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Continuous Real-Time State Monitoring in Highly Dynamic Environments

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14. ABSTRACT

The overall goal of this research is to develop continuous, real-time sensing capability for determining the state of a dynamic structure on the microsecond to millisecond timescale using piezoelectric impedance-based SHM concepts coupled with Real-Time FPGA hardware and advanced signal processing. To this end we have experimentally verified an optimized finite element model of piezoelectric impedance. Results of this numerical modeling effort have revealed some sensitivity to state change in the first thickness mode in the ~1-3 MHz range. Next, our most significant research contribution is the development of a novel, resource-efficient impedance measurement technique termed the multi-narrowband excitation approach. Multi-narrowband excitation utilizes the ability to generate custom excitation waveforms when using a DAQ-based impedance approach to 1) reduce the amount of data acquired to perform state detection, thereby 2) reducing the amount of time required to process the acquired data, to ultimately 3) realize improvements to the efficiency and speed of the state detection process. Evaluation of the technique has shown a 77% reduction in excitation time and a 94% reduction in excitation energy when compared to utilizing broadband chirp excitation. Finally, we have developed a continuous state monitoring system that utilizes a custom written LabVIEW interface to continuously monitor the state of a structure. Evaluation of the system on a non-optimized DAQ platform have shown detection times on the order of 20-200 ms. Further improvements are expected when combined with the real-time state monitoring architecture that we developed separately; testing of which showed sensitivity in piezoelectric impedance up to 3 MHz.

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(YIP) CONTINUOUS REAL-TIME STATE MONITORING IN HIGHLY DYNAMIC ENVIRONMENTS

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Multi-Scale Structural Mechanics and Prognosis

November 24, 2020

I. Summary: Objectives and Report Outline

This final report summarizes our accomplishments on the YIP program (Grant FA9550-16-1-0440) entitled "Continuous Real-Time State Monitoring in Highly Dynamic Environments," Current state-of-the-art in structural health monitoring (SHM) for characterization and assessment of in-service structures is suitable for detecting incipient damage in slowly changing structures, on the order of seconds to minutes. There is a need to advance this technology for structures operating in highly dynamic environments (e.g. shock, blast, high-velocity impact, hypersonic flight, etc.) to enable microsecond to millisecond state detection. Our research vision is to create a framework for very high-speed detection of structural states (e.g. boundary conditions, interface conditions, structural damage) during highly dynamic events that can be utilized for a wide variety of applications. The main goal of this program focuses on the develop a continuous, real-time sensing system capable of determining the state of a dynamic structure on the microsecond to millisecond timescale using piezoelectric impedance-based SHM concepts coupled with Real-Time FPGA hardware and advanced signal processing. This goal is pursued through the following three research objectives:

Objective 1: Extend the electromechanical impedance method to the MHz frequency range through electromechanically coupled physics models and experimentation.

Objective 2: Investigate efficient data collection and processing schemes to allow for in situ electromechanical impedance measurements on the microsecond to millisecond timescale.

Objective 3: Experimentally verify the real-time state detection framework developed in Objectives 1 and 2 through dynamic impact testing.

The principal investigator for this project is Professor Steven R. Anton at Tennessee Technological University. The PI also collaborated on this work with Dr. Jacob Dodson at AFRL/RWMF. The PI participated in the AF SFFP in 2015 and worked with Dr. Dodson in his lab at Eglin AFB to develop the ideas that fueled this YIP program, and collaborated with Dr. Dodson on the topic of *microsecond state detection* throughout the performance of this project. Additionally, the PI was supported by several graduate research assistants as well as graduate students not directly supported by this grant. Section II provides a brief description of the impedance SHM sensing modality while Section III succinctly summarizes our research accomplishments on each of the three objectives. Section IV lists all personnel involved in this effort, and Section V provides a list of all publications and invited lectures associated with this work. Finally, Section VI lists awards and recognition received by researchers involved in this YIP program.

II. Fundamental Piezoelectric Impedance Sensing Modality

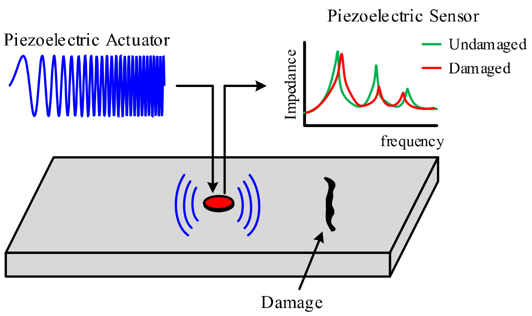

Figure 1. Schematic illustrations of impedance-based SHM technique.

