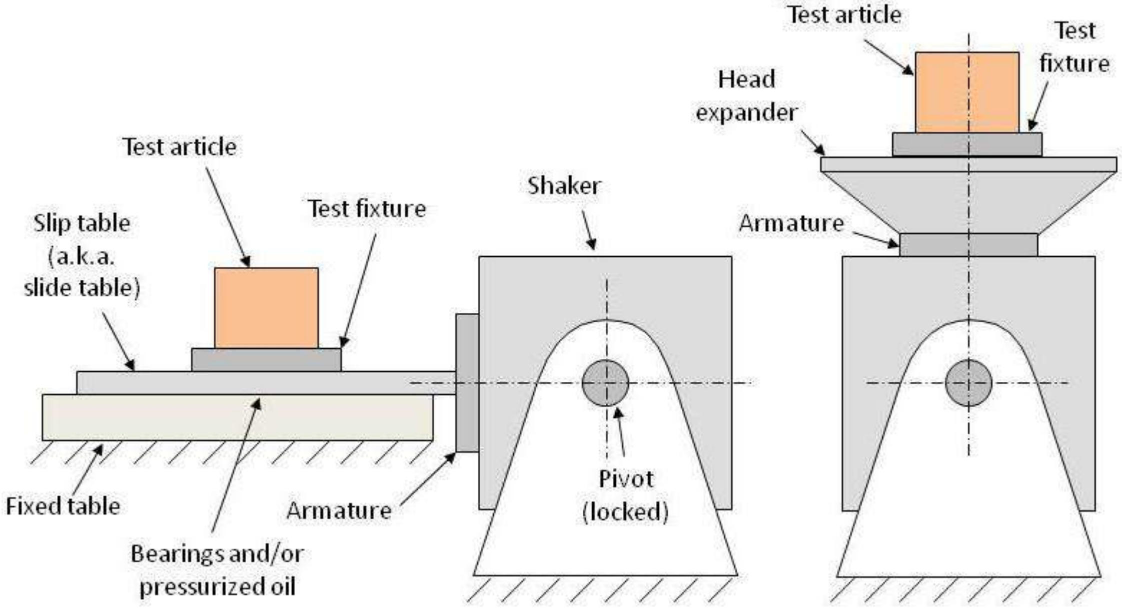

Fig. 1-1. Test Configuration on a Shaker. The armature moves relative to the fixed base to a controlled acceleration and frequency or to random acceleration and frequencies. The test fixture adapts the mounting interface of the test article (small satellite in this case) to the grid of threaded inserts in the slip table and the head expander.

Two Things All Tests Need

Every test needs two things: (1) clearly defined objectives and (2) criteria for judging whether the test met the objectives.

The reason we test a small satellite on a shaker is <u>not</u> that there is a requirement to do so. There may be such a requirement, but the test won't mean much if that's the only reason we do it. Most often, we do a vibration test to establish confidence that the satellite can withstand the launch environment and still function afterwards. The process of establishing confidence—our own and that of other stakeholders—is called ***verification***. In the space industry, verification seldom entails proof, at least not when random variables—such as those associated with launch environments—are involved. When they are, we use a combination of analyses and tests to establish confidence that the mission will be successful.

In other words, the main objective of vibration testing on a shaker is to ***verify compliance*** with certain structural and mechanical requirements, specifically to establish confidence that

- the spacecraft structure, payload(s), equipment, and other hardware can withstand—and function as needed after exposure to—the highest load during the mission (***strength*** verification and verification that relative alignment of critical components or interfaces is maintained);

- the above spacecraft hardware can withstand—and function as needed after (and during, for any equipment that must operate during launch) exposure to—cyclic loading associated with launch vibration and, to some extent, verify ***fatigue life*** of the materials;
- electrical connectors will remain seated during the launch environment;
- the satellite will maintain general integrity, e.g., no bolted joints loosening because of lost fastener preload and no parts coming loose or free from containment;
- and the satellite meets any specified constraints on natural frequencies (typically applies to the launch configuration in order to avoid dynamic coupling with the launch vehicle and subsequent high loads).

