A Modular Impact-based Experimental System for Evaluation of EMI-based Structural Health Monitoring in Highly Dynamic Environments

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Objective

The objective of this work is to develop an experimental system capable of performing Electromechanical Impedance (EMI) based structural health monitoring in a structure operating under highly dynamic environment.

Introduction

Structural health monitoring (SHM) is a method for recognizing changes of state in structures used for civil, aeronautical, and mechanical applications [1]. A change of state is any variation to the physical/geometrical features of the system that adversely affects the system dynamic response, like mass, stiffness, and boundary conditions. SHM systems are capable of improving the safety of engineering structures, and reducing the associated maintenance expenses.

Current SHM technology is suitable for detecting changes of state in slowly changing structures on the order of seconds to minutes. There is a growing need to advance this technology for structures operating in highly dynamic environments (e.g. shock, blast, high-velocity impact, etc.) to enable microsecond to millisecond detection. [2]. Examples of such structures are shown in Fig. 1).

Fig. 1: Highly dynamic environments requiring high-speed Structural Health Monitoring systems

Among different methods available for the application of SHM, the electromechanical impedance (EMI) method is an attractive option since it employs piezoelectric (PZT) transducers, which are cheap, small-scale, and easily installable.

Methodology

Electromechanical Impedance Method

The electromechanical impedance (EMI) method utilizes the electromechanical coupling properties of piezoelectric materials (PZTs) to use them as both as a sensor and an actuator simultaneously. [3] By bonding a PZT to a structure, the electrical impedance of the PZT becomes a function of the mechanical impedance of the host structure; therefore, changes in the mechanical structure are reflected in the electrical impedance of the PZT. This process is illustrated below in Fig. 2.

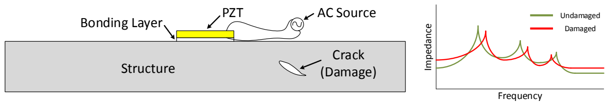

Fig. 2: EMI method being used to detect damage in a structure

Typically, electrical impedance measurements are performed with commercial impedance analyzers (e.g. HP 4194A shown in Fig. 3). Such impedance analyzers are large, heavy, expensive, and use a slow stepped sinewave measurement method.

Fig. 3: An HP 4194A impedance analyzer

Instead, this research uses an alternative measurement system developed by Baptista [4], comprising a standard data acquisition device (DAQ), with a auxiliary measurement circuit. This system is compact, inexpensive, and ideal for high-speed operation.

Impedance Measurement System

The impedance measurement system uses 2 NI 6211 DAQs (shown in Fig. 4) to generate the excitation signal and to record the response signal voltages, respectively. The DAQs are paired with an auxiliary measurement circuit (Fig. 5). The excitation signal and response signal voltages are recorded and processed by a custom measurement and analysis suite.

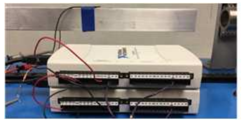

Fig. 4: NI 6211 DAQs

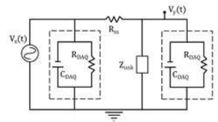

Fig. 5: Auxiliary measurement circuit

Modular Impact-based Experimental System (MIES)

A modular impact-based experimental system (MIES) is designed and fabricated for generating a dynamic event in the form of a collision between a moving striker bar and a static incident bar. Sudden Release & expansion of pressurized gas accelerates the striker bar along the launching barrel. The striker bar impacts the static, cantilever incident bar, which is instrumented with a single PZT transducer. A photoelectric sensor based velocity measurement system measures the impact velocity. The impedance of the PZT is measured by the DAQ-based impedance measurement system. Fig. 6 shows the different components of the experimental system.

Fig. 6: (a) Experimental system, (b) Incident beam with PZT, (c) Striker bar, (d) Velocity sensors

Results

Velocity Calibration

To calibrate the impact velocity of the striker as a function of the propellant gas pressure, the striker is launched at various initial stored gas pressures, and the resulting impact velocities are recorded and averaged. The mean impact velocity results are plotted as a function of time (shown in Fig. 7). A quadratic curve fitting is applied to estimate the expected velocity for a given pressure. Thus, the system's ability to produce custom, repeatable impact event is verified.

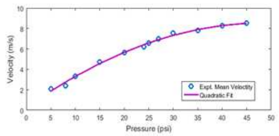

Fig. 7: Velocity calibration curve

Dynamic System State Detection

A broadband frequency sweep (shown in Fig. 8) is done on the PZT in its undisturbed state to determine its sensitive frequency range. 3 of the sensitive frequencies are selected (83.86 kHz, 84.10 kHz, and 84.54 kHz), and PZT is excited at each of these single-tone frequencies while impacting the incident bar at 2.09 m/s velocity. Then, a multi-tonal excitation signal is formed by adding these 3 frequencies, and the PZT is excited by this signal while being impacted at the same velocity. Fig. 9 shows the impedance results for both single and multi-tonal signals.

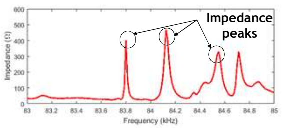

Fig. 8: PZT impedance sweep

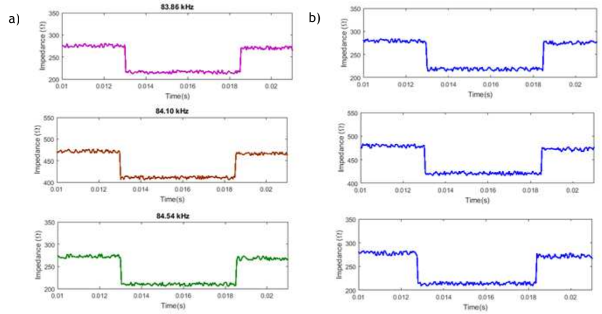

Fig. 9: Impedance results for incident beam impacted at 2.09 m/s, while being excited with (a) individual Single-tone excitation signals, (b) Multi-tonal excitation signal

Discussion

- For both the single-tone and the multi-tonal cases, the impact causes a significant drop in the impedance values, which rises up again after the effects of impact are gone. Hence, the experimental system can detect dynamic state change under impact using the EMI method.
- The post-impact impedance values are lower than the pre-impact impedance values. This can be attributed to a permanent change in the PZT-incident bar structure caused by the displacement of the incident bar support fixture, or due to the change in the bonding layer between the PZT and the incident bar.
- The impedance results for the multi-tonal signal match the results for the individual single-tone signals. Hence, instead of running separate impact tests for the single-tones, the same impedance data can be found by using only the multi-tonal signal. The reduction in the number of experiments significantly reduces the total measurement time.

Conclusions & Future Work

- The experimental system is able to create collisions between the moving striker bar and the static incident bar at different velocities repeatedly .
- The impedance measurement system can continuously detect change in the dynamic state of the cantilever incident beam under impact using both single-tone and multi-tonal excitations. To the best of the author's knowledge, this research shows the *first* ever *instance* of experimental observation of change in impedance *during* a highly dynamic event.
- To facilitate microsecond-timescale operation, the existing DAQs need to be replaced with high-speed measurement devices like field-programmable gate arrays (FPGAs) with high sampling rate (>100 MS/s).
- Additional experiments need to be performed by changing the incident bar boundary conditions (free-free, simply supported), and striker bar dimension (different length and mass).

References

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Acknowledgements

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