Structural Health Monitoring; an Enabler for Responsive Satellites

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ABSTRACT

The Air Force Research Laboratory/Space Vehicles Directorate (AFRL/RV) is developing Structural Health Monitoring (SHM) technologies in support of the Department of Defense's Operationally Responsive Space (ORS) initiative. Such technologies will significantly reduce the amount of time and effort required to assess a satellite's structural surety. Although SHM development efforts abound, ORS drives unique requirements on the development of these SHM systems. This paper describes several technology development efforts, aimed at solving those technical issues unique to an ORS-focused SHM system, as well as how the SHM system could be implemented within the structural verification process of a Responsive satellite.

Keywords: ORS, Responsive, satellite, structural health monitoring, SHM, modular, flexible

1. INTRODUCTION

The Department of Defense is working to develop an Operationally Responsive Space (ORS) capability, and has recently stood up the ORS Joint Program Office, at Kirtland AFB, NM, in support of that goal. As stated in the *Plan for ORS* [1], "ORS is focused on the timely satisfaction of the urgent needs of the JFC (Joint Force Commander) and other users." The *Plan for ORS* also describes a three-tiered approach to delivering these capabilities to our combatant commanders:

Tier 1: Utilizes existing, or on-orbit capabilities to provide the required space-based capability within days from establishing the need.
Tier 2: Utilizes field-ready, or nearly field-ready capabilities to satisfy warfighter needs within days-to-weeks of establishing the need.
Tier 3: Development of an entirely new, or unforeseen capability, within a year.

In order to meet the unique demands of this approach, the DOD research community has invested heavily in technologies that allow satellites to be designed and assembled via more modular schemes. At the Air Force Research Laboratory/Space Vehicles Directorate (AFRL/VS), there are many technology development efforts aimed at enabling these modular satellite architectures, to include: Space Plug-and-play Avionics [2], reconfigurable thermal management systems [3], autonomous satellite operations [4], satellite design tools, modular flight software, and configuration-flexible structural architectures.

However, all of these efforts are for naught if we are forced to follow the current structural surety process. This paper discusses AFRL/VS's efforts to enable rapid satellite structural check-out, based on the use of Structural Health Monitoring (SHM).

2. STRUCTURAL SURETY PROCESS

Traditionally, a satellite's structural performance is validated through three phases: static loads, environmental or dynamic loads, and coupled loads analysis (although some of these phases may be avoided at the discretion of the satellite manufacturer, launch vehicle, and launch service provider team).

1. Static loads verify the satellite structure is able to handle the highest anticipated loading scenario during the launch sequence. Typically used to validate the finite element model, so that the margin of safety/safety factor can be assessed. For ORS-class satellites (<1000kg), this test is often validated through analysis, or from the results of dynamic tests.
2. The environmental and dynamic tests assess the satellite's ability to survive the launch segment, as well as characterize the dynamic behavior of the satellite. Two series of tests are usually performed: shock and random vibration. Shock tests impart the maximum expected impulsive load into the satellite. Random vibration tests measure modal characteristics of the satellite, accomplish a workmanship baseline for the satellite, and subject the satellite to flight level random vibration spectrums customized for the launch vehicle being used for the mission. To our knowledge, no satellite has flown without undergoing dynamic testing.
3. The Coupled Loads Analysis (CLA) takes the flight-representative satellite structural model (including its test-verified dynamic behavior) of the satellite and couples it to a high fidelity model of the LV (including the expected loads producing forcing functions for each flight event). The CLA looks for interactions that could damage the satellite or cause problems with the launch vehicle control software. The value of a CLA is that it explores the impact of random vibration on all the components of the satellite (it typically outputs expected accelerations and loads at each node of interest), returning critical data required to assess the readiness of the satellite structure to survive the launch. To our knowledge, the only satellites that have not required a CLA are extremely small picosatellites.