An additional objective of vibration testing often is to acquire data that will enable correlation of the finite element model for use in coupled loads analysis and any other important analyses.

When planning and designing a test, always start with a clear definition of test objectives. Then design a test that satisfies the objectives.

To simulate and envelop the effects of launch environments, we test small satellites most commonly with sine burst and random vibration, which are described later in this paper. Some larger spacecraft are tested for sinusoidal vibration (a.k.a. "sine vibe") on a shaker, and nearly all large spacecraft are tested for acoustics in an acoustic chamber instead of shaker-driven random vibration. But sine-vibe testing is omitted for most small satellites, as any sine environment that may apply is typically encompassed by the combination of sine-burst and random vibration environments. Instead, for a small satellite we may do low-level sine-sweep tests to characterize dynamic behavior rather than to stress the hardware.

Shock testing, most often with the intent of encompassing the effects of high-frequency, low-energy shock caused by separation explosives (***pyrotechnic shock***), is less commonly done on shakers and is not addressed further in this series of papers. The force rating of the shaker limits acceleration levels such that the test could be done only if the shock environment is relatively low, and when levels are low, there is little risk of failure.

The second thing all tests need is pre-defined criteria for judging whether the test article passed the test (***pass/fail criteria***) or whether the test otherwise met its objectives (***success criteria***). If the test objective is to establish confidence in some aspect of the test article, we define pass/fail criteria; if the test is for the purpose of acquiring data, we define success criteria. There is no point in doing a test if we have no way of knowing afterwards whether the objectives were satisfied. Criteria specific to sine-sweep, sine-burst, and random vibration testing are addressed in parts 3, 4, and 5, respectively.

Before taking a closer look at types and classes of vibration tests, let's take time to understand transmissibility.

Transmissibility

To understand how a structure responds to vibration introduced at its base, consider a mass on a spring, which we refer to as a ***single-degree-of-freedom*** (SDOF) ***system***, with unit (1 *g*) sinusoidal acceleration introduced at the base of the spring. The ***transmissibility*** function, $T_R(f_{\text{ratio}})$, gives the peak response acceleration of the mass as a function of f_{ratio}, which is the ratio of input frequency, f, to natural frequency, f_n, of the SDOF system.

$$T_R(f_{\text{ratio}}) = \sqrt{\frac{1+(2\zeta f_{\text{ratio}})^2}{\left[1-f_{\text{ratio}}^2\right]^2+(2\zeta f_{\text{ratio}})^2}} \tag{1.1}$$

where ζ is the damping ratio (damping factor divided by the critical damping factor). Figure 1-2 shows the transmissibility function for several damping ratios.

