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Design and analysis of vibration test bed fixtures for space launch vehicles

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Abstract

Space Launch Vehicles are subjected to rigor dynamic environment during lift-off and ascent phase of launch. The intense sound generated by the rocket propulsion system exerts significant acoustic pressure which induces vibrations. In addition, intense vibrations are generated by space propulsion engine ignitions, shut downs, sudden transient shocks generated by solid rocket motors and separation of stages. The vibration testing poses a challenge to design and realize good vibration test fixture. Launch vehicles have to undergo vibration testing prior to launch for its design qualification and flight acceptance. Vibration testing requires a fixture to interface the specimen and vibration generating equipment. This paper briefly describes the design criticalities, analysis and material considerations and structural dynamic modifications to ensure good vibration environment simulation to launch vehicle structures.

Keywords: Space launch vehicle, vibration testing, test fixture, acoustic pressure, resonance.

Introduction

Launch vehicles have to undergo vibration testing prior to launch for its design qualification and flight acceptance. Vibration test specifications are generated from previous flight telemetric data and scale down models (Palani Swami, 1990). Vibration test specifications simulates real time dynamic environment of launch vehicles. Vibration test system consists of Electrodynamic shaker, power amplifier, vibration control system and instrumentation data acquisition system with feedback closed loop. Shaker systems generate forces or accelerations to replicate same operating conditions or to generate an input spectrum that envelops the actual environment. Vibration testing requires (John D. Bernardin & Allen G. Baca, 2009) a fixture to interface the specimen and vibration shaker. Vibration test fixtures simulates mounting interface for both the specimen and vibration shaker on either side. During the vibration testing, the effects caused by the fixture are important. Vibration test fixtures exhibit resonant and anti resonant frequencies in the test frequency range due to the mass/stiffness characteristics. The resonant and anti resonant frequencies causes significant problems to the test specimen during vibration testing. Vibration controller attempts to control the vibration energy of the shaker system through a closed loop feedback and control accelerometers. But the vibration controller controls the level of vibration input to the test specimen where the control accelerometer is bonded. It is not capable of changing the resonant behavior of the vibration fixture. The resonant behavior of the vibration fixture is dependent on the fixture itself. Launch vehicle structures vibration testing poses a challenge to design and realize a good vibration test fixture. This paper describes in detailed the vibration test fixture design criticalities, analysis and material considerations for vibration test fixture.

Test fixture design

Vibration testing is required to conduct in vertical and horizontal axes. Vertical axis testing is conducted using vibration shaker keeping in vertical configuration. The test configuration in vertical axis is shown in Fig. 1. Horizontal testing is conducted using vibration shaker keeping in horizontal position and coupled with the slip table. The test configuration in horizontal axis is shown in Fig. 2. The vibration test fixture should simulate both vibration shaker table interface in vertical axis and slip table interface in horizontal axis on one side of the fixture. The fixture should have interface to the test specimen on other side (Scarton *et al*., 1971). Test specimen size and configuration are preliminary information required to design and configure the test fixture (Harrison, 2009). Weight of the test specimen and its C.G (at least an estimate of its location) are required to calculate the combined C.G of the test specimen and the fixture to fall as close as possible to the centre line of the shaker. The axis of motion such as vertical or horizontal should be defined relative to the test item or to the assembly into which the specimen is attached in normal service. As a vibration test fixture designer the following aspects are to be considered prior to designing a fixture. Details of the shaker table such as pattern of the attachment holes, bolt size and thread sizes are to be known to which the fixture attaches and vibration shaker force capacity. Details of the test specimen such as the mounting interface Pitch circle diameter (PCD) and predicted dynamic characteristics of the test specimen. Details of the dynamic test specifications used to simulate the dynamic environment. The test specification intensities must be known for two reasons, 1) the inertia force acting on the