This research focuses on extending the well-known *electromechanical impedance (EMI) method* for SHM to the MHz frequency range for continuous, real-time microsecond to millisecond structural evaluation. Impedance-based SHM relies on the fact that the electrical impedance of a piezoelectric transducer surface bonded to a structure is a combined function of the mechanical impedance of the transducer and that of the host structure. Measurement of the electrical impedance, therefore, reveals information about the mechanical impedance of the structure, which is affected, for example, by damage, changing boundary conditions, and changing environmental conditions. A schematic showing the basic principle of impedance SHM is given in Figure 1 for reference. In order to detect damage, impedance is measured over a range of frequencies, typically from tens to hundreds of kHz, and comparisons are made to impedance spectra measured in a known, “healthy” state. Damage detection algorithms are then used to extract damage sensitive features from the impedance response to quantify the state of the structure. An advantage of the impedance method is that the same transducers are used for both actuation and sensing. The aims of the research conducted under this award include 1) extending the classical EMI method to the MHz frequency range, and 2) developing novel, efficient excitation and signal processing schemes in order to dramatically increase the speed of assessment to enable microsecond to millisecond state detection.

III. Research Accomplishments

This section summarizes the research performed under this grant. We limit ourselves here to a succinct summary and refer the reader to the publications listed in Section V for more detailed descriptions.

III.1. Objective 1: Extend the electromechanical impedance method to the MHz frequency range through electromechanically coupled physics models and experimentation.

The overall goal of this portion of our research is to develop electromechanically coupled piezoelectric impedance models of simple structures to gain an understanding of the impedance response in the MHz frequency range, and to experimentally validate the models.

A challenge associated with the development of accurate analytical and numerical models of coupled piezoelectric systems is the identification of piezoelectric material properties. These properties are generally provided by the manufacturer, however, due to the inherent variability in the manufacturing process, the tolerance on the specified properties is often as high as ±20%. When developing piezoelectric models, the variability in material properties used as model inputs leads to inaccuracies in model predictions (outputs). There is often variation from transducer to transducer, even from a single order from a given manufacturer, thus the exact material properties of a specific transducer should be accurately identified in order to develop high fidelity models. We have performed a numerical optimization routine that utilizes a finite element (FE) model of a free circular piezoelectric transducer and accurately identifies the 10 independent material properties of a given transducer (three piezoelectric coefficients (e_{33}, e_{31}, e_{15}), two electrical permittivity coefficients (ε_{11}, ε_{33}), and five mechanical stiffness coefficients (c_{11}, c_{12}, c_{13}, c_{33}, c_{44})) by continual comparison to the experimental impedance response of the transducer. Figure 2 presents a flowchart of the optimization algorithm routine and a comparison of the modeled impedance spectrum from 100 kHz – 1.5 MHz using the initial parameter set (i.e. manufacture's specifications) and those obtained from the final iteration of the optimization routine; each compared to the experimental impedance spectrum measured with an industry-standard HP 4194A impedance analyzer. Results of the final iteration validate the accuracy of the model.

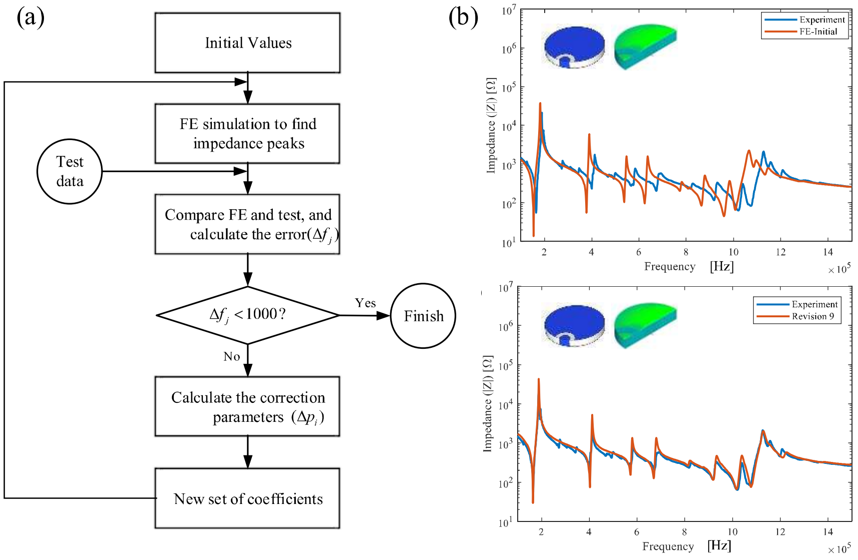

Figure 2. (a) Optimization routine flowchart, (b) comparison of initial (upper) and final (lower) simulations showing effectiveness of optimization routine in selecting piezoelectric constants.