Unfortunately, these tests and analyses procedures that have been developed for conventional satellites take much too long to conform to the timelines of ORS. For some satellites, the iterative process of testing and analysis can take over three years [6].

It is the authors' contention that structural health monitoring will prove critical for determining a responsive satellite's ability to survive the launch sequence. It can be used to determine the health of structural components, and assess mechanical connections. It can be run in parallel with other ground-based satellite check-out procedures and is amenable to ORS timelines. Additionally, unlike traditional loads testing, SHM can pinpoint the location, type, and severity of damage, enabling rapid component swap-out, maintenance action, and go/no-go decisions.

3. PROPOSED IMPLEMENTATION OF SHM

The DOD, as well as a number of other entities, have investigated methods for determining the modal characteristics of a satellite through purely model-based means. All of these efforts have demonstrated that the variability in the components of a satellite, as well their connectivity, lead to broad divergence in the modeled dynamic behavior of the system.

In the predominant vision of ORS, a minimal set of satellite components is stored in something akin to today's aircraft depot. And much like at an operational depot, each component is rigorously tested, validated, and characterized before it arrives. Additionally, as the components sit in storage, they are periodically tested to ensure that they still function properly, so that when a requirement to build a satellite comes, there is a high level of confidence that each piece of the satellite will work. Another inherent advantage is that the vast majority of components can be utilized for multiple mission scenarios (rather than using custom parts for each mission-type), ORS can reap the benefits of repeatability that come along with larger production runs. From a structural standpoint, this process of prior testing and characterization works to dramatically decrease the Model Uncertainty Factor (MUF) for each component. At that point, it is the interfaces between satellite components that pose our greatest source of variability.

This is precisely why AFRL is interested in SHM for ORS satellite applications. A satellite that is assembled in a rapid fashion cannot afford to go through the time-consumptive and onerous Quality and Assurance (Q&A) process typical of traditional satellite programs. Expedited methods must be developed to ensure the technician fastened a bolt to the specified torque, or that a bond-line is acceptable. Having the ability to accurately assess the integrity of the connections between satellite components and subsystems will dramatically reduce the variability in the model used to assess the satellite's modal properties. Additionally, the capabilities of the SHM system can be fed directly into that model, in order to bound the uncertainty at the interfaces.

The following is one vision of how a satellite's structural surety could proceed:

1. Perform a "variational CLA" (vCLA) on each pertinent launch vehicle, a priori [6]. This analysis can be used to establish envelopes detailing satellite mass, center of mass location, and fundamental frequency combinations for each launch vehicle. These envelopes greatly ease the surety process, because satellites that conform to these envelopes will not require a dedicated CLA. It is our desire that these envelopes be used as design inputs for ORS satellites.

2. The SHM system is used to periodically assess the condition of satellite structural members. These checks will search for the presence of damage, providing valuable feedback regarding storage conditions (i.e. is the humidity too high for the composite parts, has somebody dropped a panel, etc.?).

3. When the requirement for a satellite comes in, an automated software tool is used to quickly generate the design for the satellite. In parallel, the Finite Element Models of all the required components and their connections is assembled in order to assess the satellite's modal properties. Key modal properties include the satellite's fundamental frequency (to assess compatibility with the launch vehicle) as well as anti-resonances (which are critical for Guidance, Navigation, and Control purposes). As stated before, the capability of the SHM system can be used to bound the variability on the interfaces between structural members, satellite components, payloads, etc. A preliminary modal assessment can be fed back into the Satellite Design Tool as input to determine the suitability of the satellite design.

4. If the satellite does not conform to the envelope of the vCLA, a traditional CLA will need to be pursued. However, this testing can be performed in a much shorter timeline, because a high fidelity model of the satellite has already been developed, and the model possesses significantly reduced variability (when compared to current satellites of comparable mass and volume).

5. The SHM system is used to assess the integrity of the satellite's structure and connections. A lack of faults provides a degree of confidence that the satellite will successfully survive the launch sequence. The detection of faults is followed by rapid corrective maintenance actions, followed by another SHM-based assessment, until no further faults are detected.

