Control and Limiting Strategies for Random Vibration Tests on Spacecraft Subsystems

A. R. Prashant, K. Sreeramulu, B. R. Nagendra, S. Ramakrishnan, M. Madheswaran, V. Rameshnaidu, P. Govindan, and P. Aravindakshan

Abstract Controlled vibration tests on complex spacecraft subsystem some times present several challenges to test engineers. In such cases, adopting proper control strategy becomes crucial so that the test article or subsystem undergoes a vibration test as per the test profile while safeguarding the shaker system. This paper presents different control/limiting strategies that are adopted while conducting a vibration test on spacecraft subsystems considering the safety of the subsystems and shaker systems.

Keywords Random limiting · Multipoint control · Fixture cross axis · Shaker current · Slip table response · Vibration response

1 Introduction

Spacecraft is placed in an orbit by a launch vehicle that defies earth's gravitational force and endures atmospheric conditions while traveling from ground to space. During flight, the launch vehicle will experience very high aerodynamic loads due to the atmospheric barrier and its own generated structural and acoustical vibrations. The spacecraft and its subsystems, being part of a launch vehicle, also experience these dynamic loads [1]. There are two paths through which loads are transmitted to the spacecraft and its subsystems. One, the accelerations transmitted through the launch vehicle interface and the second, direct acoustic noise through the shroud. Apart from this, the spacecraft experiences dynamic loads due to ground handling and in-orbit conditions. However, these loads are relatively very low compared to the launch loads. The dynamic loads are sinusoidal and random in nature. In order to qualify or accept the spacecraft and its subsystems to these dynamic loads, dynamic vibration tests are carried out. The subsystems are subjected to sine vibration, random

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vibration, shock and acoustic loads as applicable. These tests will help in demonstrating that spacecraft and its subsystem function within its performance specification along with its structural integrity. Vibration tests for spacecraft subsystems are carried out using an electrodynamic shaker.

The typical vibration test setup for a subsystem is shown in Fig. 1. It consists of a control system, data acquisition system, signal conditioners, sensors, shaker system and power amplifier. The required input test profile is fed to the control system that generates a time-domain signal corresponding to the test profile to drive the shaker. Carrying out vibration tests on an electrodynamic shaker coupled with a real-time controller poses a variety of challenges to the vibration test engineers. The test has to be carried out while maintaining the achieved test spectrum within a given tolerance. On many occasions, due to dynamics of the shaker (particularly slip table) along with test fixture and that of test specimen, it becomes difficult to achieve the test spectrum.

In many cases, these dynamics may result in over-testing of the test specimen or may be detrimental to the shaker system. Location and number of control reference points play a major role while conducting safe vibration tests. In certain vibration testing, there is a need for limiting the vibration level [2] at a particular measurement point on test article/subsystems so that the vibration levels at that measurement point do not exceed their design limit. In certain test cases, it has to be ensured that the shaker current does not exceed its rated values while conducting the test. Hence, in such test cases, feedback of these measured parameters is taken to ensure