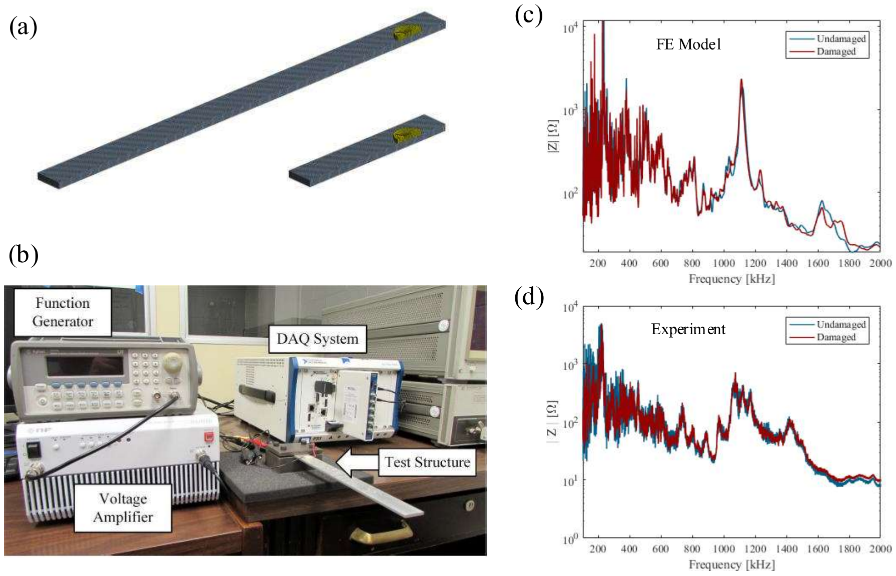

Figure 3. Analysis of cantilever beam with surface mounted circular piezoelectric disc including (a) FEM models of undamaged and damaged conditions, (b) experimental setup, (c) FE model impedance results, and (d) experimental impedance results.

With the optimized material properties identified, analysis of high frequency damage detection via piezoelectric impedance response of a circular transducer bonded to an aluminum beam is then performed. The first stage of this work involved the development of a data acquisition system (DAQ)-based impedance measurement approach and subsequent validation through rigorous comparison to the industry-standard HP 4194A analyzer. The DAQ-based measurement approach serves as the foundation of much of this research due to the fact that standard impedance analyzers are slow and do not allow for custom impedance measurement approaches which are required for micro to millisecond state detection (note, details discussing the progression of the development of the DAQ-based approach are provided in the following two sections of the report). The experiment consisted of an aluminum beam with a surface mounted piezoelectric transducer, and a National Instruments (NI) PXI chassis with a PXI-5122 Oscilloscope card (two channels, simultaneous sampling up to 100 MHz), as shown in Figure 3(b). Results of FEM predictions and DAQ-based experimental measurements for both an undamaged beam and a damaged beam (beam was cut and shortened) are given in Figure 3(c)-(d), respectively. From the results, it is apparent that while there is not an exact match between the FE model predictions and the experimental measurements, the model does capture the overall behavior (note, differences can be attributed to lack of modeling of bonding layer, assumption of homogeneous material properties of aluminum beam, boundary condition assumptions, etc.). In terms of damage detection, it is observed that the sensitivity is highest below 600 kHz, however, some sensitivity is observed for the first thickness mode around 1 MHz.

III.2. Objective 2: Investigate efficient data collection and processing schemes to allow for in situ electromechanical impedance measurements on the microsecond to millisecond timescale

The most fundamental difference between conventional SHM and a continuous, real-time architecture is the drastic reduction in allowable time for data collection and processing. The main goal of this portion of our research is to explore techniques that are useful in the *implementation* of real-time state monitoring by reducing computational time to allow microsecond to millisecond state monitoring.

A significant contribution of our research is the development of the *multi-narrowband excitation* approach to capturing piezoelectric impedance spectra in a resource-efficient manner. The general objective of the multi-narrowband excitation concept is to utilize the ability to generate custom excitation waveforms when using a DAQ-based impedance approach to 1) reduce the amount of data acquired to perform state detection, thereby 2) reducing the amount of time required to process the acquired data, to ultimately 3) realize improvements to the efficiency and speed of the state detection process to enable real-time state detection. In conventional impedance-based SHM, broad frequency sweeps are performed to assess the structure over a wide range of frequencies. Typically, only a few narrow frequency bands exhibit dynamic impedance response that is sensitive to damage. The inherent inefficiency built into this process is that the majority of the recorded data are not useful, and ultimately thrown out. To enable real-time microsecond monitoring, efficient excitation schemes must be used to eliminate recording of useless data and focus the analysis only on frequency bands of interest. To this avail, we have developed a novel multi-narrowband excitation scheme in which only the frequency ranges of interest are excited, thereby reducing the excitation and signal processing time to help allow microsecond state monitoring. The multi-narrowband excitation concept is based on the superposition of multiple narrowband sine sweeps. The general process of implementing the multi-narrowband approach involves first identifying damage-sensitive bandwidths (typically, with a surrogate sacrificial structure that can be intentionally damaged), creating the custom multi-narrowband excitation signal via a superposition of carefully selected damage-sensitive bandwidths, and utilizing a DAQ-based measurement approach to interrogate the structure using the custom multi-narrowband signals.

