JPL Standard for Spacecraft System Dynamic and Static Testing

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The JPL Standard for Spacecraft System Dynamic and Static Testing provides institutional requirements for Protoflight spacecraft level vibration, acoustic, pyroshock, structural loads, and modal testing. The standard is applicable to all JPL spacecraft programs, both integrated and tested in-house, or integrated and tested by a JPL contractor in their facilities. This presentation discusses the requirements imposed by the standard and their rationale.

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Applicability

This standard is applicable to all JPL spacecraft programs, both integrated and tested in-house, or integrated and tested by a JPL contractor in their facilities. Large spacecraft-like instruments will also be governed by this document. The requirements of this standard apply to a Protoflight System Level test program. A Protoflight System Level test program is preferrable to a Qualification System Level / Flight Acceptance System Level test program when the number of flight systems in the program is three or less, which is typical of JPL projects. The tests defined herein are applicable to each flight spacecraft on a given project. Deviations from the baseline requirements defined in section 4 below shall be documented and approved using a Category A waiver process as defined in D-15032. Non-protoflight program test requirements shall be negotiated with JPL Section 352 and Office 513.

1. Scope

1.1 Purpose. This standard establishes baseline requirements for spacecraft system protoflight dynamic and static testing. These baseline tests are required by JPL in order to uncover workmanship problems and to assure functional and structural integrity of the spacecraft when exposed to the mission dynamics and loads environments.

2. Applicable Documents

NASA-STD-5001, Structural Design and Test Factors of Safety for Spaceflight Hardware, June 21, 1996, Section 5.1.

3. Definitions

3.1 Limit Load. The limit load is defined as the maximum anticipated load, or combination of loads, which the structure may experience during its service life under all expected conditions of operation or use.

3.2 Primary Structure. Primary structure is defined as any structural element whose failure would result in the general failure of the structural support of the spacecraft or instrument or any of its major assemblies.

3.3 Protoflight Test. Protoflight tests are formal environmental tests performed on flight hardware to demonstrate both design adequacy and workmanship of the assembled item.

4. Baseline Requirements

The baseline requirements specified in this section are compatible with the requirements of the relevant NASA Standards [1-5]. However, they may not encompass all dynamic and static test requirements imposed by the launch vehicle organization. Also, for risk reduction purposes the project may elect to impose additional test requirements.

The baseline system level dynamic and static test program shall consist of all the following: an acoustic noise test, a vibration test, a pyroshock test, a structural loads test, and a modal test. The acoustic noise, vibration, and pyroshock tests shall be conducted on each flight spacecraft in the mechanical configuration and electrical power mode appropriate for the flight dynamic event being simulated. The structural loads and modal test requirements herein assume that the tests are conducted on a flight structure prior to installation of the electromechanical equipment (with mass mockups replacing equipment as appropriate) or on a fully configured flight spacecraft, or on some combination of the above. Tests for structural loads and modal verification may also utilize a flight-like or a flight spare structure. Requirements for these non-protoflight tests shall be negotiated with JPL Section 352.

4.1 Acoustic Noise Test Requirement. The acoustic noise test shall be performed as a minimum at a protoflight test level of 3 dBs above the maximum expected flight environment and as a minimum for a test duration equal to the time that the flight levels are expected to be within 6 dB of the maximum level.

4.2 Vibration Test Requirement. The vibration test shall be performed as a minimum at a protoflight test level of 3 dBs above the maximum expected flight environment and as a minimum for a test duration per axis equal to the time that the flight levels are expected to be within 6 dB of the maximum level.

4.3 Pyroshock Test Requirement. All pyrotechnic devices that produce the dominant shock source for potentially susceptible spacecraft hardware shall be fired a minimum of two times. All other devices, except embedded propulsion system pyrotechnic devices, shall be fired at least once. It is not required to fire redundant pyro initiators.

4.4 Structural Loads Test Requirement. The structural loads test shall be performed as a minimum at a protoflight level of 1.2 times the limit load. The structural design requirements in section 5.1 of NASA-STD-5001 are applicable as a minimum for all JPL projects.

4.5 Modal Test Requirement. A modal test, followed by a model correlation, shall be performed to verify the finite element model used in the coupled loads analysis.

5. Test Purpose

The primary purpose of the spacecraft protoflight dynamic and static tests is to increase the probability of mission success by detecting possible workmanship problems and validating that the system will survive the mission dynamics and loads environments. The spacecraft tests also verify assembly level test requirements and verify spacecraft analytical models.

