

Dynamic (Vibration) Testing: Design-Certification of Aerospace System

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ABSTRACT

Various types of dynamic testing of structures for certification purposes are described, including vibration, shock and acoustic testing. Modal testing is discussed as it frequently complements dynamic testing and is part of the structural verification/validation process leading up to design certification. Examples of dynamic and modal testing are presented as well as the common practices, procedures and standards employed.

1.0 INTRODUCTION

In general, an aerospace system consists of a space vehicle (satellite or spacecraft), and its launch system. Whereas, a space vehicle (satellite or spacecraft) is an integrated set of subsystems and components that are capable of supporting an operational role in space. A space vehicle may be an orbiting vehicle, a major portion of an orbiting vehicle, or a payload that performs its mission. It usually has a series of engines, which are used for either a primary propulsion function such as ascending and orbiting in addition to the secondary functions such as attitude control, spin control, stage separation, etc.

Certification of the design is part of the overall qualification process for a space system and its components. The purpose of the design certification testing is to ensure that verification/validation demonstrates design compliance with functional and performance requirements. It helps establish the proof that a product will accomplish the intended purposes (Figure 1). It is achieved through a process (verification/validation), which includes establishing a design specification defining a set of design environments for its intended use and a combination of test, analysis, demonstration, and inspection assuring compliance. Unmanned and manned spacecraft and their components are “fully” tested to help establish the design specification environment (acceleration, acoustic, and vibroacoustic and/or to determine damping etc.) followed by a different level (modal, development, qualification and acceptance tests) of testing depending upon the use.

As much as possible, these tests simulate natural and induced environments experienced by the vehicle and/or component. However, where realistic simulation is limited by physical constraints or test facility requirements that are not economically feasible, a series of building blocks test approach, along with analysis, is employed to achieve maximum confidence in performance for the intended use.

Dynamic testing is used extensively in design certification of flight structures to characterize the behavior and verify the performance of structures as built to specifications to ensure that the design intent is met. The types of the dynamic testing employed vary according to

expected environments that the vehicle and components thereof will be exposed to from assembly to the end of useful flight life. Dynamic testing programs for certification are generally designed using a building block approach, testing first at the component level and then building up to the largest assembly practical within cost and facility limits. Developmental units are subjected to more rigorous qualification testing levels to evaluate build quality and certify the design whereas production units undergo only acceptance level testing for workmanship screening.

Dynamic and modal testing approaches are distinguished by excitation methods and type. These are selected based on the size and build of the structure being tested, the frequency range of interest for the test and the type of data needed.