Experimental results from development and evaluation of the multi-narrowband excitation scheme in the standard kHz frequency range are shown in Figure 4. The experiment consisted of an aluminum beam with a surface mounted piezoelectric transducer and an NI USB-6346 DAQ device (simultaneous sampling up to 500 kHz), as shown in Figure 4(a). An HP 4194A impedance analyzer was also used for initial selection

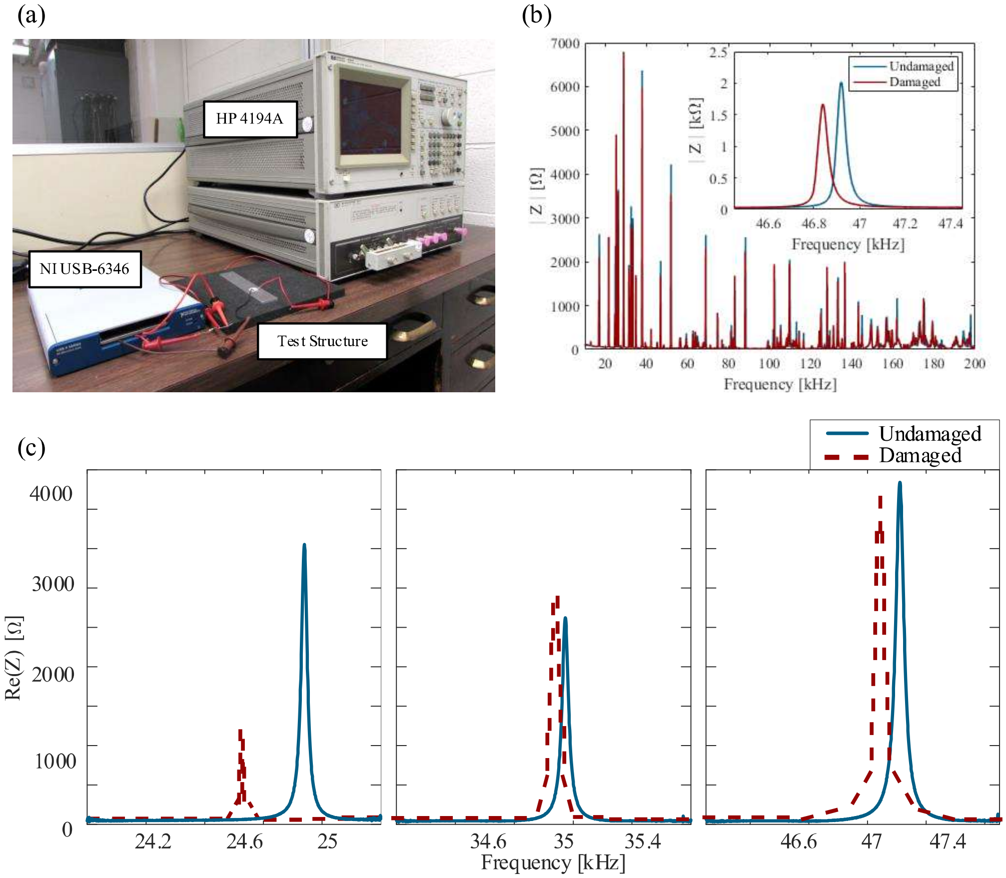

Figure 4. Experimental investiagtion of multi-narrowband excitation concept including (a) experimental setup, (b) broadband impedance comparison (taken w/ HP 4194A) showing regions sensitive to state change, with inset showing an example of a peak selected for the multi-narrowband approach, and (c) multi-narrowband impedance results (using NI USB-6346 DAQ).

Table 1. Quantitative comparison of the broadband chirp and multi-narrowband signals.

	Broadband Chirp	Multi-narrowband	Percent Decrease
Total Frequency Bandwidth	40 kHz	3 kHz	92.50%
Excitation Energy (J)	00204	0.00126	93.80%
Excitation Sweep time (s)	0.5	0.113	77.40%

of sensitive frequency bands and for validation purposes. First, broadband impedance sweeps were measured with the HP 4194A impedance analyzer of the beam in two different states (with and without hole drilled) in order to determine frequency bands sensitive to the state change. The results of these measurements are shown in Figure 4(b), where one of the sensitive bands is highlighted in the inset figure. In total, three sensitive narrow bands in the 20-50 kHz range were identified and constituted the component signals of the multi-narrowband signal. Next, a multi-narrowband signal containing only these targeted narrow frequency bands was created along with a broadband chirp for comparison. It should be noted that care was taken when generating the multi-tonal signal to match the signal energy level with that of the broadband chirp for each narrow band of interest. Finally, impedance measurements of the structure in both states were made using the multi-narrowband signal, the broadband chirp signal, and the HP 4194A impedance analyzer. The results for the multi-narrowband signal are shown in Figure 4(c). Comparison to the broadband sweeps taken with the DAQ and with the HP 4194A analyzer demonstrated that the multi-narrowband signals accurately capture the dynamics of interest within the three narrow bands. A comparison of the root-mean-square-error (RMSE) of the impedance response in the undamaged and damaged condition between the three methods reveled that the multi-narrowband approach had a percent difference in RMSE of less than 3.3% compared to the broadband chirp and the HP 4194A measurement, thus validating its accuracy.

To quantify the improvements in efficiency that arise from the multi-narrowband approach, comparisons are made between the broadband chirp and multi-narrowband measurement methods (both are DAQ-based methods) in terms of total frequency bandwidth, excitation energy, and excitation time. Results are shown in Table 1. From these results, it can be observed that a significant reduction in all three quantities is obtained by utilizing the multi-narrowband approach. Specifically, there is a 94% reduction in excitation energy and a 77% reduction to excitation time. These reductions are critical to the success of deployable, low-power, continuous, real-time microsecond state monitoring.

