Advancing Autonomous Structural Health Monitoring

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Abstract

The focus of this dissertation is aimed at advancing autonomous structural health monitoring. All the research is based on developing the impedance method for monitoring structural health. The impedance technique utilizes piezoelectric patches to interrogate structures of interest with high frequency excitations. These patches are bonded directly to the structure, so information about the health of the structure can be seen in the electrical impedance of the piezoelectric patch. However, traditional impedance techniques require the use of a bulky and expensive impedance analyzer. Research presented here describes efforts to miniaturize the hardware necessary for damage detection. A prototype impedance-based structural health monitoring system, incorporating wireless based communications, is fabricated and validated with experimental testing. The first steps towards a completely autonomous structural health monitoring sensor are also presented. Power harvesting from ambient energy allows a prototype to be operable from a rechargeable power source.

Aerospace vehicles are equipped with thermal protection systems to isolate internal components from harsh reentry conditions. While the thermal protection systems are critical to the safety of the vehicle, finding damage in these structures presents a unique challenge. Impedance techniques will be used to detect the standard damage mechanism for one type of thermal protection system. The sensitivity of the impedance method at elevated temperatures is also investigated.

Sensors are often affixed to structures as a means of identifying structural defects. However, these sensors are susceptible to damage themselves. Sensor diagnostics is a field of study directed at identifying faulty sensors. The influence of temperature on these techniques is largely unstudied. In this dissertation, a model is generated to identify damaged sensors at any temperature. A sensor diagnostics method is also adapted for use in developed hardware. The prototype used is completely digital, so standard sensor diagnostics techniques are inapplicable. A new method is developed to work with the digital hardware.
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Chapter 1: Introduction

1.1 Autonomous Structural Health Monitoring Challenges

The introduction of smart structures into real world applications is one of the more challenging engineering problems today. For any number of structures, including civil, aerospace, and mechanical engineering infrastructure, structural health monitoring (SHM) is the process of detecting damage while the structure is in use (Inman et al. 2005). Damage to these types of structures is defined as any changes to the material, system geometric properties, boundary conditions, or system connectivity which are either intentionally or unintentionally brought about. Usually, to be considered damage, these changes must adversely affect the current or future performance of the system (Doebling et al. 1998, Inman et al. 2005). By monitoring the response of sensors placed on a structure over a period of time, insight can be gained into the condition of the structure. In contrast to SHM methods, nondestructive evaluation (NDE) techniques, such as liquid penetrant inspection, magnetic inspection, eddy-current inspection, radiography, or ultrasonic inspection, are performed while the system of interest is inoperable (Doherty 1987). While SHM systems are being developed for permanent, real-time damage detection for a variety of applications, NDE techniques generally require the structure to be taken out of service or a technician to carefully inspect the area in question.

Adding more complex analysis to the structural health monitoring procedure, damage prognosis is the near-real-time prediction of the remaining useful life in an engineering system based upon the measurement and assessment of its current damaged (or aged) state and the accompanying predicted performance in anticipated future loading environments (Inman et al. 2005). Damage prognosis and damage mitigation are a natural extension to structural health monitoring and can be viewed as the next steps to developing an autonomous SHM system.
Damage problems, in increasing order of difficulty, are defined and categorized in the following list. Rytter (1993) defined the first four problems, and Inman (2001) added the final three.

1. Determining the existence of damage
2. Determining the existence and location of damage
3. Determining the existence, location, and characterization (quantification) of damage
4. All of the above and predicting the future behavior under various loads (Damage Prognosis)
5. All of the above and mitigating the effects of damage (Self-Healing Structures)
6. Combine problems 1, 2, 3, or 4 with smart materials to form Self-Diagnosing Structures
7. Simultaneous structural control and damage detection

In each of these steps, autonomous systems will play a large role in real world solutions to these problems. In the context of this dissertation, an autonomous structural health monitoring system is an integrated, self-contained, self-powered system which includes each of the following key components: local computing and memory at the sensor location, power harvesting from ambient vibration and temperature gradients, a battery or capacitor charging circuit, active sensors, and wireless transmissions. These elements should be autonomous, self-contained, and unobtrusive compared to the system being monitored.

Autonomous structural health monitoring falls into the larger scheme of autonomic structures, which are multifunctional materials with the ability to provide advanced decision making, react to various conditions, and possibly even morph into different configurations. One example of autonomic structures is self-healing composites with the ability to repair cracking due to impact or mechanical or thermal fatigue (White et al. 2001). A microencapsulated healing agent contained in the composite is released when it encounters a crack intrusion. The healing agent then flows into the crack and polymerizes, with contact from an embedded catalyst, to repair the damage. Self-healing bolted-joints are another example of autonomic structure (Peairs et al. 2004c). Using the impedance method for structural health monitoring, the loosening of bolt preload can be autonomously detected. A shape memory alloy (SMA) actuator is added to the joint in the form of a washer between the nut and structure. Once the loss of bolt preload is detected, the SMA actuator is automatically heated causing the washer to expand and
bolt tension to be restored. In this second example, as well as many others, autonomous local computing is a necessity for allowing the structure to anticipate future loading conditions and react to adverse or unpredicted events to restore material functionality. Part of this local computing is structural health monitoring for damage detection and localization, as well as damage prognosis for predicting the future life of a structure.

Many different aspects of a complete structural health monitoring system must be investigated before such a project can be confidently employed. Spencer and Nagayama (2006) summarize many of the current limitations and research gaps in trying to install such a system distributed over a large structure. These problems are broken into topics covering the sensor network as a whole, the individual sensor nodes, and the algorithms contained in each of these sensor nodes. However, once a SHM system is in place, continuous or routine interrogation of the desired structure should yield valuable information into the current state of operation for the configuration.

An interesting challenge for SHM systems is differentiating between actual damage to the structure being monitored and decreasing functionality of the sensors used to inspect for structural variations. Any changes in the sensors may inadvertently be revealed as structural damage by an automated analysis for defects, when, in actuality, the structure is unharmed. Methods for distinguishing between structural damage and sensor degradation should exist in any SHM device.

For different types of damage mechanisms, damage diagnosis algorithms in health monitoring systems may reveal different levels of change from an original state due to structural faults. For this reason, the sensitivity of the sensor and detections algorithms to various kinds of damage should be known. The operator must know what type of signal to expect for a specific varieties and amplitudes of damage. Without some sort of system calibration, the SHM output signal may indicate little or no damage for a very significant change in the structural condition.

Each individual component of a SHM system, hardware, sensors, and even software, will have to undergo extensive laboratory testing before it can be used in a critical application. After the fabrication of the complete system, experimentation must be performed to ensure the hardware and damage indication results are not adversely affected by any harsh environmental conditions. A mature SHM system has the potential to be fully integrated into the operational hardware of a host structure. If a defect is sensed, the system should have the intelligence to
determine what the best course of action should be. The decision might be as drastic as completely shutting down the entire assembly, or simply proceeding with caution until the area can be inspected.

1.2 Motivation

On May 23, 2004, after only a year of operation and 30 months after construction, the vaulted roof on the newest terminal of Paris’ Charles de Gaulle airport collapsed, killing 4 people inside (Reina 2004). The new $900 million Terminal 2E was a tube-like structure made of concrete. To increase the tube’s strength in bending, steel beams curved around the concrete shell and were affixed to the shell with steel struts. After the collapse, some of the steel struts connecting the external steel frame had punctured the concrete shell. Apparently, the concrete slowly deteriorated over time due to creep and thermal expansion, and when, the struts perforated the concrete, the whole structure collapsed in flexure.

In a 2002 report, the Federal Highway Administration stated that 5 percent of the United States’ Interstate bridges are structurally deficient, while 16 percent are functionally obsolete (Siggerud). Structurally deficient bridges are defined as bridges which may have vehicle weight restrictions or may need to be completely closed for repairs before being reopened. Functionally obsolete bridges may be structurally sound, but do not match the conditions of the surrounding interstate. As the class of road decreases from Interstate, the percentages of deficient or obsolete bridges increase.

Pyles (2003) reports that, unlike in previous generations, the US Air Force can no longer rely on the retirement of aircraft to decrease maintenance costs. Many of the aircraft in operation have been extended well beyond their designed service life. In addition, the capital required to train maintenance technicians and acquire the proper materials is perpetually increasing. Finally, it may take 20 to 35 years, including the lead times for production, to fully replace a fleet of aging aircraft.

These are only three of the many examples where an effective structural health monitoring system could decrease maintenance costs and downtime. With a SHM system installed on aging aircraft, scheduled maintenance could be reduced to a minimum, or only be performed when the monitoring system indicates cause for inspection. Bridges can be
continuously monitored for defects, and damage can be repaired in insipient stages before the bridges are deemed structurally deficient. Monitoring the integrity of buildings can prevent unnecessary catastrophes leading to loss of human life, or simply hasten post-earthquake inspections. Most importantly, the safety of the people operating or occupying structures with SHM systems will be significantly improved.

1.3 Literature Review

The purpose of this literature review is to summarize research previously conducted in the area of wireless structural health monitoring systems. Focus will be mainly limited to systems which provide local computing and decision making capabilities. General SHM hardware with wireless capabilities will first be discussed. A few hardware systems specific to the impedance method have been developed and will be summarized, along with a brief introduction to the impedance technique. Finally, autonomous health monitoring systems with self-powering capabilities will be discussed.

1.3.1 Wireless Structural Health Monitoring Systems

In a laboratory setting, most researchers are simply concerned with proving the validity of a structural health monitoring system. For implementation of SHM in a field setting, some large challenges must be overcome. Processing and transmitting data may require expensive hardware. Also, connecting sensors, processors, and other hardware can include complex wiring configurations (Sohn et al. 2003). To provide a solution to these challenges, the use of wireless sensors and networks are becoming increasingly popular as a research topic for structural health monitoring (Sohn et al. 2003, Spencer et al. 2004, Lynch and Loh 2005). In a review of smart sensing technology for civil applications, smart sensors are defined as sensors which contain an onboard microprocessor, giving the system intelligence capabilities (Spencer et al. 2004). However, with this general definition, many of the systems presented in the review simply acquire data from a structure and wirelessly pass this unprocessed information along for analysis at a later time. Besides civil infrastructure, many wireless sensors and sensor networks are also
being developed for other structures such as aircraft and ships, and extensive reviews can be found in (Lynch and Loh 2005).

Kiremidjian et al. (1997) presented one of the earliest efforts in developing a wireless health monitoring systems for civil infrastructure. Their proposed system included sensing and microprocessing, data acquisition and data transmission, as well as damage diagnostics methods. The authors noted before a system had even been built that battery powered devices would require a low power dissipation to operate and discussed various wireless methods to achieve the desired power level. A number of damage detection schemes were also proposed to find various levels of structural damage at different locations.

Sohn et al. (2003) reviewed some of the early propositions for including wireless transmissions into SHM systems. Many efforts in designing a wireless based system components are described. A cluster of wirelessly connected prototypes was constructed to introduce the architecture needed for communication between individual sensors and a central processing unit (Mitchell et al. 2000). At each cluster node, a microprocessor can analyze the sensor signal or simply pass it on to the host PC. However, this is the only research reviewed that has the capability for local data processing. The rest of the projects simply describe a means to acquire data on a structure and wirelessly transmit the data somewhere else for processing. Different transmission methods and their advantages are discussed, but computing still must be done at a host computer. Wirelessly transmitting unprocessed data is generally inefficient compared with computing results locally and transmitting only the results.

A network of sensors is used by Basheer et al. (2003) to detect strain in a structural application. Each sensor has the ability to process raw strain data using neighboring sensors and transmit the resulting information to an end user. The smart sensor note prototype, called ISC-iBlue, consists of an ARM7TDMI microprocessor, a Phillips Blueberry Bluetooth communications module, a multi-channel analog-to-digital converter (ADC), and a rechargeable battery. The focus of this work was to determine the communications necessary for a self organizing wireless sensor network with master and slave nodes. No experimentation is shown which measures strain and processes data; rather, an algorithm is introduced to achieve a tree network of sensors with self routing capability. The node and communications development here should lead to a SHM system which performs complex feature extraction, with wavelet
analysis or other methods, in conjunction with its neighboring sensors to accurately detect faults in structures.

Tanner et al. (2003) demonstrate local processing capabilities with off the shelf components in a wireless SHM system. A Mote, developed at the University of California, Berkeley, from Crossbow Inc. is used as the wireless sensing system. The Mote consists of two circuit boards. One board holds a microprocessor, ADC, and wireless transmitter, and the other is a sensor board containing two microelectromechanical system (MEMS) accelerometers. The bandwidth of the accelerometers was increased to 1 kHz from its original board settings of 50 Hz, and the microprocessor can sample eight channels at 4 kHz, but only by sequential multiplexing (the sampling rate is divided by the number of channels being used). A Mote can be powered by two standard AA batteries. To detect damage on the structure using the Mote platform, a simple statistical process control, based on the cross-correlation coefficient of the two accelerometers, is programmed in C and downloaded to the board. The structure being tested consisted of two aluminum plates, on top and bottom, connected with aluminum columns, steel angles, and steel bolts. One of the bolts incorporates a PZT ring actuator to modify the bolt preload.

After control limits have been determined for the structure, the Mote platform, with its embedded detection algorithm, can detect the loosening of the bolt preload. As the bolt is loosened, a yellow LED will flash indicating an outlier to the limits. The data is then processed, and if failure of the joint is determined, a red LED will be illuminated. A green LED flashes if the system is healthy or the preload is restored. Major limitations are pointed out by Tanner et al. in using the Mote platform. Sensing resolution and range are limited by the 10 bit ADC and low frequency bandwidth respectively. Making simultaneous measurements on different channels for feature extraction is difficult due to the low sampling rate. The flash memory of the system is small and does not allow for complex programming with floating-point calculations, and data cannot be stored with the small amount of RAM. Overall, the system is not able to resolve high frequencies, where much of the damage would be detected. It should also be noted that the SHM system does not produce its own actuation signal and relies on input from a shaker.

A wireless active sensing unit to monitor civil structures has been designed by Lynch et al. (2004a). The sensing unit is constructed of off-the-shelf components and has the ability to command active sensors and actuators. A computational core is combined with wireless
transmission and sensing circuits to allow for control of actuation and sensing, implementation of algorithms to process the acquired data, and broadcasting of the structural status. To control the overall operation of the entire unit, a Motorola PowerPC MPC555 microcontroller is used as the core. The MPC555 has 32-bit architecture and allows for embedded algorithms with floating point calculations. 512 Kbytes of external random access memory is used to store sensor data. When in service, the MPC555 can sample 32 channels at sampling rates up to 40 kHz. To provide an actuation signal of -5 Volts to +5 Volts at up to 40 kHz, a Texas Instruments DAC7624 digital-to-analog converter (DAC) is combined with an Analog Devices AD620 amplifier. Wireless radio communications are integrated into the system with a MaxStream XCite radio. All of the components and software are designed with power efficiency in mind and can be powered with a lithium battery pack.

To demonstrate the capabilities of the wireless active sensing unit, two piezoelectric patches are mounted onto an aluminum plate. One patch is actuated with the system to excite the aluminum bar with acoustic surface waves. The second pad acts as the sensor to measure the received waves. An ARX time-series model of the input-output data is generated with the embedded algorithms in the core. This ARX model will be used to detect damage in a structure by observing the shifting of transfer function poles. Lynch et al. (2004b) provide a step-by-step energy analysis for calculating the ARX time-series modeling of a 4000 point time-history record in a previous system with less efficient wireless transmitters and the requirement of communicating with a centralized server. Recently, Wang et al. (2007) extended the hardware’s capabilities to include real-time feedback structural control for bridges, buildings, and other structures.

Sazonov et al. (2004) also design a system to monitor civil infrastructure. Their Wireless Intelligent Sensor and Actuator Network (WISAN) detects bridge defects based on the method of modal strain energy. The WIMSS claims to consume less power, 67 mJ, for the same amount of data as the 3 J of the Lynch et al. (2004) system. However, this figure does not include the power required for computation as the WISAN doses not perform any local (at the sensor) data processing, but simply transmits the data to a node with a permanent power supply for computations. The Sazonov et al. system also does not utilize active sensing, so no power is consumed providing an actuation signal. Rather, WISAN relies on ambient energy provided by the bridge for structural excitation.
1.3.2 Impedance-based Structural Health Monitoring Systems

Impedance-based health monitoring techniques utilize small, self-sensing piezoelectric patches bonded to a structure to simultaneously excite the structure with high-frequency excitations and monitor changes in the patch electrical impedance signature (Park et al. 2003). Since the piezoelectric is attached directly to the structure of interest, it has been shown that the mechanical impedance of the structure is directly correlated with the electrical impedance of the patch (Liang et al. 1994a, 1994b). Thus, by observing the electrical impedance of the piezoelectric, assessments can be made about the integrity of the mechanical structure.

Using the impedance method, damage has been successfully detected on a variety of structures from simple beams and plates to bridge truss structures, airplane composite patch repairs, and pipeline structures (Park et al. 2003). Different damage mechanisms detected in these structures include cracking, bolt loosening, composite delaminations, and more. As shown in Chapter 3 of this dissertation and in other publications, a great deal of emphasis has been placed on using the impedance method for aerospace related structures (Peairs et al. 2004a). One study was able to detect damage on the bolted connections that hold the Environmental Control Chamber onto the Orbiter Access Arm of launch pad 39-B at NASA Kennedy Space Center. As the bolts holding the “white room” to the Orbiter Access Arm were loosened, the impedance technique identified each progressive loss of bolt preload (Peairs et al. 2004a).

Traditionally, the impedance method requires the use of an impedance analyzer, which is used to measure and analyze impedance in electrical components and systems. Impedance analyzers generally provide precise electrical impedance (as well as capacitance, inductance, resistance, etc.) measurements over broad frequency ranges with extensive functionality and display options. Due to their high performance intended for electronics quality control, design, and other tasks, such analyzers are bulky, expensive, and not suited for permanent placement on a structure. With the current trend of structural health monitoring heading towards unobtrusive self-contained sensors, the first steps in meeting the low power requirements resulted in the MEMS-Augmented Structural Sensor (MASSpatch) (Grisso 2004, Grisso et al. 2005a).

Giurgiutiu and Xu (2004) designed and tested a field portable impedance measurement device using standard laboratory equipment. A PC operating a LabVIEW program is connected to a function generator through a GPIB card. The function generator excites the structure being
tested, and a PCI DAQ card records the excitation signal and structural response. Both signals are fed into the LabVIEW program for analysis. Three separate data analysis methods, integration, correlation, and the Discrete Fourier Transform (DFT), were testing to obtain the impedance of the host structure, with the DFT method providing the closest results to those of an impedance analyzer. The method still requires both a computer and function generator, and is therefore not well suited for permanent field placement. No damage detection algorithm was included with the programming.