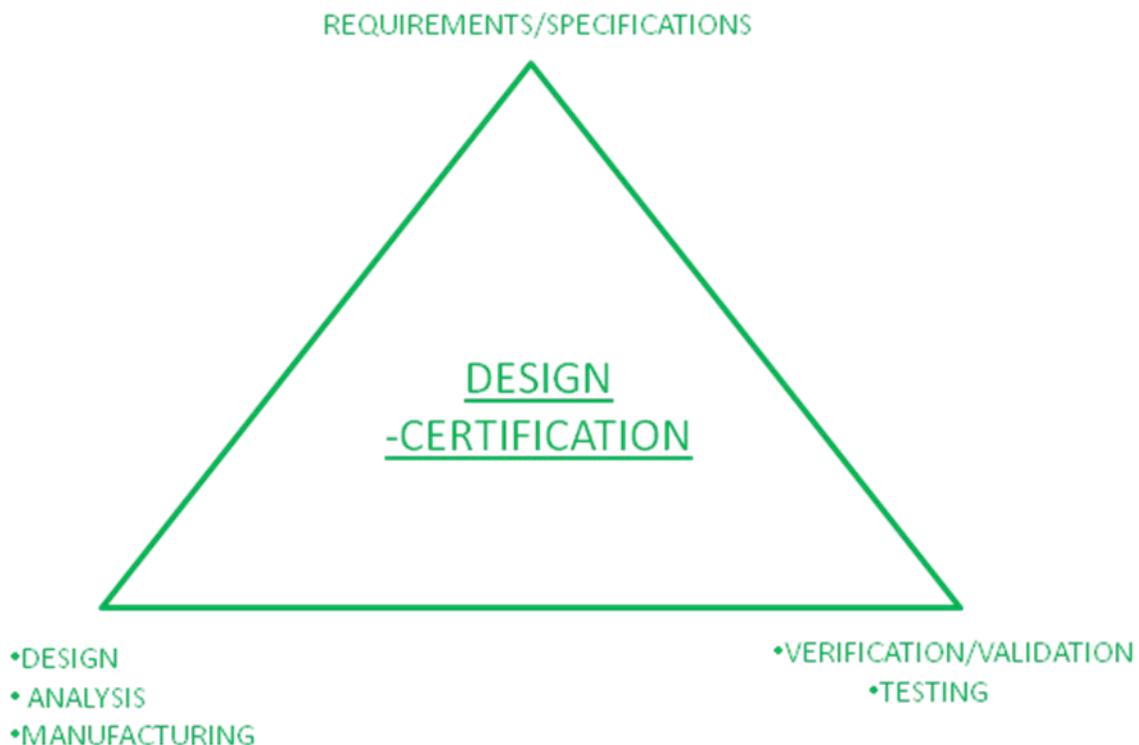


Figure 1: Design Certification Process

2.0 SOURCES OF VIBRATION

Vibration is a natural phenomenon induced by a space vehicle and by rocket engines generating vibration energy over a wide range of frequencies. The resulting vibration environment can be severe with respect to structural fatigue and damage to components. To insure the structural and functional integrity of the vehicle systems, it is necessary to determine the vibration environment of a vehicle and components. The extent of the vibration is dependent upon the frequency spectrum, amplitude and space correlation of the sound field plus the mechanical impedance of the

structure. This environment is developed by a combination of analytical methods and testing, or predicted by comparison to the known vibration levels of a similar vehicle. Subsequently, once the vehicle itself is available, the environment is further validated and/or verified by static firings, dynamic testing, and flight test. To understand the need for vibration testing for flight certification of space vehicle vibrations, it is necessary to have a general background in the various sources of these vibrations. The following is a short description and provides some general information regarding these sources and their causes.

A space vehicle may have many different causes of vibration, but each one can be characterized by one of the following sources:

- a. Acoustic
- b. Aerodynamic
- c. Mechanical

These sources of vibration vary in predominance depending upon the design of the vehicle, the design of the launch pad, the phase of the vehicle flight, and the total mission of the vehicle.

2.1 Acoustic

Sound fields provide the excitation energy for acoustically induced vibrations. Acoustic fields may be generated in a number of ways. The sound field of the rocket engine itself is caused by the acoustic energy generated in the rocket engine due to moving parts, fuel flow, and fuel combustion. The maximum acoustic environment usually occurs within a few seconds after lift-off, whereas the maximum aerodynamic environment usually occurs later during the transonic or maximum dynamic pressure segments of the flight. The acoustic test specification is usually an envelope of the highest environment.

2.2 Aerodynamic

There are several aerodynamic phenomena associated with high speed flight in the atmosphere which supply excitation energy that induces vehicle vibration. Some of the aerodynamic effects that cause vehicle vibration are:

- a. Pressure fluctuations in the turbulent boundary layer around the vehicle
- b. Flutter of a fin or panel in the airstream due to dynamic instability
- c. Turbulent wakes generated by air flow past vehicle projections in atmospheric flight
- d. Flow over recesses and cavities
- e. Oscillating shock waves that may be attached to the vehicle surface
- f. Buffet flow separation which occurs when the air in the boundary layer is forced to flow around sharp corners
- g. High velocity flow through pipes

Aerodynamically induced excitation normally reaches maximum in the vicinity of trans-sonic (mach 1) and maximum dynamic pressure (max q).

2.3 Mechanical

The main mechanical source of vibration usually comes from equipment, such as rocket engines, pumps, compressors etc. In outer space when airborne sources of excitation have ceased to exist, rocket engine operation will continue to induce mechanically coupled

vibration. Some other mechanical sources of vibration are:

- a. Transportation of the vehicle from one site to another
- b. Mechanical release of the vehicle from the launch pad by explosive bolts or a quick release device
- c. Variable thrust due to combustion
- d. Separation of the stages by mechanical means, such as explosive charges, retro rockets, and ullage rockets
- e. Landing impact of a recoverable vehicle
- f. Propellant sloshing

3.0 GENERAL TESTING CONSIDERATIONS

Spacecraft are required to be designed to avoid coupling with the launch vehicle control system. In addition, it is required to have appropriate structural stiffness to ensure structural adequacy under transient dynamic loads, and the body flexural frequencies are needed to be within the limits of the imposed control system. It is also required to avoid load induced dynamic coupling of flexible modes during launch, on orbit operations and landing and yet capable of performance within specification after exposure to vibroacoustic and shock environment. Hence, a combination of analysis and test, simulating flight operation, is made as a part of the qualification.