It is anticipated that these SHM-based tests will take a matter of hours, and can be conducted while other satellite systems are being checked. This is critical, because the truncated timeline of ORS dictate that numerous satellite checks be run in parallel; traditional satellite dynamic testing does not allow for other testing to be run in parallel.

SHM also provides a capability that is not available through other means; if there is a fault, the SHM system will pinpoint the location, type, and severity of the fault. This is helpful in that repair action can be immediate (which may be as simple as tightening a bolt) and focused. Traditional dynamic testing only points to the presence of a fault. Locating the fault often comes down to educated guesses on the part of test engineers who possess significant expertise and experience in the area.

All of the above tasks can be accomplished by developing a SHM system that operates by connecting the satellite structure to ground support equipment. However, additional benefits can be garnered by making the SHM system a stand-alone component within the satellite. Initially, it is recommended that these satellites carry excess structural margin in order to ease the testing and validation requirements. Monitoring of the structure, during the launch sequence, may indicate where some of that margin may be reduced in order to provide a more mass-efficient structure. This data may also be used to validate the models and further reduce model uncertainty. Additionally, a SHM system may provide valuable status and environmental information when used on-orbit; providing our satellites unprecedented situational awareness.

4. COMPLEXITIES OF THE PROBLEM

The development of a suitable Structural Health Monitoring system is no trivial task. Creating a robust capability that allows us to realize the vision of ORS will require that the SHM system be able to accomplish the following.

1. Interface with the Satellite Design Tool
   When the requirement for a space asset comes from the Joint Force Commander, the Satellite Design Tool will be tasked with developing the assembly instructions for that satellite. The SHM system will have to take information about the satellite's configuration, characteristics and placement of components, attachment schemes, etc., from the Satellite Design Tool, in order to assess damage with minimal false positives.

2. Flexible to accommodate numerous configurations
   This flexibility is not limited to just different structural configurations, but must also encompass near innumerable iterations regarding component and payload placements and fastener locations. Again, it must be able to take information from the Design Tool and utilize it in order to perform its health assessment tasks.

3. Detect damage in complex, multi-functional structures
   It is the opinion of this team that the satellite structures must be multi-functional to enable Responsive Space. Many parallel efforts are underway to integrate electrical and thermal functions within a structural framework, allowing rapid satellite assembly and disassembly. The goal of these efforts is to allow simultaneous mechanical, electrical, and thermal connection between structural members and components. Additionally, the spacecraft structures under consideration utilize a honeycomb sandwich lay-up or isogrid architecture. The complexities of these architectures, as well as the presence of embedded circuit boards, electrical harnessing, heat pipes, fluid loops, etc., will only make the process of structural health monitoring all the more difficult.

   However, it is important to note that the embedding of electrical harnessing and thermal management components, will significantly reduce the amount of model uncertainty. Although this complicates the SHM task, it eases the dynamic modeling effort.

4. Detect if mechanical and electrical interfaces are properly connected
   Satellites typically feature numerous bolted interfaces. It is imperative, in lieu of traditional dynamic tests, that designers are able to ensure these mechanical fasteners are connected properly, e.g. are all the bolts in place and are they torqued properly? There is also sincere on using a greater number of bonded joints in satellite assembly, and these too, will need to be adequately assessed. Additionally, other satellite check-out procedures will need to be similarly truncated. SHM systems may prove beneficial for these other check-outs, e.g. the SHM system can ensure electrical connections are properly seated as a part of their continuity check.

Requirements 3 and 4 will likely leverage heavily from ongoing SHM research [7-17]. SHM systems are continuously able to interrogate more complex structures, and recent advances have shown an ability to detect very minute changes in bolt torques. However, 1 and 2 may prove to be unique problems for Responsive Space, due to the inherent flexibility that this paradigm demands.