Extending their initial work with the computer, function generator, and DAQ card, Xu and Giurgiutiu (2006) developed a digital signal processor (DSP) based impedance analyzer system. The DSP prototype consists of a Texas Instruments CC6416T DSK board along with a Signalware AED101 analog daughter card. An operational frequency of 1 GHz is seen for the DSP on the DSK board, and the daughter card provides two channels each of analog-to-digital converters (ADC) and digital-to-analog converters (DAC), with sampling up to 80 MHz. A 50 kHz – 1.5 MHz band-pass filter is incorporated into the DAC output. A frequency by frequency approach is compared with a broadband excitation and transfer function scheme for impedance measurements. The frequency by frequency approach provides very accurate results, but for the purpose of simplified impedance hardware, the authors determine that the transfer function method is appropriate for field hardware due to its time efficiency and implementation ease. A plate structure with damage is used to compare the PC-based hardware with an impedance analyzer. The hardware showed similar results to that of the impedance analyzer, however, no damage detection algorithm appears to be programmed into either PC or DSP systems. No power analysis details are provided.

Analog Devices has recently introduced impedance measurement devices in chip format. The AD5933 chip has a 1 MHz sampling rate, can measure electrical impedance up to 100 kHz, and also comes in an evaluation board format. An impedance-based health monitoring prototype named the Wireless Impedance Device (WID 1) has been developed using the AD5933 evaluation board, an Atmel ATmega128L microprocessor, and Xbee radios for wireless communications (Mascarenas et al. 2006a). Using the microprocessor to control the evaluation board, bolt loosening was detected in a frame structure.

Overly et al. (2007a) introduced the next version of the WID (1.5) by incorporating the AD5933 impedance chip into a custom printed circuit board (PCB) design. Included on the PCB
board along with the AD5933 are an Atmel ATmega128L microprocessor as the computational core, an aerogel supercapacitor from Cooper Bussmann to provide a low current power source, and an XBee RF Module from MaxStream for wireless data communication. The WID 1.5 accurately measures real impedance, imaginary admittance, and impedance magnitude as compared with an impedance analyzer. At the devices maximum operational current draw (acquiring data with the wireless transmitter turned on), the WID draws 68 mA. The circuit requires 2.8 V to excite the structure, record the response, and transmit the data, so the power required is 190 mW.

The WID 2.0 is an upgrade over the previous two WID devices (Overly et al. 2007c). Again, a custom PCB is designed around an AD5933 impedance chip. A different microcontroller, the ATmega 1281 from Atmel, is used to operate the chip. To improve power dissipation, the Atmel AT86RF230 is included as a wireless telemetry device. To allow the system to remain in sleep mode for extended periods of time, two triggering options are implemented. A low frequency wake up chip monitors an inductor of a magnetically coupled signal, and a real time clock can turn the WID on at intervals ranging from a second to a year. Two multiplexers are included to allow the system to measure up to seven different sensors. Again, measurements taken with the WID 2.0 compare favorably to that of an impedance analyzer. Current draw is reduced to 22 mA for transmitting the data and 20 mA for measurements at 2.8 V, for a maximum power dissipation of 62 mW. However, no data analysis is performed at the sensor location. All measured data is wirelessly transmitted to a different computer for data for analysis and damage detection.

In contrast, MASSpatch is a single board computer system which interrogates a structure utilizing a self-sensing actuator and a low cost impedance method, and all the structural interrogation and data analysis is performed in near real time at the sensor location (Grisso 2004, Grisso et al. 2005a). Wireless transmissions alert the end user to any harmful changes in the structure. In the MASSpatch prototype, the computing core triggers an external function generator to provide a swept sine excitation signal. After recording the applied excitation signal and the response provided by a low cost circuit, the data is transformed to the frequency domain. By comparing any new impedance measurements in the frequency domain to a stored baseline, system changes can be discerned, and wireless telemetry alerts an end user to the presence of damage.
Unfortunately, there are some limitations with the MASSpatch prototype. The algorithm, written in C, to perform the impedance method was utilized as an executable in the DOS operating system. When using an operating system, much of the processing power is used to run the actual system, in addition to the algorithm. Determining how much energy is used for computing the actual algorithm is difficult. Also, a DAC was never fully incorporated into the system, and reliance on an external function generator was needed for structural excitation. A voltage controlled oscillator was constructed for the actuation of this prototype, but the period of the swept sine signal generated was too long. The development of the hardware discussed in this dissertation began before this issue was resolved. In Chapter 2, the development of an impedance-based prototype operating off of a digital signal processor platform will be introduced.

1.3.3 Autonomous Structural Health Monitoring Systems

Unlike any of the wireless structural health monitoring systems previously discussed, autonomous hardware has the added advantage of being completely self-contained and self-powered. With the recent advances in power harvesting research and technology, as well as the increased performance with reduced power dissipation of health monitoring hardware, it is possible to develop a system operating solely off of ambient energy available in the monitored structure or surrounding environment. The energy obtained through harvesting could be stored for later use or used to directly supply operational power to the hardware. Thus, the added maintenance tasks of replacing batteries or providing a constant source of power for detection systems are avoided. Chapter 4 of this dissertation will provide an example of autonomous damage detection for an impedance-based monitoring system.

A remote autonomous system for monitoring bolted joint preload has been developed by Todd et al. (2007). Using unmanned aerial vehicles (UAV) dispatched to individual sensor systems, sensor nodes are both wirelessly supplied power and interrogated for structural damage results. The wireless sensor node detecting peak displacement and bolt preload is known as THINNER (Mascarenas et al. 2007). Components in THINNER are an Atmel ATmega 128L microcontroller, an Analog Devices AD7745 capacitance to digital converter, and an XBee wireless radio. Two capacitive sensors are included with the node: a peak displacement sensor
and a bolted joint preload sensor. The preload sensor is placed on a bolt like a normal washer, and the capacitance of the sensor changes with the bolt preload.

To charge the THINNER sensor node, 10 GHz X-band wireless power transmissions are utilized (Mascarenas et al. 2006b). X-band radiation is transmitted to the sensor location from an antenna on the UAV. The received power is used to charge up a 0.1 F supercapacitor until there is enough energy to operate the Xbee radio. Peak displacement and bolt preload data are then transmitted. Future efforts will look to combine local energy harvesting along with the deliverable RF energy.

Guyomar et al. (2007) developed an autonomous wireless transmitter (AWT) for use in Lamb wave-based health monitoring. The goal of the research is to develop an autonomous SHM system without the use of batteries. Piezoelectric microgenerators using a synchronized switch harvesting (SSH) energy harvesting module should provide enough power for the AWT to generate a Lamb wave excitation signal (a series of square pulse waves) and a RF location identifier signal. The AWT configuration consists of a Microchip PIC16F688 microcontroller, the SSH module, a storage capacitor, and a RF transmitter. Two piezoelectric patches are attached to the AWT. The first patch is used as an ambient vibration energy harvester and is connected to the SSH module, which charges the capacitor. The second patch is connected to the digital output of the PIC through a driver and is used to generate the Lamb wave pulse. When the AWT is in standby mode, the SSH module is used to charge the capacitor. Once the energy necessary to wake up the PIC, broadcast an RF signal, and generate a Lamb wave pulse is stored in the capacitor (about 5 mJ), a threshold detector wakes up the PIC. In experiments on a cantilevered beam excited by an electromagnet, the AWT and piezoelectric patches at the base of the beam harvested the vibrational energy of the beam and sent a pulse through the beam to another piezoelectric patch on the free end of the beam. Signals recorded from the patch on the free end of the beam were analyzed to detect damage as small as 0.2 mm deep by 10 mm wide circular notches in the beam.

Expanding on the AWT work, Lallart et al. (2007) introduced autonomous wireless receivers (AWR) to record the guided waves generated by AWTs. AWR components include a PIC microcontroller, RF receivers and transmitters, a SSH module, a storage capacitor, a True-RMC integrated circuit, an amplifier, and a connected piezoelectric patch for energy harvesting. Similar to the AWT, the AWR waits in standby mode until enough energy is harvested for
operation. Once the energy threshold is reached, the RF receiver in the AWR is activated to monitor RF location transmissions from an AWT. If a RF signal is received, the microcontroller activates the remaining components of the AWR. The Lamb waves generated by the AWT are recorded, and the True-RMS IC computes an estimation of damage in the structure. The amplifier and True-RMS IC are then placed into sleep mode, and the RF transmitter broadcasts a location signal and the damage results. Once the broadcast the complete, the whole system is shut down and placed into standby/energy harvesting mode until the process repeats. A clamped-clamped beam experiment with an AWT on one end and an AWR on the other successfully identified increasing amounts of putty in between the systems. The RF locator signals from the AWT and AWR, as well as the damage index signal from the AWR, will eventually be used by a base station to estimate damage locations and magnitudes.

1.4 Dissertation Overview

1.4.1 Research Objectives

The focus of the research presented in this dissertation is to advance the progress of autonomous structural health monitoring. Specifically, topics on improving the impedance method for SHM will be addressed. A new hardware system based on the impedance method is developed and discussed. Efforts are also made to develop a completely autonomous impedance device through means of energy harvesting. The sensitivity of the impedance method is defined for complex thermal protection systems. A method of determining sensor failure from structural damage at elevated temperatures is also included. The ultimate goal of this research is to develop a completely self-contained autonomous sensor patch which can be adapted to monitor the integrity of any structure. One of the major road blocks in the advancement of autonomous SHM devices is bringing the power requirements down to a level compatible with the output of energy harvesting systems.
1.4.2 Chapter Summaries

As discussed in the literature review, a single board computer system named MASSpatch was developed as the first step towards an impedance-based chip system. In Chapter 2, a digital signal processor is used as the main component for an improved impedance hardware system. All the data processing, storage, and analysis of results are performed at the sensor location. A wireless transmitter is used to communicate the current status of the structure. With this new low cost, field deployable impedance analyzer, reliance on traditional expensive, bulky, and power consuming impedance analyzers is no longer necessary. Early work on the development of this system is detailed in (Grisso et al. 2005b).

Thermal protection systems on aerospace vehicles present a complex structure for damage detection. Due to the extreme safety importance of protection systems and the environment in which they operate, potential sensor locations for damage detection are non-ideal. Chapter 3 will introduce experimental results for sensitivity testing of the impedance method to the damage mechanisms of protections systems. A representative thermal protection system structure is constructed, and experiments are carried out over a large temperature range. Details of this work are also presented in (Grisso et al. 2006).

Chapter 4 provides the first attempts at providing a completely autonomous impedance-based SHM prototype. An all digital signal processor based prototype is introduced. This hardware employs digital output to generate a rectangular excitation pulse train for structural excitation, and receives a digital input to sense the structural response. The DC power supply to this hardware is replaced with standard nickel metal hydride and lithium ion batteries, and all power required to perform all the autonomous impedance-based SHM operations is supplied from the batteries. The batteries are recharged using only a thermoelectric generator across a temperature gradient, with the appropriate harvesting circuitry, to make the system completely autonomous. Early results from this research are described in (Grisso et al. 2007).

Health monitoring systems may continue to be reduced in size and power requirements while increasing in accuracy, but any system may still be plagued with false positive indications of damage if the sensors used for structural investigation are damaged. Sensor diagnostics allows for the separation of structural damage from sensor damage. However, sensor diagnostics techniques are sensitive to thermal changes. In Chapter 5, a technique is developed to accurately
provide sensor diagnostics at any temperature. The model developed is accurate and easy to implement on any health monitoring hardware.

Chapter 6 attempts to adapt impedance-based sensor diagnostics techniques to the digital damage detection system described in Chapter 4. The digital hardware is used to decrease form factor and power requirements, however the lack of analog data provides a challenge for implementing the standard sensor diagnostics techniques. A simple method for detecting sensor damage is presented, and experiments reveal the initial results of an all digital sensor diagnostics technique. The first attempts with this new method can be found in (Grisso et al. 2008).

The final chapter provides a brief overview of all the research results presented in this dissertation. An outline of the specific contributions this dissertation makes to the field of autonomous structural health monitoring is provided. Recommendations for future work to extend the discussed contributions are detailed at the end of the chapter.
Chapter 2: DSP-based SHM Hardware for the Impedance Method

2.1 Introduction

Currently, nondestructive evaluation techniques are used to assess the condition of many structures while they are off-line. An autonomous impedance-based system would have the ability to directly detect damage by analyzing variations the electrical impedance of self-actuating sensors bonded to the structure. The developed prototype should deploy autonomous, wireless, self-powered sensors that harvest energy from ambient vibration and thermal gradients while the host structure is in operation. In order to prevent single points of failure, each sensor is self-contained and operates independently from other sensors, but also has the ability to function in a network. The following work describes the initial steps at achieving such a wireless system.

2.1.1 Low Cost Impedance Method

Due to the size and power limitations of using an impedance analyzer for permanent structural health monitoring purposes, a method has been developed to avoid reliance on such analyzers (Peairs et al. 2004b). A low cost impedance technique has been introduced as a first step in achieving a smaller, inexpensive impedance analyzer. This low cost method requires only a sensing circuit, consisting of a resistor, and a standard FFT analyzer. By placing the sensor in series with the piezoelectric, the circuit is simply a voltage divider. The output voltage across the sensing resistor is proportional to the current through the resistor. The current through the resistor, for a low resistance, is close to the current through the piezoelectric as if the circuit
were not there. Taking the ratio of the applied voltage and resulting current, the impedance can be determined.

Using a low cost impedance method, the impedance analyzer’s weight, size, and power are taken out of the equation. However, some form of FFT analyzer must still be used, and data must be processed externally to determine whether changes in the structure have occurred. FFT analyzers can still potentially be large and expensive, so this project extends the concept of a low cost circuit by presuming that the functions of a FFT analyzer, as well as the required analysis, can all be performed on a single chip. With everything contained on a single chip, a sensor utilizing the impedance method for damage detection could be inexpensive and small enough for permanent deployment.

2.2 Hardware Development

To implement the impedance-based structural health monitoring method in a field deployable setup, hardware is assembled as shown in Figure 2.1. Using the low cost technique, accurate approximations of the structural impedance can be determined without complex and expensive external electronic analyzers. As shown in Figure 2.1 and Figure 2.2, all of the hardware needed to utilize the impedance method is condensed into a single stacked board configuration. This prototype is designed to function similarly to MASSpatch with key improvements in sampling frequency and integrated actuation. A description of each of the components to enable these upgrades follows.

![Figure 2.1. A diagram of the prototype hardware configuration is shown.](image-url)
This impedance-based prototype is based on a TMS320C6713 DSK evaluation digital signal processor (DSP) module from Texas Instruments (Texas Instruments 2005b). The DSP has an internal system clock speed of 225 MHz, 192 kB of internal memory, and external synchronous dynamic random access memory (SDRAM) of 16 MB. With a large amount of external memory, the memory space is partitioned into two major sections: samples for digital-to-analog converter (DAC) output, and samples from the analog-to-digital converter (ADC). As shown in Figure 2.1, the ADC, DAC, and SDRAM all share an external memory interface (EMIF). The DSP controls the ADC by means of a multi-channel buffered serial port (McBSP) acting in general purpose input output (GPIO) mode.

Two more evaluation boards from Texas Instruments are used as the ADC and DAC. The ADS8364 EVM ADC board has six channels of input and a 250 kHz sampling rate (Texas Instruments 2002). Conversion resolution for the ADC board is 16 bits. For the DAC, a TLV5619-5639 EVM board is used with a 5639 DAC (Texas Instruments 2001). The DAC
The evaluation board has two outputs and a maximum sampling rate of 1 MHz at 12 bit resolution. The physical orientation of the DSP kit, ADC, and DAC can be seen in Figure 2.2.

The wireless transmitter and receiver are used to indicate the current state of damage for the structure of interest. The transmitter sends a quantified amount of damage, and the receiver displays this value on a host computer. The current prototype uses Radiometrix RX2M-458-5 and TX2M-458-5 wireless sensors as the receiver and transmitter (Radiometrix Ltd. 2005). The hardware component specifications and dimensions are summarized in Table 2.1.

Table 2.1. Specifications are displayed for the prototype.

<table>
<thead>
<tr>
<th>Processing/Programming</th>
<th>Sensing/Sampling</th>
<th>Wireless Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Processor</strong></td>
<td><strong>ADC Resolution</strong></td>
<td><strong>Usable Range</strong></td>
</tr>
<tr>
<td>TMS320C6713 225 MHz Floating Point DSP</td>
<td>16 bit</td>
<td>over 1 km</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal Memory</th>
<th>Max Sampling Frequency</th>
<th>Sensor Types and Ranges</th>
<th>Data Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>192 Kb</td>
<td>250 kHz per channel 750 KHz paired</td>
<td>6 Analog at up to +10 to -10 V</td>
<td>5 kbps</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>External Memory</th>
<th>Internal Memory</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 MB SDRAM</td>
<td>192 Kb</td>
<td>DSP Board 22 x 11.5 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Actuation</th>
<th>DAC Resolution</th>
<th>Max Sampling Frequency</th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 bit</td>
<td>1 MHz</td>
<td>2 up to 4 V</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>DSP Board</th>
<th>DAC Board</th>
<th>ADC Board</th>
<th>Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 x 11.5 cm</td>
<td>13.5 x 8.5 cm</td>
<td>10 x 8.5 cm</td>
<td>4.5 cm</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Impedance Structural Health Monitoring Algorithm

As previously mentioned, when a piezoelectric material is bonded to a structure, the electrical impedance of the piezoelectric is directly related to the mechanical impedance of the structure. Therefore, by monitoring the electrical impedance of the piezoelectric, changes in the structure’s mass, stiffness, or damping can be observed. Usually, an impedance analyzer is used to acquire data, and analysis is performed independently of data acquisition.

The operational flow of the current prototype allows structural health monitoring to be performed all with one piece of hardware. The DSP board controls the entire operation. An
excitation signal is sent from the DAC board simultaneously to the ADC board and the structure of interest. The ADC reads both the voltage signals from the DAC and the voltage across the sensing resistor (seen in the bottom of Figure 2.2) of the low-cost impedance circuit concurrently. After ten excitation cycles, the signals are averaged, a FFT is performed, and one impedance measurement is generated. The first two measurements generated are baseline impedance curves. Once the baseline is stored, each measurement is compared with the baseline to determine whether there is damage in the structure by means of a damage metric. The algorithm allows for the specification of a threshold damage value. If the threshold damage value, as indicated by the damage metric, is exceeded, the wireless transmitter is activated. This signal is recognized by a wireless receiver across the room (up to 1 km away outdoors), and a LED is turned on to indicate damage. Once the damage metric drops below the threshold value, the transmitter, and thus the LED, is turned off to indicate no damage to the system.

