Electromechanical Impedance Spectral Features for Structural Health Monitoring of Satellite Structures

EVGENII VOLKOV[1], DAVID HUNTER[2], ANDREI ZAGRAI[1], BRIAN BARNETT[3], STEPHEN BARNETT[3], TASMIA TAHMID[3], JAY COMETSEVAH[1] and ASHLEIGH STEWART[1]

ABSTRACT

Structural Health Monitoring (SHM) is a key enabling technology for future smart spacecraft, providing critical capabilities for in-flight structural assessment, mission decision-making, and cost-effective vehicle management. Among various SHM methods, the electro-mechanical impedance approach stands out due to its compatibility with compact, lightweight hardware and potential for onboard processing. This study exemplifies the application of a low-power electro-mechanical impedance measurement device to SHM of bolted joints in the sattelite structure. The SHM implementation incorporates Solstar's Deke Space Communicator device. Impedance spectra were analyzed using statistical descriptors, global spectral methods (e.g., RMSD, MAPD, correlation coefficient), and alternative approaches such as band integration. The study provides recommendations on selecting damage-sensitive spectral features and supports the implementation of onboard SHM systems for space applications. These findings contribute toward enabling autonomous structural monitoring and condition reporting for space assets.

1. INTRODUCTION

Space structures are subjected to extreme environmental and operational conditions that can compromise their integrity and performance. Space environmental factors such as ionized plasma, meteoroids, orbital debris [1], in conjunction with high dynamic loads experienced during launch and orbital maneuvers, can accelerate material degradation and increase the risk of structural failure [2]. Structural health monitoring (SHM) seeks to detect, classify, and report the current condition of structural systems in orbit, thereby supporting informed decision-making for mission safety and longevity [3].

This paper presents an example of the operation of a miniaturized electro-mechanical impedance analyzer, Afalina, integrable with the Deke satellite

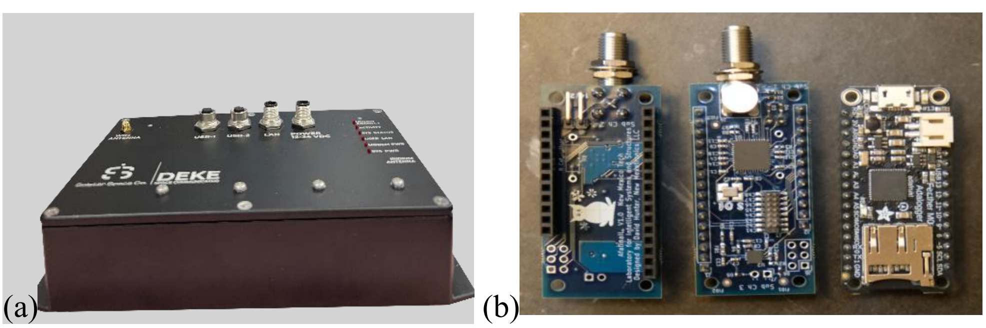
[1]Department of Mechanical Engineering, New Mexico Institute of Mining and Technology, Socorro, NM 87801, U.S.A.
[2]New Mexatronics LLC, Albuquerque, NM 87123, U.S.A.
[3]Solstar Space Co., Santa Fe, New Mexico, U.S.A.

communication system. The focus of this research is a comparison of different statistical metrics for detecting and characterizing bolted joint conditions in satellite structures using a miniature impedance analyzer. Various damage cases at different distances from the sensor are tested, and the most sensitive and reliable metrics for specific damage scenarios are identified. These findings support the implementation of real-time algorithm development for space-based SHM.