The current approach of AFRL/VS is focus on the unique aspects of ORS, thus maximizing the results from our investment in SHM technologies. For this reason, initial emphasis has been placed on developing systems and methodologies with the necessary flexibility (the design tools are not yet at a maturity that would allow for intricate cooperation). Development of that configuration flexible system has fallen into two distinct thrusts: developing a flexible SHM system architecture and developing flexible detection methodologies that do not require baselines captured on “pristine,” geometrically identical samples. A robust SHM capability for ORS will require a system that is able to detect damage and out-of-spec conditions on satellites with a near limitless variety of configurations. The envisioned system will frequently be asked to detect flaws and damage on configurations it has never been taught.

The initial efforts described below, have focused on detecting the condition of bolted connections in aluminum isogrid and aluminum honeycomb panels, which are the leading near-term structural approaches. Additionally, the schedule of the ORS assembly process implies that out-of-spec bolted connections are likely the greatest source of risk for structural non-compliance.

Although this paper outlines a very difficult problem, it is important to mention a couple considerations that must be taken into account to show that the problem may not be intractable.

1. The SHM system will only need to determine the region of damage, and not the specific location (i.e. the area of an out-of-spec mechanical connection, and not the specific bolt). Current satellite testing methods do not lend themselves to locating the source of the problem, so any directing on the part of the SHM system is of great benefit.
2. Specifically for mechanical connections, bolts will likely either be fully torqued or not torqued at all. ORS is likely to drive standard interfaces, with standard bolt torques, in order to ease the assembly process (i.e. all #10 bolts are torqued to one specified value). If that is the case, the SHM system will have to assess a binary situation (torqued versus not-torqued), instead of a problem with multiple intermediary solutions (Is the bolt torqued to the proper value?).

5. CURRENT TECHNOLOGY DEVELOPMENT EFFORTS

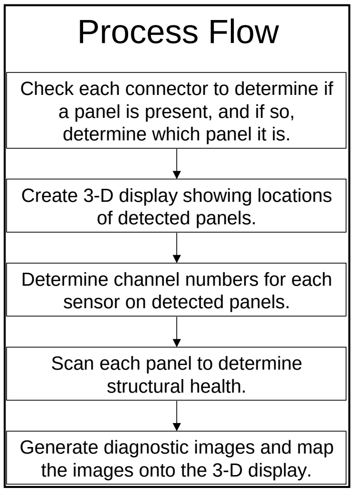
5.1 Configuration Independent Architecture

Acellent Technologies, of Sunnyvale, CA is developing a SHM architecture that will work independent of the satellite’s configuration. As mentioned before, a responsive satellite may take a near infinite variety of configurations, based on warfighter needs, technology readiness levels, satellite orbit, etc.

The SHM technology developed by Acellent was used to develop a system that can be innovatively used to:

1. detect whether the panels are configured correctly
2. assess the structural integrity of the panels in real-time
3. rapidly assess structural integrity of satellite panels and components prior to launch

Figure 1 shows the configuration of the structure used to demonstrate the capabilities of the developed system. The panels on the structure were color coded in white, blue, red, and grey for ease of identification. Using the process flow depicted to the right, the system functionality for panel and damage detection can be seen for any combination of panel removal, relocation, or damage level. To illustrate this, the red panel was removed and simulated damage was placed on the blue panel. The system easily detected both problems for easy corrective action.



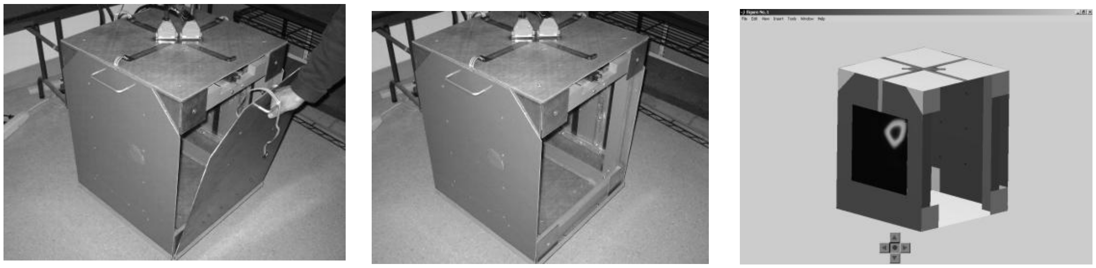


Figure 1. Blue panel shown with simulated damage after Red panel is removed.

