Curriculum Needs for the Testing of Small Satellite Systems

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The aerospace systems field has recently been attracting more and more interest. The scope of activities in this area includes vehicles for space exploration, communication, tourism and national security. This trend is expected increase as nationwide there is a strategic focus on space. This focus has materialized recently by a call by US authorities in favor of the creation of a separate branch of the military called Space Force in addition to the traditional branches of the Navy, the Marines, the Air Force, the Army and the National Guard. With this trend, demand for research, construction, testing and launch of space vehicles is expected to increase. The engineering education curriculum needs to be adapted to meet these new demands. More and better expertise will be needed for manufacturing and testing of the space vehicles in general and specifically for small satellites. Small satellites are defined as space vehicles in the range of 50-500lb (23-230 kg). Although small, these satellites are useful in several applications and require moderate size equipment for their testing.

In this paper, we describe the steps taken to engage the stakeholder's community, the overall testing environment for small satellites. The paper discusses the basic concepts of vibration testing, practices and equipment involved as well as the anticipated changes in the engineering education curriculum.

Key words: Small satellites, Testing, Vibration, Engineering Education

INTRODUCTION

The Denver area is attracting more and more aerospace companies. The scope of activities in this area includes vehicles for space exploration, communication, tourism and national security. This trend will continue to grow as the federal government revamps its focus on space. This focus has materialized recently by a call by the US President in favor of the creation of a separate branch of the military called Space Force in addition to the traditional branches of the Navy, the Marines, the Air Force, the Army and the National Guard. With this trend, demand for research, construction, testing and launch of space vehicles is expected to increase. The engineering education curriculum will need to be adapted to meet the demands created by this industry trend. The fields of engineering education concerned by these changes will include primarily (but not be limited to) mechanical, electrical, manufacturing, aerospace and systems engineering.
More and higher-level expertise will be needed for manufacturing and testing of the space vehicles in general and specifically for small satellites. Small satellites are defined as space vehicles with a payload range of 50-500lb (23-230 kg).

While Metropolitan State University of Denver (MSU Denver) is already engaged with local companies involved in the manufacturing of small satellites, there is a great opportunity for students and faculty to engage in the dynamic and vibration testing of these vehicles (payloads).

The following paper describes the basic needs in vibration testing of small satellites, the collaborative frame being put in place by MSU Denver to address these needs and the anticipated impact on the engineering education curriculum. The anticipated impact on the engineering education curriculum covers the engineering design, the instrumentation, data acquisition and processing, dynamics and vibration courses both at the undergraduate and graduate levels.

TESTING STAKEHOLDERS AND NEEDS

A few companies involved in the design, construction and exploitation of space vehicles within our area have been identified. Those companies include York Systems, Lockheed Martin, United Launch Alliance and Ball Aerospace. The authors' initial survey indicates that these companies focus on the design and construction of space vehicles while the vibration testing is mostly sub-contracted. Some of these companies have expressed the desire to use the services of MSU Denver in the testing of small satellites if those services become available. Manufacturers of testing equipment have also been approached to understand the range and limitations of their equipment's, the capabilities and the cost. Following these conversations, there appears to be an opportunity for MSU Denver Engineering Department to cooperate with this industry. The goal is to implement the technology and simultaneously solidify the knowledge base in vibration testing of satellites, since this type of testing is critical to ensure safe deployment of payloads.

While many tests types are performed on satellite systems, including electrostatic discharge, rad-hard, electronic etc…, the focus here will be on mechanical vibration testing.
The vibration experienced by the satellite system during the launch phase is severe and could potentially render the space payload nonoperational. By subjecting the space payload to a vibration environment, which simulate the launch phase, is indispensable to determine if the

space payload will survive the launch phase, which is the most strenuous of its whole trip to space.

The overall aim of the satellites testing is to demonstrate flight worthiness by avoiding failure of specimen during launch and afterwards [1]. The types of tests conducted are designed to mimic the real conditions the vehicles undergo during the launch. Careful choice of loads and frequencies applied during the testing should predict the behavior of the vehicle during the actual launch of a vehicle on a launch pad.