In general, an approach of doing multiple tests is used to take advantage such that best results can be obtained in a timely and cost efficient manner. Modal survey tests of “Flight-quality” structure is done to verify/validate mathematical models (test mode shapes, frequencies, and associated damping over the frequency range of interest is measured). Similarly, random and sinusoidal vibration, acoustic, and shock tests are done in accordance with the requirements set by the project or other available requirements such as Military Standard, Test Requirements for Launch, Upper-stage, and Space Vehicles, MIL-STD-1540.

It can be safely assumed that all components associated with a spacecraft and launch vehicle are subjected to vibration over a wide range of frequency and acceleration levels depending upon their locations (vicinity to active components, such as engine, solid rocket motor etc.) and/or vehicle dynamics during ascent. Electronic (avionics) components are most sensitive to this environment and thus go through a rigorous vibration test to assure against premature structural and fatigue induced failures.

Some other attributes which need to be considered for setting up and executing a successful dynamic certification testing are related to understanding the purpose of test factors and interaction of test fixtures, instrumentation, and recording etc. with test hardware depending upon the purpose of each test i.e., type of testing being done.

3.1 Test factor

In general a test factor is added to design vibration values to demonstrate that hardware is acceptable for flight to account for uncertainties, and to verify/validate adequate workmanship in the construction of the hardware. When defining test factor in design/test specification, various sources of uncertainty are considered such as the following:

- a. Material properties variations (strength and life)

- b. Fabrication variations (within specification)
- c. Load variations
- d. Test configuration fidelity
- e. Environment specification method fidelity
- f. Design maturity uncertainty
- g. Cost, schedule, and risk

In addition, based on individual hardware design susceptibility to a vibration environment, it may be desirable to accomplish vibration certification testing incrementally to identify vibration life capability. Where incremental testing is considered desirable, the test program shall initially demonstrate a minimum capability for required missions. The remaining demonstration may be incrementally performed to allow evaluation of any test failure relative to replacement frequency versus redesign impact.

3.2 Test Fixtures

The test fixtures are generally designed to preclude fixture resonances in the test frequency range below 500 Hz and to minimize fixture resonances above 500 Hz. For complex fixtures, cast or welded methods of construction are preferred over bolted construction. The fixtures are designed to minimize eccentric loading on the shaker and also to minimize fixture overhang as shown in Figure 2.

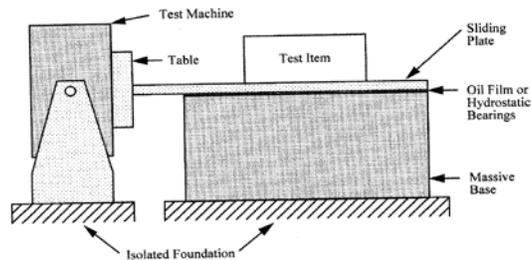


Figure 2: Test Fixtures Example

Acoustic tests of space vehicle hardware generally require no special fixtures. However, for almost all shock and vibration tests, a fixture between the test item and the test machine is required. For the usual case where the test machine generates rectilinear motion normal to the table surface, a test fixture is also necessary to reorient the test item relative to the table so that vibratory motion can be delivered along the lateral axes of the test item, i.e., the axes parallel to the plane of the test item mounting points. This requires a versatile test fixture between the table and the test item, or perhaps three different test fixtures.