The hardware demonstration shows Acellent's SHM system could be adapted to an inter-changeable structure to locate position, type, and damage in satellite panels. This is extremely advantageous, given the configuration variability inherent to responsive space. Additionally, Acellent's approach enables real-time assessments of the structure, during storage. As stated before, this capability is of critical importance to ensure the validity of the satellite dynamic model.

5.2 Configuration Independent Detection Methodology

Quartus Engineering Incorporated (QEI), in collaboration with the University of California-San Diego (UCSD), is presently developing a SHM capability designed to mitigate the lengthy Q/A certification and testing processes for adhesively bonded and bolted joint assemblies. Figure 2 illustrates the concept, where potential ORS satellite structures are pre-configured with sensor/actuators tied into a data acquisition system to continuously monitor, extract, and statistically quantify relevant data during satellite assembly.

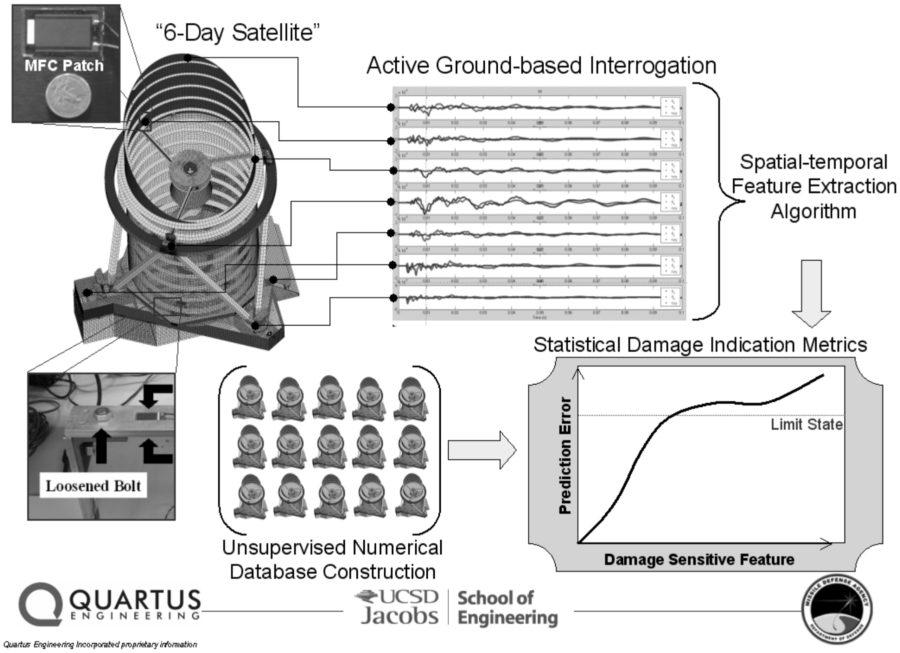


Figure 2: Conceptual SHM System Overview

The QEI/UCSD technology takes an online, data-driven approach to system verification/monitoring of bolted joints, namely, joint connectivity and bolt preload through the use of macro-fiber composite patches (MFC) and novel data processing. Using supervised learning on bolted assemblies, QEI/UCSD are developing trained computational algorithms that autonomously extract generalized correlation error features that directly couple to joint physics (preload or bond condition) and which compute statistical condition indication metrics (SCIMs), providing the user a quantifiable level of condition awareness. This is especially important given the highly variable operational and/or environmental fluctuation under which qualification could be executed. For similar structures, such as the envisioned modular satellite concept, caches of extracted features could be stored in database repositories to further enhance the sensitivity and overall performance of SCIMs for SHM in a continual on-line learning mode.