The most common methods of vibration, described in the following section, include sine vibration, random vibration, and transient (shock) testing. In addition to these methods, most recently, combinations of the above tests have been developed and they have been applied to satellite vibration tests. Amongst them are the random-on-random, sine-on-random and transient-on-random [1,2].

VIBRATION TESTING TYPES

Sinusoidal Vibration

In a sine vibration test, the vehicle is subjected to a sinusoidal excitation (acceleration, velocity or displacement) at all frequencies within a prescribed bandwidth. The application of this excitation could be of two modes: sweeping or dwelling. In sweeping mode, the frequency of the excitation changes continually within the selected frequency band. The sweep rate could be linear or logarithmic in terms of Hz/s. The amplitude of the excitation are a function of the frequency. In dwelling mode, the amplitude of the excitation is programmed as well as the frequency, during testing.

The typical frequency range is between 20 Hz and 2000Hz. The energy at each frequency is controlled to fall into a prescribed level.

Vibration testing of space payloads using sinusoidal type of excitation is extremely useful to determine the effects of resonance in the system and to analyze dominant narrowband frequency components [1,2]. The data obtained from this test will provide data indicating natural frequencies, damping and mode shapes. Exciting the structure with a frequency that coincides with the natural frequency of a given mode will lead to resonance. Such test is known as sine-dwell is typically conducted for modeling purpose.
As we will see below, random testing provides a broader frequency spectrum to explore wideband frequency components.

Random Vibration

Similar to sinusoidal vibration excitation signal, the typical frequency range is between 20 Hz and 2000 Hz. The energy at each frequency is controlled to fall into a prescribed level.

The amplitudes of the excitation signal are random with a Gaussian distribution around the desired test level. Practically one cannot excite every frequency, since frequency is a continuous parameter and there are infinite frequencies in any selected bandwidth; the common practice is to divide the bandwidth into narrow bands for frequency (known as "lines"). The bandwidth of the lines depends on the equipment and its capabilities. The amplitude is expressed in G^2/Hz. G are units of one gravitational acceleration [2].

The goal of this test is to verify the integrity of secondary structures including housing, electronics, mounting brackets. The cyclic nature of the applied stresses will also provide confidence in the response of the vehicle parts in fatigue. Careful design of this test will avoid unrealistic and excessively high loads, which will prevent failure of the structure due to excessive loads - higher than ones specified in the satellite's mission.

Transient Vibration or Shock Testing

Transient or shock testing is performed to test the effects of high frequency, high amplitude, low-energy shock, and shock waves caused by high explosions; the latter one are caused by satellite stage separation by pyrotechnic devices (explosives). There are three modes of shock tests excitation signals: classical waveforms, shock spectrum synthesis, and field transients. Classical waveforms include half-wave sinusoidal pulse, terminal peak sawtooth, square wave, triangular wave and initial peak sawtooth [2]. The operator (or program) controls the amplitude and duration of these waveforms.

Shock spectrum synthesis consist of superposition of decaying sinusoidal signals of various frequencies. The operator (or program) controls the amplitude, damping, start time and duration of these waveforms. Shaping these excitation signals, to simulate satellite stage separation, could be very complex.

Field transients are transient events recorded during the satellite in its normal environment. In theory, this could be considered the best excitation signal to simulate the satellite stage separation phases, however, there are a few potential problems with this mode of excitation: (1) field data is usually not available, (2) operational transient events have a high degree of randomness, and (3) no single transient event is statistically adequate to represent the field vibration environment.

VIBRATION TESTING EQUIPMENT

In addition to human resources and faculty expertise, the following lab resources will need to be acquired and used for teaching and research related to satellite vibration testing.
The main components of the tester are: (1) shaker, (2) field power supply, (3) power amplifier and (4) data acquisition system [1]. In the following the term shaker system will refer to the first three components above and consider the data acquisition system as separate.

Currently almost all satellite testing is done using electrodynamic shakers. These shakers include a horizontal table for lateral axes and they allow for the armature body to be rotated into a horizontal position. Horizontal tables consist of an aluminum or magnesium plate attached to one end of the shaker armature and supported by hydrostatic bearings (or oil film on a granite slab or a combination of both).