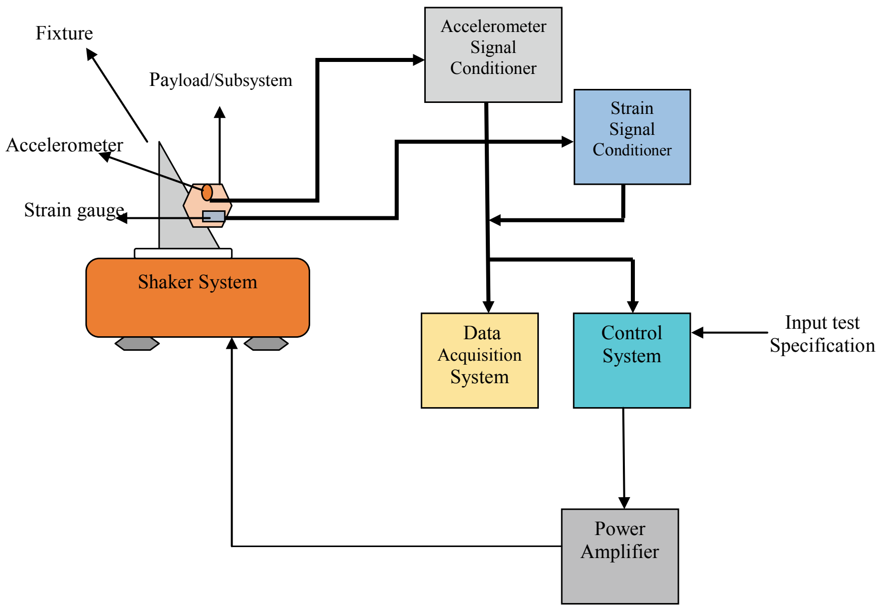

Fig. 1 Typical setup for vibration test on a subsystem

safe and satisfactory testing. In all such scenarios, the proper understanding of the coupled dynamics of a shaker with that of the fixture and subsystem plays a vital role. This paper presents different control strategies adopted for some of the spacecraft subsystem tests that were challenging to carry out random vibration testing. This paper is organized into four sections. Section 2 gives a brief description of random vibration and vibration control systems, Sect. 3 deliberates on different random control and limiting strategies adopted on spacecraft subsystems and finally Sect. 4 gives the conclusion.

2 Random Vibration and Vibration Control System (VCS)

The vibration test on any article or subsystem is characterized by various parameters. Among them, the four important parameters are test bandwidth, amplitude, duration and type of excitation. If the excitation is random in nature, then the vibration test is called random vibration test. For most of the spacecraft subsystems, the test bandwidth is from 20 to 2000 Hz. The duration and amplitude of the vibration test are based on test philosophy being adopted. The vibration amplitude level in the case of spacecraft subsystems is specified in terms of acceleration spectral density (ASD-g^2/Hz), generally referred to as power spectral density (PSD), and the overall vibration level is specified in terms of g_{rms}.

Subsystems are generally tested for vibration either to qualification or acceptance level and in some special cases, Protoflight level is adopted. Qualification level tests are intended to demonstrate that the subsystem will function within the performance specifications under simulated conditions more severe than those expected from ground handling, launch and orbital conditions. The qualification test's purpose is to uncover any deficiencies in the design. Acceptance level tests are intended to demonstrate the flight worthiness of the subsystem under simulated conditions as mentioned above. The purpose of carrying out the acceptance tests is to identify the latent workmanship defects in an already proven design and to check the performance under conditions similar to that of the launch environment. Due to cost and time constraints, the subsystems which are derived from earlier qualified programs but with minor modifications are carried out; such systems undergo Protoflight level of vibration. In case of the qualification random test, the overall vibration level, i.e. 'g_{rms}' is 1.5 times and PSD is 2.25 times the acceptance level, and test duration is twice the acceptance level duration. For Protoflight test, the level is that of qualification levels but the duration is that of acceptance duration.

In the case of a random vibration test, the vibration controller should be able to generate a true random signal to drive the shaker so that the test is conducted on the subsystem as per the specification with minimal deviation from the reference spectrum. Sections 2.1, 2.2 and 2.3 give a brief insight into the theoretical background of the random signal process, its analysis and random vibration controller, respectively.

2.1 Random Signal Process

When the excitation is random in nature, the corresponding structural responses are also random in nature. Statistical and probabilistic methods are used to quantify these random vibrations. In the statistical analysis of discrete random signals $\left(X_i = [x[1]x[2]\ldots x[n]]^T,\ \ \text{where}\, i, n \in \mathbb{N}\right)$, we are concerned with the statistical property of each observation in the signal as well as a finite collection of observations, i.e. random variable (RV). Assuming that the RV (X_i) are independent with identical probability distributions, the ensemble average for a linear process is defined as

$$\bar{X}\left(k_j\right) = \frac{1}{n}\sum_{i=1}^{n} \mathrm{x}_i\left(t_j\right) = E[X(k)]\,\text{and}\,n,\ j, k \in \mathbb{N} \tag{1}$$

For the random process, the first two statistical moments are mean and variance. For a discrete random signal, the mean and variance are given by $\mu_k = E[X(k)]$ and $\sigma_k^2 = E\left[(x(k) - \mu_k)^2\right]$, respectively. The central moments of the joint random variables between the same random signals and between two random signals are called auto-covariance and cross-covariance functions, respectively. This covariance information is very important and is frequently used for the spectral analysis of the structures.