5.1 Acoustic Noise Test Purpose. The spacecraft acoustic environment is generated by rocket engine exhaust noise at liftoff and by aerodynamic noise during ascent. The acoustic noise transmits through the fairing and impinges directly on the spacecraft surfaces. The duration of the maximum acoustic environment is usually less than one minute. Typically acoustic noise is the dominant dynamic excitation for a spacecraft above approximately 80 Hz and up to about 1000 Hz or higher. Antennas, solar arrays, shields, and other lightweight, large surface area structures are susceptible to failure by direct acoustic excitation. Random vibration induced by acoustic impingement on the spacecraft structure is typically the most severe dynamic environment for assemblies and instruments and may also induce failures in electrical and mechanical interconnections between assemblies and subsystems.

The protoflight acoustic test validates with margin the capability of the spacecraft to withstand the flight acoustic environment and reveals workmanship problems in the fully assembled flight spacecraft. The acoustic test also verifies assembly random vibration test requirements and provides an "acoustic cleaning" of the spacecraft.

5.2 Vibration Test Purpose. Vibrations mechanically transmitted to the spacecraft from the launch vehicle may be random, transient, and sometimes periodic in character. Random vibrations may be induced by aerodynamic and rocket engine exhaust noise, wind and turbulence, and motor vibrations. Transient vibrations may be induced by seismic loads, rocket motor ignition overpressure, liftoff release, engine starts and shutdowns, maneuvers during ascent, and stage and fairing separations. Periodic vibrations may be induced by engine vibrations, pogo, or solid motor pressure oscillations. Mechanically transmitted vibration is typically the dominant dynamic excitation of a spacecraft up to approximately 80 Hz, or higher for smaller spacecraft. Mechanically transmitted vibration is frequently the most severe dynamic environment for structure, non-structural hardware, and ancillary hardware. This hardware includes items such as cable harnesses, bellows, connectors, actuators, plumbing lines, brackets, dampers, shades and shields, articulation/deployment mechanisms, shunt heaters, hinges and restraints, blankets/supports, etc, which are usually responsive to low/mid frequencies. Larger assemblies and instruments may also be susceptible to mechanically transmitted vibration.

The protoflight vibration test validates with margin the capability of the spacecraft, other than primary structure, to withstand the flight vibration environment and reveals workmanship problems in the fully assembled flight spacecraft. The protoflight vibration test is not intended to verify the integrity of primary structure. Primary structure is verified in the structural loads test (see section 5.4) to levels that encompass the combined effect of all structural loadings, including quasi-steady thrust loads, vibration loads, acoustic loads, etc. However, the vibration test does provide an opportunity to augment primary structure strength tests and modal properties verification tests and may be the only strength test for non-primary structure.

5.3 Pyroshock Test Purpose. Pyrotechnic shock is generated by the activation of pyrotechnic devices used to separate structural systems, deploy appendages, and/or activate on-board operational subsystems. Pyroshock is characterized by high peak accelerations, high frequency content, and short duration (less than 20 ms). It is often the dominant dynamic excitation for a spacecraft around 1000 Hz and above. Small, stiff components are most susceptible to pyroshock. Specific examples of pyroshock failures include cracks and fractures in crystals, ceramics, epoxies, glass envelopes, solder joints and wire leads, seal failures, migration of contaminating particles, relay and switch chatter and transfer, and deformation or failure of microelectronics and other very small lightweight structural elements. Deformation or failure of major structural elements is rare.

Pyroshock testing at the spacecraft level validates the capability of the flight spacecraft to withstand the pyroshock environment. Multiple firings (two minimum) of devices producing the dominant shock levels for potentially susceptible hardware are required to enhance the probability that the test firing shock levels will not be exceeded in flight. The pyroshock test is also used to verify assembly pyroshock test requirements and verify that the flight spacecraft pyrofiring command wiring is correct and that the firing event does not generate deleterious electromagnetic interference (EMI) effects. Thus, all pyrotechnic devices are fired at least once, with the exception of pyrotechnic devices which are embedded in lines, such as propulsion pyrovalves, and are very difficult to replace. If these devices are suspected to produce the dominant shock levels for any potentially susceptible hardware, subsystem level test verification may be necessary. Firing of redundant pyro initiators is not required because the dominant shock event is generated by the fracture of metal or impact of metal on metal, rather than by the initiator explosive event. The project may impose additional spacecraft pyrofiring requirements to address issues such as the reliability of new or modified pyrotechnic systems.