Impedance signatures are, in general terms, simply frequency response functions (FRF). Impedance signatures have the general appearance of FRFs, as seen in Figure 2.5. The main difference is that the input to the sensor is voltage, and the resulting current is the output. By monitoring the changes in the peaks of these FRFs, and simple damage algorithm can be used to quantify the amount of change in the peaks, which yields the amount of damage in the structure. In this case, a variation of the root mean square deviation is used as the damage metric (Park et al. 2003). The root mean square deviation is used as a way to express the difference between two curves as a single number. A higher numeric value indicates more disparity between the curves and, in this case, greater damage in the structure.

In order to excite the structure of interest, it was decided to use sine cardinal, or simply sinc, functions as the DAC output. The sinc function has the unique property in that its Fourier Transform is a box. Having a uniform value in the frequency domain allows for a band of frequency content in one pulse. The sinc function is based on a fundamental frequency and then frequencies which build upon the fundamental, as shown in Figure 2.3. By slightly altering the fundamental frequency each time a pulse is sent out, the averaged spectrum is even smoother. The sinc function is described as (Schilling and Harris 2005)

\[
sinc = \frac{\sin(x)}{x}
\]  

(2.1)
By using a sinc function instead of exciting the structure with discrete frequencies, more frequencies can be excited in the same amount of time. The auto spectrum of the output signal will also be a straight over all the frequencies excited. Other advantages of the sinc function include needing less memory space and less traffic in the external interface (compared with a frequency sweep), as well as lower power consumption in the DSP, ADC, and DAC.

\[f_1\]
\[f_2\]
\[f_m\]

**Figure 2.3.** A diagram showing the sinc function (on the right) and how the function is built.

### 2.4 Power Analysis

Currently, the prototype runs off of DC power supplies. In a permanent setting, the sensing system will operate off of battery power recharged by harvested ambient energy. To optimize the battery life and minimize the required maintenance schedule, both piezoelectric and thermal based power harvesting can be utilized to recharge batteries. Piezoelectric materials have the unique property of being able to transform mechanical strain into an electric charge. By using this property, piezoelectrics can harvest energy by using a systems own ambient motion, transform this mechanical kinetic energy into electrical potential, and store the electrical energy, power devices, or recharge a battery using power harvesting circuitry (Sodano et al. 2003).

In order to prepare the hardware to be completely run off of a battery and power harvesting, a complete power analysis is done of the current system. In the prototype, the DSP board supplies power to the DAC board, and the DAC supplies power to the wireless transmitter. Due to the connectivity of these systems, the power consumption of the DAC and transmitter
cannot be exactly determined. However, the DAC and wireless power dissipations can be estimated. According to specifications, the maximum current the transmitter consumes is 100 mA at 5 V$_{DC}$, or 0.5 W (Radiometrix Ltd. 2005). The transmitter is being supplied with 3.3 V$_{DC}$, and is only sending out a low power signal, so 0.33 W (100 mA at 3.3 V$_{DC}$) is a high estimate. The DAC board is stated to consume 170 mA at 3.3 V$_{DC}$ and 150 mA at 5 V$_{DC}$, or a range of 0.561 W to 0.825 W (Texas Instruments 2001). In this setup, the DAC board is being operated at 5 V$_{DC}$.

The DSP board is supplied with a 5 V$_{DC}$ power supply, so the DSP, DAC, and wireless transmitter can be measured as a group. When the system is fully turned on, but the algorithm is not being performed, the DSP requires 470 mA at 5 V$_{DC}$, which is 2.35 W. While the whole impedance-based SHM operation is being performed, including wireless transmission, the current draw increases to 570 mA, giving a power of 2.85 W. So, wireless transmissions are shown not to be a significant drain on the power supply. All of these measurements are instantaneous power, but the current draw remained almost constant during a complete operational cycle.

The ADC has its own ±12 V$_{DC}$ power supply. During operation, the ADC requires 60 mA, yielding 1.44 Watts of power. So, the total amount of power required to completely perform impedance-based SHM is 4.29 W. A summary of the power analysis can be seen in Table 2.2. Comparatively, the MASSpatch prototype used around 4.5 W of power (Grisso et al. 2005a). 4.29 W does not seem like a significant reduction considering the advances in hardware and excitation efficiency, however, remember that the MASSpatch prototype relied on an external function generator to provide excitations. MASSpatch did not include its own DAC, and the function generator used was plugged into a wall outlet and consumed a considerable amount of power.

Even with 4.29 W of power, the prototype is capable of being run solely off of battery power and piezoelectric power harvesting. For instance, if this system was being continuously run for ten or more minutes (a rather excessive time), ten 1.2 V, 200 mAh capacity batteries could supply more than enough energy to the system. In actuality, the system can power on, collect data, process the result, and broadcast the damage case in under a minute. A 1 Ah capacity means that a battery will last for 1 hour if it is subjected to a discharge current of 1 A. A 200 mAh battery can be recharged to 90 percent capacity in 1.2 hours with a random vibration
signal at 0 to 500 Hz if a 6.35 x 2.375 inch piezoceramic (PZT) is used (Sodano et al. 2003). As an example, an operating space shuttle should have plenty of ambient vibration, as well as thermal gradients, to fully recharge the batteries. Chapter 4 will provide an example of a similar system being operated from thermally recharged battery power.

Table 2.2. The power consumption is displayed for all the hardware components.

<table>
<thead>
<tr>
<th>Hardware Component</th>
<th>Power Consumption (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless (estimate)</td>
<td>0.33 (max)</td>
</tr>
<tr>
<td>DAC (estimate)</td>
<td>0.825 (max)</td>
</tr>
<tr>
<td>DSP, DAC, Wireless Group</td>
<td>2.85 W during operation</td>
</tr>
<tr>
<td>ADC</td>
<td>1.44 W</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>4.29 W</strong></td>
</tr>
</tbody>
</table>

When placing an autonomous system in a permanent setting, it is important to ensure that enough energy is stored and available to complete the entire structural health monitoring procedure. That is, if the energy required by the system for operation is greater than the energy collected from power harvesting and the power previously stored in the system, the duty cycle is too short for the required application. In many systems, it would not be unrealistic to assume that checking for damage once a day is more than adequate. If the system is being recharged in one to two hours on average, one day is an acceptable duty cycle.

2.5 Experimental Validation

To validate this new hardware, the system’s capabilities are demonstrated in the laboratory. A bolted joint, as seen in Figure 2.4, is tested for the initial experiments. The bolted joint structure consists of two aluminum beams with 11.5 cm of overlap connected with four bolts. Both 4 mm thick beams are 61.5 cm long and 5 cm wide. Two rows of bolts are centered 4 and 7.5 cm from the ends of the beam and 1.5 cm in from the beam sides as shown in Figure 2.4. A 2.7 by 2.1 by 0.0267 cm type 5H4E piezoceramic from Piezo Systems, Inc. is attached to this structure; the piezoelectric acts as a self-sensing actuator. Damage is induced in the bolted joint by tightening or loosening one or more of the bolts.
2.5.1 Impedance Analyzer Testing

Using traditional impedance techniques (a HP 4194A impedance analyzer), a standard for the bolted joint experiment is generated for comparison with the new system’s results. Initial bolted joint testing shows that the impedance method readily detects damage induced by loose bolts. Only loosening one of the four bolts by a quarter turn significantly changes the impedance signature. The bolts were initially manually tightened as much as possible using wrenches. Loosening the bolt by a quarter turn does not change the tightness when hand checking the bolts; in other words, the bolts are still tight without using a wrench to turn the bolts. The actual tightness of the bolts was not the focus as much as providing a means of consistent comparison for damage cases. Figure 2.5 shows impedance curves generated using an impedance analyzer.
Figure 2.5. The baseline and damaged impedance signatures for the bolted joint are shown.

As displayed in Figure 2.5, the peaks of the impedance signature change as damage is introduced to the structure by loosening bolts. The more the structure is damaged, the more the peaks shift from the baseline. A frequency range of 10-30 kHz was selected for easy comparison to the prototype. In general, impedance measurements for structural health monitoring purposes are taken over a range of frequencies from 10 kHz to 400 kHz (Park et al. 2003). This frequency range ensures the wavelength of excitation is smaller than the size of damage to be detected. Also, at these high frequencies, the method is generally insensitive to boundary condition changes, operational vibrations, or variations like mass loading. It is also important to note that the impedance method is a local detection method, not a global method; in other words, the peaks seen in the impedance curves of Figure 2.5 are not structural natural frequencies but local modes. A variation of the Root Mean Square Deviation (RMSD) damage metric is utilized to analyze changes in these local modes and determine the amount of damage present. The RMSD method for finding the damage metric, $M$, can be described as

$$M = \sqrt{\sum_{i=1}^{n} \frac{[\text{Re}(Z_{i,1}) - \text{Re}(Z_{i,2})]^2}{[\text{Re}(Z_{i,1})]^2}},$$

(2.2)
where $Z_{i,1}$ is the baseline, or healthy, impedance of the PZT, and $Z_{i,2}$ is the impedance used for comparison with the baseline measurement at frequency interval $i$. Figure 2.6 displays this damage metric in bar chart form.

![Figure 2.6](image)

Figure 2.6. The damage metric compares the baselines and damaged curves.

For this experiment, three separate baselines were taken. One of these baselines will act as the undamaged case, or $Z_{i,1}$ curve, for each of the other values. In Figure 2.6, the first two bars, labeled “Baselines” compare the second and third baselines (healthy measurements) with the first baseline. The bars are simply the $M$ values generated by the RMSD equation. Ideally, with no variance in the system, the first two bars would be zero, meaning that all three baselines are identical. It should be noted that changes smaller than the noise in the system could potentially go unnoticed as damage. The next two bars, labeled “Bolt 1 – ¼ Turn”, compare the two impedance signatures acquired with bolt one loosened to the first baseline measurement. Looking at Figure 2.5, there is a significant difference between the baseline curve and the curve where bolt 1 is loosened a quarter turn. As expected, these differences show up as an increase in the RMSD value, which indicates damage to the end user. Similarly, the final two bars, labeled “Bolts 1 and 4 – ¼ Turn”, compare measurements taken with both bolts one and four loosened to the first baseline. Again, the RMSD value increases indicating more damage to the structure.
2.5.2 Prototype Testing

Using the same bolted joint, the prototype could be directly compared with standard impedance measurement methods. Code Composer Studio software allows for visualization of what the damage detection algorithm is doing in the DSP core (Texas Instruments 2005a). At each step in the algorithm, the real impedance measurement (as data is acquired) is displayed along with the baseline, the averaged real impedance measurement used to compare to the baseline, the original DAC sinc function output, and the ADC sampled output. The most important part of the display is the damage metric value, which is updated with each measurement to indicate how much damage is present in the structure. Impedance measurements are taken over the range of 10-32.1 kHz. Based on the sampling speed of the ADC, this frequency range is selected to allow for accurate sampling and digital representation of acquired data within the typical impedance measurement range. Also, a high density of structural modes is seen in this frequency range, ensuring that there is a good dynamic interaction between the patch and host structure and allowing for damage detection.

The auto spectrum of the output can also be displayed, as shown in Figure 2.7. As expected from a sinc function, the auto spectrum is a flat line, indicating that every frequency of interest is being excited. In Figure 2.7, it should be noted that 512 frequency components are displayed, representing 0 to 64,200 Hz. In reality, only half of the spectrum is used, so 256 frequency lines represent 0 to 32,100 Hz.

![Figure 2.7](image)

**Figure 2.7.** The auto spectrum is displayed for the sinc function.
Initially, measurements are taken with all of the bolts completely tightened. With no
damage to the structure, the baseline and damaged impedance signature should be the same. As
Figure 2.8 shows, the impedance curves for the new measurement and original baseline are
almost identical. Figure 2.8 is generated by Code Composer Studio, and allows for graphical
displays of what is actually occurring at specific memory locations in the hardware. All of the
computations are performed on the DSP, and the graphs just show the results. The damage
metric value displayed is 0.02. It should be noted that the damage metric values generated in this
experiment should not be directly compared to those given in the previous section. The
prototype here and the impedance analyzer from the previous section measure and acquire
impedance signatures with two different methods and the curve amplitudes are different. Thus,
with different impedance curve values, the generated RMSD values will also be different. A
more direct comparison between the two methods is the peak frequencies that the different
systems measure, which will be discussed in the next section.

![Figure 2.8](image)

**Figure 2.8.** The measurement with no damage to the structure is compared to the baseline.

One interesting thing to note is that the impedance signatures from Figure 2.8 and Figure
2.5 are similar. Both show a good number of peaks in similar locations over the range of 10-32.1
kHz. Also, the frequency is displayed by a frequency index, \(i\), from 0 to 256, where \(i = 256\)
corresponds to 32,100 Hz. The RMSD is then taken over the frequency indices of \(i = 79\) to 256
(or 9,906 – 32,100 Hz), even though the whole frequency range from 0 - 32,100 Hz is displayed.
Now, damage was induced on the bolted joint by loosening one of the bolts a quarter turn. This
loosening is just enough turn the bolt while still keeping the bolt tightened by hand tight
standards, but the prototype easily recognizes the difference as shown in the peak changes of the
measured impedance seen in Figure 2.9.
Comparing the two curves in Figure 2.9, the damage metric increased to 0.13. This is a 550 percent change from the original damage metric. For this experiment, the damage metric threshold value was preset to 0.10. After the bolt was loosened and RMSD values were calculated, the wireless transmitter was activated, and the LED was turned on to indicate damage. The damage metric easily indicates that the structure has changed, even for damage undetectable by hand tightening. Next, a second bolt was also loosened by one quarter of a turn. Figure 2.10 displays the difference for this damage case.

As seen in Figure 2.10, with even more damage, the peaks of the measured impedance signature show even more variation from the baseline. The damage metric also detects the change and calculates a new value of 0.21. The wireless transmitter and LED remained on, indicating the continued presence of damage. However, when both bolts were retightened to their original positions, the RMSD value decreased to near its original value, the transmitter stopped broadcasting, and the LED turned off to indicate no damage.

As previously mentioned, the threshold value for this experiment was set to a value of 0.10. This value was based on previous user knowledge of the system, which is an inherent flaw in using the non-model based impedance method. Often, the impedance method is used as an
indicator of structural damage presence and not necessarily to quantify the damage. Studies have been performed comparing the damage metric to the actual amount of damage in a system, including the torque in a bolted joint. Using a torque wrench to measure bolt tightness, different levels of damage, from a high load of 56.5 N·m down to hand tight in steps of 11.3 N·m, are clearly indicated using a damage metric (Allen et al. 2004). The loosening at each step was observed by the damage metric before an operator would have noticed with a hand check. In this study, the interest was not so much in matching the damage metric value to a specific amount of damage (calibrating the prototype to the bolted joint), but providing a repeatable experiment for validation of the new hardware. The results presented here are also comparable with an analysis performed with standard impedance measuring equipment.

### 2.5.3 Impedance Analyzer and Prototype Comparison

As another method of validating the device, frequencies displayed by both the HP 4194A impedance analyzer (Figure 2.5) and the new prototype (Figure 2.8) are directly compared. Using the impedance analyzer, data was taken in the range of 10,000 – 32,100 Hz. Table 2.3 shows a comparison between select peaks shown in both Figure 2.5 and Figure 2.8.

<table>
<thead>
<tr>
<th>HP 4194A (Hz)</th>
<th>Prototype (Hz)</th>
<th>Difference (Hz)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,663</td>
<td>10,532.9</td>
<td>130.1</td>
<td>1.22</td>
</tr>
<tr>
<td>13,094</td>
<td>13,040.8</td>
<td>53.2</td>
<td>0.41</td>
</tr>
<tr>
<td>15,580</td>
<td>15,548.6</td>
<td>31.4</td>
<td>0.20</td>
</tr>
<tr>
<td>18,011.25</td>
<td>17,931</td>
<td>80.25</td>
<td>0.45</td>
</tr>
<tr>
<td>21,215.75</td>
<td>21,191.2</td>
<td>24.55</td>
<td>0.12</td>
</tr>
<tr>
<td>21,547.25</td>
<td>21,442</td>
<td>105.25</td>
<td>0.49</td>
</tr>
<tr>
<td>26,575</td>
<td>26,457.7</td>
<td>117.3</td>
<td>0.44</td>
</tr>
<tr>
<td>28,840.25</td>
<td>28,714.7</td>
<td>125.55</td>
<td>0.44</td>
</tr>
<tr>
<td>31,897</td>
<td>31,849.5</td>
<td>47.5</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Obviously, this is only a small sampling of the frequency peaks between 10 and 32 kHz. Also, as is expected, each device is slightly more sensitive to some peaks than the other, so some peaks may be missed simply as a function of the frequency resolution. However, even when some peaks may appear to be well apart from one another, they are generally well within the
frequency resolution of the machines being used. The impedance analyzer takes data from 10 to 32.1 kHz in 400 points, yielding a frequency resolution of 55.25 Hz. This prototype has a frequency resolution of 125.39 Hz. The percent difference is with respect to the HP 4194A impedance analyzer, which is assumed to be the true value for these experiments.

2.6 Conclusions

This chapter presents the first fully self-contained system that performs impedance-based structural health monitoring. In previous research, a system was developed which performed most of the health monitoring steps, but needed the use of an external function generator for actuation. The current system effectively replaces an impedance analyzer and MATLAB. All of the structural excitation, data acquisition, and health monitoring analysis are performed in a matter of seconds. With traditional impedance techniques, after the data is acquired, all of the analysis must still be done using processing software to determine whether there is damage. Now, damage in a structure can be found almost immediately.

Also described is the first use of impedance excitation with targeted sinc functions. The use of sinc functions has the potential to save both excitation time and computational power. By slightly varying the fundamental frequency with each pulse, the structure will be excited at every frequency in the range of interest.
Chapter 3: Impedance Detection of Thermal Protection System Damage

3.1 Introduction

Thermal protection systems (TPS) on spacecraft are crucial for the survival of the vehicle during Earth reentry. The complex nature of thermal protection systems and extreme reentry temperatures do not allow for easy access to monitor the condition of the external surface of the spacecraft. As discussed in the previous chapter, an active sensing system is proposed to interrogate the exterior of the surface and provide automated damage detection, diagnostics, and prognosis. While such an active sensing system is being developed, the ability of the impedance method for structural health monitoring to detect damage in protection systems is verified.