2. SHM IMPLEMENTATION FOR SPACE SYSTEMS

Solstar Space Company (Solstar) is a space communications company developing satellite terminals and services to provide 24/7 convenient, bi-directional communications links to spacecraft payloads and subsystems, such as the Afalina impedance measurement SHM system described further in this paper. Solstar has developed its Deke Space Communicator (See Figure 1(a) for illustration) to be integrated as a hosted payload to provide continuous bi-directional data transmission for such purposes and has successfully performed live end-to-end ground systems testing with New Mexico Tech's Afalina SHM in a lab environment. During the test, live data from the Afalina SHM subsystem attached to the Deke on a simulated spacecraft was sent through a commercial satellite constellation down to a desktop computer in the lab. This successful test demonstrated how spacecraft structural information can be sent down to a spacecraft operator in real-time, enabling the operator to send commands up to the spacecraft based upon what it learns from the SHM results. The Afalina SHM system connects to the Deke via USB or through Deke Wi-Fi network. Solstar's Deke Communicator is scheduled to fly to low-earth-orbit in early 2026, aboard a spacecraft owned and operated by Momentus.

The electro-mechanical impedance measurements, including SHM, are typically performed using laboratory scale phase-gain impedance analyzers; for example, HP4192A, Keysight E4990A. Miniaturized custom-built impedance measurement circuits were also considered, which primarily used the AD5933 impedance measurement chip from [4]. Availability of a new generation of impedance measurement chip – AD5941, prompted the development of a new miniaturized impedance measurement device with custom-made channel boards attached to a microcontroller. The channel boards are identical, each hosting one



(a) (b)

Figure 1. (a) Solstar Deke Space Communicator (Photo Credit: Solstar Space Company), (b) Afalina - a miniaturized impedance analyzer. The photo shows impedance measurement and microcontroller boards.

AD5941 impedance analyzer on a chip. Each channel board also includes a low-noise linear regulator to power the AD5941, a crystal oscillator, calibration resistors, and address configuration pins. The microcontroller is an off-the-shelf Arduino-compatible system hosting an ARM M0 microcontroller, micro-SD card slot, battery controller, and a USB port as illustrated in Figure 1(b).

The AD5941 features include a digital to analog converter (DAC), trans-impedance amplifier (TIA), 16-bit 1.6 mega-sample per second analog to digital converter (ADC), and associated support circuitry [5]. As configured for use in the Afalina, the DAC generates an excitation waveform that can range from 1 to 250kHz. This waveform is filtered, amplified, and output to the piezoelectric wafer active sensors (PWAS). The other side of the PWAS is connected to the input of the TIA, which converts the current drawn by the PWAS to a voltage signal and feeds it into the ADC for sampling. The digital data is filtered using sinc2 and sinc3 filters, then fed into a DFT engine. The DFT engine correlates the excitation signal and input signal to measure the impedance.

The newly developed impedance analyzer – Afalina - supports multiple simultaneous impedance measurements by stacking multiple boards. Each channel board has an address selection pin to set the channel number. To run simultaneous tests the microcontroller queues a set of instructions into the sequencer onboard the AD5941. Once instructions are loaded for every channel, the microcontroller triggers the tests via a dedicated trigger line. Every channel then executes the queued instructions simultaneously, catching the results in onboard memory. The cached data is downloaded individually and processed. The experiments presented below were conducted using the Afalina miniaturized analyzer.

3. ELECTRO-MECHANICAL IMPEDANCE METHOD

The electro-mechanical impedance method utilizes PWAS, acting simultaneously as actuators and sensors [6], to assess local structural response in the kHz frequency band. Mechanical impedance of structures is sensitive to damage (e.g., delamination, cracks) and changes in boundary condition due to improper assembly or dynamic loads. Such local changes might not affect the dynamics of the whole structure but cause changes in the local frequency response reflected in the electro-mechanical impedance spectra, Z(ω), in accordance with Equation (1) [7].

$$Z(\omega) = [i\omega c(1 - k_{31}^2 \frac{Z_{str}(\omega)}{Z_{PZT}(\omega)+Z_{str}(\omega)})]^{-1} \qquad (1)$$

where C – capacitance, k_{31} – PWAS electro-mechanical cross-coupling coefficient.