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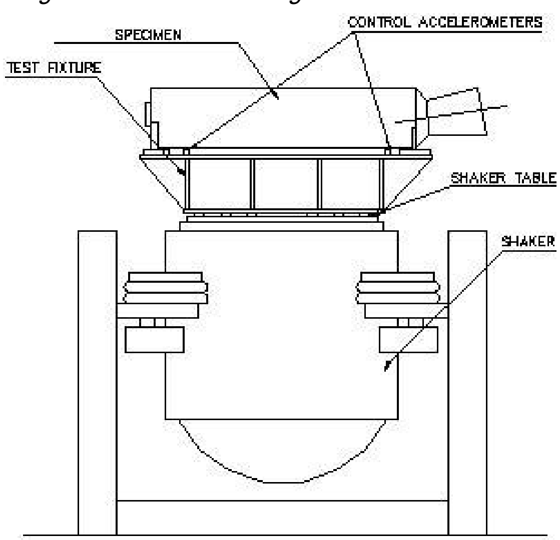
test item $F=W_t A$ must be with stood by the bolts or other fasteners connecting the test item to the shaker 2) there is a limit to fixture weight that can be allowed without exceeding the force rating of the shaker, since mass of the moving table (W_a) and mass of the test specimen (W_t) are fixed. Anticipated/repeated usage of the fixture is also to be known prior to designing the fixture.

Dynamic characteristics of test fixtures

A dynamic characteristic of the test fixture plays a major role during the vibration test. It is necessary to consider the dynamic properties of the materials used for fixture fabrication (Hieber, 1974).

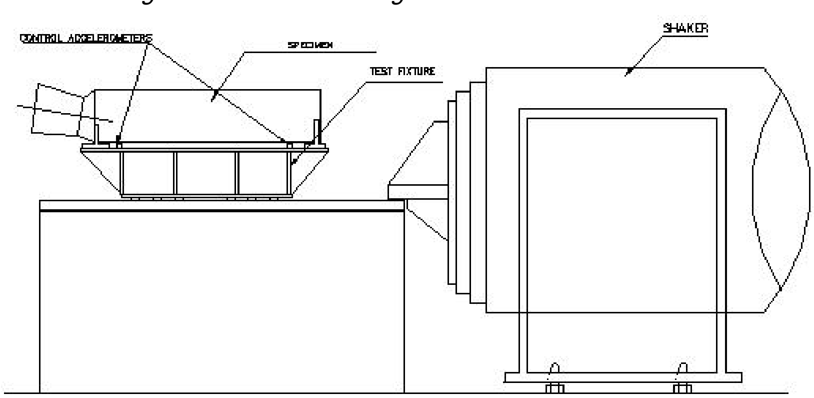
Fig. 1. Vibration test configuration in vertical axis



Mechanical Impedance

The concept of mechanical impedance helps explain the interaction between vibration shaker, fixture and specimen (Scarton, 1969). A simple definition of mechanical impedance is the force required to produce a desired motion to the test specimen. Launch vehicle equipments are exposed to random vibration excitations during launch and are functionally designed to survive random vibration testing. During vibration testing, the random vibration design levels are applied at the vibration shaker-interface. For light weight aerospace structures, the mechanical impedance of the equipment and of the mounting structure are typically comparable, so the vibration of the combined structure and the load involves modest interface forces and responses. The complex space launch vehicle vibration test fixtures exhibits resonant and anti-resonant frequencies in the testing frequency band. At anti-resonant frequencies, force exceeds the capability of vibration shaker to maintain the required test level. The extra force requirement leads to infinite mechanical impedance. So, the test fixture has to be designed in such a way that it should not induce mechanical impedance to the specimen during testing.

Fig. 2. Vibration test configuration in horizontal axis



Transmissibility

The fixture must be as stiff as possible so that it is not deflected by the specimen load and transfers motion with high fidelity. This quality is called transmissibility, which is a comparison of the output to the input. At a transmissibility of 1.0, the output faithfully follows input. Ideally, a dynamic test fixture couples the motion from the vibration shaker table to the specimen with zero distortion at all amplitudes and frequencies. This ideal is approached, if the test frequency range is narrow or if the test specimen is small. Practically, the ideal cannot be met and the limitation of the fixture must be known. The basic fixture shortcoming is insufficient stiffness. An infinitely stiff fixture, the natural frequency of the fixture is made as high as necessary to prevent resonances in the testing frequency band and provides transmissibility of 1.0 (Avitable, 1999). High stiffness necessitates a large mass to the fixture, but it limits the shaker force capacity. Since this is not achievable in practice, it is always a trade-off between the stiffness and mass relationships. Usually, the natural frequency of the fixture lies within the test specification range as shown in the Fig. 3. In this case, the motion delivered to the test item is higher than the input in the region around resonance and lower than the input above resonance.