Most shaker systems are designed to operate over a frequency range of 5 to 2500 Hz. For the purpose of vibration testing of small space vehicles (up to 500 lb.), we are considering electrodynamic shakers with a frequency range of 20 to 2000 Hz and an amplitude range between 10 kN and 60 kN. Accelerometers and data acquisition systems are aligned to handle these levels of force and frequency.

The control of the shaker system is done by digital control systems. The data acquisition system includes charge amplifiers to convert signals from accelerometers to voltage that is sampled and analyzed by a high-speed, high-accuracy digital signal processing system. Additional equipment such as digital logic analyzers, oscilloscopes, voltmeters and signal-conditioning circuits are also part of the test equipment used.

VIBRATION TESTING CRITERIA AND PROCEDURES

Vibration testing is done by introducing a forcing function into a structure. A vibration test shaker is used to introduce such forcing function. Besides qualification testing, this equipment is used for fatigue testing, system performance, stress screening, etc.

The most common shakers used for this purpose are the electrodynamic and servo hydraulic shakers. Electrodynamic (ED) shakers could be used for most vibration tests and offer several advantages over alternative approaches. Compared to hydraulic shakers, ED shakers are capable of much higher frequencies. These high frequencies can be very important in testing electronics and electronic assemblies. ED shakers are also capable of reproducing a wide range of shock and Shock Response Spectrum (SRS) pulses in addition to general vibration testing. In addition, ED shakers have very linear behavior, so controlling the vibration test may be easier or possible when not otherwise possible.

The criteria and procedures are directly dependent on the launch vehicle dynamics and generally obtained and published by the organization responsible for launching the space vehicle [2].

Sinusoidal Vibration Criteria

Single sine sweep provides a single sine input with varying frequency, phase and amplitude. Swept sine vibration tests includes all frequencies, measured or not, by using a continuously varied sine oscillation of controlled amplitude. Swept sine testing is useful for the study of structural response at resonance. In addition, structural resonances can be excited at high response levels, making this a good test type for fatigue tests. Digital tracking filters, with user selectable fixed or proportional bandwidths are used to ensure the sine signals are accurately measured and controlled in high noise environments. Test levels, frequency bands, and frequency band duration depends on the launch vehicle dynamics and will be addressed on the case-by-case basis.

When searching for resonances, the system uses sine sweeps to obtain a transfer function for evaluation of resonance characteristics. User selectable input parameters, such as frequency range, amplitude threshold, and minimum Q factor, are used to determine which modes should be further evaluated or tested.

Besides resonance searching we can also do resonance dwelling. Resonance dwelling is useful for fatigue testing of many mechanical components. Resonance tracking automatically detects shifts in resonance frequency and adjusts the sine excitation signal to track those shifts precisely. Multi-frequency sine excitation test has been developed as a method of durability testing using multiple simultaneous swept sine vibration testing. One advantage of using this approach is the creation of a uniform method for qualifying components while reducing testing and development costs. This test technique divides the sweep frequency range into multiple intervals and allows multiple frequencies to be simultaneously active. This method uses the orthogonality properties of sine waves to ensure that a test item has been exposed to every frequency in the sweep range for the required duration of time even though the test itself does not last as long.

Random Vibration Testing Criteria

Random vibration testing provides statistical confidence with random time data that has an average targeted frequency content and amplitude over the duration of the test. By controlling amplitude and frequency, test data can be correlated to real world data sets. Applications of this type of test range from production stress screening of electronic components to prototype testing and qualification of products to mission critical product standards. Random testing excites all resonant frequencies simultaneously, and due to this and the statistical nature of random data, it is well suited for vibration qualification tests. Note that along with this test, the system (integrated of off-line) must include tools such as continuous convolution algorithm, amongst others.

Random tests are usually specified in Power Spectral Density (PSD) plots. These PDS plots consist of logarithmic plots of either amplitude vs frequency breakpoints or slope vs frequencies connected by straight lines [1,2]. The criteria should specify the maximum filter bandwidth to limit the frequency resolution. Filter bandwidth of 10 Hz is the minimum resolution often used in the industry. Narrower filters could be implemented but the penalty is the increase of control difficulty.