During the first phase of their effort, QEI/UCSD has successfully demonstrated the detection of bolt torques on a variety of structural configurations. The team investigated joints with multiple bolts and was able to correctly identify the torque status (loose, finger tight, and fully torqued to the specified value) for each of the bolts over 85% of the time. If the problem statement is eased to the binary statement of "fully-torqued or not," the system demonstrated an accuracy of 100%. Of particular note, the detection test cases were run on situations that had not been previously learned. This ability to correctly identify status, on conditions outside the learning set, shows extreme promise for implementation on potential ORS systems. Figure 3 shows the test set-up for the experiments investigating multiple bolted connections.

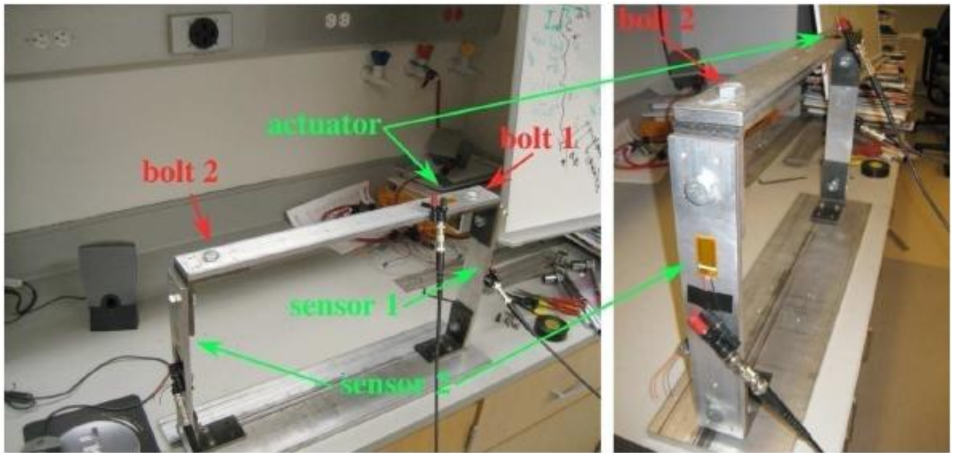


Figure 3: Multiple Joint Experimental Configuration

5.3 Basis Research on Satellite SHM

Structural health monitoring of OSR satellites poses substantial challenges related to system complexity, integration with structural design, validation practices, and variability of deployment scenarios. Many of these challenges require development of in-depth understanding of physical processes governing system/component behavior and structural integrity. A basic research initiative was established to improve understanding of critical technical issues and facilitate advances in space-oriented SHM technologies.

A research team at New Mexico Institute of Mining and Technology (NMT) is investigating physical properties of structural assemblies that would impact assessment of component's integrity, enable prediction of structural performance and assist in determining qualification margins for structural envelopes. The proposed approach is illustrated in Figure 4, where physical properties measured with a SHM system would contribute into updating the satellite structural model. The updated model, which carries information acquired from individual structural components, is utilized in modal analyses for particular satellite configurations. The ability of the SHM system to determine actual physical properties (e.g. material parameters) is important because of a direct connection to physics-driven theoretical descriptions that form a basis of large-scale analytical and numerical models used in satellite qualification. Availability of such properties would potentially allow for obtaining a certain estimate of satellite structural dynamics from the data furnished by the SHM system.

