VIBRATION TESTING FOR SMALL SATELLITES

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Most people involved in the design and construction of small satellites are unfamiliar with vibration testing. Yet most satellites undergo vibration testing to qualify them for flight. Some familiarity with the basic aspects of vibration testing is needed to insure that a vibration test on a satellite is valid.

This paper sets forth the basic equipment, practices and concepts of vibration testing. It provides guidelines for specifying a vibration test, designing fixtures, attaching instrumentation, acquiring data and data interpretation for a satellite vibration test.

INTRODUCTION

The vibration environment for space payloads during the launch phase is typically quite severe. Subjecting a proposed payload to a vibration environment that simulates the launch phase is useful for determining if the payload will survive the rigors of the ride to space. Achieving a good simulation of the launch vehicle vibration environment is quite difficult to achieve.

The goal of vibration testing is to reproduce in the laboratory the dynamic environment of the satellite. If this is done accurately enough the testing will determine if the item tested will function properly in its intended environment.

TYPES OF VIBRATION TESTING

Classical methods of vibration include Random vibration, Sine vibration and Transient or Shock testing. More recently combinations of these events have been developed and used i.e. Random on random, sine on random and gunfire (transient on random).

RANDOM VIBRATION TESTING

Random vibration testing subjects the satellite to excitation at all frequencies within a prescribed bandwidth, typically 20 to 2000 Hz. The energy at each frequency is controlled to a specified level. The actual amplitudes are random with a gaussian distribution around the desired test level. In general random vibration provides the best simulation of many actual environments and is the predominant method for vibration testing.

In practice one cannot excite every frequency in a bandwidth as there is an infinite number of them. To do random testing the
bandwidth is divided into narrow bands of frequencies or "lines." The bandwidth of a line (filter bandwidth), is determined by the capability of the vibration control system and the operators preference. Amplitude levels are normally specified in units of $G^2/\text{Hz}$. The Hz. units are in reference to the filter bandwidth. Dividing by the filter bandwidth normalizes the data. This makes two data plots that were plotted with different filter bandwidths directly comparable.

SINE VIBRATION TESTING

Sine sweep testing exposes the satellite to a sinusoidal excitation that either sweeps across a frequency band or dwells on a single frequency. The sweep rate for a sine sweep may be either linear, expressed in terms of Hz. per second or logarithmic, usually specified in octaves per minute. An octave change is a doubling or the frequency when sweeping up or halving the frequency when sweeping down. The amplitudes of sine sweeps are generally a function of the frequency and are specified in units of acceleration, velocity, displacement or a combination of these. Sine dwells are controlled to a specified amplitude which also can be specified in terms of acceleration, velocity or displacement.

Sine testing is useful for determining the effects of resonance conditions and simulating environments that have dominant narrowband frequency components. It is generally inferior to random testing when a broadband frequency spectra needs to be excited.

TRANSIENT (SHOCK) TESTING

Transient testing is used to simulate the effects of short duration, high amplitude phenomena such as impacts, pyrotechnic device detonation, shock waves caused by high explosions etc. For satellites stage separation using pyrotechnic devices is a common form of shock.

Waveforms used for transient testing are generally divided into three categories; classical waveforms, shock spectrum synthesis, and field transients.

Classical wave forms include half sine pulse (haversine), terminal peak sawtooth, square wave, triangle and initial peak sawtooth. Amplitude and duration of these waveforms are controlled to achieve the desired response.

Shock spectrum waveforms are generated so as to produce a specified shock spectrum. They are composed of a superposition of short duration transcendental functions such as decaying sinusoids of different frequencies. The damping, amplitudes, start points and
initial direction of these components are adjusted to produce a desired shock spectrum response. Shaping these transients requires considerable skill on the part of the operator. Shock spectrum waveforms generally produce a much more realistic simulation of transient events in the operational environment than do classical pulses.

Field transients are transient events that are recorded during the operation of the satellite in its normal environment and then used as the input or reference waveform for the test. Intuitively this may seem like the best approach to transient testing but it has some serious drawbacks. Field data is generally not available and operational transient events typically have a high degree of randomness. No single transient event is statistically representative of the overall field environment. In order get acceptable data for test criteria a large number of shocks need to be measured and some statistical averaging done to get a representative test profile. Once a representative shock spectrum is determined it can be used as the test criteria.

A word about shock spectrum. This is undoubtedly the least understood aspect of vibration testing. Shock spectrum plots are usually in Gs vs. frequency on a log scale. Many people who use this data do not realize that the G levels on these plots do not represent actual acceleration responses. G levels on a shock spectrum plot are the computed responses of a simple mechanical system composed of a bank of idealized damped spring mass systems that are excited by the waveform being analyzed. The resonant frequencies of these spring mass systems are sequentially higher by a fixed octave spacing e.g. 1/3 octave, 1/6 octave etc. Shock spectrum data provides a means of measuring the relative damage potential of two different transient pulses. It cannot be used to predict stress, strain or other physical phenomena.