Due to the importance of TPS for reusable spacecraft, damage detection of such structures has been an active area of research for many years. NASA has been actively developing techniques for acoustic emission and impact damage detection (Madaras et al. 2005). Testing with these methods has been performed on both Shuttle thermal protection tiles and reinforced carbon-carbon panels. Analyzing changes in mode shapes and natural frequencies, Derriso et al. (2004) displayed the feasibility of detecting fastener loosening in a mechanically attached TPS. Wave propagation has also been investigated as a possible technique for detecting damage in TPS tiles and aluminum plate systems (Sundararaman et al. 2005). Initial studies show promise in detecting external tile damage.

In this chapter, the first investigation into the ability of the impedance-based structural health monitoring technique to detect damage in representative orbiter thermal protections systems is presented. The methodology of simulating both Shuttle Orbiter tiles and the Shuttle fuselage is described. A variety of damage cases, changing both location and severity, is induced...
to the structure, and measurements are taken from piezoceramic self-sensing actuators at different locations on the fuselage. Thermal variations are introduced to the fuselage to verify the detection of damage at elevated temperatures.

### 3.2 Shuttle Fuselage Simulation

Due to the complicated configurations of thermal protection systems, an experimental setup is utilized in order to gain insight in the ability of the impedance method to detect damage in such structures. The goal in this testing is to develop a more realistic structure representative of a space shuttle fuselage. Sensors will only be placed in locations where they might be located on an actual vehicle.

#### 3.2.1 Tile Construction

The bottom of the Space Shuttle Orbiter is covered with black High-temperature Reusable Surface Insulation (HRSI) tiles (Sawyer 1984). These HRSI tiles are 2.54 to 12.7 cm thick depending on location and have a density of 0.144 grams per cubic centimeter (Sawyer 1984). Based on materials with similar densities and available thicknesses, calcium silicate is chosen as the material to construct representative tiles. Calcium silicate is a common high temperature insulation material and has a density of 0.232 grams per cubic centimeter. Silicate tiles are 3.81 cm thick and are cut into squares approximately 14.6 cm on a side.

The fuselage undergoes considerable temperature fluctuations during a mission, and thermal stresses are therefore induced. In order to protect the relatively fragile tiles from these thermal stresses, felt is bonded directly to the underside of the tile, and the felt is what is actually bonded to the shuttle fuselage. These strain isolation pads (SIP) must obviously be flame retardant and able to withstand high temperatures (gaps are left between the tiles to avoid touching), so Nomex Aramid fibrous material is used (Sawyer 1984). For these investigations, the same Nomex Aramid felt found on the actual HRSI tiles is used. SIPs are cut into 12.7 by 12.7 cm squares and are 0.318 cm thick.

Just as with real HRSI tiles, RTV silicone is used to bond the felt to the tile and the felt to the fuselage (Sawyer 1984). For these experiments, GE RTV 106 Silicone Rubber is used. RTV
106 is an extreme temperature silicone and retains its properties from -60 to 260 degrees Celsius. Tiles bonded to the structure can be seen in Figure 3.1(a).

![Figure 3.1](image)

**Figure 3.1.** Four tiles are bonded to the fuselage (a), and PZTs are bonded to the back of the fuselage (b).

### 3.2.2 Fuselage Construction

With representative shuttle tiles finished, a structure to bond these tiles to is fabricated. To simulate a section of fuselage, a 60.96 by 91.44 cm sheet of aluminum is used. In the Shuttle, the fuselage is wrapped around a stringer frame structure and attached with rivets (Sawyer 1984). Solid aluminum angles 0.159 cm thick are used to simulate stringers. The stringers are 3.81 cm on a side. Two stringers are riveted to the sheet, one to a 60.96 cm side of the sheet, the other parallel to the first one in the center (45.72 cm along the 91.44 cm side) of the sheet. Twelve aluminum rivets are used for each stringer. The rivets are 2.54 cm from each edge and run along the stringer spaced 5.08 cm apart. A picture of the completed fuselage can be seen in Figure 3.1.
3.3 Tile Delamination Testing

Three piezoceramic patches (5H4E PZT from Piezo Systems, Inc.) are bonded to the fuselage structure to monitor the tile with the impedance method, as seen in Figure 3.1(b). One PZT is bonded to each stringer, and the other PZT is mounted in the center of the fuselage between the two ribs. Each patch is approximately 1.2 x 1.3 cm. This setup is meant to be representative of where a sensor might be placed on an actual space vehicle. The tiles on the Shuttle exterior will need to be monitored from the inside of the Shuttle fuselage due to temperature and sensor integrity concerns. For the following experiment, four tiles are bonded to the fuselage structure in between the stringers as seen in Figure 3.1(a).

3.3.1 Delamination Damage Cases

For each of the three PZTs, four baseline impedance measurements are recorded using an HP 4194A impedance analyzer for two separate frequency ranges. A good number of peaks can be seen at each PZT location in both the 40 to 60 kHz and 100 to 120 kHz ranges. As seen in Figure 3.1(b), only PZT 3 is on the same surface as the external tiles. The other two PZTs are bonded to the stringers. A riveted bonding condition connects the self-sensing actuator to the object of interest. Access to actual thermal protection systems may be limited to such extended sensor/tile interaction.

Most tile failure occurs due to adhesion degradation between the SIP and fuselage (Sawyer 1984). The loss of adhesion leads to delamination of the tile and SIP from the fuselage, which is a dangerous situation during reentry. All the damage for this experiment is due to delamination of the bond between the felt and aluminum. Nine different damage cases, all cumulative, are used during this testing. For each damage case, two impedance signatures are acquired at each of the three PZTs.

The first damage case is a 2 by 2 cm delamination of the upper left corner of tile 1, as seen in Figure 3.1(a). Further damage is incurred with a 2 cm delamination between the SIP and fuselage along the whole left side of tile 1. A 2 by 2 cm delamination of the lower right corner of tile four is the third damage state, which is followed by a 2 cm delamination along the bottom edge of tile 4. Tiles 1 and 4 are then removed for the fifth and sixth damage cases, respectively.
A seventh state of damage comes from a 2 cm delamination along the left side of tile 3. The last two damage cases come from removing tile 3 followed by the removal of tile 2.

Each of these cumulative amounts of damage is monitored from all three PZTs. A visual summary of these damage cases obtained from PZT 1 can be seen in Figure 3.2. Not all of the collected impedance measurements are shown; only one curve from the original undamaged baseline through having all of the tiles removed is displayed. As shown in both frequency ranges of Figure 3.2, the changes in the peaks while monitoring the tiles through a riveted boundary condition are subtle, but shifting can clearly be seen.

![Figure 3.2. The impedance signatures from PZT 1 are shown for each damage case in both frequency ranges.](image)

### 3.3.2 Analysis of Impedance Curves

As seen in Figure 3.2, the impedance signatures change as the bonding conditions change. The changes in these signatures can be used to determine the amount of damage. The Root Mean Square Deviation (RMSD) is used as a simple method to assess changes in the peaks.
of the impedance signatures by comparing individual peaks to see how much they changed. The RMSD method for finding the damage metric is defined in Equation 2.2. Applying the RMSD metric to the curves of Figure 3.2, damage can be readily identified and is shown in Figure 3.3.

![Figure 3.3](image)

*Figure 3.3.* The RMSD damage metric is shown for the curves described in Figure 3.2.

The calculation of the RMSD damage metric easily exposes the changes in these curves. Just as would be expected, the damage metric consistently increases for both frequency ranges as the cumulative amount of damage increases. In the bar chart summarizing the damage metrics (Figure 3.3), the first three bars compare the first baseline measurement to the remaining three baselines (dark blue). The bars are then grouped in pairs corresponding to the damage states indicated in the legend. For example, the fourth and fifth bars (dark green) correspond to damage case 1, a 2 by 2 cm delamination of the upper left corner of tile 1. The final two bars (maroon) then reveal the quantified amount of damage for the removal of all the tiles. Each pair of bars follows the damage progression previously described and seen in the legend of Figure 3.2.
Similarly, the next figure shows the collected curves and analyzed damage results for PZT 2. As expected, the curves and damage metrics for PZT 2, which is located on the center stringer, are similar to those for PZT 1. One interesting observations is that, in the 40 to 60 kHz range, the quantity of damage is not distinguished as clearly as is shown from PZT 1.

![Figure 3.4.](image)

(a) The impedance signatures (a) and damage metrics (b) are shown for PZT 2.

The results from PZT 3 are slightly different that those of the first two PZTs. With PZT 3 being bonded directly behind the tiles on the actual fuselage, these results are not completely unexpected. Without having to detect damage through stringers and rivets, the impedance method should be much more sensitive to damage. Figure 3.5 displays the impedance signatures recorded from PZT 3.

As expected, the impedance curves shown in Figure 3.5 are more sensitive to the damage than the PZTs bonded to the stringers. Shifts in the peaks are much more apparent. Most notably, in the frequency range from 40 to 60 kHz, most of the peaks display a large variation from the baseline measurements.

Applying the RMSD damage metric to the impedance signatures for the PZT bonded directly to the back of the fuselage, the values displayed in Figure 3.6 are generated. The damage metric appears to be especially sensitive the removal of tiles. The large leaps in damage metric at both frequency ranges occur when tiles are removed from the structure. Also, the damage metric jumps significantly at greater amounts of damage.
Figure 3.5. The impedance signatures are shown for PZT 3.

Figure 3.6. The RMSD damage metric is shown for the impedance signatures of PZT 3 in Figure 3.5.
The results of these experiments are particularly significant when considering the amount of overall change the structure undergoes when damage is introduced. The fuselage mass is 1,185 g, while each of the calcium silicate tiles weighs 188 g. With four tiles bonded to the fuselage, the total mass is 1,937 g, not counting the felt or silicone. Thus, the removal of one tile from the structure would only be 9.7 to 13.7 percent of the total structural mass, depending on the amount of tiles remaining on the fuselage. Even with this small change, the sensors in non-optimal locations can detect the damage. With lighter tiles and the inclusion of all the material, the percent change in mass would be lower.

Detecting individual delaminations of the tiles is even more noteworthy. With respect to all the bonded surfaces, the first two damage cases (a 2 cm by 2 delaminaiton and a 2 cm by 12.7 cm delamination) represent only 0.6 and 3.9 percent debonding. Minor delaminations are easily detected with the impedance method. The amount of debonding for the remaining seven damage states are 4.5, 8.4, 28.9, 50, 53.9, 75, and 100 percent of the total surface.

### 3.4 High Temperature Testing

The goal of the HRSI tiles is to prevent the aluminum Orbiter fuselage from reaching temperatures above 175 degrees Celsius (NSTS Shuttle Reference Manual 1988). However, the aluminum is still exposed to temperatures as high as 175 degrees Celsius. A new experiment is developed to test the fuselage structure and an attached tile at higher temperatures. Instead of four tiles, only one tile is placed in the location of where tile 2 from the previous experiment was located.

The whole fuselage is placed inside a Tenney VersaTenn III Environmental Test Chamber, which allows for a controlled temperature and pressure to achieve desired atmospheric conditions. For this experiment, only PZT 3 is used to collect data. Data is collected with an HP 4194A impedance analyzer at temperatures ranging from 32 degrees Celsius all the way up to 150 degrees Celsius. At each temperature, two baselines are acquired in two different frequency ranges, 40 to 60 kHz and 100 to 120 kHz. All tests are conducted at atmospheric pressure. Essentially, a library of PZT baselines is created for a number of different temperatures.

Due to the increased complexity of adjusting the temperature while testing, only two damage cases are used for this step. The first damage case is a large delamination between the
SIP and fuselage along the top of the tile. Removing the tile is the second damage state. With so many signatures acquired due to the six different temperature settings, only one typical result is shown. The following figure displays the impedance signatures and damage metrics for the data collected at 120 degrees Celsius in the 100 to 120 kHz range.

As Figure 3.7 reveals, the impedance technique is sensitive to the damage caused by the removal of an extremely light tile from a fuselage even at higher temperatures. Changes in the peaks can clearly be observed, and the damage metric quantifies this change nicely. In the bar chart, the first bar compares the second baseline with the first. The next two sets compare the first and second damage case with the first baseline.

![Figure 3.7. The impedance signatures and damage metrics are shown for PZT 3 at 120 degrees C.](image)

3.5 Conclusions

These experiments verify the ability of impedance based health monitoring techniques to detect damage in space shuttle thermal protection system representative structures. Damage from degradation of bonding conditions was detected, even through complex boundary conditions. Even at temperatures as high as 150 degrees Celsius, delamination could be detected from a single tile.

The ability of the impedance method to see damage in with the thermal protection system tiles is noteworthy considering each tile weighs only 188 g. An actual HRSI tile of the same size
would weight 117 g. Damage detection from a structural change with such a small mass is a considerable result for the impedance method. One of the key advantages of the impedance method is the insensitivity of the technique with regards to changing mass loading conditions (Park et al. 2003). At first, this experimental sensitivity testing might look an attempt to contradict the mass loading insensitivity. In this case, however, the damage is not a mass loading change, but an actual structural change. Bonding each tile and SIP with the RTV ensures a complete structure in contrast to just placing and removing tiles, or other objects with similar masses to that of the silicate, from the fuselage to simulate damage.

The most significant result may be the ability of impedance method to see through complex connections. Normally, impedance measurements for health monitoring are taken directly on the surface of interest. The self-sensing actuators might not necessarily be near the damage location, but they are at least on the same continuous surface. The tests conducted in this research placed the sensors at more realistic sensor locations. While all of the damage to the structure was introduced on the external, or “hot”, side of the fuselage, the sensors are on bonded to the internal, “cool” side. Other structural health monitoring techniques, specifically Lamb wave damage detection, are generally not well suited to detecting damage through boundary changes or with sensors located on a different surface than the damage. In many applications, non-optimal measurement locations may be the norm. To see through connections, it should be noted that the lower range of typical impedance frequencies might need to be used.
Chapter 4: Thermal Energy Harvested to Power Digital SHM Hardware

4.1 Introduction

In Chapter 2, hardware was developed utilizing a DSP, ADC, and DAC to replace an impedance analyzer for use in the impedance-based SHM technique. The goal of this continuing hardware development is to reduce the power consumption of such systems to levels which are able to be harvested from ambient structural energy. It was mentioned that the hardware in Chapter 2 could be operated from battery power. An example was included which demonstrated that vibration-based energy harvesting with a piezoelectric patch could then recharge these batteries, and the hardware could be operated with a duty cycle of once or twice a day. In this chapter, a new hardware system will be presented and power to the system will be provided from harvested energy from thermal gradients.

Energy harvesting is a term used to describe the process of extracting useful electrical energy from a different type of ambient energy source using a special material called a transducer, which has the ability to convert one form of energy into another. Various energy sources, including solar, thermal, or vibration have been used to harvest electrical energy. Vibration-based power harvesting using piezoelectric materials has recently been a research topic of great interest. Using the ambient vibrations of a structure, piezoelectric devices can be designed and optimized to extract electrical energy from these vibrations. Sodano et al. (2004) review the research in power harvesting from vibration using piezoelectric materials, and Anton and Sodano (2007) provide the most recent summary review of piezoelectric-based energy harvesting.
In contrast to vibration-based energy harvesting, thermoelectric materials utilize the Seebeck (1822) effect to transform an applied temperature gradient into a voltage. Wu (1996) proposed the concept of a waste-heat thermoelectric generator. Using the appropriate circuitry and a power storage mechanism, these thermoelectric materials can be used as energy harvesting devices to gather energy from ambient thermal gradients.

In this chapter, an impedance-based SHM system will be operated with batteries as the sole source of power for all the operations necessary to find damage in a structure. Thermoelectric generators will then use temperature gradients to recharge batteries, making the system completely autonomous. The battery charging and discharging characteristics will be described, and duty cycles for hardware operations will be defined for each thermal gradient.

4.2 Digital Impedance Hardware

As described in Chapter 2, a completely functional prototype for conducting impedance-based SHM was developed. This prototype was the first fully self-contained, impedance-based prototype of its kind. The system utilizes DSP, ADC, and DAC evaluation module boards in a stacked configuration to effectively replace an impedance analyzer and post-processing techniques. However, due to the somewhat bulky and fragile stacked board configuration and relatively large power dissipation, the ability of this system to be effectively used in a field operation is limited. The following discusses the next generation of the impedance-based SHM hardware efforts.

A new version of the hardware developed by Kim et al. (2007a) is implemented on a TMS320F2812 evaluation board, with a 150 MHz DSP, from Texas Instruments. As shown in Figure 4.1, the 32-bit fixed point DSP is supplemented with two Texas Instruments Opamps, OPA4342 and TLV2770. Three channels of the OPA4342 are used for including two buffers and a comparator into the system, and the TLV2770 is employed for PZT excitation and sensing. Miscellaneous components such as resistors and an LED are also included. Further details about the hardware configuration can be found in (Kim et al. 2007a). For this testing, the prototype is set to operate at the lowest operating clock (15 MHz) and peripheral clock (1.25 MHz) frequencies to minimize power consumption. From previous testing, the power consumption is
expected to be at 790 mW without structural damage and 900 mW with damage to the structure (Kim et al. 2007a).

Figure 4.1. The existing prototype is contained on a TMS320F2812 DSP evaluation board and external circuitry.

The hardware operation is completely digital to minimize power consumption. Digital rectangular pulse trains of various frequencies, generated by the pulse width modulation (PWM) signal generator of the DSP, are utilized to excite the structure (Kim et al. 2007b). Structural response through the piezoelectric bonded to the structure is also only measured via the digital signal representation of the voltage, rather than quantization of multiple voltage levels. Variations between the signal directly generated by the PWM and the signal passing through the piezoelectric and comparator circuit represent the impedance of the structure. A baseline of
variations is created and used for comparison to each subsequent measurement. Further information about the damage detection algorithm can be found in (Kim et al. 2007b).

Structural excitation, data acquisition, and health monitoring analysis are all performed at the sensor location in under a minute. The end user is alerted to any damage with the illumination of a LED. In this setup, wireless transmissions to indicate damage are replaced with a LED to focus more on the hardware and algorithm development. A wireless transmitter will be included in future models of impedance damage detection systems. The LED is activated when the damage metric, found by comparing the current measurement to the baseline, surpasses a preset threshold. This prototype, the hardware discussed in Chapter 2, and all the impedance systems detailed in Section 1.3.2, all rely on external power supplies to provide the necessary operational power. The next step is to remove the standard power sources and replace them with standard batteries.