5.4 Structural Loads Test Purpose. The main purpose of the structural loads test is to verify with margin the structural integrity of all primary structure for the anticipated mission dynamics and loads environments. The primary structural elements include structural members, their connections, and their interfaces with all major spacecraft assemblies. A secondary purpose of structural loads testing is to obtain test data for the verification of analysis. Primary structure is one of the few subsystems which is a single point failure. Higher design margins mitigate, but do not eliminate the risk or need to perform structural loads verification tests.

The highest loads in structural elements are typically caused by events attributed to the launch vehicle system, such as liftoff release, engine transients (ignition and burnout), engine ignition overpressure, maximum aerodynamic pressure, stage and fairing separations, propulsion system induced loads such as pogo and, for STS payloads, landing. Payload planetary landing may also induce high loads. The forcing functions for most of these events, except the maximum aerodynamic pressure, occur over a short time period on the order of a few seconds. The forcing function for the maximum aerodynamic pressure may last for up to 30 seconds. The frequency content of the dominant dynamic excitation is governed by the launch vehicle characteristic frequencies and typically is in the range from about 1 to approximately 50 Hz.

The margin for structural loads testing is intended to cover the unknown unknowns and is specified in Reference 1 as 1.2 times the limit load. Uncertainties in the analysis are covered by the design safety factor. Uncertainties in the model and the forcing functions are covered by the Model Uncertainty Factor (MUF). Uncertainties in material properties are covered by the material statistics of the "A" and "B" value definitions.

Typically there is some overlap between the structural loads test and the vibration test. The vibration test, section 5.2 above, is implemented by specifying an acceleration input at the base of the spacecraft to bound a flight environment. The objective of the structural loads test is to induce the expected member loads, stresses or strains into the structural members. Due to differences in boundary conditions between the launch configuration and the test configurations the prescribed input acceleration in the vibration test generally does not replicate the flight loads. The vibration test is implemented with the imposed requirement that during this test, the loads in the primary structure are not allowed to exceed the limit loads times the appropriate test factor, and therefore serves to only augment the strength qualification.

5.5 Modal Test Purpose. The purposes of the modal test are to measure the basic dynamic characteristics of the spacecraft and to provide experimental data for the verification of the finite element model used in the coupled loads analysis. The specific purpose is to measure the frequency, damping, linearity, and mode shape of all significant modes of the test article in the launch configuration. Following the modal test, the model correlation is conducted to obtain agreement between the finite element model and the experimental measurements.

6. Test Implementation

Acceptable state of the art test methods currently employed by JPL and its contractors are described below. The implementation of alternate test methods by a project shall be negotiated with Section 352.

6.1 Acoustic Noise Test. Traditionally, acoustic tests are conducted in dedicated, hard wall, reverberant acoustic test chambers, which typically have thick concrete walls. The sound sources are electro-pneumatic drivers with large horns, which protrude into the walls of the chamber. The acoustic waves reverberate off the walls many times, so that the acoustic intensity impinging on the test item is approximately uniformly distributed in angle.

An alternative direct acoustic field approach has been developed for use by satellite manufacturers without convenient access to a reverberant acoustic chamber. In a direct field acoustic test, the spacecraft is surrounded by a large number of electro-dynamic speakers placed several feet away from the test item. The spacecraft is typically located in a high bay or a vibration test facility.

In both the reverberant and the direct acoustic test approach, the average output of a number of microphones, located some distance from the surface of the spacecraft and the chamber walls, or the speakers in the case of the direct field approach, are used to control to the acoustic specification given in one-third octave frequency bands. In the case of the reverberant chamber, three or more microphones will suffice, but in the case of the direct field test, eight or more microphones are required because of the spatial non-uniformity of the sound field.

As stated in section 4, the acoustic test is to be performed as a minimum at a protoflight level of 3 dBs above the maximum expected flight environment. In the case of launch vehicles with mild payload acoustic environments, this level may not be adequate to satisfy the workmanship portion of the test purpose. A minimum workmanship spacecraft acoustic test level of 138 dB overall with a duration of one minute, as specified in Reference 3, is recommended.

6.2 Vibration Test. As described in section 5.2 above, the vibration environment mechanically transmitted to the spacecraft from the launch vehicle may be random, transient, and sometimes periodic in character. The preferred spacecraft vibration test method is force limited random vibration because a) random vibration tests are safer and are more effective at revealing workmanship defects than are sinusoidal or transient vibration tests and b) force limiting alleviates the severe over test at hardware resonances inherent in conventional vibration tests.