The range of frequencies from 20 kHz to 820 kHz was considered, with a resolution of 125 Hz, in order to identify the most significant range of frequencies based on two primary criteria: the presence of the highest amplitudes of peaks and the highest number of peaks. This range is illustrated in

Figure 2. Following a thorough analysis, the 100 kHz–150 kHz range was identified as the optimal frequency range for the study. Measurements were conducted with 50 Hz resolution to ensure accuracy and precision in the data acquisition process.

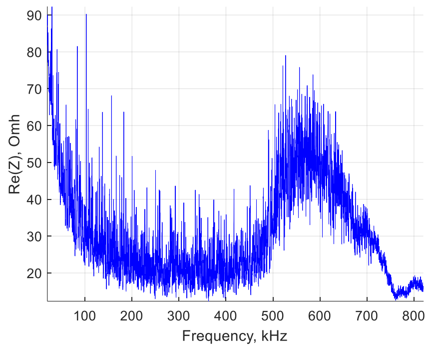


Figure 2. The broad EMI spectrum of the satellite panel.

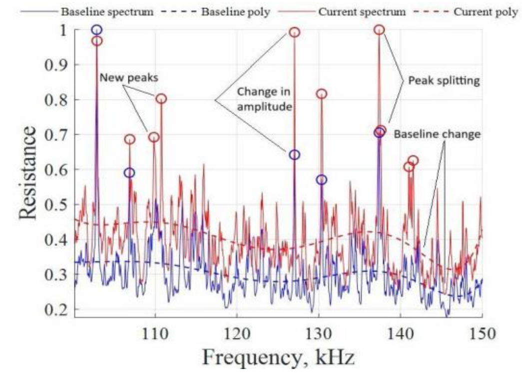


Figure 3. An example of EMI spectra corresponding to baseline, "healthy", and current structural states. Indicated are spectral features used in assessment of structural state.

The electro-mechanical impedance method involves the use of current and baseline spectra. The baseline spectrum represents the initial state of the structure, which is denoted as "healthy". The second spectrum corresponds to the current state of the structure under investigation.

Figure 3 illustrates these comparative spectra, highlighting several key diagnostic features such as appearance of new peaks, changes in peaks amplitude, peaks splitting and increasing level of baseline. A comparative analysis is then employed to assess the state of the current structure conditions and establish a prognosis regarding the structure's lifetime. Statistical, global spectral and artificial intelligence approaches are generally applied to evaluate the differences of electro-mechanical impedance spectra and detect/locate damage.

4. EXPERIMENT ON THE REPRESENTATIVE SPACE STRUCTURE

Bolted joints are extremely common in space structures. Hence, PWAS connected to Afalina, the extremely lightweight and low power EMI measurement device, was used to evaluate integrity of the 6U satellite bolted joint as illustrated in Figure 4. The experimental setup consists of a 34 cm long and 20 cm wide aluminum panel with 3 bolted joints located at the increasing distance (7.2, 17.2 and 28 cm) from the PWAS installed using Henkel LOCTITE EA 9309NA AERO adhesive. The real part of the electrical impedance was measured using the Afalina within the 100-150 kHz frequency range, as shown in Figure 5.

As demonstrated in Table I, the study considered 7 SHM cases and 3 damage scenarios. In scenario 1 the structure is undamaged – all bolted joints are secured; hence, labeled with S in Table I. This scenario is considered to be the reference to all other damage scenarios. A loose scenario, labeled L, for the bolted joint is imitated by applying a minimal torque on the bolt - a condition often referred to as "finger-tight." In the third scenario, labeled A, the bolt is entirely absent. The obtained experimental EMI results are summarized in Figure 5. The figure shows normalized resistance variations corresponding to SHM cases 1, 2, 4, and 6 in Table I. Although a direct visual comparison indicates that the loose bolt at position 9, which is closest to the sensor, produces the most significant variation in the resistance spectra, the trends for bolted joints located farther from the PWAS are less apparent and necessitate algorithmic analysis of the spectra to draw plausible conclusions.