The test specimen is supported from the test fixture in a manner in which duplicates or simulates the actual vehicle installation, as closely as possible, between the specimen and the defined environment input location. The method of support is defined in the procurement document and/or qualification test procedure of the test specimen. Whereas, for acceptance and qualification the test article is supported on a test fixture in a manner which allows for a hard-mount installation to assure that the acceptance vibration level is achieved on the test article and not just at the interface between the test fixture and the excitation equipment, or

the interface between the test fixture and the test article. Some additional factors that should be addressed which need to be addressed for dynamic testing are as follow:

- a. Test Axes
- b. Test Levels
- c. Test Conditions
- d. Test Accelerometer System
- e. Test Recording
- f. Test System and Calibrations

3.2.1 Test Axes

The dynamic environments for space vehicle hardware are typically multiple-axis, i.e., the excitations occur simultaneously along the three orthogonal axes of the hardware. Acoustic tests naturally simulate a multiple-axis excitation. However, all other dynamic testing is generally conducted in three mutually perpendicular axes, unless otherwise specified. The test axes and their relationship to the test specimen or special requirements for the test specimen orientation shall be defined in the procurement document and/or the qualification test procedure for the test specimen.

3.2.2 Test Levels

Test levels are defined in the design specification. All test levels represent inputs to the test specimen or test specimen support unless otherwise specified.

3.2.3 Test Conditions

Unless otherwise specified, all tests and measurements are conducted at room ambient temperature, atmospheric pressure, and relative humidity. If conditions other than room ambient are required during vibration, the conditions and associated procedures are specified in the procurement document/design specification.

3.2.4 Test Accelerometer System

The vibration input is measured and controlled at one or more points in each axis by accelerometers located on the test fixture as near as possible to the fixture/specimen interface. The use of two control accelerometers, one with a wider range setting, is generally required to provide test data in cases of testing anomalies. The accelerometer shall be attached to the test fixture by bolts, studs, or non-elastic cement, with the sensing axis parallel to the direction of excitation. Orthogonal sensing accelerometers may be added in addition to the prime axis sensing accelerometer to detect cross-coupled acceleration and prevent confusion in failure assessment.

3.2.5 Test Recording

The output of the accelerometer is recommended to be continuously recorded whenever power is applied to the test system throughout all vibration testing in a form capable of being reproduced and analyzed in order to verify that the correct vibration levels were induced.

3.2.6 Test System Calibrations

Prior to each test or each time the control accelerometer system electronics are altered other than the normal sinusoidal to random conversion (i.e., the changing of any system

component, gain setting, etc.) the system is subjected to an end-to-end system calibration verification/validation.

4.0 VIBRATION TESTS

As stated earlier, the primary purpose of most dynamic tests of spacecraft is to simulate the flight dynamic environments, which are typically so severe as to cause failure of many electronic components, mechanisms, optics, and structures were these items not designed to survive them. These high levels of vibration and sound are generated by the launch vehicle dynamics/acoustic and other sources such as the firing of pyrotechnic devices or the impact of a spacecraft landing on another planet. The most straightforward way of testing for these environments is to simulate the flight environment as much as possible by determining the type of testing depending upon the selection and/or availability of the test article (prototype or proto flight), purpose of the test (acceptance, development, and/or, qualification) and type of vibration test required for simulating flight environment. A detail certification/test plan is developed to do these testing at an appropriate level. Figure 3 below further depicts various vibration tests done per design certification. Appendix A highlights the comparison between these tests and associated risks of failure during testing which need to be understood for a planning of successful testing.