4.3 Hardware Powered By Batteries

This research focuses on eliminating the external power supplies and fully incorporating power harvesting to make the prototype autonomous. Therefore, the standard $5\text{ V}_{\text{DC}}$ power supply is replaced with common batteries. Two types of batteries will be used: nickel metal hydride (NiMH) and lithium ion (Li-ion). For each of these operational tests, current is measured using a Radio Shack 46 Range Digital Multimeter with a PC Interface. The data can be recorded using a RS 232 cable and provided software. Data is sampled and recorded at a rate of 1 Hz. At the same time, voltage is recorded with an Omega OMB DAQ 56. The prototype is looking for variations in the range of $12 - 25\text{ kHz}$.

The structure being tested consists of three beams with varying amounts of damage, as shown in Figure 4.2. Each of the 30 cm by 3.8 cm by 3 mm beams is equipped with a 0.27 mm thick type 5H4E PZT from Piezo Systems, Inc., measuring approximately 3 cm by 2 cm. The first beam is damage free, while the second and third beams have 0.635 cm and 0.714375 cm diameter holes in the center of them respectively. The PZT leads are attached to a rotary switch for easy comparison between the three beams. The switch output is connected to the digital impedance prototype. To provide consistent cases of damage or no damage, the first two beams are used. No damage indicates beam one is being excited and the LED is off. Beam two is used
for comparison with beam one when testing with damage, and the LED is illuminated after the baseline is acquired from beam one and the prototype signal is switched to beam two. Usually, 1 to 7 seconds are required to find damage after the signal is switched to beam two.

![Figure 4.2](image.png)

**Figure 4.2.** Three beams equipped with PZTs connected by switch are used for experimental testing.

Typically, different structures are never compared with each other while using the impedance method. The lack of a model for the impedance technique generally relegates damage detection to a case by case basis. In this experiment, identical beams with different levels of damage are successfully identified with the prototype. The baseline for detecting damage is only taken on a single beam, not each beam individually. While this is not a complex example, this demonstration shows that there may be a time in the future when the impedance method is developed enough to detect damage without the use of baselining.

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4.3.1 Nickel Metal Hydride Batteries

The first batteries to provide power to the hardware are three 1.2 V, 700 mAh AAA Radio Shack nickel metal hydride (NiMH) batteries. One of these batteries is shown in Figure 4.3. A 1 Ah capacity means that a battery will last for 1 hour if it is subjected to a discharge current of 1 A. The three batteries are placed in series, which yields a source of 3.6 V at 700 mAh.

![Figure 4.3. A 1.2 V, 700 mAh AAA NiMH battery is displayed.](image)

For these experiments, the batteries are fully charged. Two trials are run, one with damage and the other without damage. The battery discharge characteristics for the case with damage are displayed in Figure 4.4. Both the test with damage and test without damage are summarized in Table 4.1.

In Figure 4.4, the voltage continuously drops over the time that the testing occurs. The current draw, however, remains constant, with minor spikes, over the course of the test. With a constant current, the power consumption decreases proportional to the voltage. The spike decrease in battery voltage, and concurrent spike in current draw and increase in power consumption, at the beginning of the test occur when a test signal is sent to the structure to ensure the hardware is operating properly. The damage detection algorithm starts immediately after the test signal is sent out.
Table 4.1. A summary of the hardware characteristics operating with three 700 mAh NiMH batteries is shown.

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Maximum Voltage</th>
<th>Minimum Voltage</th>
<th>Power Range</th>
<th>Total Run Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Damage</td>
<td>0.145 A</td>
<td>4.10 V</td>
<td>3.18 V</td>
<td>461 - 595 mW</td>
<td>1 hr, 44 min, 5 sec</td>
</tr>
<tr>
<td>Damage</td>
<td>0.169 A</td>
<td>4.15 V</td>
<td>3.19 V</td>
<td>539 - 701 mW</td>
<td>2 hr, 50 min, 32 sec</td>
</tr>
</tbody>
</table>

As seen from Table 4.1, the hardware ran for 1 hour and 44 minutes without damage (the LED is off) and 2 hours and 50 minutes with damage. The prototype obtained a baseline in 13 seconds and found damage in 3 to 7 seconds, so this operation time is well beyond what is necessary. The power levels (701 mW maximum, with damage) were also well below what was previously measured in (Kim et al. 2007a). In the case with damage, the batteries were charged to a higher initial voltage level, which results in the counterintuitive result of a longer operation run time. If the batteries had been charged to 4.15 V instead of only 4.10 V in the case without structural damage, the run time is expected to have been well over three hours.
4.3.2 Lithium Ion Cells

The second type of source to be connected to the prototype, seen in Figure 4.5, is a Powerizer 3.7 V, 170 mAh lithium ion cell (Li-ion). In this test, the cell is fully charged, and no damage is indicated with the LED. The prototype ran for 57 minutes before the voltage level became too low to run the hardware. A more thorough characterization of the Li-ion battery testing is presented in the next section after the battery has been recharged.

![Figure 4.5. A 3.7 V, 170 mAh Li-ion battery, which weighs 3 grams, is shown.]

4.4 Recharging Batteries with Thermal Energy

The ability to convert thermal energy into electrical energy is facilitated by a special material property known as the Seebeck effect (Seebeck 1822). Seebeck noted that a current flow resulted when two different metals were kept at different temperatures. The Seebeck effect is a phenomenon that occurs when a voltage $V$ is induced in proportion to an applied temperature gradient $\Delta T$ related by

$$V = \alpha \Delta T$$  \hspace{1cm} (4.1)

where $\alpha$ is the Seebeck coefficient.

Four commercially available Melcor R high temperature thermoelectric coolers are chosen for the harvesting device. The four 3 x 3 x 0.36 cm devices are electrically connected in
series to sum their output voltages. High temperature silicon gasket material is injected into each generator to decrease heat leakage between the two ceramic faces. To improve and ensure heat transfer, a flat aluminum plate is mounted to the hot side of the generators, and an aluminum fin heat sink is attached to draw heat away on the cold side. The complete generator is shown in Figure 4.6.

![Four thermoelectric generators, an aluminum base plate, and cooling fins are shown.](image)

**Figure 4.6.** Four thermoelectric generators, an aluminum base plate, and cooling fins are shown.

A high efficiency DC-DC converter is used to modify the output and produce a larger voltage. The National Semiconductor evaluation board for LM2621, a low input voltage, step-up DC-DC converter, is used in these experiments. The converter is capable of starting from input voltages as low as 1.25 Volts and produces an output voltage of approximately 4.88 Volts.

Each of the two kinds of batteries is connected to the thermoelectric generator and DC-DC converter. The thermoelectric generator is placed on a hot plate to provide a temperature gradient across the generator. First, a 1.2 V, 720 mAh nickel metal hydride battery is charged for 48 minutes. The hot plate is set to and held constant at about 155 °C, while the cold side of the generator is 90 °C. The overall ΔT ranged between 62 °C and 70 °C. The temperature differential is calculated by taking measurements from two type J thermocouples from Omega. One thermocouple records the base temperature at the hot plate boundary, while the other thermocouple records the cool side temperature. The Omega OMB DAQ 56 is again used to record the resulting thermocouple voltages.
The 3.7 V, 170 mAh lithium ion battery is now connected to the generator. Two different thermal gradients are used to recharge the battery. A thermal gradient of 80 °C charges the battery to a maximum of 3.5 V in about 1 hour and 18 minutes. Finally, charging the battery for 4 hours and 10 minutes at a thermal gradient of 43 °C yields a maximum voltage of 3.4 V. The charging curve and temperature gradient for the lithium ion battery at a thermal gradient of 43 °C are shown in Figure 4.7.

![Charging Curve](image1.png)

**Figure 4.7.** The charge curve of a 3.7 V, 170 mAh lithium ion battery versus time and temperature gradient are shown.

### 4.5 Operating Digital Hardware with a Recharged Lithium Ion Cell

The Li-ion battery recharged with ambient thermal energy is now reconnected to the hardware. A battery charger is more efficient at recharging than an energy harvesting device. A full charge cannot be achieved using energy harvesting due to the lower charge current when using less sophisticated electronics. Determining operational times for the prototype with the thermally charged batteries will provide a more realistic operating condition. Both the 43 °C and 80 °C thermal gradient cases are used to power the prototype. As Table 4.2 reveals, the higher
gradient charge yields a longer run time. The larger gradient produces a higher maximum voltage in the battery, so this increased performance is expected. Though these trials are run without damage, more than sufficient time is available for the hardware to determine whether or not the target structure is damaged.

Table 4.2. Hardware operating characteristics are shown with recharged 3.7 V Li-ion cells.

<table>
<thead>
<tr>
<th>AT</th>
<th>Current (A)</th>
<th>Maximum Voltage (V)</th>
<th>Minimum Voltage (V)</th>
<th>Power Range (mW)</th>
<th>Charge Time</th>
<th>Run Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>43 °C</td>
<td>0.14</td>
<td>3.415</td>
<td>3.18</td>
<td>445 - 478</td>
<td>4 hr, 10 min, 39 sec</td>
<td>3 min, 2 sec</td>
</tr>
<tr>
<td>80 °C</td>
<td>0.145</td>
<td>3.526</td>
<td>3.19</td>
<td>463 - 511</td>
<td>1 hr, 17 min, 54 sec</td>
<td>5 min, 21 sec</td>
</tr>
</tbody>
</table>

4.6 Duty Cycle

With the run times of batteries recharged with a thermoelectric generator being significantly lower than those of fully charged batteries, basing the duty cycle on the batteries with harvested energy seems more reasonable. For the battery charged with a 43 °C thermal gradient, the prototype ran for 3 minutes and 2 seconds, while it took 4 hours, 10 minutes, and 39 seconds to charge the battery. This yields a duty cycle of 1.2 percent. The hardware was operational for 5 minutes and 21 seconds with an 80 °C thermal gradient across the generator. 1 hour, 17 minutes, and 54 seconds were needed to charge the battery, which gives a duty cycle of 6.4 percent. Obviously, if there is more ambient energy available, the duty cycle would increase.

However, remember that the hardware generated a baseline in around 13 seconds, and only took 3 to 7 more seconds to find damage. If the system only needs to be operational for 20 seconds to find damage, the battery will not be nearly as depleted. The charge times will be much shorter, and the duty cycles should increase accordingly. In 20 seconds of hardware operation with the Li-ion battery recharged from a thermal gradient of 80 °C, the battery voltage decreased 0.029 V from 3.306 V to 3.277 V. Looking at the charging curve for the cell at 80 °C, it takes just under 28 seconds to charge from 3.269 V to 3.306 V. In this example, the duty cycle would be 71.4 percent. If the operation and charging take place at voltages well lower than the maximum battery voltage (where the most amount of time is needed to charge the battery) with
plenty of ambient energy available, increased duty cycles should be expected. However, after charging a battery, placing a load across the battery usually decreases the battery voltage to a level lower than the unloaded final charge voltage. Charging the battery to a higher level than 3.306 V would most likely be required, causing the duty cycle to decrease. While a duty cycle of 70 percent might not be possible, expecting duty cycles above 10 percent is certainly not unreasonable.

4.7 Conclusions

An impedance-based structural health monitoring prototype operating solely from of battery power is presented. These batteries were recharged using only energy harvested from a thermal gradient across a thermoelectric generator. All of the temperature gradients used are within a range which might be seen on a real world vehicle. In a recent study on harvesting energy from motorcycle waste heat, typical gradients ranged from 45 °C to 80 °C depending on the driving speed of the motorcycle (Schlichting et al. 2008). The harvested ambient energy in this study provided more than enough power for the hardware to fully complete its damage detection operation. As expected, the duty cycle of the hardware and battery increases with a larger amount of ambient energy. The results of this chapter mark the first time that an impedance-based SHM system has operated completely autonomously. In the next chapter, sensor diagnostics, another key component in autonomous structural health monitoring, is introduced.
Chapter 5: Sensor Diagnostics and Temperature

5.1 Introduction

In the previous chapters, focus has been concentrated on developing structural health monitoring techniques through hardware development, defining the sensitivity of impedance techniques for critical protection systems, and exploring the possibility of autonomous detection systems with incorporating power harvesting circuitry. While the importance of continuing to develop structural health monitoring systems seems obvious for both critical safety and financial factors, developing sensor diagnostics for these detection systems may be just as important. Sensor diagnostics allow a health monitoring system to infer the integrity of the sensors and separate sensor damage from structural defects.

Many damage detection systems will require a large number of sensors distributed over a structure for effective coverage. Many of these sensors will be required to be in locations exposed to adverse operational and environmental conditions. Even sensors bonded in a protected location have the potential to be damaged with large impacts, collisions, or other unexpected catastrophic events. If a sensor connected to a monitoring system yields no output, either from ambient or external excitation, declaring the sensor to be damaged is a likely conclusion. However, the sensor may be still be partially functional, respond to an excitation signal, and provide what seems like an adequate response even if the sensor has degraded in some way. A sensor with breakage or inadequate bonding, potentially from exposure to some form of solvent, impact events, or even fatigue, may significantly change signal characteristics and lead to false positive or negative damage detection results. To provide the best possible
indication of structural integrity, the condition of each sensor should be verified before each measurement is taken.

Various studies have looked at the influence of the bonding layer on impedance measurements. Most recently, Bhalla and Soh (2004) investigated the influence of shear lag through the bonding layer for the electromechanical impedance models of piezoelectric actuation and sensing developed by Crawley and de Luis (1987) and Sirohi and Chopra (2000), respectively. By incorporating the effects of shear lag loss through the adhesive, and extending the previous models to 2D, Bhalla and Soh reveal that the bonding layer can play a large role in the measured electrical admittance signals. To minimize the influence of the boundary layer in recorded measurements, the authors suggest using a thin layer of an adhesive with a high shear modulus, along with the smallest piezoelectric patch necessary. Bhalla and Soh also identify that the susceptance, or imaginary part of the admittance measurement, is most sensitive to changes in the bonding layer and can be used for identifying debonding. However, this model, as well as other bonding layer models, does not provide a method for detecting bonding defects and only outlines what measurements result from improper bonding.

Saint-Pierre et al. (1996) introduced a technique to detect bonding defects in a piezoelectric embedded element by monitoring the electrical impedance. After developing a new model, the modifications to the electrical impedance signal are calculated based on the percentage of unbonded sensor area. Both the model and experimental results reveal that as the bonding defect area becomes larger, the thickness of the piezoelectric resonance becomes sharper and more distinct. In contrast, the amplitude of the host structure resonances is reduced. A delaminated area as small as 1 percent is able to be detected by monitoring the piezoelectric resonance. Giurgiutiu et al. (2002) also investigated sensor adhesion for structural health monitoring of aging aircraft. The authors noted that sensor bonding defects are indicated by the increasing of sensor resonances while the structural resonances diminish. While these techniques clearly indicate sensor disbonding, the electrical impedance changes due to sensor breakage are not addressed. The methods also rely on monitoring the resonance of the piezoelectric patch. Any sensor fracture will change the piezoelectric resonant peaks, while structural damage will alter the structural resonant peaks. How to distinguish between sensor breakage, structural damage, and sensor debonding is unclear.
A closed-loop detection scheme is developed by Sun and Tong (2003) for piezoelectric debonding in beams. Using Timoshenko beam theory, a model is derived with partially detached actuator and sensor piezoelectric patches to illustrate the influence of sensor debonding on vibrational control of a beam. The control parameters are set such that even a slight (0.1 percent debonding) shift in piezoelectric frequency, presumably due to delamination of the piezoelectric from the structure, will cause the control system to become unstable. An unstable control system is therefore an indicator of an unhealthy bonding condition. While the closed-loop control system is sensitive enough to be destabilized by even a small sensor delamination, the influence structural or sensor damage would have on the control system is not completely addressed.

Bach et al. (2007) utilized sensor diagnostics for the impedance method to detect damaged sensors caused by simulated harsh aerospace environments. Exposing the piezoelectric sensors to different conditions, including bonding the sensor to a dirty surface and submerging the sensor in a Methyl-Ethyl-Ketone solvent and hot water. Results indicate that with proper sealant and adhesive, sensor degradation due to these conditions is minimal. However, without the sealant, changes in sensor bonding are revealed by the piezoelectric susceptance. The authors also investigate the changes of the imaginary part of the piezoelectric admittance as a result of temperature variations. Results of this testing indicate that temperature compensation is required for every piezoelectric measurement. Blackshire et al. (2006) also investigated bonded PZT sensors in an operational aircraft environment in order to improve the durability of these types of sensor in harsh environments.

Lee and Sohn (2007) have investigated the use of Lamb waves to detect the presence of damaged sensors in guided-wave structural health monitoring. Using two time reversal based indices, piezoelectric debonding is successfully identified. The Lamb wave mode ratio is utilized to estimate PZT cracking. The authors claim these methods are able to discern sensor damage from changes in temperature, but, as of yet, there is no experimental work to support these features being temperature independent. Park, G. et al. (2006a) also investigated the effect of broken sensors on performing Lamb wave damage location.

Recently, an updated model was introduced for impedance-based sensor diagnostics. This model modifies the diagnostics method developed by Park, G. et al. (2004, 2006a, 2006b) which is based on the single degree of freedom impedance method model developed by Liang et al. (1994a, 1994b). Liang et al. (1994b) used a mass-spring-damper system to come up with an
expression revealing that the electrical admittance of a PZT patch $Y(\omega)$ is a combination of the structure’s mechanical impedance $Z_s(\omega)$ and the electrical impedance of the piezoelectric $Z_a(\omega)$, as shown in

$$Y(\omega) = i\omega \frac{w l}{t} \left[ \varepsilon_{33}^T (1 - i \delta) - d_{31}^2 Y_p^E + \frac{Z_a(\omega)}{Z_s(\omega)} + Z_s(\omega) d_{31}^2 Y_p^E \left( \frac{\tan \kappa l}{\kappa l} \right) \right] \quad (5.1)$$

where $w$, $l$, and $t$ are the width, length, and thickness of the PZT, $\varepsilon$ is the dielectric constant of the PZT, $\delta$ is the dielectric loss factor for PZT, $d$ is the piezoelectric coupling constant, and $Y_p^E$ is the complex Young’s Modulus of the PZT at zero electric field. The subscript 33 indicates that the charge density is along the $z$-axis, and the superscripts $E$ and $T$ indicate quantities measured at zero electric field and zero stress. $\kappa$ is the wave number of the PZT patch described by

$$\kappa = \omega \sqrt{\frac{\rho}{Y_p^E}} \quad (5.2)$$

where $\rho$ is the density of the PZT.