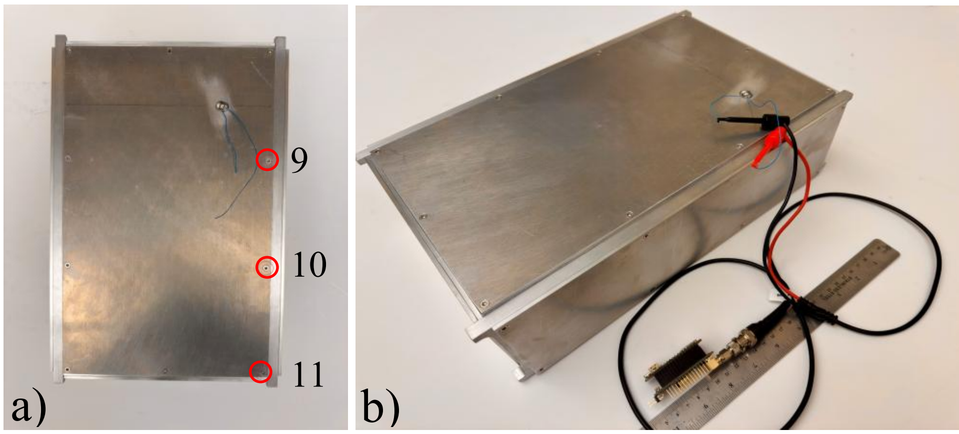


Figure 4. Experimental setup: a) top view of the 6U satellite showing the aluminum panel with attached PWAS and selected bolted joints; b) the experimental setup showing Afalina – a miniaturized impedance analyzer.

TABLE I. SHM CASES FOR DIFFERENT CONDITIONS OF BOLTED JOINTS: S – SECURED; L – LOOSE; M – MISSING (ABSENT)

	Bolted-joints condition		
Case	Bolt 9	Bolt 10	Bolt 11
1	S	S	S
2	L	S	S
3	M	S	S
4	S	L	S
5	S	M	S
6	S	S	L
7	S	S	M

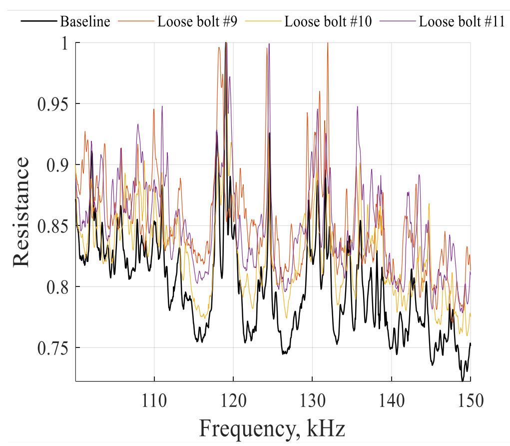


Figure 5. Normalized EMI resistance spectrum for SHM cases 1,2,4, and 6 in Table I.

TABLE II. STATISTICAL FEATURES OF EMI SPECTRUM

Damage metric	**Spectral feature**
RMSD [8], [9], [10]	Number of significant peaks
MAPD [8], [9]	Average value of shift of significant peaks
Correlation Coefficient (CC) [8], [9], [11]	Average value of the amplitude of significant peak
Entropy [12]	Number of significant disappeared peaks
Mean frequency difference	Number of significant new peaks
Kurtosis [13]	Average CC of the shapes of significant peaks
Flatness [13]	Average RMSD of the shapes of significant peaks

5. STRUCTURAL DAMAGE-SENSITIVE FEATURES IN THE ELECTRO-MECHANICAL IMPEDANCE SPECTRUM

To assess trends in the EMI spectra relevant to identifying the location and severity of damage, a comprehensive set of spectral and statistical features was considered, as outlined in Table II.