III.3. Objective 3: Experimentally verify the real-time state detection framework developed in Objectives 1 and 2 through dynamic impact testing

An impact-based experimental setup has been designed and fabricated as part of this research in order to create a repeatable and tunable *highly dynamic* environment within which the various real-time state monitoring technique aspects can be evaluated. The setup, which is shown in Figure 5(a), borrows several aspects from the typical pneumatic Split-Hopkinson pressure bar setup. The system is controlled using a custom LabVIEW interface and includes a laser micrometer for accurate measurements of the impactor bar position relative to the incident bar, allowing the impact velocity (slope of displacement vs. time), the moment of impact, and the response of the "bounce back" to all be clearly identified. A velocity calibration has been performed on the system, which has been shown to provide repeatable impact events with impact velocities on the order of 2-6 m/s. A finite element model has also been developed to describe the dynamic vibration response of the incident and striker bars after impact. Some results are given in Figure 5(b) for an impact velocity of 2.09 m/s which show that the acceleration spectrum is strongly dependent on the placement of the piezoelectric sensor. Additionally, results show that the striker bar is in contact with the beam for about 30 μs when no interface material is present (aluminum on aluminum contact), while the contact time is increased to 1.8 ms with the inclusion of a soft polymer material placed at the interface, thus giving the ability to tune the impact during with the use of a programming material. Several preliminary impedance-based state monitoring tests have been conducted using the impact-based experimental setup but no conclusive results have been obtained to date, primarily due to the fact that the real-time, continuous

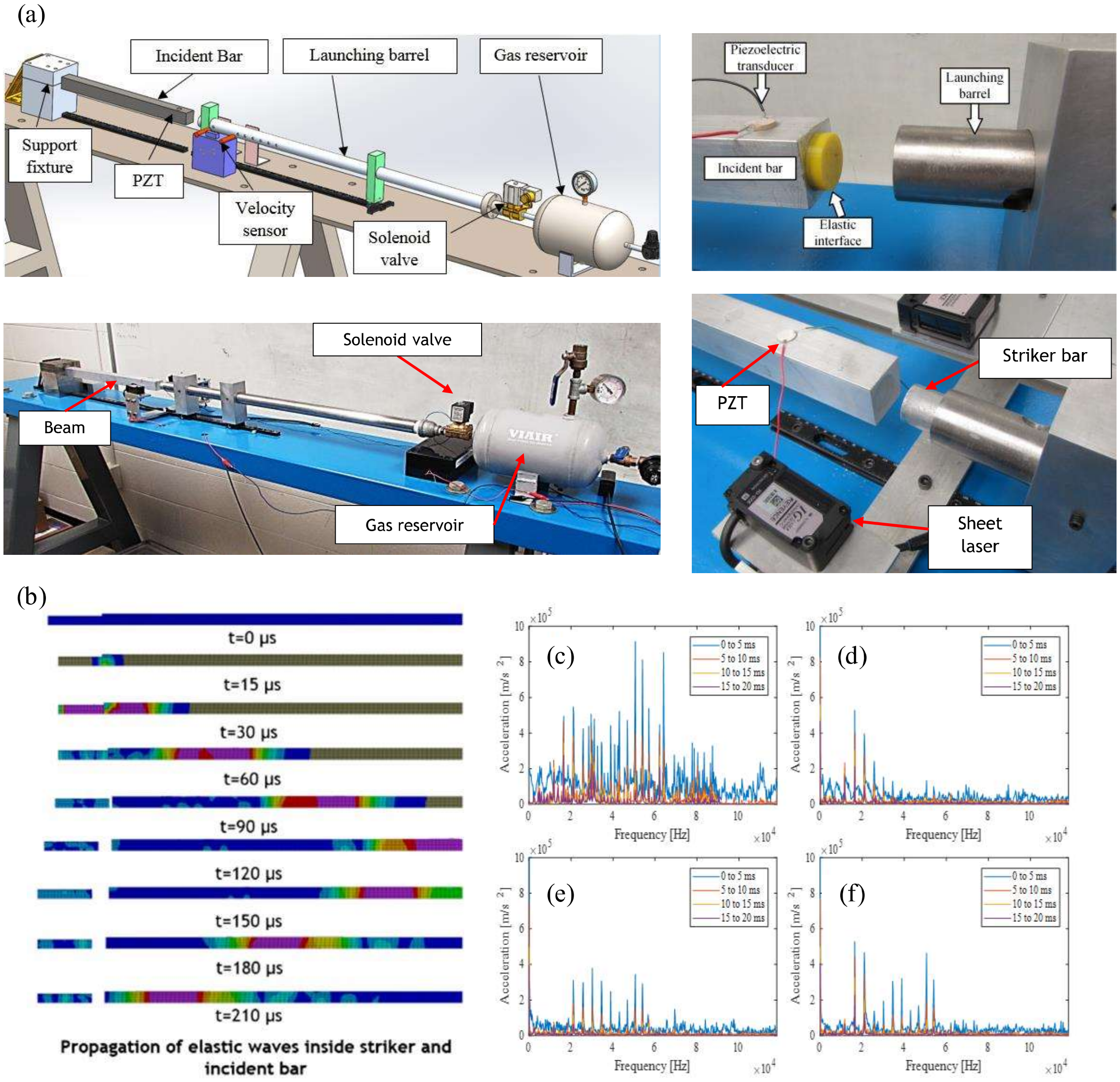

Figure 5. Impact-based experimental setup including (a) CAD rendering and photographs of setup, (b) FEM results of wave propagation during 2.09 m/s impact with no programming materal at the interface, and corresponding acceleration frequency spectrum at (b) tip, (c) 1", (d) 3", and (e) 5" from the tip.

state monitoring measurement system described next is still in the final stages of development and the short duration of contact during impact requires data acquisition on the order of MHz.