To understand how monitoring the admittance of the PZT works for sensor diagnostics, we can look at the admittance of an unbonded patch (Sirohi and Chopra 2000).

$$Y_{\text{free}}(\omega) = i\omega \frac{w l}{t} \left[ \varepsilon_{33}^T (1 - i \delta) \right] \quad (5.3)$$

Now, looking at Equation 5.1, if we let the mechanical impedance $Z_s(\omega)$ go to infinity, the equation simplifies to

$$Y(\omega) = i\omega \frac{w l}{t} \left[ \varepsilon_{33}^T (1 - i \delta) - d_{31}^2 Y_p^E \right] = Y_{\text{free}}(\omega) - i\omega \frac{w l}{t} \left[ d_{31}^2 Y_p^E \right] \quad (5.4)$$

In most cases, assuming that the mechanical impedance is infinity is not unrealistic as the sensors are generally much smaller compared to the structures they are bonded to. The magnitude of the
mechanical impedance of the PZT is generally several orders of magnitude lower than that of the structure, so the PZT mass and stiffness are nearly negligible, especially at lower frequencies. Comparing Equations 5.3 and 5.4, we can see that the only difference is due to the PZT modulus of elasticity and the piezoelectric coupling coefficient. Thus by bonding the PZT to a structure, we should expect a reduction of the admittance by a factor of $\frac{Wl}{l} \left[ d_{31}^2 Y_E \right]$. It is also interesting to note that these changes only influence the imaginary part of the admittance, or susceptance $B$.

Park, S. et al. (2007) now takes this a step farther by using a model developed by Xu and Liu (2002). At a low frequency range of excitation, especially when the excitation is much lower than the PZT resonant frequency, the term $\tan(\kappa l)/\kappa l$ is close to 1. Equation 5.1 can then be simplified to

$$ Y(\omega) = i\omega C \left[ 1 - \kappa_{31}^2 \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} \right] \quad (5.5) $$

where $C = \frac{Wl}{t} \varepsilon_{33}^t$ is the PZT capacitance and $\kappa_{31}^2 = \frac{d_{31}^2 Y_E}{\varepsilon_{33}^t}$ is the electromechanical coupling factor for the PZT (Liang et al. 1994b). The Xu and Liu model introduces a bonding layer shear-lag coefficient $\xi$ based on including a single degree of freedom dynamic model of the bonding layer between the structure and PZT.

$$ Y(\omega) = i\omega C \left[ 1 - \kappa_{31}^2 \frac{\xi \cdot Z_s(\omega)}{\xi \cdot Z_s(\omega) + Z_a(\omega)} \right] \quad (5.6) $$

The shear-lag coefficient is defined as $\xi = \frac{1}{1 + K_s/K_b}$, where $K_s$ is the dynamic stiffness of the structure, and $K_b$ is the dynamic stiffness of the bonding layer ($Z = K / i\omega$).

Equation 5.6 includes shear-lag from the bonding layer, but still does not include a characterization of sensor quality or bonding layer. To effectively model sensor and bonding conditions, Park, S. et al. (2007) add two control parameters to Equation 5.6. The first parameter describes sensor quality. A broken or damaged sensor would cause a downward shift in the
slope of the susceptance, which is effectively a decrease in PZT capacitance. A capacitance control parameter \(a\) is added to Equation 5.6 in the form of

\[
\tilde{C} = a \cdot C = a \cdot \frac{w}{l} \epsilon_{33}^T \quad 0 \leq a \leq 1.
\]  \tag{5.7}

\(a = 0\) would mean complete sensor failure, and \(a = 1\) represents a completely healthy sensor. Essentially, a break causes the dimensions of the PZT to change, which leads to a decrease in the capacitance.

The second parameter describes the quality of the bonding layer. As the bond degrades and the sensor delaminates from the structure, the sensor will approach a free-free condition. To capture this condition, an electromechanical coupling factor control parameter \(b\) is also added to Equation 5.6.

\[
\tilde{\kappa}_{31}^2 = b \cdot \kappa_{31}^2 = b \cdot \frac{d_{31}^2 \hat{Y}_E}{\epsilon_{33}^T} \quad 0 \leq b \leq 1
\]  \tag{5.8}

\(b = 0\) indicates that the PZT is completely delaminated, or free-free, and \(b = 1\) indicates perfect bonding conditions between the PZT and structure. With these parameters, Equation 5.6 becomes

\[
\tilde{Y}(\omega) = i \omega \tilde{C} \left[ 1 - \tilde{\kappa}_{31}^2 \frac{\xi \cdot Z_s(\omega)}{\xi \cdot Z_s(\omega) + Z_a(\omega)} \right] = i \omega a \cdot C \left[ 1 - b \cdot \kappa_{31}^2 \frac{\xi \cdot Z_s(\omega)}{\xi \cdot Z_s(\omega) + Z_a(\omega)} \right].
\]  \tag{5.9}

A sensor diagnostics model now exists which includes parameters for incorporating the amount of sensor degradation and debonding. Experimentally, Overly et al. (2007b) showed that the slope of the susceptance is directly correlated with the amount of debonding or breakage. These experimental results match what would be expected from the new Park, S. et al. (2007) model.

The problem with the sensor diagnostics method, as shown by Overly et al. (2007b), is that any temperature fluxuations can change the slope of the susceptance just as much as a
damaged sensor. A recent study analytically estimated that for a (70 x 10 x 0.1 mm³) type 5A PZT patch, a 5.5°C temperature change yields a 1 percent change in the PZT capacitance (Simmers et al. 2004). Type 5H PZT has even higher temperature sensitivity. For this reason, a technique needs to be developed to compensate for any temperature variations. Temperature compensation has been used to correct the real part of impedance (Park et al. 1999, Park 2000, and Koo et al. 2007), used for damage detection, for temperature, but only one study has looked at temperature changes on the imaginary part of the admittance (Overly et al. 2007b). The model used to identify damaged sensors developed by Overly et al. (2007b) is a temperature independent method. However, a limited range of thermal measurements were taken on a plate test structure, which is free of any boundary conditions which may be influenced as a result of a temperature change. Also, while the developed algorithm correctly identifies damaged sensors, each sensor must be compared to the others several times to identify sensors which are statistically different from the group. This algorithm may be computationally taxing to implement on an autonomous hardware system and does not compare each individual sensor to a standard guideline of what a healthy sensor’s output should indicate. The research presented here will attempt to address these issues for sensor diagnostics on complex structures in varying thermal environments.

A few studies, including Raghavan and Cesnik (2007a), have looked at the effect of temperature on guided-wave structural health monitoring. Using experimental results, a model provides a correction for changes in time-of-flight values due to temperature increases and allows for accurate damage location. The main factor leading to the change of arrival time due to temperature variations is a change in the Young’s Modulus. This same conclusion of the modulus of elasticity being the key parameter in altering the time-of-flight was reached by Grisso et al. (2004) when developing a simple temperature correction technique for wave propagation damage location to supplement impedance-based health monitoring.

The work here is an initial attempt to generate a model to separate temperature changes from sensor degradation for impedance-based health monitoring. With the recent emphasis on developing autonomous SHM hardware, this model should be as simple as possible to reduce algorithm power consumption. The method proposed here assumes that temperature readings will be acquired with each impedance measurement.
5.2 Structure Fabrication

Many times while experimentally verifying new SHM methods, a structure is used that allows for easy implementation of damage. Often these structures could be beam or joints with bolted connections which can be loosened or tightened to apply different damage conditions. Other times, attaching magnets can be used as a non-destructive means of simulating damage. However, with loosening and tightening bolts, obtaining repeatable conditions between baseline and damaged states is nearly impossible. While magnets are good for initial impedance sensitivity testing, the structure is not actually damaged. The magnets can be seen as a boundary condition change and will only show up as damage at the lower frequencies of the impedance testing range (Park et al. 2003, Bouteiller et al. 2006).

With the focus of this research being on detecting defective sensors, it seems more desirable than ever to have a repeatable method of inducing damage on the structure of interest. Instead of the traditional bolt loosening, a straight line action clamp is used to replace the standard bolt and nut connector. The clamp chosen is model 602 from DE-STA-CO, which can be seen in Figure 5.1.

![Image of DE-STA-CO 602 straight line action clamp](image)

*Figure 5.1.* The DE-STA-CO 602 straight line action clamp has an 889 N capacity.
The DE-STA-CO 602 clamp has a handle which moves the plunger forward or backward and locks at either end position. The base of the plunger is threaded to allow the clamp to be mounted to a structure or panel with a jam nut. Also, the plunger is internally threaded, allowing two pieces to be clamped together. The maximum load capacity of the clamp is 889 N.

A frame structure is used to implement the clamps. 5.08 cm wide, 3.175 mm thick aluminum is used to construct a 30.48 cm tall, 60.96 wide frame. 12.7 cm corner angles are used to connect the structure together at the corners. Four bolts and nuts with lock washers affix the frame pieces to the brackets at each corner, two on each side of the frame. However, on the top of the frame, the line clamps are used instead.

To attach the clamps, four holes in the top of the beam are drilled and tapped. The threads at the base of the clamp plunger are then screwed into the top of the beam and secured with a jam nut. Two clamps are centered in the top beam 3.81 cm and 11.94 cm from the left end, and two more clamps are placed symmetrically from the right side. Hex screws are then inserted into the plunger with two washers so that when the clamp is locked with the plunger completely retracted, the top of the frame is attached to the corner angles and, therefore, the rest of the structure. A picture of the completed frame structure can be seen in Figure 5.2(a). To show how the clamps attach to the top beam and hold structure together, clamps in with their plungers partially extended and completely retracted are shown in Figure 5.2(b).

![Figure 5.2. The completed frame structure (a) and clamping mechanism (b) are shown.](image-url)
A frame is chosen for a few reasons. One, the structure has real boundary conditions that will be affected by changes in temperature, as opposed to a free-free beam or plate. These boundary conditions will also affect any piezoelectric material bonded to the structure more than a simple structure. The frame is also more complex than a beam or joint and a realistic representation of a real world structure.

With the clamps either locked to join the beam and angle or unlocked acting as the source of damage to the structure, the repeatability issues of loosening and retorquing a bolt should be avoided. To allow for different levels of damage to the structure, each clamp is set to apply a different force to the structure. The force \( F \) that each clamp holds with at its locked position is obtained from

\[
F = \frac{\tau}{0.2D}, \tag{5.10}
\]

where \( \tau \) is the torque place on the screw, and \( D \) is the nominal thread diameter of the screw (Juvinall and Marshek 2000). To set the clamp forces, each clamp was screwed into the top beam of the structure and secured with the jam nut. The clamp was set to its locked position (right clamp in Figure 5.2(b)), and the screws were set to the appropriate torque to obtain the desired force. So, when the clamps are locked, there is a set force, and when the clamps are released, they apply no load to the structure. The clamp force increases with each ascending clamp number. Clamp 1 is set to 333 N, Clamp 2 applies a 445 N force, Clamp 3 is at 556 N, and Clamp 4 is set to 667 N. The clamp positions on the top of the structure can be seen in Figure 5.3.

![Figure 5.3](image)

**Figure 5.3.** Clamp 1 (333 N) is on the right of the frame structure.

As seen in Figure 5.3, Clamp 1, with the lowest preload, is on the right of the structure, and Clamp 4 is on the opposite side. Each of the regular bolts and nuts were tightened to a torque of 2.6 N·m (or 1606 N applied force). On all of the threaded surfaces, an epoxy is applied
when tightening to prevent loss of preload. Epoxy is used to keep the structure consistent, especially while the structure is expanding and contracting under different thermal loads. The epoxy used is Five Minute Epoxy Gel, a high strength (17.24 N/mm² shear tensile), high temperature range (-40 to 93.3 °C) quick setting epoxy from Devcon.

5.3 Sensor Selection

With the structure complete and the clamping forces set, a piezoelectric material needs to be selected to act as self-sensing actuators for the impedance method. The material chosen is a 0.27 mm thick PSI-5H4E material from Piezo Systems, Inc. Square pieces of the PZT, 1.8 cm on a side, are cut to bond to the structure. Before the patches are bonded to the structure, the susceptance for each of the patches in a free-free condition is measured and can be seen in Figure 5.4(a). The susceptance is shown in the frequency range from 1 kHz to 20 kHz.

![Figure 5.4](image)

**Figure 5.4.** The free-free PZT susceptances are shown (a), along with an enlarged view (b) to match the PZTs.

As Figure 5.4(a) shows, all of the PZTs are very similar in their unbonded responses. However, as Figure 5.4(b) reveals, when enlarging a section of the susceptance, the PZTs are clearly matched in pairs. Each of these pairs of patches will be matched with one being a healthy sensor and one being a damaged sensor. PZTs 4 and 6 become PZTs A and AA, 2 and 5 are now B and BB, and PZTs 1 and 3 are renamed C and CC.
In the frame structure, all of the bolted connections are adhered with epoxy and should be immobile. The only side that should change with damage, and therefore the only side of interest, is the top section with clamps. For this reason, all of the PZTs will be placed on the top section. PZTs are bonded to the beam with cyanoacrylate, and a piece of copper tape affixed to the underside of each PZT allows for leads to be soldered to each patch. PZT A is centered 17.8 cm inches from the right side of the structure, as shown in Figure 5.3. PZT C is bonded 17.8 cm from the left end, and PZT B is placed directly in the center of the top beam.

To verify the sensor diagnostics algorithm developed in this research, affixing unhealthy sensors to the structure is also necessary. The rest of the three sensors are attached to the structure with some type of deformity. As these sensors are matched to the first three, they are bonded in the same location as their healthy counterpart but on the underside of the top beam (PZT AA is directly under PZT A, etc.). Each of the three sensors is adhered with a different condition. PZT AA is bonded to the structure normally, but then the top 25 percent of the sensor is broken off to simulate the sensor being struck by a projectile. PZTs BB and CC are both not fully attached to the structure. The top 25 percent of PZT BB is delaminated from the beam, as is the top half of PZT CC. Delamination of a PZT is achieved by placing a piece of release paper under an area the patch to facilitate the desired amount debonding. After the cyanoacrylate bonding the PZT and structure has been mostly cured, the release paper can be removed to allow the patch to be bonded with the appropriate amount of debond. Examples of healthy, broken, and delaminated sensors are illustrated in Figure 5.5. A line is drawn of the picture of PZT CC (Figure 5.5(c)) to show where the delamination occurs.

![Images](image1.jpg)

**Figure 5.5.** Images of PZT C – healthy (a), PZT AA – broken (b), and PZT CC – delaminated (c) are shown.
With all of PZTs bonded to the structure, the susceptibility from 1 kHz to 20 kHz is reacquired. The PZTs are attached to the structure now, so the slope of susceptibility will change and peaks due to structural response will show up in the signatures. Bonded and unbonded susceptibility is shown in Figure 5.6.

As expected, Figure 5.6 reveals that unhealthy sensors can be detected by the slope of the susceptibility. PZT AA, which is 25 percent broken, has a significantly lower slope than the slopes of the healthy sensors. PZTs BB and CC have a larger slope than those of the healthy patches. This higher slope for debonded transducers makes intuitive sense when comparing the slopes to those of the unbonded PZT. As the sensor becomes more and more delaminated, it moves closer to free-free conditions, so the slope should increase. It is expected to see the slope of the susceptibility also reflect the extent of the damage to each sensor (Overly et al. 2007b). No significant difference is seen between PZTs BB and CC. With the difficulty in attaching delaminated patches to a structure, a somewhat imprecise amount of debonding is not entirely unexpected. However, the amount of debonding has already been correlated to the slope of the

---

**Figure 5.6.** All six bonded PZTs and two unbonded PZTs are shown to illustrate how sensors affect susceptibility.
susceptance (Overly et al. 2007b), and the focus of this research is to simply detect faulty sensor at different temperature levels.

5.4 Experimental Investigations

The completed frame, equipped with both healthy and damaged sensor, is now ready to be tested at temperatures other than room temperature. A limited temperature range from 15 °C to 65 °C, at 5 °C increments, is decided upon to initially observe the thermal characteristics of the structure and PZT. The whole structure is placed in a Tenney VersaTenn III Environmental Test Chamber, which allows for a controlled temperature and pressure to achieve desired atmospheric conditions. Pressure was maintained at atmospheric conditions for the duration of testing. A picture of the frame viewed through the door on the test chamber is shown in Figure 5.7.

![Figure 5.7. The frame structure is partially viewed through the Tenney Environmental Test Chamber window.](image)

As each desired temperature is entered into the test chamber control panel, the chamber is allowed to stabilize for 30 minutes prior to data acquisition. This time allows the temperature controller and heat exchanger to settle and the contents of the chamber to come to equilibrium. Any temperature fluctuations while testing are generally within a tenth of a degree.

Data is collected with an HP 4194A impedance analyzer. The chamber has testing wires built in to allow the structural PZT to be connected to the impedance analyzer. Using a laptop
operating a LabView code, the real and imaginary components of the impedance are collected. A frequency range from 100 Hz to 104,080 Hz is obtained with a frequency resolution of 20 Hz. Medium integration with two averages is used at an excitation amplitude of 1 Volt. The analyzer can only collect 400 points at a single time, so 13 loops are required to obtain each signature. At each temperature, 4 impedance signatures are collected for each PZT. With sensor BB and CC being so close to each other in initial slope, only data from PZT CC will be collected (5 PZTs in total). To obtain data useful for sensor diagnostics, the susceptance $B$ is found from the real and imaginary impedance components using the equation

$$B = \text{Im}(Y) = \frac{-X}{R^2 + X^2}, \quad (5.11)$$

where $Y$ is admittance, $X$ is the imaginary component of the impedance, and $R$ is the real part of the impedance. The susceptance at 45 °C for all five sensors is shown in Figure 5.8.

![Figure 5.8](image_url)

**Figure 5.8.** The the susceptance from 1 – 20 kHz for all 5 sensors is shown at 45 °C.
As Figure 5.8 shows, the same basic trend of the susceptance slopes displayed in Figure 5.6 holds true for the signatures at 45 °C. The debonded sensor has a higher slope than the healthy sensors, while a lower slope is seen for the broken sensor. These three figures are typical of all signatures for every PZT at each temperature. All signatures generally have very good repeatability amongst the four samples. The curves consistently overlapping without shifting is an excellent indication that the temperature was constant at the chosen level throughout the duration of each test.

As has been previously shown, the slope of the susceptance reveals the health of the structure. However, the susceptance slope also changes with temperature. Therefore, a method needs to be in place to determine whether a slope change is due to a type of sensor defect, or whether there is simply a change in the temperature. In the next section, a model will be generated to make this distinction.