Cross axis response

The armature assembly (shaker moving table) is designed to move in one direction and is held centrally by a suspension system. This system is designed to have high stiffness at right angles to the vibration axis. The overturning moments applied to the armature are high, and then the suspension guide will be compromised. The cross axis force applied during vibration needs to be understood and kept low to avoid damage to the bearings and armature. Design a fixture as light and stiff as possible is assists in preventing unwanted cross axial motion. The C.G. should be precisely calculated and each fixture should be rigidly coupled to the armature or slip table. If the C. G of the payload is kept low and aligns with the armature centre then cross axial stress is minimized (Poncelet, 2005). However, if the payload C.G is high or offset, then a turning moment is introduced during vibration. Each vibrator has some allowance for cross axis forces and limits the payloads C.G positional distance to the mounting face.

Fixture-Specimen resonance

A simple way to model the fixture-specimen dynamic system is to assume that the test specimen is an ideal, resonant-free mass that loads the fixture. An idea of the fixture design problem in terms of stiffness of the fixture is obtained from the formula

$D = (3.13/Fn)^{2,}$

D = the fixture static deflection caused by the specimen that produces the desired F_n in inches.

F_n = The desired resonant frequency of the specimen-fixture system.

Preferably, F_n is higher than the test spectrum, but usually this ideal is impractical or impossible. For instance, many specifications call for testing up to 2,000 Hz. If, to keep transmissibility close to 1.0, F_n is targeted for 3,000 Hz, the above equation shows that the fixture must not deflect more than 1 milli inch under the weight of the specimen. In most cases, such a stiff fixture is not feasible. Thus, often it is more convenient to develop a fixture, compute stiffness, and then solve for F_n using the above equation. The important factor left out of the equation is the mass of the fixture itself which acts to reduce F_n. The amount of reduction varies according to the test configuration and the ratio of the fixture mass to the specimen mass.

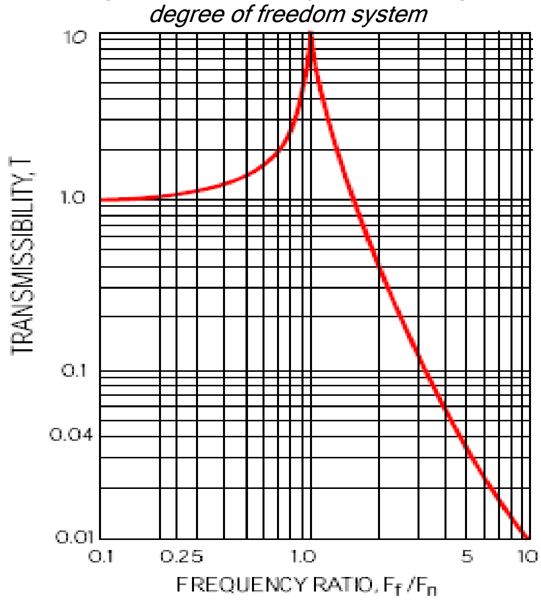
Material characteristics

The material should be as low in mass as possible without detriment to the stiffness. As F=M x a, the material mass will have an influence on the shakers thrust ability. The fixture is sculptured and material removed to reduce the mass. The dynamics of the fixture remain unchanged but the stiffness and strength is compromised and is considered. The fixture sees high stress levels from the applied vibration or the specimen response and must be strong enough to transmit the forces and survive the tests. Materials generally considered for vibration fixtures like Stainless steel, Aluminum, Magnesium have similar E/ρ ratio (ratio of Young's modulus to density) not affecting the natural frequency of the fixture. However, when the shakers are operating at their full performance level, the weight of the fixture dominates the selection of the material. Composite materials though are ideal for fixture to test large and heavy specimen, fabrication of the same is highly difficult. Though Magnesium is a lighter metal, fabrication issues and availability of indigenous fabrication techniques have compelled to choose Aluminum alloy as the fixture material for most of the applications. Welding is the fabrication method generally adopted for vibration fixture fabrication.