The first aspect of our research towards an integrated hardware/software platform to allow continuous, real-time state monitoring is the development of a continuous state monitoring architecture whereby the state of a structure is continually interrogated and monitored. To this end, we have developed a custom written LabVIEW program for implementing continuous monitoring of piezoelectric impedance for structural monitoring, as shown in Figure 6(a). The program operational flowchart is given in Figure 6(b) and shows the various processes performed by the continuous state monitoring program including 1) interrogation of the structure via piezoelectric impedance measurement using sine sweep or multi-narrowband excitation and simultaneous measurement and subsequent calculation of impedance, 2) acquisition of a running baseline whereby only the most recent measurements are recorded as averaged as an up-to-date baseline (in this way, the system is insensitive to incipient changes and is only sensitive to sudden changes), 3) the continuous comparison of the current measurement to the running baseline and calculation of damage

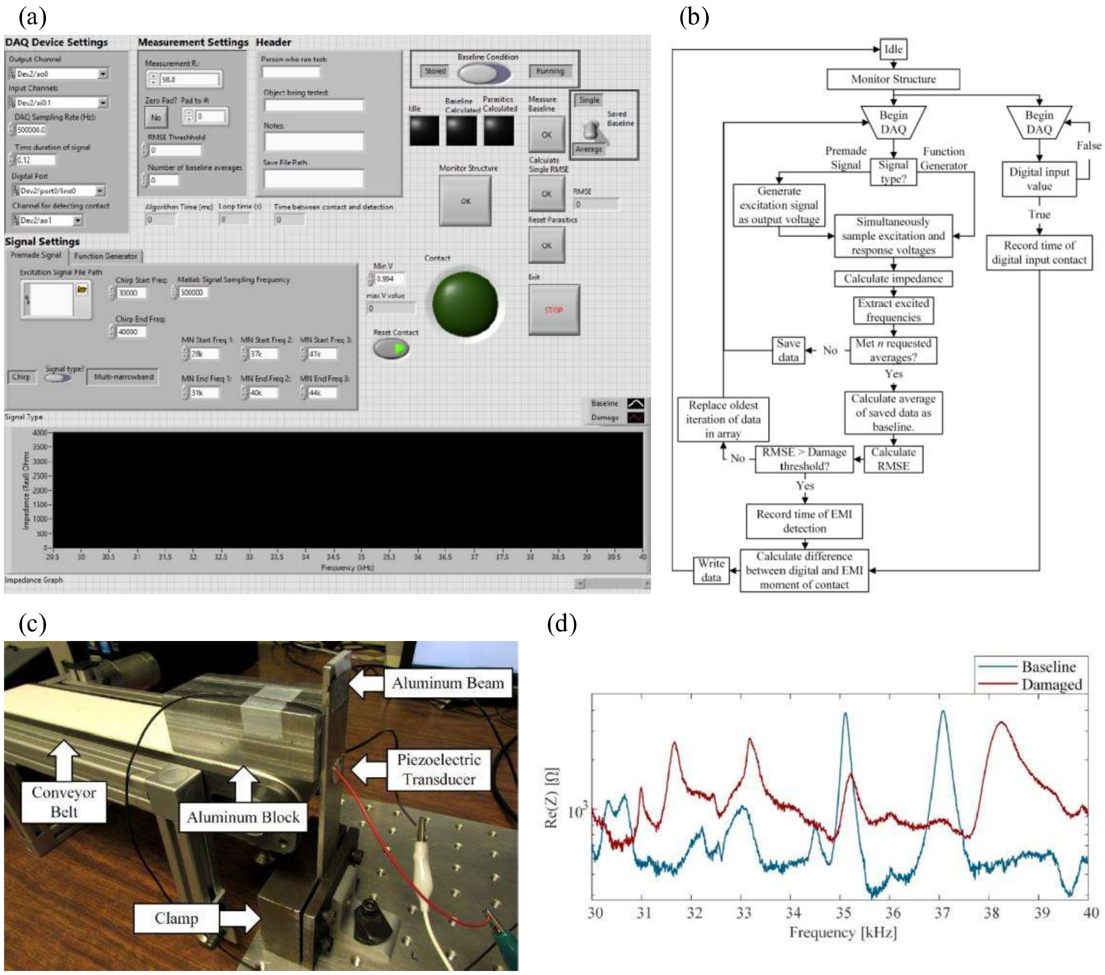

Figure 6. Continuous state monitoring platform including (a) custom written LabVIEW program for continuous state monitoring, (b) program operational flowchart, (c) evaluation test stand for repeatable state change, and (d) example impedance signatures comparing a stored baseline and the impedance measurement taken the instant the structure experiences a change of state (labeled "Damaged" in plot).

