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Testing of Small Satellite Systems and Impact on Engineering Curriculum

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My name is Julio Proano, Ph.D., I am assistant professor at Metropolitan State University of Denver, having finished my Bachelor's degree in Electrical Engineering, I worked for NASA at a Satellite Tracking Station in Ecuador Subsequently I obtained my M.S. and Ph.D. in Electrical Engineering with a minor in Applied Mathematics at the University of Colorado, Boulder. My Ph.D. dissertation work (on Neural Networks applied to control systems and automation) went to the DOD in Virginia. My formal graduate academic training was in Control Systems, Telecommunications and Applied Mathematics. After receiving my Masters and Ph.D. degrees in EE, I joined AT&T Bell Laboratories. During my tenure at Bell Labs, I became skilled in the formal methodology and processes of Systems Engineering and Systems Architecture applied to large systems. Throughout my career, in the high-tech semiconductor and telecommunications industries, I worked in the following technologies: Mobile phone integrated systems, high-speed optical/copper LAN/WAN Ethernet, Storage Area Networks, Optical Transmission Networks, IP telephony, Cable-TV, Cable Networks architectures, Analog Broadcast Video, Voice/Data Network, Hard Disk Drive technology, etc. I am co-inventor of nine US patents, and I have an additional US patent application pending, the areas of invention include Optical networks, Storage Area Networks (SAN), SONET, Ethernet, and Hard Disk Drives/read-channel technologies, etc. Four years ago I joined the faculty of the Metropolitan State University and I have developed curriculum for the following courses: Digital Signal Processing, Very-large-scale Integration Circuit Analysis, Electromagnetic Fields, Electronics, [Mathematical] Transform Methods for Electrical Circuits, Process Control Systems, Programmable Logic Controllers, Hardware Description Language, Introduction to Engineering, Robotics.

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Abstract

The aerospace systems field has recently been attracting more and more interest in the industry, academic and government sectors. The scope of activities in this area includes vehicles for space exploration, communication, tourism and national security. This trend is expected to increase nationwide, as there is already a government strategic refocus on space.
While some universities are well positioned in the manufacturing side of these small satellites, there is an opportunity for students and faculty, at MSU of Denver, to engage in the multidisciplinary testing aspects of these vehicles. Stakeholders from such collaboration include the university, the industry, the faculty and the students as well as the community.
In this paper, we describe the steps taken by the Metropolitan State University of Denver to engage the stakeholder's community, the testing system breakdown into subsystems, and 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 curriculum.

Keywords: Dynamics, Vibrations, Testing, Systems Engineering

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, the Air National Guard and the Army National Guard. With this trend, demand for research, construction, testing and launch of space vehicles is expected to increase. 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 with a payload range of 50-500lb (23-230 kg).

While the 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 dynamics and vibration testing systems of these vehicles (payloads).

The following paper describes the testing facility as a system, the breakdown into subsystems, the alternatives considered, and the decision made on the equipment needed. Next, the paper discusses the basic needs in vibration testing of small satellites, the collaborative frame being put in place by our university to address these needs and the anticipated impact on the curriculum. The anticipated impact in the systems engineering curriculum covers the design, the instrumentation, data acquisition and processing, dynamics and vibration courses. We emphasize the systems engineering approach to system testing design and implementation.

Vibratory Testing Systems Stakeholders

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 were 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 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 systems, since this type of testing is critical to ensure safe deployment of payloads.

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 dynamic testing system is to demonstrate flight worthiness by avoiding failure of specimen during launch and afterwards. 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.

Dynamic Testing System and Subsystems Analysis

After the identification of the needs and stakeholders, a discussion on the breakdown of the system into subsystems will describe the complexity of the dynamic testing system. The objective is to establish a list of all the required components, the possible alternatives and an assessment of performances leading to a decision on which components to purchase [1].
Fig.1 indicates the breakdown of a dynamic testing into subsystems. The main subsystem is the small satellite itself or any of its component being tested. A different breakdown methodology could well consider the small satellite as a system by itself [1]. The increasing use of small satellites in missions is justified by the reduced time from design to implementation, the cost and the flexibility in the selection of new technology [2].

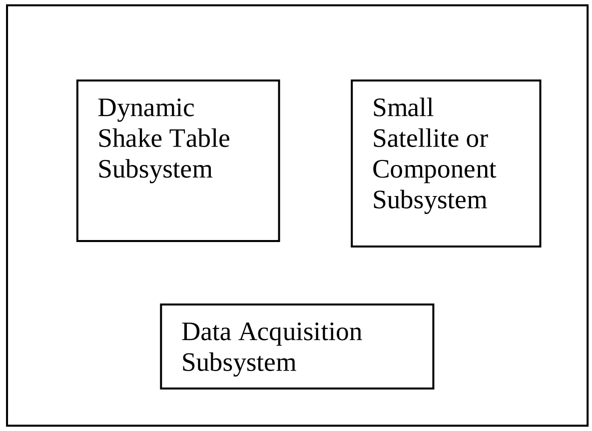

Fig.1 Dynamic Testing System and Subsystems

Sometimes, a component of the small satellite could be tested instead of the whole satellite. In this case, this component will be considered as a subsystem of the testing system.
The next subsystem to consider is the shaking table, referred here as the shaker, which generates the appropriate motions required for testing. The third subsystem discussed is the data acquisition that collects data from sensors placed on the small satellite or a component for further processing.