Specifications for spacecraft vibration tests are traditionally derived by enveloping the peaks of the acceleration spectrum measured or predicted at the launch vehicle and spacecraft interface, while ignoring the valleys, or notches, in the interface acceleration. This process leads to severe over testing, since the notches occur at the fixed base resonance frequencies of the spacecraft, where it acts like a vibration absorber. In force limited vibration tests, force gages installed between the spacecraft and the shaker are used to measure and control the interface forces to the predicted flight limit loads. Force limiting automatically puts the appropriate notches back into the interface acceleration and minimizes over testing of the spacecraft. See Reference 6 for details on developing force limit specifications and implementing force limited vibration tests.

The spacecraft is mounted on the shaker via a rigid fixture, with force gauges sandwiched between the spacecraft and fixture at each mounting bolt. Typically two or more input accelerometers are located on the fixture near mounting bolts. The vibration test is controlled to the input acceleration and force limit specifications. Selected critical spacecraft response locations are also monitored with accelerometers and response limits can be included in the control system or used to manually notch the acceleration input if necessary to protect critical structure from over test. Spacecraft vibration tests are usually performed in three orthogonal axes, one being the longitudinal (thrust) axis. A lesser number of vibration test axes may be negotiated with Section 352 if technical justification exists.

As stated in section 4, the vibration test is to be performed as a minimum at a protoflight level of 3 dBs above the maximum expected flight environment. In the case of launch vehicles with mild payload vibration environments, this level may not be adequate to satisfy the workmanship portion of the test purpose. A minimum workmanship spacecraft vibration test level of a flat spectrum of 0.01 G**2/Hz or higher from about 10 to at least 200 Hz and a duration of one minute per axis is recommended for medium to large spacecraft.

6.3 Pyroshock Test. Spacecraft pyroshock tests are performed by firing of flight pyrotechnic devices, preferably activated by the spacecraft bus pyrofiring command circuitry. The spacecraft may be suspended slightly above a soft pad for stage separation firings. Alternately, the spacecraft weight may be counterbalanced such that when the separation device is fired, the spacecraft moves up, off the lower stage. For deployment firings, special fixtures may be required to minimize gravity effects. Only first motion of the deployment is required for purposes of protoflight pyroshock testing, but full deployment may be required for deployment functional verification purposes.

6.4 Structural Loads Test. As discussed in section 5.4 above, the objective of the loads test is to qualify the primary structure for the highest loads anticipated during the mission. The goal is to induce the desired test loads into as many members and assembly interfaces as possible using a minimum number of test configurations. Test loads are obtained by applying a test factor, Reference 1, to the limit loads.

The system static test is the traditional test method. Pretest analysis is performed to arrive at a suitable suite of system test loading configurations to verify critical structural elements, their detail connections, and also structural assembly interfaces.

The system static test is performed using the complete assembled structure. Usually the test article consists of the "bare structural skeleton" of the spacecraft without on-board equipment. This facet of the hardware makeup of the static test allows the test to occur much earlier in the test series. Loads are induced using hydraulic actuators configured to maximize the number of structural elements and their connections loaded to the desired level. The method provides latitude to allow different external loadings to achieve critical element loads from different times of a launch event, or from different events, with a minimum number of test configurations. The loading can be tailored to address certain interfaces where it is desired to target detail areas down to a combination of load components to a given fastener. The system static test provides the ability to induce the desired load in each structural element or structural assembly interface without over test of other elements or interfaces. This test approach is usually essential for complex structures with multiple response modes.

While the system static test is the primary method, other methods of test verification are sometimes employed depending upon the hardware or the nature of the loading condition. The assembly or subsystem static test can be used either to get early verification of structural integrity, or to achieve the desired load in certain structural elements, which are impractical to properly load in the system static test. This type of testing is usually performed as an augmentation to a system static test.

The centrifuge test exposes the entire test specimen to a near uniform acceleration field along selected axes. The centrifuge test approach is more appropriate when the dominant flight structural loading is quasi-static.

In the shaker pulse test, ideally the pulse frequency is equal to or lower than that associated with the maximum flight dynamic loads. Since the excitation pulse causes some resonant motion of the test item, it is important that the load distribution within the test article be predicted by analysis and verified during the test by instrumentation and test control to reduce undue risk to the test article.