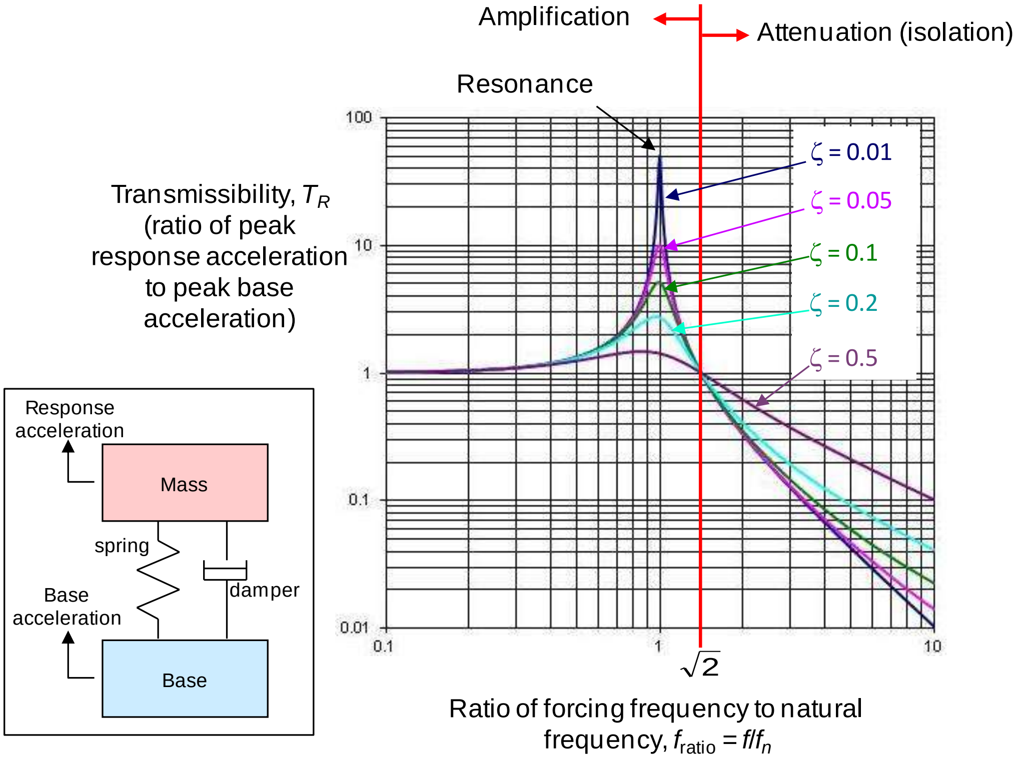

Fig. 1-2. Transmissibility.

Resonance, which occurs when a maintained sinusoidal forcing frequency is the same as the system's natural frequency, is an equilibrium condition in which the energy added by the next cycle of input is balanced by the energy lost from damping. Thus, at resonance, the peak response is limited by the damping in the system. The ***quality factor***, Q, is the transmissibility at resonance and is approximated by

$$Q \cong \frac{1}{2\zeta} \tag{1.2}$$

At forcing frequencies well below the system's natural frequency, the mass moves very nearly with the mounting base, with little dynamic amplification. If the forcing frequency exceeds about 1.41 (square root of two) times the natural frequency, the mass responds with less acceleration than that of the base, a situation referred to as ***isolation***.

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Understanding transmissibility is key to understanding how a structural assembly responds to testing on a shaker, regardless of whether the shaker imparts sinusoidal acceleration at a single frequency (sine-burst, sine-sweep, sine-vibe, or sine-dwell test) or at multiple, simultaneous frequencies at random amplitude and phase (random vibration test). A sine burst is at low frequency, well below the test article's fundamental frequency, to avoid dynamic response, and a random vibration test excites all modes within the test spectrum simultaneously at random amplitudes. When damping is relatively low—say, below 10% of critical—response of any mode of vibration, as characterized by acceleration measured at a particular location, is essentially sinusoidal, just like the mass on the spring.

Common Types of Tests on a Shaker

In a ***sine-burst test***, the shaker introduces a sinusoidal acceleration at the base of the test article, with gradually increasing, then maintained, and finally decreasing amplitudes, all at constant frequency. The sinusoidal frequency is selected to be significantly lower than the fundamental vibration frequency of the test article in order to minimize dynamic response or amplification of the acceleration. In this way, we subject the test article to near-uniform acceleration, analogous to a quasi-static load, which is often used for structural design.

The objective of a sine-burst test is to verify that the satellite's ***primary structure***—the body structure and the launch vehicle (LV) interface—has enough strength to withstand the maximum expected loads during launch, which we refer to as ***limit loads***. The test may be run to some factor above limit loads, depending on the test philosophy or criteria, as discussed below.

In a ***random vibration test***, an electro-dynamic shaker is controlled to introduce vibration at frequencies typically between 20 and 2000 Hz in the space industry. All frequencies within the applicable range are introduced simultaneously at random amplitude and phase.

One of the objectives of a random vibration test is to verify strength of ***secondary structures***, which include equipment housings, mounting brackets, and electronics boards. Because the test is not truly flight-like, we must be careful to avoid unrealistic and excessive loading, i.e., loads significantly higher than the maximum expected mission loads, which is of most concern for the primary structure. When properly justified, ***force limiting***, which is discussed in Part 6 of this series, is an accepted method of ***notching*** (reducing the input environment at certain response frequencies) to avoid excessive loading.