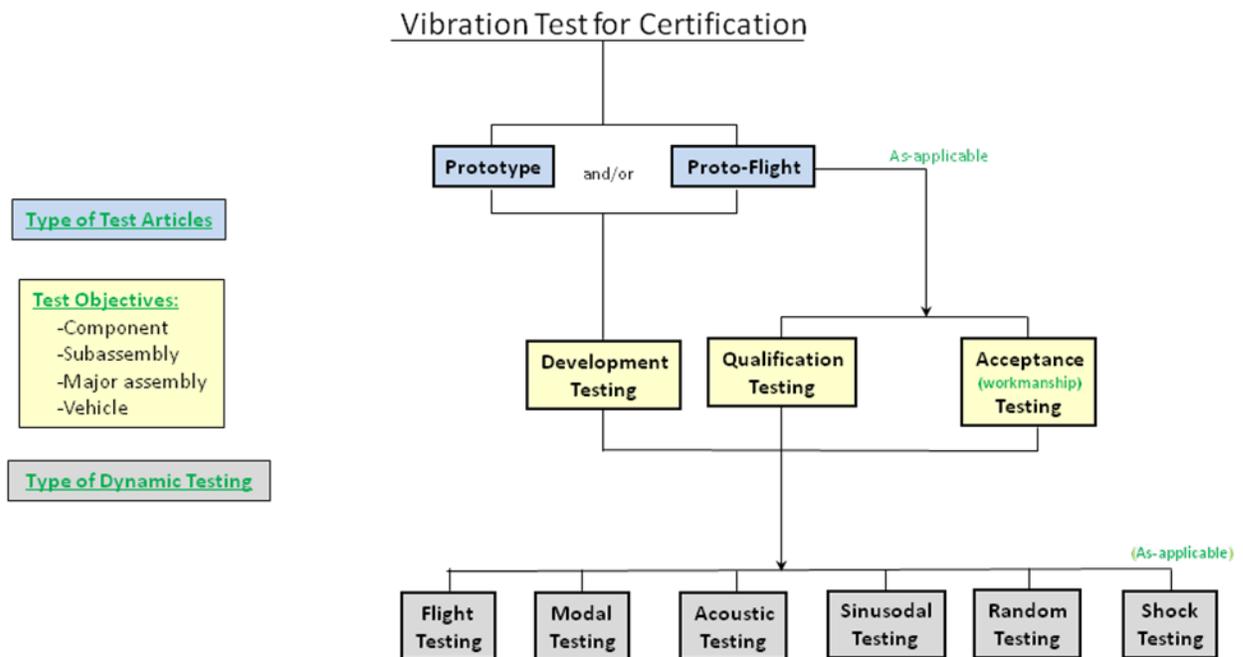


Figure 3: Vibration Test for Certification

4.1 Prototype Testing

Prototype dynamic testing is performed on dedicated test hardware, which is produced from the same drawings and using the same materials, tooling, manufacturing processes, inspection methods, and level of personnel competency as used for the flight hardware.

Prototype tests demonstrate, with margin, the design adequacy of the hardware for its intended mission use.

4.2 Protoflight Testing

Protoflight testing refers to a strategy where no test-dedicated qualification article exists and all production (flight) hardware is intended for flight. Protoflight tests serve the purpose of both the prototype and flight acceptance test. That is, the tests assess the design adequacy of the hardware, demonstrating by the satisfactory performance of the flight hardware relative to the expected environment, and reveal inadequacies in workmanship and material integrity. Generally, the protoflight test approach is used only for low-risk applications since no design margin for fatigue, wear, or yield is demonstrated and the protoflight testing exposes all flight hardware to testing at qualification magnitudes for acceptance durations.

4.3 Development Testing

Development tests are exploratory in nature and are usually conducted to establish design approaches and solutions, determine interface compatibility, establish validity of analytical approaches and assumptions, detect unexpected response characteristics, and demonstrate test approaches for qualification and acceptance. Due to this broad nature of objectives, a requisite degree of latitude is required in development testing and test article is dedicated to provide design and test information to evaluate design changes, to develop the qualification and acceptance test procedure, and to help establish higher fidelity test and design requirements.

4.4 Qualification Testing

Qualification testing is used for demonstrating that a given design and manufacturing approach will produce hardware that will meet all performance specification when subjected to conditions (with predefined margin) expected during its intended use. Qualification testing is conducted to verify that hardware and systems design, materials, and manufacturing processes have produced equipment that conforms to development specification requirements. Qualification testing includes integrity tests that verify that the hardware functions during and after exposure to the specified environments (e.g., functional/performance and leakage). Qualification testing is a risk mitigation strategy for potential design deficiencies. The testing typically exercises (vibration level and duration) the hardware and systems beyond the design operating and non-operating conditions to ensure that positive margins exist for design requirements and material and process variability. The qualification test article shall be “identical” to flight article and produced from the same drawings, using the same material, and manufacturing process. In general, the test article is randomly selected from the built lot.

4.5 Acceptance Testing

Acceptance testing provides the assurance that the flight/operations hardware is in compliance with functional, performance, and design requirements and hardware is ready for shipment for flight use. It also serves as a quality control screen to detect workmanship deficiencies (most workmanship defects are related to “infant mortality “associated with electronic circuit boards, which are tested and remedied at lower levels of assembly). Acceptance testing is required to verify acceptable functionality and performance, verify

adequate workmanship and material quality, and provide evidence of overall product acceptability for delivery to the customer. Acceptance testing includes integrity tests that verify that the hardware functions during and after exposure to the specified environments (e.g., functional/performance and leakage). Acceptance testing is a risk mitigation strategy that verifies that the manufacturing and assembly process has been accomplished in an acceptable manner and that the product performs within specified parameters. Although the main objective of acceptance (workmanship) dynamic tests of spacecraft and its components is to identify workmanship defects, which if undetected would cause problems or failures in flight, it also helps to identify interface and interconnection problems that can only be detected in the system level tests. In general, the design specification identifies a set of minimum random vibration test levels, for acceptance test which are sufficiently high to detect workmanship problems below the flight environment so that an undue fatigue is not introduced in flight components.