Both the centrifuge and shaker pulse test approaches are sometimes used when it is impractical to apply hydraulic actuators to the test item at the appropriate locations. In these tests, the load distribution within the test article needs to be predicted by analysis to assure that local structural details are verified. Assembly static loading tests may also be required to verify structural elements predicted to experience higher flight loads than that of the structure c. g.

6.5 Modal Test. The primary modal test methods are: a) fixed-base configuration modal test - test article is cantilevered from its launch vehicle interface on a seismic mass; b) free-free configuration modal test - test article is suspended from its launch vehicle interface on a suspension system, and c) base-drive configuration modal test - test article is base-mounted on a vibration test shaker.

Both fixed-base and free-free configuration modal tests provide a complete set of modal data that is valid for the verification of a finite element model. However, the latter cannot directly verify the cantilevered modes used in the coupled loads analysis.

The base-drive configuration modal test typically augments an environmental vibration test to obtain frequency verification and qualitative mode shapes measurement of the first 2 to 3 primary modes. The modal data obtained from the base-drive configuration modal test are not sufficient for a rigorous verification of a finite element model.

The fixed-base configuration modal test is the technically preferred test method. Selection of alternative modal test methods should be negotiated with Section 352. To verify the finite element model used in the coupled loads analysis, the modal test, followed by a model correlation, needs to be conducted before the verification loads cycle (VLC).

7. Combining Dynamic Tests

Sometimes the schedule, funding, logistics, or other special circumstances do not permit conduct of the full cadre of dynamic and static tests described previously. In this case a combined dynamic test may be considered in which two or more tests are conducted sequentially while the test item is base-mounted on a vibration test machine (a shaker). This sequence of dynamic tests could consist of up to four mechanical tests (a shaker pulse structural loads test, an environmental vibration test, a base-drive configuration modal test, and sometimes a direct acoustic test). This combined dynamic testing approach provides an opportunity to obtain abbreviated loads verification and modal data for the primary structure, and sometimes spacecraft validation for the acoustic environment, with minimal increase in testing schedule, cost, and hardware handling over an environmental vibration test alone.

While there are some technical advantages to conducting modal and loads tests on a shaker, e.g. realistic excitation location and amplitude, it is often considered that the shaker base-drive configuration test is not a replacement for the fixed-base or free-free configuration modal and the structural loads tests. In some cases the combined test may need to be augmented by some specialized modal and loads testing, e.g. to excite local or rotational modes or to simulate complex loading configurations, which may result from local loading. Additionally, it may be desirable from a scheduling and risk reduction viewpoint to perform the structural loads and/or modal tests on the complete primary structure well before the fully configured flight spacecraft is available for the vibration and acoustic tests.

8. Waivers

Waivers to selected baseline requirements of section 4 may be based on technical or on cost/schedule vs. risk considerations. Waivers based primarily on technical considerations must demonstrate that the project has satisfied by alternate means the test purposes cited in section 5. As an example, it might be acceptable to perform certain baseline tests at only the subsystem level if interactions between subsystems involving qualification and workmanship issues can be adequately addressed. These waivers should be discussed with Section 352 and Office 513 and submitted early in the spacecraft program planning phase.

In general, projects should allow in their spacecraft program planning phase for the cost and schedule impacts of performing the entire baseline verification program of section 4, unless deletion of selected baseline requirements is technically justified. If subsequent events require a tradeoff of risk vs. cost/schedule to complete the program, Section 352 and Office 513 should be involved early on. Factors that will affect the risk involved in eliminating selected baseline requirements of section 4 include the following: similarity of design to qualified (and flown) spacecraft, conservatism in structural margins, analysis approaches, fundamental frequencies, thoroughness and conservatism of assembly/subsystem test and analysis program, complexity of structural configuration, severity of launch/flight dynamic excitations and responses, extent and relevance of dynamics developmental tests and analyses, etc.

9. References

1) NASA-STD-5001, *Structural Design and Test Factors of Safety for Spaceflight Hardware*, June 21, 1996.

2) NASA-STD-5002, *Load Analyses of Spacecraft and Payloads*, June 21, 1996.

3) NASA-STD-7001, *Payload Vibroacoustic Test Criteria*, June 21, 1996.

4) NASA-STD-7002, *Payload Test Requirements*, July 10, 1996.

5) NASA-STD-7003, *Pyroshock Test Criteria*, May 18, 1999.

6) NASA-HDBK-7004, *Force Limited Vibration Testing Handbook*, May 16, 2000.

7) NASA-HDBK-7005, *Dynamic Environmental Criteria Handbook*, March 13, 2001.

Document Information

Revision History

There are no previous revisions.