Random vibration testing also builds confidence in general structural integrity for structures as small as solder joints, whose materials are stressed by a vibration environment. In a random vibration test, we are trying to confirm that fasteners won't loosen and electrical connectors won't separate during the vibration of launch. Because it causes cyclic stress in materials, random vibration testing also establishes confidence in material fatigue life, although the extent of this confidence depends on whether the test is on the flight hardware or on test-dedicated hardware, as discussed in the section below on class of test.

In a ***sine sweep*** or a ***sine-vibe test***, the shaker imparts a sinusoidal input at gradually increasing or decreasing frequency, most often as a logarithmic function of time. If the test is done to envelop any sinusoidal vibration during launch[1] and thus be a test for structural integrity, it is traditionally referred to as a ***sine-vibe test***, and the input acceleration may vary with frequency. A ***low-level sine sweep*** refers to a test done at a low, constant acceleration in order to obtain response data that indicate natural frequencies and damping. With accelerometers to measure response at multiple locations, we can acquire data on mode shape as well.

A random vibration test also can be conducted at a low, constant level across a frequency spectrum in place of a sine sweep to acquire information on natural frequencies, mode shapes, and damping.

A sine sweep or a low-level random vibration test is typically done before any other tests in each axis in order to establish a baseline response plot over the frequency range of interest. We repeat the low-level test after each of the full-level sine-burst and random vibration tests. We then compare pretest and post-test response plots to see if anything has changed in the structure as a result of the full-level test.

A ***sine-dwell*** test is one in which sinusoidal vibration is input at constant frequency, same as for a sine-burst test, but in this case the frequency is intended to coincide with the natural frequency of a target mode, and the input is maintained until resonance is achieved. Such tests are used to acquire data typically for the purpose of correlating a model or investigating an anomaly.

Most small satellites are tested for sine burst and random vibration, with either sine sweep or low-level random for diagnostic purposes. Large satellites, on the other hand—if tested on a shaker at all—are typically tested only to specified levels of sine vibe along with low-level diagnostic tests. In place of random vibration testing on a shaker, a large spacecraft is tested in an acoustic chamber because, during launch, most of the random vibration in the spacecraft will be driven by acoustic response of the spacecraft's low-mass panels and shells rather than by vibration at the mounting interface. In place of sine-burst testing, the structure of a large spacecraft is typically tested with static loads. Such loads are commonly introduced with hydraulic jacks, with a computerized system to control pressure to make the load in each jack, as measured by calibrated load cells, equal to the target value per the test design.

A static loads test is generally a better strength test than a sine burst if the bulk of the launch loading environment on the primary structure is from steady-state acceleration rather than from vibration. This is the case for most large spacecraft as well as the primary structure of the launch vehicle. Part 4 of this series addresses limitations in the types of structural failures that can occur in a sine-burst test.

Spacecraft in the 500 – 1000 lb (227 – 454 kg) class are in the gray area in that it may not be obvious whether we should test them as small satellites, with sine burst and random vibration on a shaker, or as large spacecraft, with static loads and acoustic testing (and perhaps sine-vibe testing as well). Whether acoustic testing is more appropriate than random vibration testing depends on the spacecraft configuration, i.e., whether there are large-surface, low-mass panels and shells that respond highly to acoustic pressure. Analytical predictions[2] should guide us into the proper test.

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[1] If the launch services provider (LSP) specifies a sine-vibe environment, ask to find out whether the LSP requires the test or is providing the environment as a service in case you want to test for it. If the test is required, find out if it simulates an actual environment, and you have to achieve certain levels of response, or if the test is required only as a workmanship screen without trying to envelop any actual sine environment during launch.

[2] Section 7.7 of Ref. 3 demonstrates a relatively simple method of vibro-acoustic response analysis.

Class of Test

A structural or environmental test can be classified as a qualification test, a protoqualification or protoflight test, or an acceptance test.