4.6 Modal Testing

Modal (dynamic) testing is performed either on a component and/or at an integrated system level. Development modal tests may be performed to obtain information to verify mathematical models, which are used to predict frequency, mode shapes, damping, and loads seen by the space vehicle and its components and used to do appropriate design. The parameters obtained during modal testing are Eigen values (frequency), Eigen vectors (mode shapes), modal damping, and modal forces. These are used to verify the model and also to determine the best location to mount components needed for guidance, navigation, and control of vehicle and other components sensitive to the induced dynamic environment (e.g., avionics boxes). A modal test is usually done first to survey a structure and identify its key frequencies before the higher excitation levels of dynamic testing are applied. Whereas full dynamic testing would often be impractical, modal testing is often done at the complete integrated vehicle level to provide data for structural dynamic loads and Guidance, Navigation and Control (GN&C) analysts to correlate analytical models and thus update flight loads and performance predictions as part of the design certification process prior to first flight. The objective of the modal test is to provide an independent method of evaluating the accuracy of the math model used to compute the low frequency structural behavior of a dynamic system, such as a launch vehicle or payload, in its various mission configurations. For modal tests, large or heavy hardware items are either installed or mass-simulated. Smaller or lighter hardware items such as cables, tubing, etc are often omitted. After the structure is modally tested and if the math model is adequately verified and forcing function finalized, all prior uncertainties in the analysis can be safely eliminated. However, if the model verification/validation is inadequate, an appropriate uncertainty factor may be required in the last or verification/validation load cycle (Figure 4).



Figure 4: Modal Test of Space Shuttle Example

4.7 Shock Testing

The shock test verifies the capability of the component/assembly to operate or survive, as required, the design level shock environment as specified in the design specification. Examples of high-frequency shock include, but are not limited to, stage and fairing separations and pyrotechnic device deployment of payloads, solar arrays, and antennas. A major assembly shock test is configured such that the mechanical transmission paths and mass distribution are flight-like. The objective of the test is to measure the input source and response accelerations in order to validate the design specification shock levels at the various component locations and directions of interest. The test item is often tested mounted to a plate with a flight like pyrotechnic device installed and appropriately suspended or by simulating high-frequency shocks by high velocity metal-to-metal impacts (e.g., drop test) with dominant energy above 2 kHz (Figure 5).

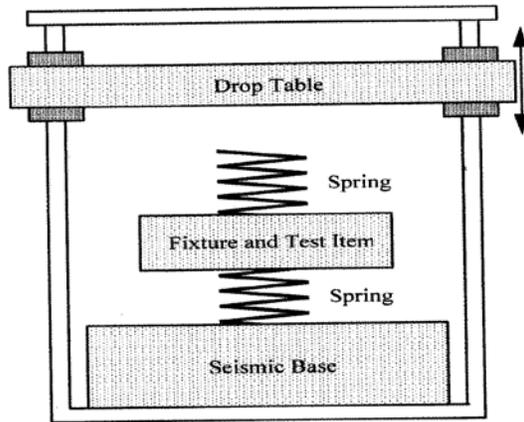


Figure 5: Shock Tests Example

5.0 ACOUSTIC VIBRATION TEST

Acoustic testing verifies the capability of the component/assembly to withstand the design acoustic environments as defined in the design specifications and to serve as a screen for latent manufacturing and workmanship defects during acceptance testing. Acoustic tests are conducted when it is judged that the acoustic environment, rather than a random vibroacoustic vibration environment, will be the worst-case condition. Aerospace hardware that requires testing for acoustic verification/validation are usually large area-to-weight ratio structures, such as skin panels, reflectors, dish antennae, and solar panels that respond significantly to the direct impingement of the acoustic environment. Two types of components require both vibration and acoustic testing: (1) those components which are mounted with vibration isolators, and (2) those components which consist of significant piece parts with first resonant frequencies greater than 2000 Hz.