First, the threshold for identifying significant peaks was established using the following approach: a polynomial approximation was applied to each EMI spectrum to define the response trend (RT), and the threshold level was set by adding 40% of the dynamic range to the RT. This method provides a rational basis for evaluating peak variations within the bandwidth, and only a limited number of peaks satisfy the defined criterion. An illustration of this approach is presented in Figure 6. Figure 7 presents a comparison of spectral features between the healthy baseline spectrum and the spectrum corresponding to the loose bolted joint at position #9. Figure 8 illustrates results of the algorithmic processing of spectra with selected damage metrics presented in Table II. To facilitate a direct comparison of damage metrics, results were normalized to range from 1 (identical) to 0 (completely different). As could be seen in Figure 8, there is a monotonic change in the feature functions with increasing

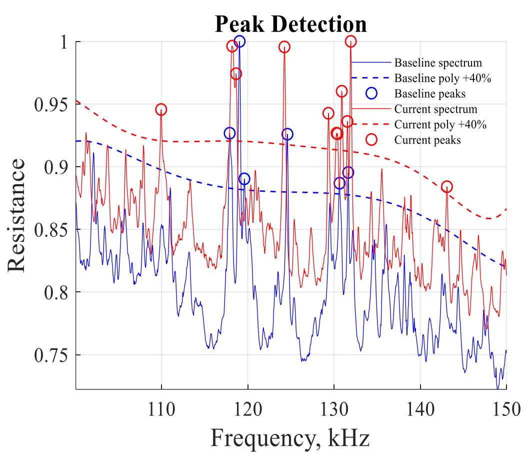


Figure 6. Peak detection algorithm for loose bolted joint #9 and baseline spectra

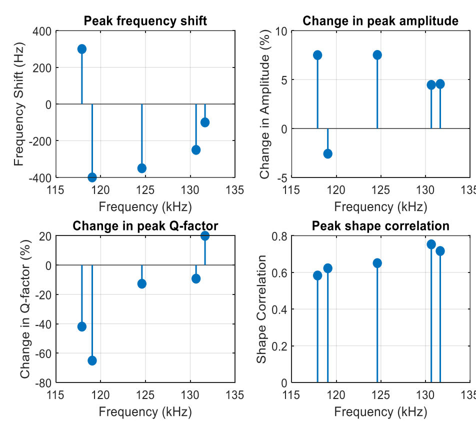


Figure 7. Peak features indicating differences between loose bolted joint #9 and baseline spectra

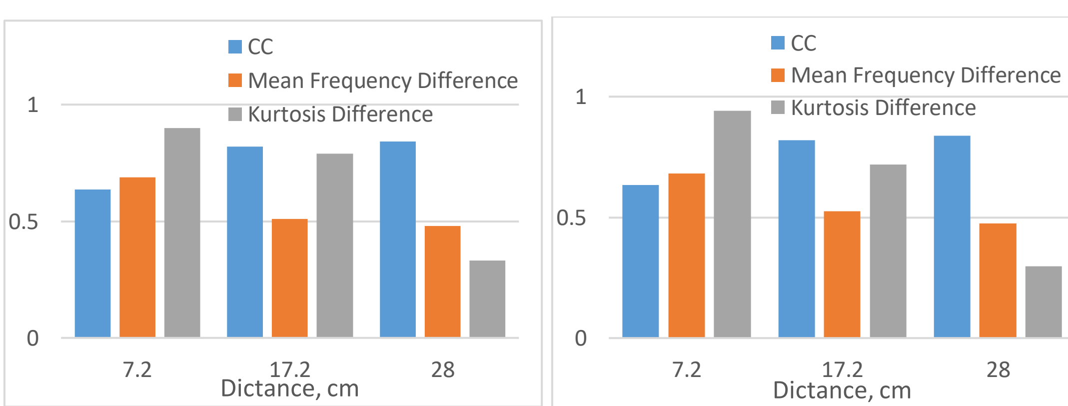


Figure 8. Monotonic feature functions for loose bolted-joints – left and missing bolted-joints – right