A ***qualification*** (or simply ***qual***) ***test*** is done on dedicated hardware that is not intended to fly, with the objective of establishing confidence in a design; if the hardware passes the test, we say the ***design is qualified***. The qualification hardware is built to the same design and with the same manufacturing processes as the flight hardware, and it's tested to environments that are more severe than anything the flight hardware will see.

A successful qualification random vibration test establishes a ***qualification margin***—the difference between the qual environment and the maximum predicted environment (MPE) for the mission, which is the most severe environment the flight hardware should ever see. The qualification margin is intended to account for build-to-build variation between the qual hardware and the flight hardware. To some extent, it also accounts for the possibility that the actual launch environment exceeds MPE, which is statistically based.

For ductile materials, most failures occurring in a random vibration environment are fatigue failures, so duration is an important parameter for qualification random vibration testing in order to ensure adequate margin is demonstrated for fatigue life. For qualification random vibration testing, the military standard, SMC-S-016 (Ref. 1), calls for levels that are 6 dB higher than MPE and a test duration up to three minutes per axis. The NASA standard, per NASA-STD-7001A (Ref. 2), is 3 dB higher than MPE, two minutes per axis. (See Part 5 for a tutorial on random vibration environments, as they are traditionally defined, as well as decibels and other terminology.)

An ***acceptance test*** is a test done on flight hardware, typically to MPE. If the design has already been qualified by successful qualification testing, the purpose of acceptance testing is to confirm process control, including workmanship. In other words, although the qualification margin accounts for some degree of build-to-build variation, we test each build for acceptance to screen out defects that are outside the demonstrated qualification margin. Military and NASA standards (Refs. 1 and 2) agree on one minute of random vibration testing per axis for acceptance.

A ***protoqualification*** (a.k.a. ***protoqual***) test (military term) and a ***protoflight*** test (NASA term) are very nearly the same thing—a test of the flight hardware to levels that are more severe than MPE in absence of a previously qualified design—although there are subtle differences that we won't explore here. This test approach may be selected in lieu of separate qualification and acceptance tests when production volume is low and building and testing dedicated test hardware is not affordable. It's a common approach for one-of-a-kind spacecraft that are to be launched without a flight crew. With this approach, if multiple spacecraft of the same design are built, the first-built vehicle is tested for protoqual or protoflight levels and durations, and subsequent builds are tested for acceptance to MPE levels. If only one spacecraft is built, it is tested the same as would the first-built spacecraft of a fleet.

There is more mission risk with the protoqual approach because there is no practical way of knowing whether the flight hardware has enough fatigue life after testing to make it through the mission. Testing flight hardware for random vibration is effective at screening out failures that occur within the first few high-level loading cycles—failures referred to as ***infant mortality failures***—but, without reliable post-test inspections for cracks, there's no sure way of knowing whether the test caused fatigue cracks that may propagate to failure during the mission. Accordingly, the protoqual or protoflight approach may not be acceptable to stakeholders for missions that have high consequence of failure, such as manned missions. When the protoqual or protoflight approach is adopted, it makes sense to put more emphasis on fatigue analysis as a supplement to the test program.

Structural Qualification Testing Prior to Vehicle Integration

Even when a program selects protoqualification or protoflight testing of the flight structure in lieu of traditional qualification testing of nonflight hardware, the spacecraft structure should be tested before the flight payloads and equipment are installed. Doing so avoids risk of structural failure late in the program, when recovery may not be viable and when such a failure could damage flight payloads and equipment. In addition, performing a sine-burst test of the structure prior to vehicle integration allows that test to be omitted at the vehicle level of assembly. From our experience, a sine burst is the most difficult environment for a shaker to control; we've seen several instances in which inability to control a pure sinusoidal input led to dynamic loads in the test article that significantly exceeded the intended loads.