Finite element analysis

Finite element analysis (FEA) is a computer based analytic tool for solving structural problems. The FEA for structural design starts with modeling of the structure by dividing it into an equivalent system of simple elements, such as rectangles or triangles, with easily obtained stress and deflection characteristics. Upon specifying the material, material properties, boundary conditions, and loads, the analysis is completed by computer programs, utilizing arrays of matrix equations. FEA allows the determination of free vibration natural frequencies and the associated mode shapes of a structure, stress distribution and deformations. It provides valuable information for use in the design stages of a program, allowing optimization of the design by varying key parameters. The major issue with the use of FEA is the relatively high cost associated with modeling, imputing properties and loads, debugging, running of the computer analysis, interpreting of results etc.

Fig. 3. Transmissibility curve for single degree of freedom system



Performance evaluation

After design and realization of vibration test fixtures, it is necessary to evaluate the performance of test fixture. Performance evaluation is carried out by conducting resonance search, sinusoidal vibration test and random vibration test (Curtis *et al.*, 1971). Sometimes natural frequencies can be computed during design. But often the stiffness and mass cannot be predicted accurately enough for meaningful calculations. Resonance search test is used in two ways. First, it can identify the frequencies at which delicate subcomponents in a structure are likely to be damaged. The second use for-resonance search is finding the overall resonant frequency of the fixture assembly. During a resonance search, accelerometers should be used not only to determine motion of critical components, but also to monitor input to the assembly.

Sinusoidal Vibration is a special class of vibration. The structure is excited by a forcing function that is a pure tone with a single frequency. Sinusoidal vibration is not common in nature, but it provides an excellent engineering tool that enables us to understand complex vibrations by breaking them down into simple one tone vibrations. The motion of any point on the structure can be described as a sinusoidal function of time. When performing a sine test, one frequency is exited at each time. During sine vibration test each part of a complex structure is resonate at a different frequency.

Random vibration test simulates the realistic dynamic Environment to the structures. Unlike sine vibration test, in random vibration test all frequencies in the test band are present at all times. The random vibration test has a non-deterministic nature ie. the vibration levels cannot predict at any time in the future.

Modification of dynamic behavior of test fixture

Modak and Gandhare (2005) dynamic design is the process that aims to obtain desired vibration/dynamic characteristics of the products, equipment and structures by specifying the right shape, size, configuration, materials and manufacturing of various elements. Desired vibration characteristics include reduced vibration and noise levels, shifting of natural frequencies or avoidance of resonances, higher dynamic stability and desired mode shape. Structural dynamic modification methods are the techniques that intend to determine the changes in the vibration characteristics as a result of a certain design modification like addition of a mass, spring, stiffener of damper. Thus, these techniques form the basis for performing dynamic design at the computer level. The method of experimental structural dynamic modification using transfer function is applied to improve the vibration test fixture dynamic behavior. The responses at any points on the fixture are predicted utilizing the experimental data. Structural dynamic modification of the fixture is performed so that the spectra at the mounting points meet the specified reference spectrum. The values of the added masses attached on the fixture are used as design variables for removing the under tests in vibration test. From the experimental results of vibration test control applied to the modified fixture and unmodified fixture, this method is shows effective one.

Conclusions

Vibration test fixture is an important element of the vibration test setup. The fixture should simulate both the specimen and vibration equipment interfaces. The test fixture should have high stiffness, low mass, and unit transmissibility, minimal cross axis response and high resonant frequencies. Various configurations are conceived before arriving at the final configuration. Evaluation is carried out by vibration shaker system with a slip table in both vertical and horizontal axes. The first Eigen frequency of the fixture from the FE analysis is compared with the experimental value. The transmissibility (peak) measured from the analysis is compared to the experimental value. All the accelerometers responses at the fixture top flange are similar indicating a good design. The most important factor in fixture design is a high natural frequency above the frequency of interest. Weight is a drawback as it infringes the capability of the vibrator to deliver enough acceleration to the specimen. Cost considerations influence whether several single-purpose fixtures or one general purpose fixture will be built. Weight and cost considerations almost always compromise fixture performance. After performance evaluation, the test fixture dynamic characteristics are improved by using structural dynamic modification method with transfer function application.

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