### 5.5 Sensor Diagnostics Model and Algorithm

At every temperature from which data was collected, the susceptance is observed in the range of 1 kHz to 20 kHz for each PZT. For each sensor, at each temperature, the slope of the susceptance in this range is calculated using a linear least-squares fit (‘polyfit’ command in Matlab) and recorded. An example of fitting a line to the data for PZT B can be seen in Figure 5.9.
After each slope is recorded as described in Figure 5.9, the overall trend of the slopes needs to be observed. Plotting the susceptance slope value versus temperature yields an interesting result. For each of the three healthy sensors, the slope of the susceptance is plotted as a function of temperature in Figure 5.10.
As Figure 5.10 reveals, the slope of the susceptance increases linearly with temperature in the range of 15 °C to 65 °C. The only exception seems to be at 15 °C. However, when testing at 15 °C, the test chamber could not maintain a steady temperature, and the temperature readout was often above 15 °C. Thus, for the purposes of modeling, the slopes at 15 °C will not be considered.

With the healthy sensors showing a linear trend of susceptance slope over the initial temperature range, it is expected that the two broken sensors should follow the same pattern. The slopes values of the susceptance should be liner, constantly above (debonded) or below (broken) the healthy sensors. Figure 5.11 displays the susceptance slope values of the two broken sensors along with the slopes of the healthy sensors.
Figure 5.11. The slope values for the two broken sensors are added to the healthy slope values of Figure 5.10.

As expected, the slope of the broken sensor is consistently below the slopes of the healthy sensors. PZT CC, the debonded sensor, shows slope values higher than the healthy slopes susceptance values. PZT AA, the PZT with a 25 percent smaller area than the healthy sensors, has slope susceptance values consistently lower than each of the three healthy sensors for each temperature.

Now it is time to come up with a model to represent the healthy sensors and effectively sort out the broken sensors. This model will need to be implemented on SHM hardware similar to the system described in Chapter 4, so it is most logical to ensure that the model is as simplistic as possible. When permanently installed on a structure, the hardware should be completely autonomous with all the required operational power being harvested from ambient energy. Any savings in energy from reducing the computational power by keeping the algorithm efficient will help the goal of operating the system with energy harvesting as the sole source of power.

In the case of this structure, it seems that the most obvious solution is to model the slopes of the healthy sensor susceptances versus temperature seen in Figure 5.10. Using the same
technique to obtain the slopes of the susceptance, the line equations are generated for the three healthy sensors. To generate a single line, the mean of these line equations is used in order to base the model on the expected value of a healthy sensor. The slope of the susceptance $S$ is taken to be

$$ S = \mu_m T + \mu_b, \quad (5.12) $$

where $T$ is the temperature in degrees Celsius, $\mu_m$ is the mean of the susceptance slope values, and $\mu_b$ is the mean of the susceptance slope y-intercepts. This equation is based on the equation for the susceptance values $B$ as described in Figure 5.9.

$$ B = mf + b \quad 1000 \text{ Hz} < f < 20,000 \text{ Hz} \quad (5.13) $$

Here, $m$ is the slope of the susceptance, and $b$ is the y-intercept value. Obviously this equation does not describe the peaks seen in Figure 5.9, but only a straight line describing the expected value between 1 kHz and 20 kHz.

With the expected susceptance slope value for a healthy sensor defined, an expression of an acceptable range for healthy sensors needs to be characterized. A straightforward method of defining the boundaries is simply using the standard deviations of the susceptance slope values and susceptance slope y-intercepts. High $S_{\text{high}}$ and low $S_{\text{low}}$ susceptance slope boundaries can be described as

$$ S_{\text{high}} = (\mu_m + n\sigma_m)T + (\mu_b + n\sigma_b) \quad (5.14) $$

$$ S_{\text{low}} = (\mu_m - n\sigma_m)T + (\mu_b - n\sigma_b) \quad (5.15) $$

where $\sigma_m$ is the standard deviation of the susceptance slope values, $\sigma_m$ is the standard deviation of the susceptance slope y-intercepts, and $n$ is the number of standard deviations to use.

A model should be defined which describes the expected slope values of a healthy sensor for the frame structure at any temperature. Within some acceptable range, the sensors will be deemed healthy, but outside this range, it is likely the sensors have some sort of defect. Using
this newly generated model, the values taken experimentally in Figure 5.11 will be used to
determine if the model accurately represents what is happening with the structure. Three
standard deviations are used \((n = 3)\), and the new model and previous experimental values are
displayed in Figure 5.12.

**Figure 5.12.** The model accurately bounds the healthy sensors and identifies the defective sensors.

The model correctly identifies the defective sensors at each temperature. The healthy
sensors are bounded with the high and low slope model, and the broken sensors are both well
outside of this range even when using three standard deviations. The figures used to generate
this model (an example is seen in Figure 5.9) for each sensor at each temperature can be seen in
Appendix A. The values generated from this modeling are seen in Table 5.1.

With this model based only on experimental data, it is necessary to ensure the accuracy of
the results. In this case, the sample variation of the acquired data should not being greater than
sensitivity of the model. In Figure 5.9, four separate susceptance measurements are shown. All
four of the curves sit directly on top of one another and show little, if any, variation. Each of
these measurements is also averaged 2 times with the impedance analyzer. So, for each
temperature used to create the model, 24 averages are essentially used, with almost no variation
among each measurement. This yields a good indication that, in fact, the sensitivity of the model
is greater than the sample variation.

Table 5.1. The values used for the susceptance slope model are shown.

<table>
<thead>
<tr>
<th>$\mu_m$</th>
<th>$\mu_b$</th>
<th>$\sigma_m$</th>
<th>$\sigma_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.264 \times 10^{-9}$</td>
<td>$1.0703 \times 10^{-7}$</td>
<td>$2.212 \times 10^{-11}$</td>
<td>$3.712 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

A simple and effective model is now in place to detect any defective sensors. Next, it
would be desirable to use the sensors on the structure to look for any structural defects. Using
broken sensors when looking for damage is not acceptable, therefore, an algorithm is developed
to exclude the use of defective sensors in damage detection calculations. This algorithm
compares the slope of the susceptance for any acquired measurement to the values given by the
model. If the sensor is found to be defective, it will be excluded from any further damage
detection use. The algorithm used to simultaneously sort sensors and detect damage is detailed
as follows:

1. Enter the temperature. When this algorithm is implemented on hardware, the temperature
will be read automatically.
2. Open the data.
3. Find the susceptance from the real and imaginary curves using Equation 5.11.
4. Find the slopes of the susceptance for each sensor from 1 kHz to 20 kHz using the linear
least-squares approach previously described.
5. Set the number of standard deviations to use when defining the high and low model
boundaries.
6. Load the model values defined in Table 5.1.
7. Find the high and low boundaries using the temperature defined in Step 1.
8. If the susceptance slope for any of the sensors is higher than $S_{\text{high}}$, display ‘Sensor is
Damaged (Possibly Delaminated)’.
9. If the susceptance slope for any of the sensors is lower than $S_{low}$, display ‘Sensor is Damaged (Possibly Broken)’. 

10. If the sensor passes Steps 8 and 9, the damage detection process occurs. 

11. Using the Root Mean Square Deviation (RMSD) damage metric, real impedance signatures over a specified frequency are compared to a baseline. 

12. The real impedance curves and the damage metric values are the displayed in a figure. 

The RMSD described in Step 11 is used as a simple method to assess changes in the peaks of the impedance signatures by comparing individual peaks to see how much they changed. The RMSD method for finding the damage metric, $M$, can be described as

$$M = \sqrt{\sum_{i=1}^{n} \left( \frac{\text{Re}(Z_{i,1}) - \text{Re}(Z_{i,2})}{\text{Re}(Z_{i,1})^2} \right)^2},$$ 

(5.16)

where $Z_{i,1}$ is the baseline, or healthy, impedance of the PZT, and $Z_{i,2}$ is the impedance used for comparison with the baseline measurement at frequency interval $i$ (Park et al. 2003). It should be noted that Equation 5.16 is the same as Equation 2.2 and only placed here for convenience. Before the susceptance slopes are generated, the real impedance for each sensor is plotted to allow the user to detect any potential errors or hardware glitches from the data acquisition.

5.6 Model Verification

Using an initial temperature range from 15 °C to 65 °C, a model was generated to separate healthy from unhealthy sensors. Debonded sensors will be above the acceptable bounds for a well bonded sensor, and broken sensors will have lower susceptance slope values than the healthy sensors. A model working well in the temperature range it was defined in is expected, but now the robustness of the model needs to be tested in an expanded temperature range.

To verify the model for use over an expanded thermal range, the frame structure was placed back into the environmental test chamber. Again, a HP 4194A impedance analyzer is used to obtain measurements. The data acquisition settings remain the same, but for these experiments, data is only collected from PZTs B, AA, and CC. As with before, an appropriate
amount of time is allowed for each temperature to stabilize before the data collection process begins. Three temperature settings, 75 °C, 85 °C, and 95 °C, are used to test the model in an extended range. Figure 5.13(a) shows the slope of the susceptance at the new temperatures compared with the previously collected slopes. In Figure 5.13(b), the model is generated and plotted over the values.

![Figure 5.13](image)

**Figure 5.13.** The susceptance slopes at the new temperatures are shown with the previously collected values (a) and then compared with the model boundaries (b).

As Figure 5.13(a) shows, the slope of the susceptance at higher temperatures continues to follow the same linear trend as seen at the lower temperatures. Even more noteworthy is that when the model is overlaid with the experimental data (Figure 5.13(b)), the slopes at higher temperatures follow the guidelines set by the model. The susceptance slopes of PZT B are well within the acceptable bounds of the model, and are generally close to the expected value of the model. All of the slope values for PZT CC at elevated temperatures are greater than the high boundary, and, likewise, PZT AA slopes are less than the lower model boundary. These results indicate that the simple model generated in the previous section is well suited for sensor diagnostics detection at different temperatures.
5.7 Model Verification with Damage

The simple expected value model has proven to be effective at temperatures outside the initial thermal range. With the confidence in the model gained from the testing, the sensor diagnostics and damage detection algorithm is ready to be tested. While data was being collected to verify the model in the previous section, measurements at 75 °C, 85 °C, and 95 °C were also being taken with different damage states.

First, baseline real impedance measurements were taken for each temperature. As with the previous section, PZTs B, AA, and CC are used for this testing. The chamber was then reopened, and Clamp 2 was released. Disengaging the clamp should effectively simulate a loss of bold preload. To ensure a constant temperature for at each damage level for a valid comparison, the frame was brought back up to the desired temperature and allowed to come to equilibrium again before measurements were taken from each signal. The same process is then repeated, but, instead, Clamp 3 is opened and Clamp 2 is locked back into position.

Once all the data is collected, the sensor diagnostics and damage detection algorithm is executed. For this example, the 95 °C data is used, and the number of standard deviations is set to three. The frequency range used for damage detection is set from 30 – 50 kHz. Figure 5.14 shows the damage detection plot generated automatically by the algorithm.
On the display screen, the algorithm states that PZT CC is possibly delaminated. From Figure 5.13(b), this is deemed to be a true statement. Also the algorithm has successfully identified PZT AA as being broken. The output shown in Figure 5.14 is the damage detection plot calculated from PZT B, which, in this case, is the only healthy sensor. As seen in the top of Figure 5.14, the three real impedance curves lay on top of each other with variations in the peaks due to opening the two clamps. The consistency of the curves indicates that the structural temperature was the same for each test. In the bottom of Figure 5.14, the RMSD values are displayed. The bar colors match up with the corresponding real impedance signature color. The first bar compares two baseline measurements. A low, but non-zero, value is expected due to noise in the measurements. The second bar compares the signature acquired with Clamp 2 open to the baseline, while the third bar shows the comparison of Clamp 3 being open to the undamaged structure. Both of the damaged states are easily detectable. For this structure, a RMSD damage threshold level of around 0.5 seems reasonable. Anything above this level would likely be detected as damage. Also assuring is that the damage due to Clamp 3, with a greater force, is higher than that of Clamp 2.

For each of the other two temperatures, similar results were generated. The algorithm correctly excluded the two damaged PZTs from the damage detection process. Also, the results
of the damage detection remained the same, with the damage metric value for Clamp 3 being open greater than that for Clamp 2. Both of these damaged conditions are easily identifiable from the non-damaged state. For the frame structure, both the expected value model and the algorithm generated are very effective at temperatures within and outside of the initial model thermal range. With this model being effective on a structure with complex boundary conditions, it stands to reason that this type of sensor diagnostics modeling could work for any number of real world structures subject to varying temperatures.

5.8 Conclusions

In this chapter, a technique to separate temperature variations from sensor defects is presented for the impedance-based structural health monitoring technique. A frame structure is fabricated to simulate a real structure with complex boundary conditions for experimental testing in various thermal environments. The frame is equipped with locking clamps to provide a consisted method for applying damage. Three healthy and three damaged PZT patches are attached to the structure.

After acquiring impedance measurements in an initial limited temperature range, a model is developed to separate damaged from healthy sensors. The model is based solely on healthy sensor readings and temperature measurements. An algorithm is then formed using the model to exclude damage sensors from participating in damage detection on the structure. Experimental verification of the model and algorithm in an extended temperature range correctly identified damage sensors, carried out damage detection with the healthy sensors, and provided damage identification of the host structure.

Perhaps the greatest advantage of this temperature influenced sensor diagnostics method is the simplicity of the model. Only a few values need to be stored for the algorithm to be implemented on autonomous hardware. Obviously, temperature measurements will need to be included with the acquisition of each impedance signature. Adding temperature readings to hardware systems will only require a low amount of power dissipation. In the next chapter, sensor diagnostics techniques will be adapted for implementation on the hardware described in Chapter 4.
6.1 Introduction

In Chapter 4, the first autonomous impedance-based SHM system is described. With new structural excitation and sensing techniques, a completely digital prototype is developed. By avoiding reliance on ADC and DAC operations for sensing and excitation, the prototype’s physical dimensions and power dissipation are greatly reduced. The research presented in Chapter 5 introduces temperature compensation for the impedance sensor diagnostics technique. Sensor diagnostics allows for the detection of degraded sensors bonded to a structure. By excluding measurements from these sensors when interrogating for damage, the potential for misidentifying structural damage can be avoided. The model introduced in Chapter 5 allows for the sensor diagnostics method to be performed in cases where the temperature of the structure has changed from the baseline temperature. A method of adapting the sensor diagnostics technique described in the introduction to Chapter 5 will be adapted to the digital hardware described in Chapter 4 and presented in this chapter.

6.2 Sensor Diagnostics Simulation

As shown in Equation 5.9, by looking at the slope of the susceptance, one can not only characterize that a sensor is damaged but also quantify the amount of degradation. However, this physical representation of sensor condition does not easily translate directly to a completely digital system. The hardware introduced in Chapter 4 uses a rectangular digital signal to excite the structure at various frequencies. Structural response through the piezoelectric bonded to the
structure is also only measured via the digital signal representation of the voltage rather than multiple voltage levels. Variations between the reference signal directly generated by the pulse width modulator of the DSP and the measurement signal passing through the piezoelectric and comparator circuit represent the impedance of the structure (Kim et al. 2007a, 2007b). A baseline of variations is created and used for comparison to each subsequent measurement.

A variation count between these signals does not measure the admittance directly, but the generated signal is related to the admittance (Kim et al. 2007a, 2007b). The differences between the reference and measurement signals are caused by the phase delay of the signal passing through the PZT bonded to the structure. If the structure changes, the phase delay also changes and allows for the detection of damage by counting variations between these two signals.

Similarly, if the sensor breaks or delaminates, a change between the reference and measured signal should be observed. A completely intact and perfectly bonded sensor will have the greatest amount of interaction with the host structure. As the sensor degrades or delaminates, the ability of the PZT to both excite the structure and infer damage from structural response will be reduced. In Equation 5.9, when the capacitance control parameter $a$ or the electromechanical coupling factor control parameter $b$ are reduced, the equation is essentially saying that there is less dynamic interaction between the piezoelectric and the host structure. The signal generated by the measured path should therefore also change, but in a manner different than changes caused by damage. While a digital system does not allow for the slope of the susceptance to be directly observed, observing another feature might allow for the sensor changes to be identified.

In this chapter, it is proposed to monitor the variance of the variation count to detect sensor degradation. The variance $s^2$ of a set of $N$ measurements is defined as the sum of the squared deviations of each measurement from the mean of all the measurements and is described as

$$s^2 = \frac{\sum_{i=1}^{N} (y_i - \overline{y})^2}{N-1}$$

where $\overline{y}$ is the mean of the of the measurements (Ott and Longnecker 2001). As the dynamic interaction between the sensor and structure decreases, the ability to excite a high density of modes may be diminished. A lower variation over time could be observed for unhealthy sensors.
Saint-Pierre et al. (1996) and Giurgiutiu et al. (2002) noted that as a sensor delaminates from the structure, the magnitude of the structural peaks on the impedance signature diminishes. These lowered peak magnitudes, or even the disappearance of structural peaks, would cause the overall variance of the impedance signature to decrease. This general method, as opposed to measuring the slope of the susceptance, is what will be adapted to the digital impedance hardware. The main difference is that Saint-Pierre et al. and Giurgiutiu et al. focused on observing the piezoelectric resonance while this method will avoid the piezoelectric resonance and focus on structural peaks.

To test the ability of the variance of the variation count to be an indicator of defective sensors, an experiment is conducted on the frame structure detailed in Chapter 5. Using PZTs B, healthy (PZT B), broken (PZT AA), and delaminated (PZT CC) sensors, data is collected with an HP 4194A impedance analyzer. The real and imaginary components of the impedance are collected in the frequency range of 1000 to 32,980 Hz with a frequency resolution of 20 Hz. The frequency range is within both the range used for damage detection and the range usable by the digital impedance system described in Chapter 4. Medium integration with two averages is used with an excitation amplitude of 1 Volt. Seven measurements are taken for each of the three sensors.

As shown in the previous chapter, the susceptance shows a clear difference in the slopes of these three signals. With the digital hardware limitations, the susceptance cannot be generated. The closest signal obtainable with an impedance analyzer to the measurements generated with the digital hardware is the phase of the admittance. Figure 6.1 displays an example of the phase for each of the three sensors.

The phase changes shown in Figure 6.1 are largest for the PZT B, the healthy sensor. PZT AA and PZT CC show significantly reduced phase changes. The signal generated by the digital hardware is related to the phase change, so the concept of identifying damaged sensors with the variance is promising.

For each of the acquired measurements, the variance of the phase is calculated. As expected, PZT B, the healthy sensor, has the highest variance. The two variances for the broken and debonded sensors are significantly lower. Table 6.1 summarizes the average variance for each of the three sensors.
Table 6.1. The average variance over seven measurements for each of the three sensors is summarized.