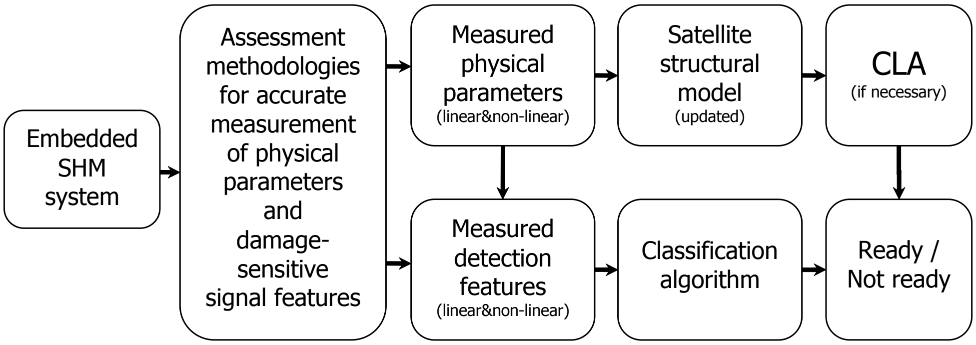


Figure 4: Proposed integration of the SHM data into satellite structural model and condition assessment algorithm.

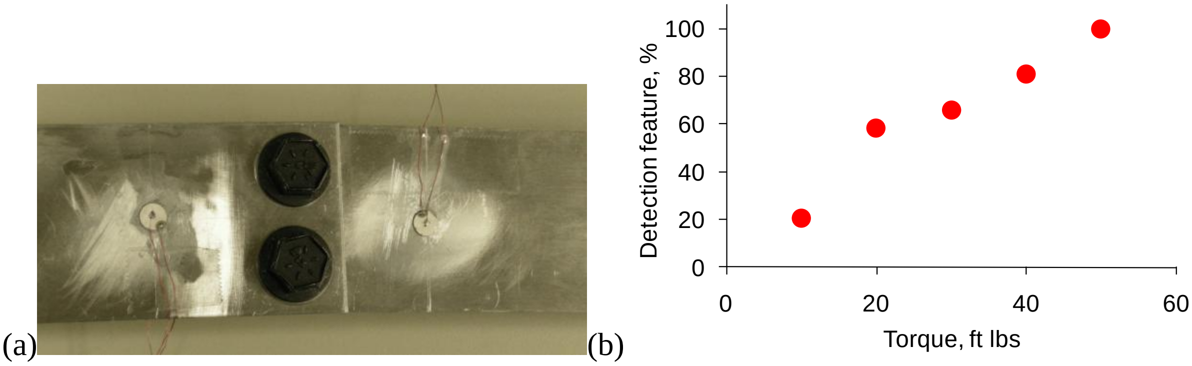


Figure 5: (a) a bolted joint with piezoelectric active sensors bonded to structural surface, (b) results of the joint integrity test showing dependence of the detection feature on the applied torque.

Current research activities at New Mexico Tech are focused on the fundamental aspects of joints behavior and utilizing relevant physical parameters for structural integrity assessment. In the bolted joint experiment depicted in Figure 5(a), a pair of piezoelectric active sensors was utilized to study elastic wave propagation through the joint. The elastic wave data was acquired at various levels of torque applied to the joint. Results of the test are presented in Figure 5(b) showing a dependence of the damage detection feature versus the torque. Red dots in the figure represent measurement points calculated as average values of 8 tests. Experimental investigation revealed a distinct dependence of the elastic wave data on the torque in the joint and indicated opportunities in quantifying the load. Further studies are directed towards understanding behavior of the bolted joints in complex structures.

Epoxy joints were simulated using Hysol® EA 9309NA epoxy and aluminum panels similar to those presented in Figure 5(a). Two specimens were considered: a specimen with the intact bond and a specimen with de-bonded area of approximately 1 square inch. Piezoelectric active sensors were installed 1 inch away from the edge of the lap joint. An additional receiving sensor was placed at the distance of 7 inches or 1 inch from the end of the plate. Figure 6 provides comparison of the spectral data obtained from the good bond (GE3), the bad bond with a sensor located near the joint (BE3) and the bad bond with a sensor located far away from the joint (BE4). The figure indicates a substantial level of higher harmonics typically associated with the nonlinear behavior. It is possible that spectral features reflecting the system's nonlinearity may be used to discriminate good and bad bonds.