A random signal is said to be strictly stationary if all of its statistical properties remain invariant to shifts in time. In reality, rarely does a random signal exist that satisfies the strict requirements of stationarity as defined. Since it is very difficult to verify stationarity at every instant in time, an alternative is to calculate time-averages over short segments of the random signal and test for their invariance with respect to time. An assumption of this approach is that the time-average is a suitable representative of the ensemble average which is the condition called ergodicity. Although no random vibration signal, in reality, remains the same with the passage of time, we assume that the analyses of time-scales are short enough to deem the changes insignificant. For linear processes, the first two moments are of prime interest. With this motivation, we can have a relaxed requirement called a weakly stationary process. A random signal $x(k)$ is said to be weakly stationary or of wide-sense stationarity if the mean is invariant with time. The signal should have finite variance and the auto-covariance between any pair of observations of the signal and should be dependent on lag between samples but not on time.

2.2 Random Signal Analysis

The term power spectral density (PSD) is commonly used to specify a random vibration level, and acceleration spectral density (ASD) [3] is more appropriate when acceleration is being measured as it is usually the accelerometer that is used to measure the vibration level in structural vibration testing. The power spectral density for a discrete-time random signal for a finite window $(1 < n < N)$ is given by Eq. 2,

$$\dot{\hat{S}}(\omega) = \frac{(\Delta t)^2}{T}\left|\sum_{n=1}^{N} x_n e^{-i\omega n}\right|^2 \tag{2}$$

where $X(n)$ is random signal variable sampled at discrete times $X(n) = X(n\Delta \mathrm{T})$ for a total measurement period $T = N\Delta \mathrm{T}$

This is a single estimate of the PSD. For typical vibration analysis, one would typically average this single-measurement PSD over many times for a more accurate estimate. The root mean square acceleration (g_{rms}) is the square root of the area under the ASD. The g_{rms} value is typically used to express the overall energy of a particular random vibration event. If two random signals possess power spectral densities, then the cross-spectral density can similarly be calculated. The cross-spectral density and auto spectral density are used to estimate the frequency response function (FRF) between two signals.

2.3 Digital Random Vibration Controller

The digital random vibration control system (VCS) is a computer system that generates a true random time-domain signal in order to conduct a closed loop test in conjunction with a vibration shaker. It generates a low-level voltage signal that is fed to the power amplifier, which then drives the electrodynamic shaker. The control reference sensor signal is fed back to the VCS. The control reference signal is usually measured using one or more accelerometers. In the closed loop test, the control signal must follow the given test profile.

The control algorithm in a controller performs two tasks. One is to shape the drive spectrum to match with that of the reference or limiting spectrum, and second, to abort the test in case the test level exceeds the specified level.

The typical control algorithm structure [4] consists of two loops as shown in Fig. 2. It uses the time-domain and frequency-domain approach. To calculate the PSD, it makes use of the frequency domain and to give the final control drive, time-domain randomization process is involved.

In Fig. 2, the inner loop is used to acquire time signals from control, limit and response channels and computes the average PSDs. For control purposes, only control and limit channels are used for computing the new 'control PSD'. It is updated, by considering the present average PSD and previous control PSD. This new control PSD is checked for abort and alarm conditions, before the transfer function is calculated. Then inverse transfer function is computed to generate a new time-domain drive signal to drive the amplifier/shaker. Here time-domain randomization is carried out. This process is repeated until the specified test duration has elapsed (Control strategies listed in Table 1).

This statistical confidence in estimating is a function of both the number of averages taken during a single loop and the weighting factor applied to the old control