metric (in this case, Root Mean Square Error, RMSE), and 4) the continuous monitoring of the moment of state change. Figure 6(c) shows the test stand used to validate the continuous state monitoring system whereby contact between the test structure and a mobile block is used as a controllable change of state. The continuous state monitoring algorithm is implemented using a NI USB-6346 DAQ device connected to a standard PC. Example results from testing are provided in Figure 6(d), which show the change in impedance signature between the running baseline and the signature measured just after the moment of contact. On average, the continuous state monitoring system was found to be able to identify state change with a total loop time (time from the moment that data sampling begins until the RMSE has been calculated and a decision is made regarding the state of the structure) of 230 ms, and an algorithm time (the amount of time elapsed from the moment data has been collected until the RMSE is calculated and a decision is made regarding the state of the structure) of 20 ms. These speeds are quite promising for millisecond state detection and can be further increased by 1) optimizing the LabVIEW program (which contains several ancillary debugging features) and 2) operating in a real-time environment.

The second aspect of our development of a continuous, real-time state monitoring platform is a measurement and signal processing system capable of acquiring data with MHz acquisition rates and processing the data in real-time. The system we have developed through this research for this purpose,

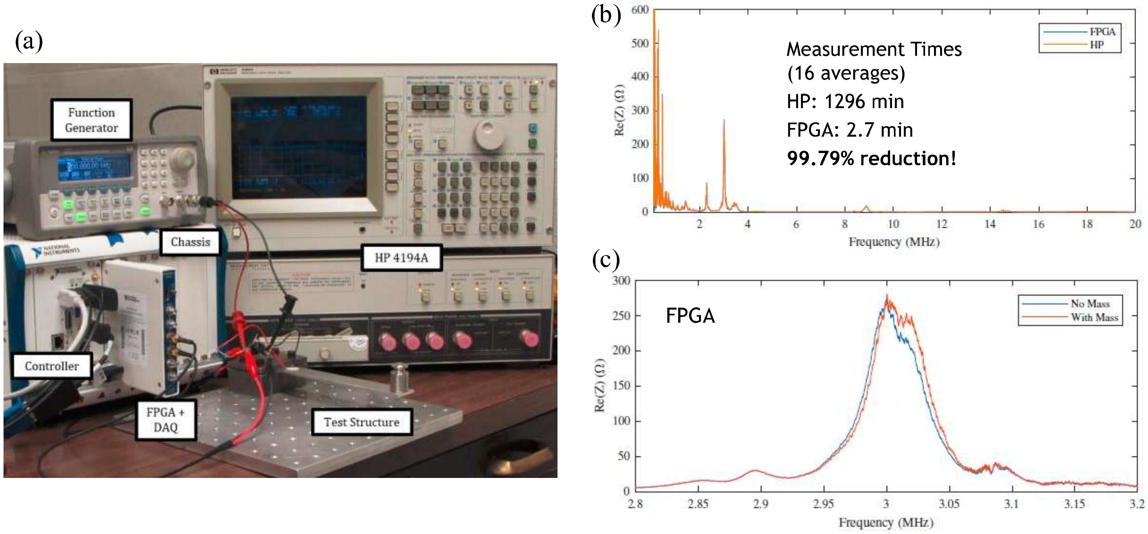

Figure 7. Real-time FPGA-based state detection system demonstration showing (a) experimental test setup, (b) overall impedance measurement, and (c) zoomed-in view of MHz frequency range.

shown in Figure 7(a) utilizes National Instruments hardware and consists of a PXIe-1082 8-slot chassis with a PXIe-8840 2.6 GHz Quad-Core Controller, a PXIe-7975 FlexRIO FPGA Module with a Kintex-7 FPGA and 2 GB of RAM, and an NI-5782 Transceiver Adapter Module with 500MS/s sampling rate, 2 analog input channels, and 2 analog output channels. This system allows impedance measurement to be made up to frequencies around 100 MHz, and allows for real-time processing of acquired data in hardware. The most significant advantage of using FPGAs for data acquisition and processing is that data processing is done in a real-time, highly deterministic environment and calculations occur directly on the FPGA hardware, thereby allowing ultrafast and repeatable computations; a critical capability for our application. We have developed a custom LabVIEW program that utilizes both the Real-Time Module as well as the FPGA Module to collect and process piezoelectric impedance data in real-time. The system accounts for the parasitic effects of the wiring and erroneous circuit effects to improve accuracy of the measurements. Preliminary state detection experiments have been performed on a static beam, as shown in Figure 7(a). For the broad frequency sweep up to 20MHz shown in Figure 7(b) using 16 averages, a remarkable 99.97% reduction in measurement time has been achieved using the FPGA-based system compared to the HP 4191A analyzer used for validation. This reduction is critical for enabling microsecond state detection. Furthermore, the impedance response in the 3 MHz range shows promise for utilizing MHz frequencies for real-time state detection. While these preliminary results are certainly quite promising, the system has yet to be completed (i.e. with full custom multi-narrowband excitation, efficient on-board FPGA-based signal processing for optimal performance, and integrated into the continuous state monitoring architecture described above) and implemented on the impact-based experiment in real-time. This is the current focus of the PI and his team as we continue our research in continuous, real-time state detection.