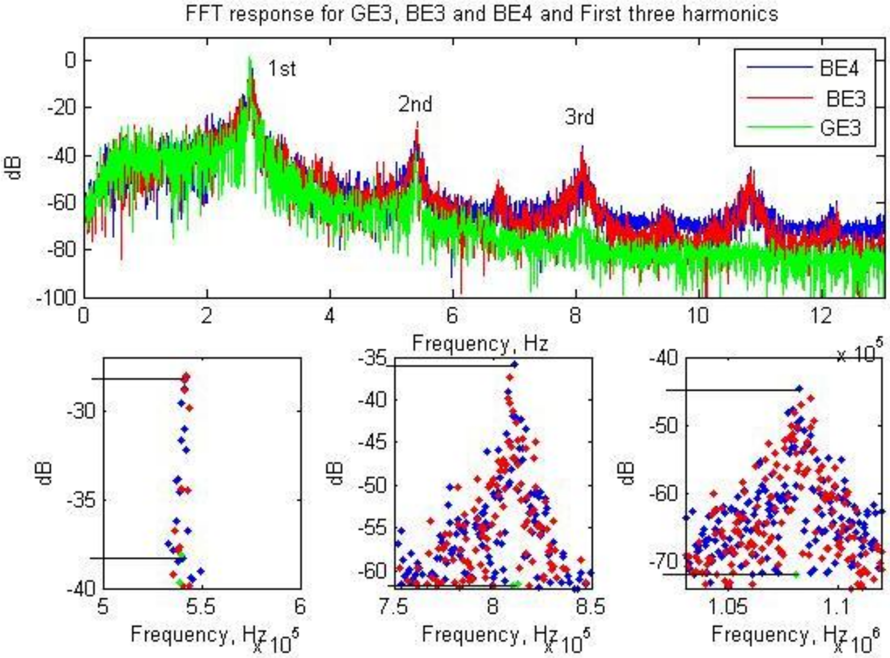


Figure 6: (a) Spectral characteristics of good (GE3) and bad (BE3 and BE4) bonds.

6. CONCLUSIONS

Structural Health Monitoring is a critical technology for enabling Responsive Space. Current methods to assess the satellite's structural surety are not amenable to the short timelines of Responsive Space. When a mission is requested, the SHM system can perform an immediate assessment of the satellite's structure to validate the assumptions of previously performed analyses and testing. SHM can not only truncate test requirements, it can also direct rapid repair actions, and allows other check-out procedures to be run in parallel.

In order to reach its full potential, the SHM system must be able to detect and assess flaws in complex, multifunctional structures, be able to interrogate mechanical connections, and assess system level modal properties. Improving the resolution of the SHM system reduces the amount of structural margin that must be built into the structure (translating into reduced mass and cost), reduces the amount of "pre-testing" that must be performed, and increases the configuration flexibility of potential responsive satellites.

Responsive Space may drive unique requirements on its SHM system. Applicability to Operationally Responsive Space (ORS) implies that the SHM system must be amenable to a wide range of satellite configurations, missions, and architectures. The ultimate SHM system will be designed to work on a structure for which it has no, or very minimal, a priori knowledge. The system will essentially "go in blind," get pertinent information regarding the configuration of the satellite through interaction with the Satellite Design Tool, and be expected to perform its job of detecting, locating, and analyzing damage. This team cannot think of another application where the SHM system is expected to perform such a complex mission with so little upfront information.

SHM may also be able to provide other benefits to the satellites. Data from the SHM system may lead to structural revisions that reduce excess mass and provide our assets an unprecedented level of on-orbit situational awareness. SHM can provide our satellites with game-changing capabilities; we are just now starting to see these benefits. It will be exciting to see what additional benefits can be construed once we scratch below the surface.

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