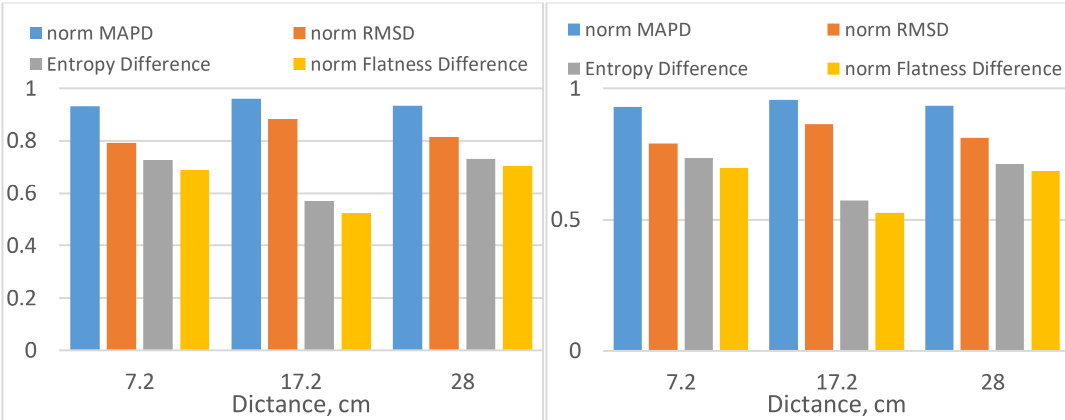


Figure 9. Irregular feature functions for loose bolted joints – left and missing bolted-joints – right

distance from the PWAS, suggesting potential in locating the loose bolted joint. However, Figure 9 shows that a number of damage metrics experience nonmonotonic, irregular changes as distance from the PWAS to the damage increases, suggesting that they cannot serve as reliable indicators for determining the location of the loose bolt. The missing and loose bolted joint scenarios exhibited similar monotonic and nonmonotonic trends in damage metrics, indicating a comparable influence of these damage mechanisms on the EMI resistance spectra.

The result of the analysis of the significant peaks according to the previously mentioned procedure is presented in Figure 10. A monotonic change in peak frequency and correlation coefficient (CC) with damage location from PWAS was observed. Non-monotonic outcomes were observed for RMSD, peak amplitude change, and number of new and disappeared peaks.

6. CONCLUSIONS

This study demonstrates the effectiveness of the electro-mechanical impedance method for structural health monitoring in spacecraft applications. Experimental

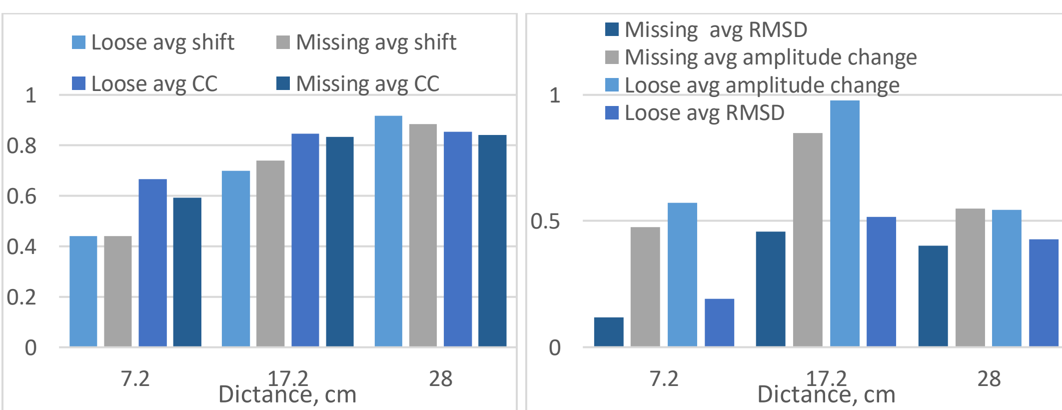


Figure 10. Significant peak analysis. Monotonic feature functions – left and irregular feature functions – right