IV. Personnel

The following provides a list of personnel who have worked on research supported in part or in whole by the Air Force Office of Scientific Research under Grant FA9550-16-1-0440:

IV.1. Academic Faculty

Professor Steven R. Anton, Mechanical Engineering, Tennessee Tech University

IV.2. Graduate Students Supported by the Grant

Mohammad Alshaikh Ali, MS in Mechanical Engineering (expected graduation date: Dec 2021)

Eric Nolan, MS in Mechanical Engineering (graduation date: May 2020)

Mohsen Safaei, PhD in Mechanical Engineering (graduation date: May 2019)

Ekramul Ehite, MS in Mechanical Engineering (graduate date: May, 2018)

Mohammad Mohammadzadeh-Keleshteri, PhD in Mechanical Engineering (departed university due to personal issues after 6 months of work on the project)

Ryan Kettle, MS in Mechanical Engineering (graduation date: May, 2018)

V. Publications and Invited Lectures

The following provides a list of publications supported in part or in whole by the Air Force Office of Scientific Research under Grant FA9550-16-1-0440:

V.1. Publications

1. Alshaikh Ali, M., Nolan, E. C., Safaei, M., and Anton, S. R., An Impact-based Experimental Setup for Evaluation of Rapid Electromechanical Impedance-Based Structural Health Monitoring, Proc. ASME SMASIS, 2020, SMASIS2020-2438 (11 pp.).
2. Nolan, E. C. and Anton, S. R., Electromechanical Impedance Based Structural Health Monitoring Measuring System in the Millisecond Timescale, Proc. SPIE, 2020, Vol. 11381, 113812P (11 pp.)
3. Nolan, E. C., Safaei, M., and Anton, S. R., Evaluation of SHM with the Electromechanical Impedance Method using a High Voltage Excitation Signal in High Frequencies, Proc. ASME SMASIS, 2019, SMASIS2019-5556 (9 pp.).
4. Safaei, M., Nolan, E. C., and Anton, S. R., Finite Element Evaluation of EMI-Based Structural Health Monitoring in High Frequencies, Proc. SPIE, 2019, Vol. 10972, 109720C (12 pp.).
5. Ehite, E. H. and Anton, S. R., A Low-Cost Modular Impact-Based Experimental Setup for Evaluation of EMI Based Structural Health Monitoring at High Rates, Proc. SEM IMAC, 2018 (10 pp.).
6. Kettle, R. A. and Anton, S. R., Multi-tonal Based Impedance Measurements for Microsecond State Detection, Proc. SEM IMAC, 2018 (7 pp.).
7. Kettle, R. A., Ehite, E. H., and Anton, S. R., Development of an Electromechanical Impedance Based Condition Monitoring System with Multi-Tonal Excitation, in Proceedings of the Vibration Institute Annual Conference, 2017 (10 pp.).
8. Kettle, R. A., Dodson, J. C., and Anton, S. R., High Frequency Impedance Measurements for Microsecond State Detection, in Proceedings of the SEM IMAC Conference, 2017 (9 pp.).

V.2. Invited Lectures

1. Anton, S. R., Microsecond State Monitoring: Enabling Real-Time Structural Health Monitoring, University of Tennessee, Knoxville, TN, April 12, 2018.
2. Anton, S. R., Microsecond State Monitoring: Enabling Real-Time Structural Health Monitoring, Florida State University, Tallahassee, FL, February 16, 2018.
3. Anton, S. R., Microsecond State Detection for Real-Time Structural Health Monitoring in Highly Dynamic Environments, Michigan Technological University, Houghton, MI, September 8, 2016.

VI. Honors and Awards

The following provides a list of recognition received by researchers for their efforts in support of Grant FA9550-16-1-0440 from the Air Force Office of Scientific Research:

1. Prof Anton received the Brown-Henderson Outstanding Engineering Faculty Award from the College of Engineering at Tennessee Tech in 2020 in recognition of his contributions to research, teaching, and service.
2. Prof Anton received the Wing's Up 100 Award from TTU President Phil Oldham in 2019 in recognition of his track record of external research funding.
3. M.S. student, Eric Nolan, awarded the National Defense Industrial Association (NDIA) Space and Missile Defense Working Group 2019 Graduate Fellowship - $5,000 awarded, 2019
4. Prof. Anton received the Rising Renaissance Engineer Faculty Scholar Award from the College of Engineering at Tennessee Tech in 2017.
5. Prof. Anton received the ASME Distinguished Researcher Award from the Tennessee Tech Student Chapter of ASME in 2016.
6. M.S. student, Ryan Kettle, awarded the National Defense Industrial Association (NDIA) Space and Missile Defense Working Group 2016 Graduate Fellowship - $5,000 awarded, 2016