COMPOSITE TEST METHODS

Composite test methods are combinations of the basic test methodologies, random, sine and transient. They include Random on Random: swept narrow band random signals on a broadband random signal, Sine on random: several sine sweeps usually harmonically related sweeping a narrow bandwidth and superimposed on a broadband random signal, and Gunfire simulation which superimposes transient events on a broadband random. These test methods are generally not applicable to satellite testing and are mentioned only for completeness.

TEST EQUIPMENT

The primary device for vibration testing is the electrodynamic
shaker with its attendant field power supply and power amplifier system. The largest of these devices can generate force ratings of up to 50,000 lbf. and operate over a frequency range of 5 to 2500 Hz. They can generate any desired waveform within the constraints of their peak acceleration, velocity and displacement ratings. Almost all testing for satellites is done on electrodynamic shakers.

Many electrodynamic shaker systems incorporate some kind of horizontal table for testing the lateral axes. Most electrodynamic shakers are configured so that the armature body can be rotated into a horizontal position. Horizontal tables consist of a thick magnesium or aluminum plate that attaches at one end to the shaker armature and is supported by linear hydrostatic bearings or on an oil film on a granite slab or a combination of both.

Other vibration test equipment available include electrohydraulic shaker systems and shock testers. Hydraulic shakers can achieve very high force ratings and large displacements but are limited in frequency range and suffer from high distortion of the desired waveform. Mechanical shock testers can achieve very high force and/or large displacement shock pulses but are limited in the type of waveforms they can produce.

Control of electrodynamic and hydraulic shaker systems is almost universally done with digital systems based on modern minicomputers. These systems combine digital to analog and analog to digital hardware with a fast general purpose computer and often some type of high speed coprocessor to achieve vibration control. Software for these units accomplish the various types of vibration testing with high speed and generally good control. They can be programmed to do any of the vibration testing mentioned above. In many vibration test laboratories they double as the data analysis equipment. They are almost always equipped with hardcopy devices of some type to output test data.

Equipment commonly used in support of vibration testing include charge amplifiers to convert the signals from accelerometers to voltages suitable for recording or digitizing, tape recorders both analog and digital, oscilloscopes, voltmeters, oscillographs, signal conditioners and digital acquisition and analysis systems.

TEST CRITERIA

GENERAL

Test levels, frequency bands durations etc. are a function of the launch vehicle dynamics and are generally obtained and published by the organization responsible for the launch vehicle. Specific criteria for the location where the satellite is to be carried should
be provided. If not it can usually be obtained from the launching organization. Often the requestor finds himself dealing with new and unfamiliar material once he locates the vibration test criteria for a particular vehicle. The following paragraphs provide the basics of how vibration test criteria is presented and what information is necessary to specify a test.

Two levels of testing may be included. One level at the expected flight vibration levels and a higher level for qualification. Initial testing to the more conservative (higher) levels is recommended.

The point where the input levels are to be measured needs to be established. This is the point where the control accelerometer for the vibration control system should be attached. It should correlate with the point on the launch vehicle where the test criteria data was taken. This may be detailed in the published specifications. If not and this information cannot be obtained, a good practice is to control the testing near one of the principal mounting points where the satellite attaches to the test fixture.

RANDOM TEST CRITERIA

Random test requirements are almost always specified in Power Spectral Density (PSD) plots. Two formats are common: Amplitude vs. frequency and slope vs. frequency with the amplitude of the first breakpoint given. The overall GRMS value is sometimes specified also. PSD plots are typically in log format and the data consists of amplitude vs. frequency breakpoints or slope (in dB/octave) vs. frequency connected with straight lines. Random tests may also be specified with frequency/amplitude breakpoints in tabular format. Any of these formats should be acceptable to the vibration test facility.

The criteria may specify a maximum "filter bandwidth" or "number of lines" which are different ways of specifying the required frequency resolution. In the absence of this information a filter bandwidth of 10 Hz or 200 lines of resolution are about the minimum acceptable. Modern digital controllers can usually do considerably better. It is always a good idea to consult the test facility where the test is to be done and agree in advance on this parameter. More lines of resolution or narrower filter bandwidths provide a more detailed view of the test articles dynamics but may be more difficult to control.

Test specifications must always include the duration of the random event. Normal practice in random testing is to start the test at a low level and increase the gain in operator selected dB increments to full level. These test schedules generally do not
appear in test specifications and can be left to the discretion of the test facility or agreed upon in advance. Lower level durations are typically short e.g. five to ten seconds. Some vibration controllers will stay at lower levels until adequate convergence to the required PSD profile is achieved.