When testing the spacecraft structure on a shaker before the payloads, equipment, electrical harness, and other items are integrated, it's important to include mass simulators that represent all sizable payloads and equipment, mount the simulators in a flight-like manner, and make the overall mass properties of the test article representative of those predicted for the flight vehicle. Total mass should be at least as high as the integrated satellite's ***design mass*** (or ***mature mass***), which is the predicted mass plus applicable growth allowance. To ensure the test is adequate given uncertainty in the final mass of the vehicle, it may be wise to add additional mass to the test structure, over and above the design mass, thus demonstrating margin. Doing so, however, is a viable option only if analysis shows (a) the structure can withstand the associated extra load and (b) the additional mass does not cause modes of vibration to change in a way that would lead to some of the structure being under-tested. Note that the second consideration (b) should be expanded to ensure any measured environments to be used for component testing are not understated.

Center of gravity (CG) of the test article is also a consideration when designing mass simulators. The CG of the fully assembled structural qualification article, including mass simulators, should match that predicted for the flight vehicle within a reasonable tolerance. A suggested target tolerance is 1% of the satellite's dimension in the corresponding axis (e.g., lateral location of CG within 0.20 inch of the flight-vehicle prediction for a satellite with a lateral dimension of 20 inches).

Dry-running the Test

Shakers are electromechanical devices with many parts that can fail. The consequence of such a failure can be a harsh loading environment that can damage the test article. In addition, the closed-loop control system, working off of measured acceleration at the base of the test article, may have difficulty keeping the environment within acceptable tolerance (error) from the specified environment. Sine-burst testing in particular is subject to such control difficulty. See Part 4 of this series for further discussion.

To reduce risk of damaging expensive flight hardware, plan to dry run the test ahead of time with the test fixture installed on the shaker and, preferably, with dead weights representing the mass of the test article. Run through each planned test to full levels of acceleration. Doing such a dry run doesn't guarantee that problems won't show up during the test, as sometimes it's the test article's modes of vibration that cause difficulty with the control system, but it can screen out many potential problems that may occur.

Limitations of Testing on a Shaker

Two types of limitations should be considered when planning a vibration test on a shaker: the limitations of the shaker itself and the limited effectiveness of base-driven vibration tests regarding the simulation of launch loading environments.

Every shaker has two important limitations: force rating and stroke. The ***force rating*** is the maximum force, F, the shaker can exert to move a mass, m. Recall that $F = mA$, where A is acceleration, so the maximum acceleration achievable in test is proportional to the shaker's force rating. The mass, here, is not just the mass of the test article; it includes everything that is moving: the test fixture, the slip table or head expander, and the armature. ***Stroke*** is the maximum range of displacement for the shaker, typically in terms of peak-to-peak (plus/minus) motion. The stroke limits the achievable acceleration at any given frequency. (See Part 4 of this series.) To address both of these shaker limitations, be sure to coordinate early with the test lab, and ask the lab personnel to confirm that the shaker can achieve the needed test environment for the test configuration.

Although testing small satellites on shakers is standard practice (and usually required by mission stakeholders), doing so does not give absolute assurance that failure won't occur during launch. For the most part, a random vibration test on a shaker to properly specified levels is more severe than flight random vibration, but that's not always the case. Let's take time to understand some important limitations related to test effectiveness:

- A shaker introduces acceleration uniformly across the interface with the test article, whereas, in flight configuration, the interface with the mounting structure can distort, meaning acceleration can vary from one location to the next at any point in time. As a result of this aspect of a shaker, most of the test article tends to be over-tested, but the interface itself tends to be under-tested because it is typically over-constrained. (See Part 2 for discussion of boundary conditions.)
- A traditional shaker imparts acceleration in a single translational axis, whereas acceleration during flight can be in all six degrees of freedom simultaneously. (Multi-axis shakers exist but are mostly used for research, as engineers attempt to learn how to best use them.) This aspect of vibration tests suggests the satellite will be under-tested. However, for random vibration testing, other aspects of the test, such as uniformity of input acceleration and the manner in which the test environment envelops the flight environment, normally ensure that testing in each of three orthogonal axes is more stressful than flight vibration. For sine-burst testing, we should design the test levels to ensure the primary structure is stressed at least as much as it will be stressed in launch. (See Part 4 for a detailed look at sine-burst testing.)
- Random vibration testing on a shaker simulates only the flight random vibration that is introduced at the mounting (LV) interface, whereas flight random vibration also includes the effects of random acoustic pressure impinging directly on the satellite. For small satellites, acoustic

response is often assumed to be negligible, but, as the satellite's surface area increases, this assumption becomes less accurate. Part 5 of this series addresses this issue.