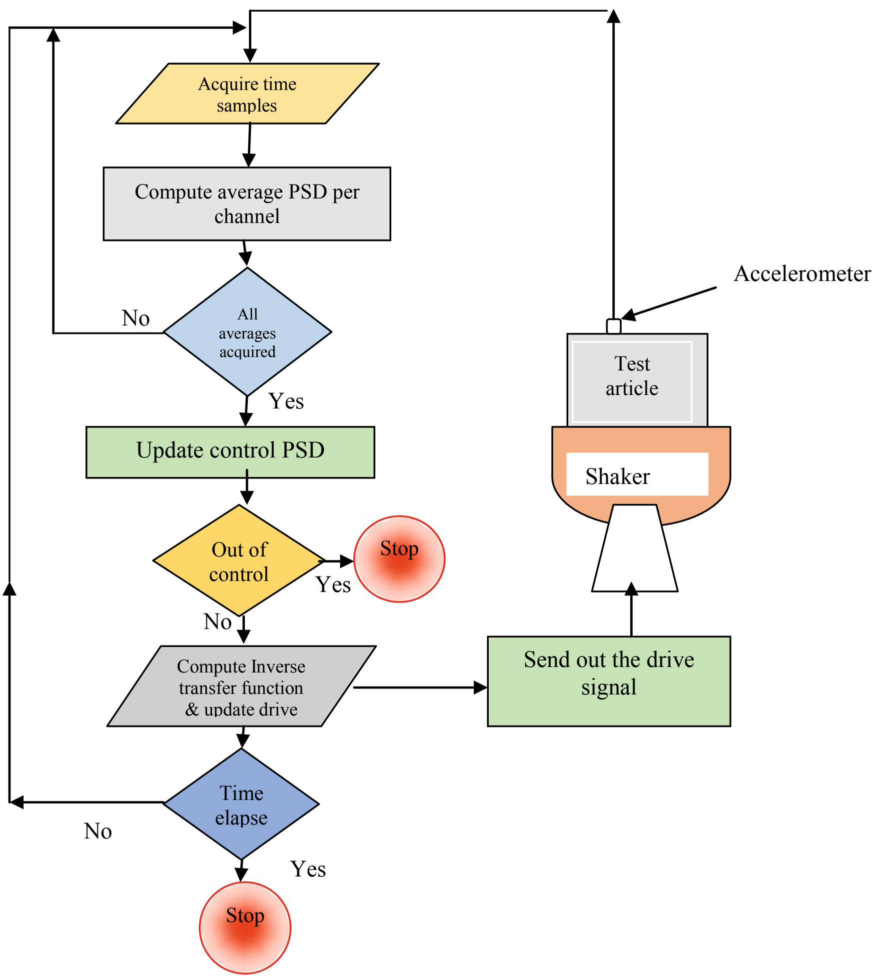

Fig. 2 Typical control algorithm used in the LMS control system [4]

Table 1 Different control strategies

Control Strategy	Remark
Maximum	To avoid over-testing on the subsystem
Minimal	To ensure minimum level of vibration is imposed on the subsystem
Average	Averaging of all spectral lines in the PSD blocks

PSD. The more the averages taken, the greater the confidence and it is also influenced by the weighting factor applied in computing the final new PSD. This statistical confidence is uniquely quantified by a parameter Degrees Of Freedom (DOF). The number of DOFs is given by the equation, DOF = 2 M × (2 W−1) where 'M' is the number averages in the inner loop and 'W' is the weighting factor. Generally, 120 DOF is set for spacecraft subsystem testing.

3 Random Control and Limiting Strategies on Spacecraft Subsystem

To carry out a random vibration test, the subsystem is mounted onto the fixture, which in turn is mounted onto the shaker table or slip table. The control reference sensor (single or multiple accelerometers used for controlling purposes) is generally mounted onto the fixture near to the base of the subsystem. The control system uses a reference accelerometer signal for controlling purposes. Carrying out vibration tests on electrodynamic shaker along with a real-time controller presents a variety of challenges to the vibration test engineers. Location and number of control reference points play a major role while conducting a safe vibration test. In certain vibration tests, there is a need for limiting the vibration levels on test article/subsystems so that the vibration levels on the subsystem do not exceed their design limit. Many a time, it has to be ensured that over-testing of the subsystem does not occur because of slip table dynamics and cross-axis dynamics of shaker/fixture combination. In certain test cases, it has to be ensured that the shaker current does not exceed its rated values while conducting the tests, as it results in aborting of the test due to tripping of the amplifier system. Considering these aspects, different control or limiting strategies are adopted during subsystem tests. Apart from mounting control accelerometers along the test axis, the accelerometers are mounted on important locations of a subsystem, onto the fixture for cross-axis measurement and onto the slip table end. In some tests, the armature current of the amplifier is also used as one of the limiting channels, which is measured using a current transformer at the power amplifier output.