analysis of bolted joints using a low-power EMI measurement device confirmed the practical viability of this approach for space-based SHM systems. Several damage metrics—including statistical descriptors, global spectral methods, and band integration—were evaluated for their sensitivity to structural damage severity and location. The results indicate that selected frequency bands and several damage metrics, such as correlation coefficient, mean frequency difference and others, offer optimal detection capabilities, supporting real-time classification in onboard systems. The compact and lightweight design of the hardware is particularly advantageous for space applications, addressing stringent constraints on mass and power consumption. These findings support the advancement of integrated SHM systems capable of in-flight structural assessment and condition reporting, thereby improving mission efficiency and enhancing safety through early detection of structural anomalies.

7. REFERENCES

1. Pisacane, V. L. 2008. "The Space Environment and its Effects on Space Systems," American Institute of Aeronautics and Astronautics. ISBN 978-1-56347-926-7
2. Bedingfield, K. L., Leach, R. D., and Alexander, M. B. 1996. "Spacecraft System Failures and Anomalies Attributed to the Natural Space Environment," NASA Ref. Publ. 1390, Marshall Space Flight Center, AL.
3. Mancini, S., Tumino, G., & Gaudenzi, P. (2006). Structural health monitoring for future space vehicles. *Journal of Intelligent Material Systems and Structures, 17*(7), 577–585.
4. AD5940/AD5941 datasheet: https://www.analog.com/media/en/technical-documentation/data-sheets/AD5940-5941.pdf
5. Hunter, D. C. (2018). *Adaptation of electro-mechanical impedance structural health monitoring for use in spacecraft* (Master's thesis). New Mexico Institute of Mining and Technology.
6. Guirgiutiu, V. and Zagrai, A.N. (2000). Damage detection in simulated aging-aircraft panels using the electro-mechanical impedance technique. In: *Proceedings of Adaptive Structure and Material Systems Symposium,* ASME Winter Annual Meeting, Orlando, FL, 5-10 Nov.
7. Giurgiutiu, V., Zagrai, A., & Bao, J. (1999). Experimental investigation of E/M impedance health monitoring for spot-welded structural joints. Journal of Intelligent Material Systems and Structures, 10(10), 802–812.
8. Tseng, K. K.-H., & Naidu, A.S.K. (2002). Non-parametric damage detection and characterization using smart piezoceramic material. *Smart Materials and Structures, 11*(3), 317–329.
9. Wang D, Song H, Zhu H. Numerical and experimental studies on damage detection of a concrete beam based on PZT admittances and correlation coefficient. *Construction and Building Materials* 2013; 49: 564–574.
10. Zagrai, A., & Giurgiutiu, V. (2002). Health monitoring of aging aerospace structures using the electro-mechanical impedance method. In T. Kundu (Ed.), *Smart Nondestructive Evaluation for Health Monitoring of Structural and Biological Systems* (Proc. SPIE Vol. 4702, pp. 289–300).
11. Enciu, Daniela, Ioan Ursu, and Adrian Toader. "New Results Concerning Structural Health Monitoring Technology Qualification for Transfer to Space Vehicles." Structural Control and Health Monitoring 24, no. 10 (October 2017).
12. Naidu, Akshay S.K. "Electromechanical Admittance Signature Analysis of Piezo-Ceramic Transducers for NDE." Materials Today: Proceedings 5, no. 9 (2018): 19933–43.
13. Tashakori, Shervin. "Novel Structural Health Monitoring and Damage Detection Approaches for Composite and Metallic Structures." PhD. Dissertation, Florida International University, 2018.