Test specifications also must call out tolerances for the test. These are typically given in ±dB. (3 dB to 6 dB are typical).

SINE TEST CRITERIA

Sine test criteria must include the following parameters:

a) Minimum and maximum frequencies

b) An acceleration profile in either Gpk or Grms vs. frequency

c) The sweep rate in Hz per second (linear sweep), octaves per minute or decades per minute (log sweep)

d) Number of sweeps

e) Start frequency and direction

f) Tolerances.

Sine sweeps often sweep the frequency band several times changing the direction of sweep every time an end frequency is reached. Sweeps can be started at any frequency and begin sweeping either up or down. This is useful if the test has been aborted and is to be continued from the point of abort.

TRANSIENT TEST CRITERIA

Transient test criteria may be specified in either time history in the case of the classical waveforms or in terms of the desired shock spectrum response. Again tolerances are normally included.

The resolution for shock spectrum calculations should also be specified but may not accompany the published criteria. In the absence of published octave spacing, 1/6 to 1/12 octave spacing is usually adequate.

TEST PLAN

In addition to the criteria needed to accomplish the actual vibration testing, a number of other activities usually constitute the overall test program. It is recommended that all these
activities and the criteria be incorporated into a written test plan that is coordinated with and agreed to by all applicable parties especially the test facility prior to starting the test. It should include the following items as required:

a) Pre test visual inspection to verify that the satellite has arrived at the test facility undamaged. This ought to be done by the customer rather than test facility personnel.

b) Functional checks. Proper operation of the satellite should be verified immediately prior to and following vibration testing. If the satellite is to be operative during the launch phase it may be valuable to monitor its functioning during vibration tests.

c) Location of instrumentation. The test plan should detail where the accelerometers and other required instrumentation should be attached to the satellite. The method of attachment and who’s responsible for instrumenting the satellite should also be specified. If instrumentation is to be installed inside the satellite provision must be made for routing the signal cables to the outside.

d) Failure criteria. The conditions that must be met for passing the vibration test must be determined. If the satellite fails what action is to be taken? What problems may be fixed and testing resumed or restarted?

e) Data required. This should include all accelerometer data and data from other types of transducers if used. Attention should be given to annotation of data. Annotation should include at a minimum the nomenclature of the satellite, the test date, the axis of vibration, and the test level. Each plot should also include the identification and type of transducer the data was taken from and its calibration, location and orientation.

f) Test log. A comprehensive record should be kept either by the organization for which the testing is done or by test facility personnel. Often both keep a record of the testing. If a test log is required of the test facility the test plan should specify the minimum requirements for information to be entered in the log.

g) Safety considerations. If the satellite has any potential hazards associated with it i.e. dangerous chemicals, high pressure gas tanks, etc. The test plan should include warnings and proper handling instructions. Avoid these types of hazards if possible.

h) Fixturing: The fixture design and the party responsible for designing and fabrication of the test fixture must be established. Test facilities will seldom have a suitable test fixture on hand. Designing and fabrication of a fixture can be time consuming so some
advanced planning is in order here.

i) Test report: If a test report from the test facility is desired it should be specified. Generally this is a desirable document to have. Most test facilities will have an experienced dynamicist on their staff who can provide material assistance in understanding and interpreting the test data. The test report should include at a minimum:

1) The test log if kept by test facility personnel.
2) All requested test data.
3) A copy of the test plan.
4) Details on the instrumentation equipment used including calibrations, filter settings etc.
5) Analysis of the data by experienced personnel at the test facility if possible.

FIXTURING

All vibration tests require some sort of fixturing. A fixture is the mechanical interface between the satellite and the shaker. A poor or improper fixture can invalidate the test, damage the satellite, or cause control problems.

A good fixture must do several things. First it should simulate the mounting interface between the satellite and the launch vehicle. Second it should not have any undesirable response characteristics which may transmit unwanted vibration into the satellite. Third it must transmit the forces produced by the shaker to the satellite with minimal loss. The second two objectives are usually accomplished by making the fixture very stiff and highly damped. The best material for this is magnesium but it is expensive and somewhat hazardous to work with. A good substitute is a soft weldable aluminum such as 6016-T6. Steel does not work well because it lacks sufficient internal damping.

Fixtures can be designed for a single axis or for multiple axes testing. In general multi-axis fixtures are most suitable for small test articles such as a small satellite.

Fixtures may be fabricated by welding or bolting together. Welding is preferable if the capability is available. Bolting can produce an acceptable fixture if care is exercised in the design. The key here is to design for stiffness not simply mechanical strength. Ideally a fixture should be designed so that its first
resonant mode is above the maximum frequency in the test criteria. This is not difficult for small satellites but may pose problems for a larger one.