Duration of the random events are normally in the range of five to ten seconds, with some exceptions when controllers must stay at lower levels until convergence is achieve towards the PDS profile. Tolerances for random vibration tests are in the range of 3 dB to 6 dB typically [2].

Transient Vibration or Shock Testing Criteria

Classical shock testing on a shaker could be an efficient alternative to drop testing, having the advantages of better accuracy and repeatability. However, performing shock testing using shakers imposes physical limitations due to the available armature displacement and shaker/amplifier power ratings.

Transient vibration testing might be specified in terms of either time history (case of classic waveforms) or desired shock spectrum response. In the latter one, if the specification of shock spectrum resolution is not given, it is customary to use 1/6 to 1/12 octave resolution spacing.

SRS (Shock Response Spectrum) shock control, or shock response spectrum control, is typically used to simulate the complex vibration environment seen in earthquakes and pyrotechnic shock [2].

Wave Form Replication

Waveform replication allows for reproducing long duration time waveforms in the lab instead of in the field using random or sinusoidal waveforms.

Waveform replication will prove that the product or component under test will work on that given data set but lacks the statistical variation of random data. Generally, random testing can be much shorter in duration than waveform replication since random data is a better real-world representation for many cases.

SIGNAL PROCESSING AND CONTROL REQUIREMENTS

Data Acquisition System

The Control/Data-Acquisition system should support more than 50 channels (default 75 channels) [3].
The data acquisition system should support at least a 100 dB of dynamic range (default 120 dB)
It should support the following modes:

- Random in input mode
- Single/multiple-sine stimulus
- Mixed (sine/random) stimulus
- Sine resonance search and dwell
- Classic shock
- SRS synthesis tests
- Transient control
- Waveform replication

Additional Hardware Requirements

The system should be able to support ADC and DAC conversion with conversion time not greater than 10s per signal for all channels for at least 25 channels simultaneously [3]
The digital signal processing for the system should use no less than 32-bit floating arithmetic.

Signal Processing Software Requirements

Most of the analysis could be executed off-line using MATLAB and Mathematica software packages.
The control system should be able to provide high performance digital filtering implemented in HW /SW or a combination of the two, for all for input/output signals. The control system must provide high performance DSP processing to generate all possible of input-testing signals.

ANTICIPATED IMPACT ON ENGINEERING EDUCATION CURRICULUM

The vibration testing criteria, testing needs, and equipment have been discussed earlier. The courses of vibrations and dynamics should address the different types of vibrations described and their analyses. The data acquisition, time domain and frequency domain analyses as well as modal analyses, leading to system identification of these vehicles, should also be included in signal processing courses. The fixturing systems including the mechanical interface between the satellite systems and the shaker need to be discussed in courses of engineering design. The correct design and performance of the fixturing systems is critical in preventing those fixtures from interfering with the dynamic response of the satellite to the vibration generated by the shaker. The instrumentation course will review all the accelerometers, gauges and sensors utilized in the data acquisition process. Their correct installation, positioning and calibration is critical for the quality of information provided by these instruments. Courses of Finite Element Methods and Computer Aided Engineering will allow the modelling of the satellite systems and the shaker excitation to predict the different outputs expected from the sensors. Accurately defined failure criteria will prompt a proper course of action based on the measured data or the models' prediction. The courses of Experimental Mechanics will address the design of experiments and emphasize the proper test planning and the required reports to produce.

CONCLUSIONS AND FUTURE STEPS

The paper has discussed growing needs in the aerospace industry in our region and the potential implications on the engineering curriculum. These growing needs will require more expertise in the manufacturing and testing of space vehicles and specifically of small satellites. The scope of activities in this area includes vehicles for space exploration, communication, tourism and national security. This trend is expected to increase as there is a strategic focus on space, at the federal and states level. The vibration testing criteria, testing needs, and equipment have been discussed. The paper has also suggested modifications on areas of focus, concerning existing and new courses to address specific needs of the testing environment for small satellites. Future steps will include the pursuit of funding to purchase the needed equipment. Next, will follow the training of the personnel and the progressive implementation of the laboratory to test the small satellites. With this initiative, we seek to continue to improve the collaboration between the space industry and the university.

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