Acoustic tests are often viewed as a good candidate for the workmanship test of flight spacecraft, because acoustic tests seldom result in failures of primary structure, and in comparison to vibration tests, are relatively immune to over-testing caused by input spectra enveloping and test equipment failure. In programs with a development test model spacecraft, acoustic tests may be conducted on the development models early in the program to define/refine the random vibration test environments for flight instruments and components mounted on the spacecraft.

Acoustic tests have typically been conducted with the test items located in large reverberant chambers, and are excited with one or more electro-pneumatic drivers fitted with horns mounted into the walls of the chambers. The preponderance of the sound waves in an acoustic test conducted in a reverberant chamber bounce off the chamber walls many times before striking the test item, and this results in an acoustic field that is relatively uniform in frequency and space, i.e., it approximates a diffuse field, at least in the mid and high frequencies. An alternative acoustic test configuration employs a large number of electro-dynamic speakers arranged in close proximity to the test item, and may be located in a vibration or acoustic test chamber, a clean room, or in a large open space, such as a high bay

or loading area. In this configuration the test item is in the “direct” acoustic field of the speakers, which means that most of the sound waves travel directly from the speakers to the test item without first striking another surface (Figure 6).

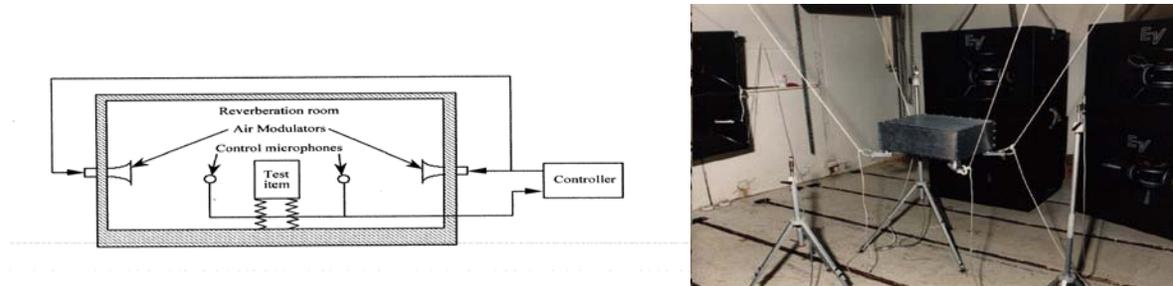


Figure 6: Acoustic Test Set-Up

6.0 SINUSOIDAL VIBRATION TEST

The basic purpose of the sinusoidal or sine test is to qualify spacecraft hardware for the low-frequency launch environment and to provide a workmanship screen for hardware which does not respond significantly to the vibroacoustic environment, but may respond significantly to mechanical vibration transmitted through the spacecraft interface to the launch vehicle. Examples of such types of hardware include wiring harnesses, stowed appendages, blankets and supports, flex-hoses, brackets, and mechanisms with clearances and/or bearings. The sine test is also an alternative test method to verify the behavior of the as-built flight hardware under the simulated dynamic inputs from the launch environment while on the ground. It should be noted that the system level sinusoidal vibration test is not intended to be a strength qualification test but is rather intended to verify that the system performs as expected after being exposed to flight-like low-frequency vibration input. The sinusoidal vibration test verifies the capability of the component/assembly to withstand and, if appropriate, to operate at the specified levels of the sinusoidal vibration environment.

This test is a qualification test only and is generally not required for component acceptance testing. The sweep rate for the sine test is selected to induce approximately the same number of vibration cycles at each specified frequency per design specification. This limitation on the number of vibration cycles at each frequency is sometimes difficult to achieve with a reasonable sweep rate.

7.0 RANDOM VIBRATION TEST

The random (vibroacoustic) vibration test verifies the component’s capability to meet applicable functional/performance requirements during or after exposure to the service life random vibration environments. This includes acceptance testing to screen production units for latent manufacturing, material, and workmanship defects. Random vibration testing is required for essentially all electrical, electronic, and electromechanical components and mechanisms. Exceptions are large area-to-weight structures, which may be subjected to acoustic testing in lieu of random vibration and hardware not practical to vibrate at the component level such as structures, electrical cabling, plumbing lines, blankets, etc. that may be deferred to the system level vibration or acoustic test. Compact payloads are subjected to

system level random vibration testing unless an analysis shows that the payload responses are clearly dominated by the direct acoustic environment. The test specimen is subjected to random vibration with a Gaussian amplitude distribution in each of three orthogonal axes. Random vibration testing is performed by controlling the acceleration spectral density (g^2/Hz) in the frequency range from 20 to 2000 Hz (Figure-7).