The shaker interface must match the bolt pattern of the shaker armature for longitudinal (vertical) vibration or the horizontal bearing table for lateral (horizontal) vibration. Usually there will be two lateral axes perpendicular to each other so a horizontal fixture mounting hole pattern must match the table bolt pattern in two directions. Horizontal bearing tables often have symmetrical mounting hole patterns which can simplify the hole pattern design. A multi-axis fixture must match both the armature and the horizontal table mounting patterns.

INSTRUMENTATION AND DATA RECORDING

INSTRUMENTATION

Placement of response accelerometers, strain gauges and instrumentation plays a key role in determining the dynamic response of the satellite during vibration test. It could be argued that if a satellite was instrumented with only the necessary control accelerometer and it passed the vibration testing there would be no need for further instrumentation. However if there is a failure such a simplistic approach would probably not provide sufficient information to pinpoint the cause of failure or to make a determination as to what modifications need to be made to correct the problem.

Proper installation and setup of instrumentation channels is equally important in obtaining meaningful data from a vibration test. Accelerometers must be rigidly mounted to assure that they move with the structure they are attached to and have no vibration modes of their own.

Accelerometers are either glued on or attached with small screws. Using screws requires drilling and tapping the structure where the accelerometer is to be mounted. This is generally not acceptable for attaching them to the satellite itself although it is perfectly acceptable for mounting an accelerometer on the fixture. Only a few adhesives are suitable for gluing accelerometers. Dental cement is best. Small accelerometers can be attached with super glue. Epoxies that set up hard and rigid also work well.

Avoid thin flexible panels and rough or curved surfaces when selecting accelerometer locations. Flexing of the mounting surface during vibration can break the glue joint. Strong glue joints are hard to make on rough or curved surfaces.
It is a good practice to instrument points where the satellite mounts to the fixture at points other than the one used for control. At certain frequencies the control point may experience an anti-resonant condition causing the vibration controller to drive very hard to meet the test criteria. This can usually be avoided by proper fixture design but should always be monitored during test. Dealing with such a situation if it occurs is beyond the scope of this paper. Generally if such a condition is unavoidable and not considered desirable in terms of a good simulation the offending frequency can be notched in the test criteria profiles and the test continued. Test facility personnel can often be helpful here.

Other transducers should be mounted per the manufacturers directions.

Filters: To prevent a phenomena known as aliasing or foldback than can occur when data is digitised, Data channels including control need to be lowpass filtered. This is accomplished using quality analog filters. Aliasing causes errors by folding frequencies above one half the digitizing sample rate back into the lower frequencies. Once this occurs there is no way to digitally filter it out or remove the erroneous data.

DATA RECORDING

In order to use the output of a transducer some signal conditioning must be done. For accelerometers the output signal must be changed from picocoulombs to volts and amplified using a charge amplifier to obtain a suitable signal for recording or digitizing. The outputs of other transducer types also must be changed to volts and amplified prior to recording or digitizing. This type of equipment is usually provided by the test facility.

The amount of amplification combined with the sensitivity of the transducer itself combine to determine the sensitivity of the data channel. Amplification should be set so as to make good use of the dynamic range of the recording device or digitizer without saturating it at the peak output levels.

EVALUATING TEST RESULTS

If a satellite passes vibration testing without any anomalies an in depth analysis of the vibration data may not be necessary. But even a properly setup and executed vibration test does not guarantee that the satellite will endure the launch environment. If components or parts of the structure and/or the whole assembly manifest resonance conditions (responses that are significantly higher than the input levels) particularly in the low and mid frequencies there is potential for stress levels that could damage the satellite. If
configurations that have high response (resonance) modes can be improved prior to flight the risk of vibration damage will be reduced. This may be done by adding dampening material or modifying the structure.

Resonance conditions must be evaluated on a case by case basis. Generally the higher the frequency the lower the risk of damage as displacement is inversely proportional to the square of the frequency.

**DESIGN FOR VIBRATION**

Properly packaged electronic components can endure a brutal amount of vibration without failure. Wires, connectors, solder joints and threaded attachment points usually fail first. The following design practices will greatly improve the vibration hardness of a satellite:

a) Use lock washers or locktite on all threaded fasteners.

b) Support all PC boards on at least two edges preferably the longest edges.

c) Avoid mounting equipment or components in a cantilever configuration.

d) Clamp long wires and wire bundles every two to three inches.

f) Mount discrete electronic components on PC boards as low as possible. Pot them in PVC if you can.

g) Avoid large unsupported panels.

h) Shock mount components that may be particularly susceptible to vibration.

i) Avoid designing components and structures that have high length to width and or thickness ratios.

**SUMMARY**

Vibration testing is a key function in preparing for a satellite launch. A properly executed vibration test will measure the satellites response characteristics and provide its designers the information they need to determine its ability to withstand the rigors of a space launch. Designing for vibration hardness is a key element in any satellite design.