The control system generates a single time-domain random control drive (CD)signal. This CD is a function of the responses from different control responses (C), slip table response (LSR), responses on subsystem (LR), cross-axis fixture responses (LXFR) and armature current of power amplifier (LA).

$$CD = f\begin{pmatrix} C_{11}, C_{21}, \ldots\ldots C_{n1}, \\ LSR_{11}, \\ LR_{11,} LR_{21}, \ldots\ldots\ldots LR_{n1}, \\ LXFR_{12,} LXFR_{22}, \ldots\ldots\ldots, LXFR_{n2}, \\ LXFR_{13,} LXFR_{23}, \ldots\ldots\ldots LXFR_{n3}, \\ LA \end{pmatrix} \tag{3}$$

The first subscript in Eq. 3 is the channel number and the second subscript specifies the sensing direction of the accelerometer. 1 is considered as along the test axis direction, and 2 and 3 are the other orthogonal axes of the test. L signifies that these channels are used as limit channels. It may be noted here that first a low-level random vibration test with single-point control on the fixture is carried out. Based on the responses of this low-level test, appropriate control strategies are adopted which are discussed below.

3.1 Control Strategy 1: Multipoint Controlled Vibration Test (MCVT)

During random vibration testing of the subsystem, the fixture-controlled excitation is adopted to ensure the required excitation level at the base of the subsystem. For the subsystem with larger footprint, the fixture is also large to accommodate the subsystem mounting. A single-point control test using such large fixture and large subsystem leads to a nonuniform excitation at the base of the subsystem due to the combined dynamics, leading to over-testing in certain frequency bands. In order to safeguard the subsystem, a multipoint controlled vibration test is adopted. Basically, MCVT is a conservative approach to random testing. Here, a minimum of two control reference sensors are required that are mounted on the fixture. The control drive for a general MCVT test for '*n*' control reference is given by Eq. 4,

$$CD = f\left(C_{11}, C_{21}, \ldots\ldots C_{n1},\right) \tag{4}$$

The control strategy of either maximum, minimum or average is used. For the spacecraft subsystem, a maximal control strategy is adopted. Then Eq. 4 for control drive for maximal control is given by Eq. 5,

$$CD = f\left(\max[C_{11}, C_{21}, \ldots\ldots C_{n1]}]\right) \tag{5}$$

One of the typical subsystems that has undergone a two-point maximal control test is shown in Fig. 3. With the two-point control method, the composite control from two sensors is achieved as per the test profile which is shown in the upper plot. The individual control responses are shown in the bottom plot.

Observations:

- Neither of the control responses exceeds the reference profile, and hence, the subsystem never gets over-tested than the specified reference profile.
- Generally, multi-point control is adopted for larger subsystem tests.

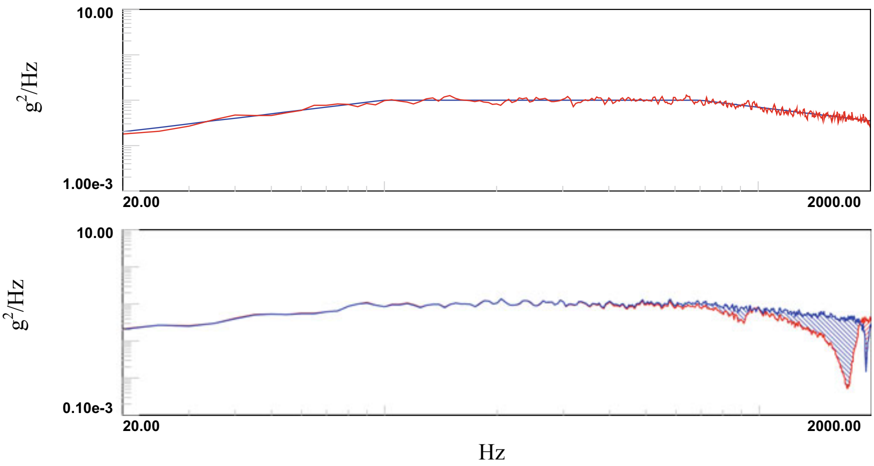

Fig. 3 Combined control reference spectrum and individual control reference channel spectrum