Vibration Testing Types

The most common methods of vibration, described hereafter, 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 [3, 4].

Sinusoidal Vibration

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 [3, 4]. 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.
The typical frequency range is between 20 Hz and 2000Hz. The energy at each frequency is controlled to fall into a prescribed level.

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 [4].

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 ones 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 [4]. 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’s normal operations after launch. In theory, this could be considered the best excitation signal to simulate the satellite stage separation. 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.

Shaker subsystem alternatives and Selection

The shaker components are: (1) the shaking table, (2) the field power supply and (3) the power amplifier [3, 5]. Alternatives include the hydraulic shakers, generating high forces and low frequencies; and the electrodynamic shakers for low amplitudes and high frequency range. Currently almost all satellite testing is done using electrodynamic shakers. These shakers include a horizontal table for lateral axes and they allow 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.

Signal Processing and Control Requirements

Data Acquisition System

The Control/Data-Acquisition system should support more than 50 channels
(default 75 channels) [6,7].
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 [4,5]
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.

Initial Costs

The total cost estimate of 468,000 USD received from equipment suppliers include the acquisition and installation costs only. The operating and maintenance costs are not included.

Impact on Curriculum

The impact of the systems engineering approach to small satellite testing and the potential changes in the curriculum are discussed below.

Students will be guided to follow a basic system engineering approach to the overall project of testing small satellites. Each satellite to be tested has common and special characteristics and requirements that need to be identified and addressed in the process of generating the testing procedures, scheduling and implementation.

The approach discussed here follows the engineering practices and basic procedures established by INCOSE (International Council of Systems Engineering) [8].

Systems engineering has two major responsibilities: functional requirements and functional architecture. Systems engineering applied to testing small satellite is involved in writing the testing requirements, design/implement fixtures, schedule-testing activities and include contingency activities for the final validation and acceptance goals. It is important to point out that simulation is an integral part of test, integration and validation activities.

Testing Environment

Students will start by identifying and defining a reasonable Tier 1 level (testing environment). This includes the macro-view of the overall testing goals, ranges, and correlations. The main activities include the discussion with customers (small satellite space companies) and the aligning of our lab capabilities with customer requirements. This information will be discussed, collected and recorded in the Tier 1 document. The Tier 1 document is not necessarily shared with the customer, unless otherwise agreed upon in advance.

Customer Requirements

In the second phase, immediately after (or even during initial discussions), students will collect detail customer testing requirements for the small satellites. Internally we call these phase Tier 2. The Tier 2 document contains the clear definition (agreed by both parties, the space company and university) of the testing requirements, conditions and expected results. These requirements are soft and could change overtime; and students are advised to continuously verify customer expectation throughout the testing project. Changes in customer requirements, typically, alter plans, schedules, hardware and software designs/implementations and need to be monitored constantly and carefully.

Tier 2 requirements could include non-technical specifications and customer preferences that need to be addressed in a timely manner.

A very important characteristic of these customer requirements is that all these need to be implementable within the range and capability of the equipment and knowledge base of the faculty overseeing these tests.

Testing Structure (Architecture)

This phase starts early in the project. Before the Tier 2 requirements are finalized, students start to put together the overall structure, organization, contingencies, correlations for the all the testing activities.
This phase includes the breaking of the project/system in subsystems (test-sets) and the choice of interrelations/correlations between the subsystems.
In this phase students will establish and organize the following test components:

- Sequence(s) of tests
- Scheduling of equipment (shakers, data acquisition system, etc.)
- Fixtures' design specifications (including attachments and miscellaneous hardware (bolts, nuts, probes, etc.)
- Time-schedule for analysis, testing, re-testing, contingencies due to failures and delays.

The overall structure of the testing is officially documented in the Architecture document. This document is reviewed by the testing team and the customer to validate the approach, schedule, etc. In the case of testing small satellites, one does not need to include subsystems (test-sets) interface/interaction document (aka Tier 3), because of the limited level of interaction involved. The interaction and correlation between tests will be addressed in the Architecture document and enforced in the next level documentation (Test Design Requirements/Specifications).

Test Design Specifications

Once the testing architecture is initially reviewed, the students will proceed to design every subset of tests. This level is also known as Tier 4. At this level, students will collect tests that are affine based on schedule, purpose, parameters, inputs, outputs, etc.
Students will design the body of each test (within the affine test set); this includes the equipment involved, parameters to be measured, the fixtures, attachments, probes, etc., associated with each subsystem (test-set) which we will call test modules.
For most small satellite testing, the anticipation is to have three or four test modules.
The documents associated with this phase are the Tier 4 documents (one per test module).

Tests Implementation

Once the Tier 4 document for a test module is revised and approved, students proceed to build the hardware, write the software for the data acquisition system, and acquire the additional probes, attachments, and miscellaneous hardware.

Verification Tests Plans

Internal test procedures are executed to verify the validity of the test specifications in each of the Tier 4 modules.

Validation/Acceptance Tests Plans

Once all the verification test plans are approved, students will proceed to implement the final validation/acceptance tests.
Final tests procedures are executed and demonstrated to the customer. All the tests must validate the Tier 2 requirements above.

Conclusions and Future Steps

The paper has discussed growing needs in the aerospace industry in the Denver region. 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. The testing system needs, and equipment have been discussed. Using a system engineering approach, the paper has 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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