- Vibration testing is most effective at detecting strength deficiencies ("single-passage failures") for brittle materials and fatigue-life deficiencies for ductile materials. Part 4 addresses the effectiveness of sine burst as a strength test.
- Not all modes of vibration can be excited by single-axis translational input. (See discussion below.)

The extent to which a mode of vibration can be excited on a single-axis shaker depends on the modal effective mass for the test article when grounded at its base, as it is in test configuration. ***Modal effective mass*** essentially tells us two things: (1) how much of the system's mass is moving simultaneously in a given direction for that mode and (2) how easily the mode can be driven by motion in a particular direction. For example, if a mode has a high percentage of effective mass in a horizontal direction (say, the Y axis) and also in rotation about the other lateral axis (X), that mode can easily be excited in a Y-axis test, and exciting that mode causes high force in Y and moment about X at the mounting interface. Figure 1-3 shows an example of the first two bending modes of a cantilevered beam, with the first having much higher modal effective mass in lateral translation and rotation (moment) about the orthogonal axis than the second. The mathematics behind modal effective mass are outside the scope of this paper, but it is easily calculated with a finite element model.

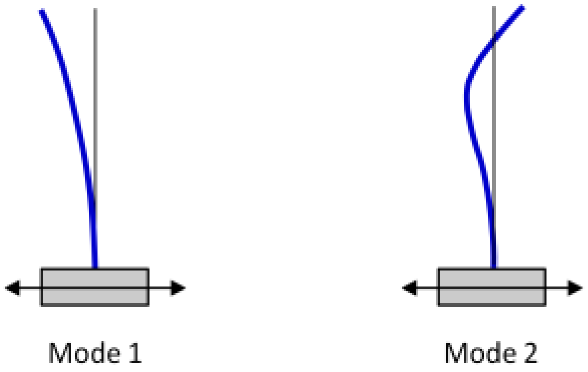

Fig. 1-3. Qualitative Comparison of Modal Effective Mass for Two Modes. Mode 1 can be more easily excited by lateral base motion than mode 2 because mode 1 has more effective mass in lateral translation. As the mode shapes show, all of the mass of the beam other than that right at the base is moving in the same direction at any point in time, whereas mass is moving in opposite directions for mode 2.

A torsion mode is a good example of a mode that single-axis base motion may not be able to excite. Such a mode has little or no effective mass in translation, depending on lateral offset of the CG relative to the mounting interface and on asymmetry of the structure's cross section.

If you must excite a particular mode in order to meet the test objectives, and if that mode can't be excited by base input, you need to design a different test!

As stated at the beginning of this paper, we're not doing a vibration test for the sake of doing a vibration test, so that we can check off a requirement that says we have to do it. To establish appropriate confidence, we must design the test to meet the objectives.

Remember the test objective:

The objective is not to do a test; it's either to verify compliance with mission requirements or to obtain information—or both.

To verify compliance with the applicable requirement (e.g., ability to withstand flight environments and function afterwards), we may have to design a nonstandard test.

Part 2 of this series addresses test configuration, fixtures, and instrumentation.

References

1. SMC Standard SMC-S-016. "Test Requirements for Launch, Upper-Stage, and Space Vehicles." 13 June 2008. Air Force Space Command, Space and Missile Systems Center. (replacement for MIL-STD-1540)
2. NASA-STD-7001A. "Payload Vibroacoustic Test Criteria." January 20, 2011. National Aeronautics and Space Administration.
3. Sarafin, Thomas P., ed. *Spacecraft Structures and Mechanisms: From Concept to Launch*. Microcosm Press. 1995.

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