3.2 Control Strategy 2: Fixture Cross-Axis Limited Test (FCALT)

Random vibration tests on subsystems are conducted individually for all three axes. Different test levels are specified for each axis. For fixture-controlled test, the cross-axes responses of the fixture in certain frequency bands gets excited due to the combined dynamic behavior of shaker, slip table, fixture and subsystem. If the fixture cross-axis responses are allowed to go more than the test levels specified for that corresponding axis, then the subsystem gets over-tested. In order to protect the subsystem in such situations, the FCALT is adopted. Here the cross-axis sensors are also included in closed loop control, and these cross-axis sensor responses are limited to the given test profile pertaining to that corresponding axis. The control drive for the general FCALT test for single reference control and n cross-axis sensors is given by Eq. 6,

$$CD = f\begin{pmatrix} C_{11}, \\ LXFR_{13,} LXFR_{23}, \ldots\ldots\ldots LXFR_{n3}, \\ LXFR_{13,} LXFR_{23}, \ldots\ldots\ldots LXFR_{n3} \end{pmatrix} \tag{6}$$

Figure 4 shows the control (upper plot) and cross-axis response (lower plot) on one of the typical subsystems where the cross-axis limited test was carried out. The reference test level was set to 7.8g_{rms} for frequency bands from 20 to 2000 Hz. The cross-axis response especially out of the plane was limited and the overall test level achieved was 7.36 g_{rms}.

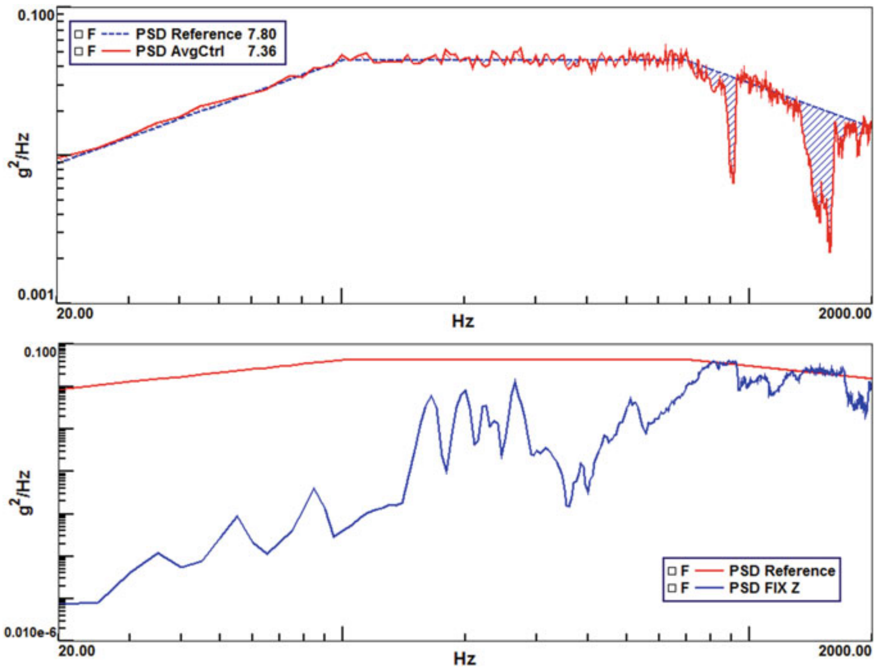

Fig. 4 Control reference spectrum and corresponding cross-axis response limit channel

Observations:

- Invariably such tests are conducted for larger subsystems using head expander type of fixture for lateral axis testing.
- In the majority of tests, the out of plane responses take over as a limiting channel.
- Limiting generally happens at a high frequency beyond the resonance of the slip table.

3.3 Control Strategy 3: Shaker Current Limited Test (SCLT)

The power amplifier amplifies the low-level voltage signal from the control system to the required level to drive the electrodynamic shaker. The driving current of the amplifier is proportional to the control reference acceleration. Due to the combined dynamics of the subsystem, shaker and amplifier, the current demand is different across test bandwidths. In some special cases of test profile, there can be a large demand of peak current in certain frequency bands of the test, exceeding its current handling capability of the power amplifier. Due to this, the amplifier may trip or power amplifier modules may fail. To safeguard the amplifier and shaker, the current limited test is adopted. The control drive for single reference control and the limit on armature current is given by Eq. 7,