Figure7: Random Vibration Test

8.0 FLIGHT TEST

As stated above, design certification of an Aerospace System requires establishing requirements for performance of vehicle and components, followed by design/manufacturing and analysis and testing to assure that the design will accomplish its mission. Aerospace system testing follows the “test as you fly-fly as you test” motto as far as feasible. Hence, a detailed test specification/program is established for verification/validation. Dynamic (vibration) testing is an integral part of the test program along with other testing (thermal, pressure, static load etc). In addition, in general, the first few flights of a new space vehicle are dedicated as development flights and are heavily instrumented to collect flight data at critical component and at global vehicle level to help verify/validate the design analysis and/or make appropriate changes to assure continued success. In addition, propellant systems like liquid rocket engines, thrusters, and solid rocket motors go through a series of development testing to screen the design against vibratory fatigue and other design flaws

followed by “qualification” testing on flight-like articles. In addition, acceptance testing is done for each liquid engine unit and a lot acceptance testing is done for solid motors.

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GLOSSARY OF TERMS

Component: A functional subdivision of a subsystem or system (e.g., avionics boxes, transmitter, gyro system, actuator, motor, etc).

Design Specification: A document which details functional and physical requirements for an article, usually at a component and/or assembly level. It delineates functional requirements which generally evolve through the project life cycle to reflect progressive refinements in performance, design, configuration and test requirement along with environment, physical characteristics, and margins. It also provides the basis for technical and engineering management control. It may also present alternative strategies and associated test requirements that can be applied when appropriate.

Margin: The amount by which hardware capability exceeds the mission requirement.

Service Life: The life of an equipment item starting at the completion of fabrication and continuing through all levels of acceptance testing, handling, transportation, storage, prelaunch processing, all phases of flight, recovery, refurbishment, retest, and reuse as required or specified.

Vibroacoustic: An environment induced by high intensity acoustic noise associated with various segments of a flight profile (lift-off, ascent, engine/motor operation etc.). It manifests itself throughout the vehicle components/payload in the form of directly transmitted acoustic excitation and as structure-borne random vibration excitation.

Vibration: It is a term which describes oscillation in a mechanical system. It is defined by the frequency and amplitude.

Mechanical Shock: It is a non-periodic excitation of a mechanical system that is characterized by suddenness and severity, and usually causes significant relative displacements in the system.

Sinusoidal: A simple harmonic motion is motion such that the displacement is sinusoidal function of time; sometimes it is designated merely by the term harmonic motion.

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Appendix A

Comparison of Various Tests

The various types of dynamics tests have different purposes as related to equipment, effective frequency ranges, and risks, so it is important to tailor the test program to fit the needs, reliability requirements, schedule, and cost, of each program. Different organizations, and even different programs within organizations, have different approaches to defining dynamic test programs for certification. All dynamic tests entail some risk in that even handling a

built-up spacecraft involves risk. In general, the risk of a dynamic test increases in proportion to the test severity, i.e., the ratio of the test level to the limit loads.

Comparison of Different Dynamic Tests

Type of Test	Purpose(s)	Sensitive Equipment	Effective Frequency Range for Test	Risk (of accidental failure during test)
Acoustic	Workmanship and Qualification of Sensitive Equipment	Panels, Reflectors, and Large Subsystems	50 – 2000 Hz	Low to Moderate
Random Vibration	Workmanship & Qualification of Sensitive Equipment	Secondary Structure	20-2000Hz	Moderate
Sine Vibration	S/C Qualification of sensitive Equipment and S/C Workmanship	Interfaces, Buildup, Primary and Secondary Structure	5-100 Hz	Moderate
Flight	Acceptance (qualification and development)	Primary Structure, engine, thruster, solid motor	5-10,000 Hz	High
Shock (Firings)	Workmanship	Electronics and Packaging	50 –10,000 Hz	Low