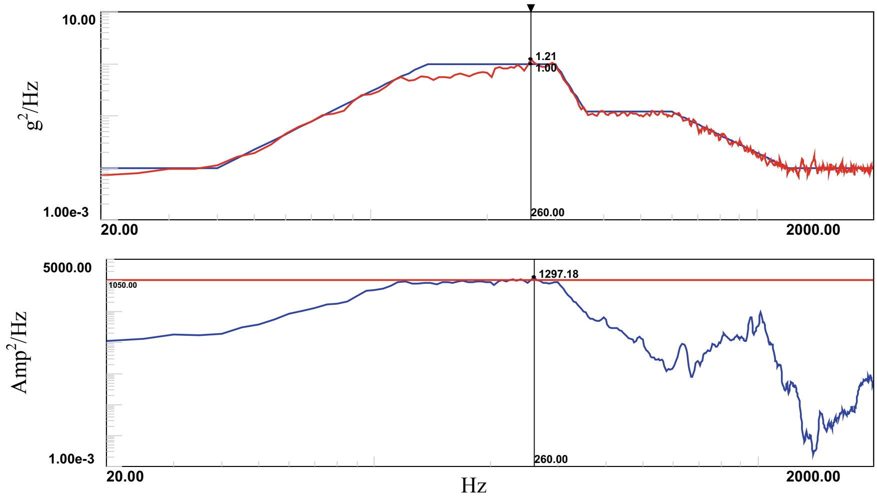

Fig. 5 Control reference spectrum and corresponding armature current limit channel

$$CD = f(C_{11}, LA) \tag{7}$$

During testing on one of the subsystems on the slip table, the current notching was implemented and observed that the PSD of reference spectrum came down in the frequency range 100–250 Hz as shown in Fig. 5. The control reference spectrum and amplifier current are both shown in Fig. 5.

Observations:

- For the same acceleration density, the current demand by the shaker at a low-frequency band is high compared to a high-frequency band. For a test specification with overall g_{rms} well within the shaker capability and if acceleration density at low-frequency is high, then such current limited test is adopted.
- In the case of fixture isolation at any frequency, the peak current demand can also be high, and the current limited test protects the shaker system.
- When employed in the testing of heavier test specimens with multiple fixture control, this limiting strategy is helpful in case of improper estimation of the weight of the subsystem thus avoiding damage to the shaker and amplifier system.

3.4 Control Strategy 4: Slip Table Response Limited Test (STRLT)

Slip table is coupled to the shaker to carryout vibration tests on the subsystem in lateral axes. The fixture is mounted on to the slip table, over which subsystems are mounted to carry out the tests. In certain subsystem tests, there exists isolation in certain frequency bands between fixture and slip table. In such cases, the slip table's end will experience very high vibration levels in those isolation frequencies. These higher levels of vibration can cause severe damage to the bearing of the slip table or to the shaker armature. Hence, the slip table response limited test is adopted in such cases to ensure the safety of the shaker system. The control drive for a single reference control and slip table limit response is given by Eq. 8,

$$CD = f(C_{11}, LSR_{11}) \tag{8}$$

Figure 6 shows the control reference spectrum (upper plot) on the fixture and slip table response (lower plot). It can be seen that limiting has happened in a frequency band around 1495 Hz. The slip table is limited to 1 g^2/Hz.

Observations:

- It is observed that larger slip tables with fewer supporting bearings will have more isolation frequencies within the frequency range of testing.
- Due to limiting of the slip table, the control reference amplitude level will be reduced at those isolation frequencies ensuring the safety of the shaker system.

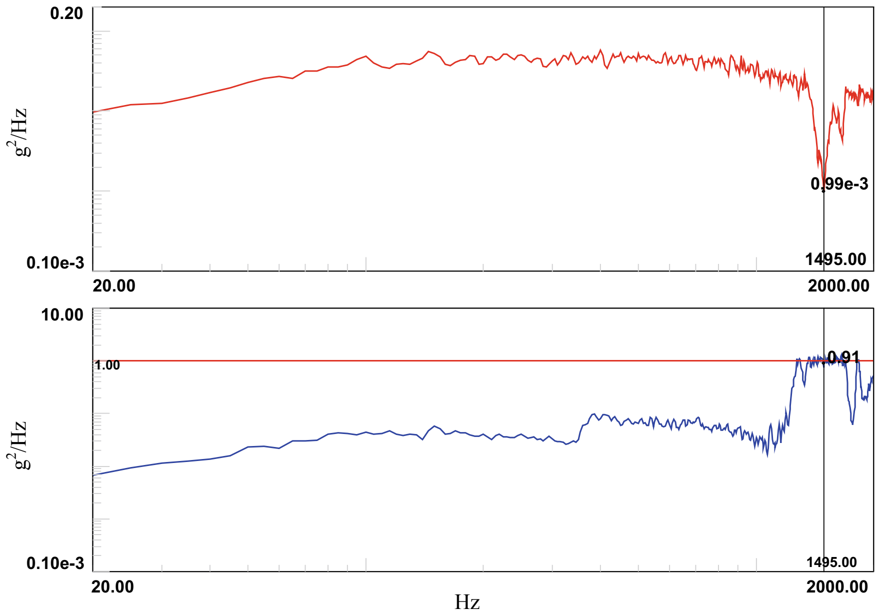

Fig. 6 Control reference spectrum and corresponding slip table response limit channel

3.5 Control Strategy 5: Vibration Response Limited Test (VRLT)

Subsystems are mounted onto the spacecraft decks. The vibration test levels for a subsystem are arrived at based on the launch vehicle, mass of the subsystem and location of the subsystem in the spacecraft deck. The mechanical impedance offered by the shaker to the subsystem during vibration tests is very high compared to the expected values during launch. This is due to the floating condition of the launch vehicle. Due to this, the vibration response on a subsystem during the shaker-mounted test may exceed the expected level as seen by the subsystem during launch. This may be damaging to the subsystem. In such cases, the vibration response limited test is adopted wherein the reference control input is notched at those critical frequencies, which ensures that the response level on the subsystem never exceeds the expected level. The limiting is carried out manually or automatically. In the case of manual limiting, the reference input is manually set to a low value in the desired frequency band, whereas in automatic limiting the control system limits the response on the subsystem by reducing the reference input in those critical frequency bands. The control drive for a single reference control and ‘n’ limit response channels is given by Eq. 9,

$$CD = f\left(C_{11}, LR_{11,} LR_{21}, \ldots\ldots\ldots LR_{n1}\right) \tag{9}$$

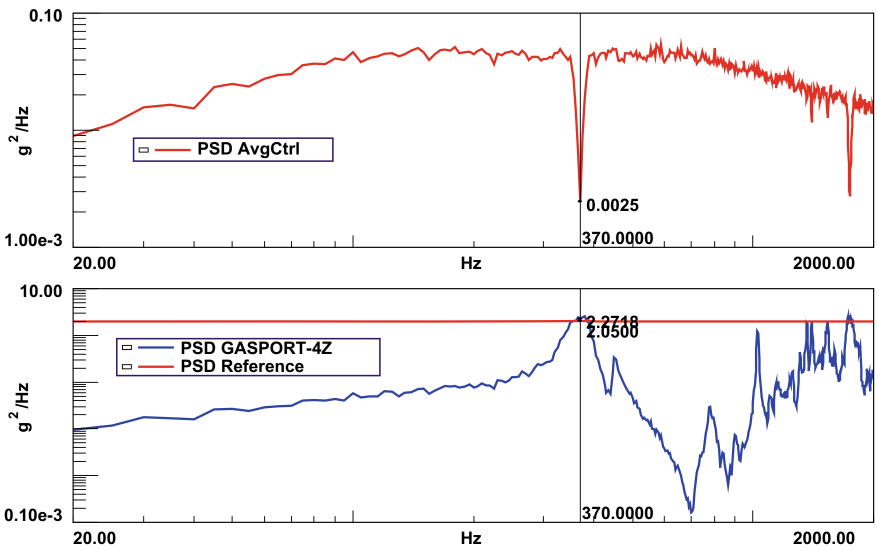

Fig. 7 Control reference spectrum and corresponding response limit channel

Figure 7 shows the automatic notching of control reference input (upper plot) by limiting the response channel (lower plot) on the subsystem to 2.2 g^2/Hz.

Observations:

- Generally limiting of the response is carried out near the first fundamental mode of the subsystem.

4 Conclusions

This paper presents various control strategies being adopted during the random vibration test on a spacecraft subsystem. The control strategies mentioned in this paper help in conducting a safe random vibration test on the test article while safeguarding the shaker and the power amplifier system.

Single point controlled vibration tests are widely practiced in industry. Multi-point control strategy and other limited response control strategies discussed in this paper are practiced in the aerospace industry. The fixture cross-axis limited test is to safeguard the subsystem from getting excited in cross-axis due to the combined dynamics of slip table, fixture and subsystem. The slip table limited response test is to safeguard the shaker system, and the shaker current limit test is to safeguard the power amplifier.

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