<table>
<thead>
<tr>
<th></th>
<th>PZT B (Healthy)</th>
<th>PZT AA (Broken)</th>
<th>PZT CC (Delaminated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
<td>8.0 x 10^{-4}</td>
<td>2.3 x 10^{-4}</td>
<td>6.0 x 10^{-4}</td>
</tr>
</tbody>
</table>

Table 6.1 reveals the possibility of the variance in detecting damaged sensors. Without being able to examine the actual signal generated by the hardware, the result of this test are only preliminary. Each sensor’s measurement group is now expanded to 35 readings from the impedance analyzer. The variance for the admittance phase in recalculated. The average variances of the phase changed to 8.3 x 10^{-4} for PZT B, 2.2 x 10^{-4} for PZT B, and 6.3 x 10^{-4} for PZT CC.

Of course the main concern with checking the variance of the phase is that when an intact sensor is completely detached from the structure, the piezoelectric resonance amplitude could influence the phase enough to cause a large variance shift. Saint-Pierre et al. (1996) and Giurgiutiu et al. (2002) noted that as a sensor debonds, the magnitudes of the mechanical peaks diminish, but the piezoelectric natural frequency peak is more distinct. The frequency range of
interest here (1-32.98 kHz) is well below the first PZT resonance (around 88 kHz) for this PZT type and size. However, the unbonded admittance phase and phase variance should still be checked. Figure 6.2 displays the admittance phase for the three sensors.

![Figure 6.2. The admittance phase of three unbonded sensors is shown from 1000 to 32980 Hz.](image)

As revealed in Figure 6.2, the phase for each of the three sensors shows minimal change over the frequency range used for damage detection. Without a piezoelectric resonance in the frequency range of interest, the phase change for a free-free sensor should be minimal. The variance for these phases should also be small for this frequency range. However, a piezoelectric resonance has a significant influence on the phase. Figure 6.3 shows the admittance phase for each of the three unbonded sensors over a larger frequency range from 1000 to 104,080 Hz. Around 88 kHz, the PZT resonance, a resonant phase change is seen for each of the sensors.
Figure 6.3. The admittance phase of three unbonded sensors is shown from 1000 to 104,080 Hz.

Figure 6.3 visually demonstrates the effect of a piezoelectric resonance on the phase. The variance of the admittance phase for each of the three sensors in both frequency ranges seen in Figure 6.2 and Figure 6.3 are calculated and displayed in Table 6.2. Including a piezoelectric resonance in the variance calculation is numerically demonstrated in the results of Table 6.2.

Table 6.2. The variances for unbonded PZTs in two frequency ranges are shown.

<table>
<thead>
<tr>
<th></th>
<th>PZT B (Healthy)</th>
<th>PZT AA (Broken)</th>
<th>PZT CC (Delaminated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000-32,980 Hz</td>
<td>1.3 x 10^-4</td>
<td>2.0 x 10^-4</td>
<td>1.4 x 10^-4</td>
</tr>
<tr>
<td>Variance</td>
<td>0.77</td>
<td>0.78</td>
<td>0.79</td>
</tr>
<tr>
<td>1000-104,080 Hz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The piezoelectric resonance increases the admittance phase variance by four orders of magnitude. As expected, the phase variances in the 1000 to 32,980 Hz range are on the same order of magnitudes as the values displayed in Table 6.1 for the various bonded sensor conditions. Of particular interest is that the phase variances for each of the unbonded sensors are
all smaller than the 50 percent delaminated sensor’s phase variance and significantly lower than the healthy sensor variance. As the sensor moves closer to free-free conditions, the variance should decrease toward the unbonded sensor variance. With these initial results, this sensor diagnostics algorithm is introduced to the impedance-based SHM prototype. As long as the piezoelectric resonance is out of the measured frequency range, this method should be effective at identifying unhealthy sensors.

### 6.3 Digital Hardware Sensor Diagnostics Implementation

As introduced in Chapter 4, a digital impedance-based health monitoring system is used for these experiments. The prototype is implemented on a TMS320F2812 evaluation board with a 150 MHz DSP from Texas Instruments. For this testing, the prototype is set to operate at the maximum operating clock (150 MHz) and peripheral clock (150 MHz) frequencies.

To observe sensor health, the variance of the variation count will be observed. Results from the previous section would indicate that using the variation may lead to an inability to distinguish broken and delaminated sensors from each other. However, the goal of this testing is to distinguish unhealthy from healthy sensors.

To test the ability of the variation to detect defective sensors, the PZTs on the frame structure are connected to the hardware. The variance of the variation count is measured for each of the healthy PZTs (A, B, and C) as well as the broken (AA) and delaminated (CC) sensors. For each sensor, the variance is calculated with each variation count measurement (related to the admittance phase) generated, and ten variances are averaged for comparison. The results of this testing are summarized in Table 6.3.

<table>
<thead>
<tr>
<th></th>
<th>PZT A (Healthy)</th>
<th>PZT B (Healthy)</th>
<th>PZT C (Healthy)</th>
<th>PZT AA (Broken)</th>
<th>PZT CC (Delaminated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
<td>5278</td>
<td>7944</td>
<td>6799</td>
<td>3567</td>
<td>4799</td>
</tr>
</tbody>
</table>

As Table 6.3 reveals, the average variance for the two damaged sensors is noticeably lower than the variances of the three healthy sensors. Remember that PZT AA is bonded directly underneath PZT A on the top of the structure. The same relation holds true for PZTs C and CC.
The variance value for broken PZT AA is 32 percent lower than variance of healthy PZT A. PZT CC, the debonded sensor, has a variance 29 percent less than PZT C, one of the healthy sensors. The average of the two unhealthy sensor variances values are 39 percent less than the three healthy sensors. As expected with this metric, there is an inability to distinguish between broken and delaminated sensors, and only an indication of whether the sensor is healthy or damaged is shown. With this variance metric, as long as the variance is measured with each impedance signature, sensors should be detected as they degrade. Similarly to determining damage, a threshold variance reduction percentage could be established and compared with the average sensor variance. If one or more of the sensor variances decreases below this threshold, the sensor may be damaged.

As described in Chapter 2, Code Composer Studio software allows for the visualization specific memory locations in the DSP core (Texas Instruments 2005a). To provide another indication that this sensor diagnostics scheme is working, Code Composer Studio is used to observe the variation count signatures for healthy and unhealthy sensors. When calculating the variance, the average of the variation count values for each of the sensors is nearly identical. However, for the healthy sensors, larger individual peaks are seen. These larger peaks indicate a larger dynamic interaction with the host structure and are what lead to a larger variance value. Figure 6.4 displays the variation count measurements for PZT A (a) and PZT AA (a).

![Figure 6.4](image)

Figure 6.4. The variation count measurements for PZT A (a) and PZT AA (b) are shown.

As seen in Figure 6.4(a), there is one large peak different from that of Figure 6.4(b). While the rest of the peaks curve remains similar for both figures, this one large peak is what
distinguishes the variance values between the two. The overall y-axis range is much larger in Figure 6.4(a). This same trend is seen in the variance count measurement figures for PZTs C and CC.

While the variance sensor diagnostics metric appears to distinguish between healthy and damaged sensors when the structure is unchanged, the metric should also do the same for a damaged structure. Any structural change should cause changes in measurements seen in both healthy and damaged sensors, unless the sensors are completely delaminated or broken. However, with a greater dynamic interaction in the healthy sensor and structure, the change should be greater for the healthy sensors and the variance of the broken sensor should still be distinctively lower. Clamp 2 on the structure is released, measurements for each of the sensors are reacquired, and the variances are recalculated. From the previous testing, it is observed that the variance values did not vary much over the ten measurements, so only five averages are taken for each sensor in this testing. The new variances for each of the sensors are displayed in Table 6.4.

<table>
<thead>
<tr>
<th>PZT</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4450</td>
</tr>
<tr>
<td>B</td>
<td>4014</td>
</tr>
<tr>
<td>C</td>
<td>4334</td>
</tr>
<tr>
<td>AA</td>
<td>2979</td>
</tr>
<tr>
<td>CC</td>
<td>3957</td>
</tr>
</tbody>
</table>

Table 6.4. The average variance over five measurements is displayed for each PZT with Clamp 2 released.

Again, the broken and delaminated sensor average variances are lower than the healthy sensor. At each sensor location, the unhealthy sensor is distinguishable from the healthy sensor. A variance difference of 33 percent and 9 percent are seen for the broken and delaminated sensors as compared with the healthy sensor at their same location. PZT AA, the broken sensor, is expected to be slightly more influenced by the damage than PZT CC as it is closer to Clamp 2, and indeed there is less distinction then without damage. Even with damage, it seems that the variance should still be able to determine which sensors are unhealthy. All of the sensor variances will change; however, a damaged sensor’s variance will remain below that of a healthy sensor. As one last check, Clamp 2 is reengaged and Clamp 3 is released. The results are presented in Table 6.5.
Table 6.5. The average variance over five measurements is displayed for each PZT with Clamp 3 released.

<table>
<thead>
<tr>
<th></th>
<th>PZT A (Healthy)</th>
<th>PZT B (Healthy)</th>
<th>PZT C (Healthy)</th>
<th>PZT AA (Broken)</th>
<th>PZT CC (Delaminated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
<td>4045</td>
<td>3687</td>
<td>4333</td>
<td>2968</td>
<td>3853</td>
</tr>
</tbody>
</table>

For the broken sensor, a 27 percent decrease in variance is seen from the healthy case. An 11 percent decrease in variance is seen for the delaminated PZT. As expected, with damage closer to PZTs C and CC, the sensor differences are slightly more noticeable, while the broken PZT is slightly less distinguishable. Also, more of PZT AA is in contact with the structure that PZT CC, so the relative change between PZTs A and AA with structural damage may be less than the change between sensors C and CC.

### 6.4 Conclusions

In this chapter, a new sensor diagnostics scheme is developed for use with digital, autonomous SHM hardware. By observing the variance of the generated variation count signatures, unhealthy sensors can be distinguished from healthy sensors. This new method is similar to the techniques developed by Saint-Pierre et al. (1996) and Giurgiutiu et al. (2002). However, in the previous methods, observing the piezoelectric resonance was crucial to determining whether or not a sensor was debonded from the structure. In this new technique specifically for digital impedance hardware, the piezoelectric resonance is avoided. This new method is also able to detect broken sensors as well as delaminated sensors, where Saint-Pierre et al. and Giurgiutiu et al. only observed sensor debonding.

To test the validity of this new technique, initial experiments are conducted with an impedance analyzer. Using the frame structure with attached PZTs from Chapter 5, the phase of the admittance is observed. The admittance phase is used due to its relation with the measurements generated with the digital prototype. Calculating the variance of the admittance phase, the unhealthy sensors are distinguishable from healthy sensors. This techniques is then implemented on the digital hardware described in Chapter 4. With or without damage to the structure, the unhealthy sensors display a noticeably lower variance than the healthy sensors. A higher dynamic interaction is seen between the healthy sensors and the frame structure, which leads to structural peaks with a larger magnitude and an increased variance.
Chapter 7: Conclusions

Autonomous structural health monitoring is an essential component in developing the multifunctional, autonomic structures of the future. In this dissertation, many of the key research topics for developing autonomous SHM systems have been presented. Specifically, the research presented here focused on the development of the impedance method for SHM. When using the impedance method, high frequency excitations are generated to stimulate the structure of interest with a piezoelectric patch bonded to the surface. The piezoelectric patch acts as a self-sensing actuator to simultaneously excite the structure and record structural response. By comparing impedance signatures to a previously stored baseline, indications to the health of the structure can be inferred. This chapter will provide a brief summary of the results, indicate research contributions, and provide recommendations for future work.

7.1 Brief Dissertation Summary

In Chapter 2, the development of a digital signal processor based prototype is described in relation to continuing efforts for realizing a fully self-contained active sensor system utilizing impedance-based structural health monitoring. The active sensing system detailed in this research interrogates a structure utilizing a self-sensing actuator and a low cost impedance method. The DSP core of the system controls structural excitation, data acquisition, and all the damage detection analysis. Any damage findings are wirelessly transmitted to an end user. A complete power analysis of the prototype is performed to determine the validity of power harvesting being utilized for self-containment of the hardware. Experimental validation of the prototype on a representative structure is also performed and compared to traditional methods of damage detection.
Thermal protection systems on aerospace vehicles are an extremely important component in maintaining the overall health of the vehicle. The research presented in Chapter 3 provides insight into the ability of the impedance method to detect damage on complex TPS. A structure is fabricated to resemble the fuselage and external TPS tiles of a Space Shuttle Orbiter. This representative fuselage is equipped with piezoelectric sensors at three different locations. Damage is cumulatively introduced to the tiles in the form of delaminations, and the impedance technique is shown to be sensitive to this damage. The whole fuselage is placed in a temperature controlled chamber, and damage sensitivity to the TPS tiles is still maintained.

Energy harvesting from ambient thermal gradients is achieved when thermoelectric materials transform temperature gradients into a voltage. Using the appropriate circuitry and a power storage mechanism, these voltages can be used to charge standard, commercially available lithium ion cells and nickel-metal hydride batteries. In Chapter 4, the standard DC power supply to an impedance-based prototype is removed, and the batteries provide the only power source for the digital, DSP hardware. All operations required to perform autonomous impedance-based SHM are supplied power with the batteries. Both the battery discharge and recharging characteristics are described. The time available for SHM operation with batteries, along with the system duty cycle, are also disclosed.

Chapter 5 provides an introduction to sensor diagnostics for the impedance method. While the sensor diagnostics technique described is very useful in detecting damaged sensors bonded to a structure, the method is very susceptible to temperature variations. A frame structure with both healthy and damaged sensors is fabricated. This structure is placed in an adjustable temperature chamber, and the piezoelectric sensor response is recorded over a range of temperatures. The susceptance of the piezoelectric sensor is used to generate a model predicting piezoelectric susceptance slope at any temperature. The structure is placed back in the environmental chamber, and the model is validated with an extended temperature range.

Completely digital hardware for the impedance method provides a good basis for developing a low-powered autonomous system which can be permanently attached to a host structure. However, losing the ability to analyze sampled analog data can provide challenges for incorporating different types of structural health monitoring functionality, including sensor diagnostics. In Chapter 6, a new technique utilizing the variance of the variations between two comparative signals is proposed to act as a digital method for impedance-based sensor
diagnostics. Initial testing indicates that the variance sensor diagnostics algorithm can successfully identify degraded PZTs from healthy sensors. However, there is a limitation of not being able to distinguish broken from delaminated patches.

### 7.2 Contributions

The first fully self-contained impedance device is developed in Chapter 2. In the previous hardware system MASSpatch, embedded structural excitation was not included in the final system package. An external function generator was used to excite the structure while MASSpatch recorded the response and carried out the rest of the SHM operation. In contrast, the system described in Chapter 2 performs all of the health monitoring steps automatically. By switching to a DSP platform from a single board computer, reliance on an operating system is avoided, and the damage detection process and algorithm can be optimized for power reduction. The need for post processing measurements taken by an impedance analyzer is also avoided. The current system effectively replaces an impedance analyzer and MATLAB. All of the structural excitation, data acquisition, and health monitoring analysis are performed in a matter of seconds. Each new impedance-based hardware system will build on the knowledge gained from this prototype. As seen in Chapter 4, a system has already been developed to operate completely autonomously.

A second contribution is the first use of sinc functions for exciting structures when using the impedance method. The use of sinc functions provides multiple advancements in developing autonomous SHM hardware. First, the time required for excitation is greatly reduced by exciting multiple frequencies in a single sinc pulse. Prior to sinc functions, typical structural input was swept sine signals or exciting each frequency individually, recording the response, and moving on to the next frequency. By reducing the time required to excite the structure, the power consumption of the hardware is also greatly reduced.

Thermal protection systems are generally very complex, making damage detection a difficult process. In addition to the complexity these structures, the availability of optimal sensor locations for monitoring the structure is limited by the nature of vehicle reentry into Earth’s atmosphere. The research presented in Chapter 3 illustrates the ability of the impedance method to detect damage in complex TPS. Small delaminations from the fuselage of a 188 g tile are
detected with the impedance method. All of these measurements are conducted from what would be the inside, or “cool” side, of the fuselage. Two of the sensors are even able to detect this damage through riveted boundary conditions. Other structural health monitoring techniques, specifically Lamb wave damage detection, are generally not well suited to detecting damage through boundary changes or with sensors located on a different surface than the damage. The impedance method was also shown to still be sensitive to this damage at elevated temperatures.

The results of Chapter 4 illustrate the first impedance-based SHM device to operate completely autonomously. All of the other hardware developed for the impedance method has relied on external power supplies to operate. In this study, the power supply is removed, and all the power required for the impedance-based damage detection is supplied from battery power. These batteries are charged using thermal energy harvesting. The thermal gradients used are typical of what might be found in a real operational structure or vehicle.

A model for accurately performing impedance-based sensor diagnostics at elevated temperatures is developed in Chapter 5. In previous research, a technique was developed to separate unhealthy from healthy sensors independent of the temperature (Overly et al. 2007b). The developed algorithm correctly identifies damaged sensors, but each sensor must be compared to the others several times to identify sensors which are statistically different from the group. An algorithm like this may be computationally taxing to implement on an autonomous hardware system and does not compare each individual sensor to a standard guideline of what a healthy sensor’s output should indicate. In contrast, the model developed in this dissertation only requires each sensor be compared to a value predetermined by the model. To generate the model, a structure with complex boundary conditions was tested in an extended thermal range, and the temperatures were expanded to validate the model. The Overly et al. (2007b) method was performed on a free-free plate, and only a limited temperature range was used.

Perhaps the greatest contribution of this model is its simplicity. This uncomplicated model is well suited for implementation on hardware. Only four numbers need to be stored in the hardware to generate the model. Once the temperature measurement is recorded, the slope of the susceptance for each piezoelectric is calculated and compared with the high and low values generated by the model. The low complexity of this algorithm will help to reduce the overall power consumption of an autonomous system so that the device can be used with energy harvesting.
In Chapter 6, a new sensor diagnostics method is developed for use with digital hardware. The features used for sensor diagnostics presented in Chapter 5 are inaccessible with a digital system. A new method based on the variance of the variation count between the two prototype measurement signals is introduced. The variation count is related to the phase of the admittance. Saint-Pierre et al. (1996) and Giurgiuțiu et al. (2002) noted that as a sensor delaminates from the structure, the magnitude of the structural peaks on the impedance signature diminishes. If the magnitudes of the peaks are decreased, the overall variance of the admittance phase will decrease. This technique is developed around avoiding the resonance of the piezoelectric patch, where Saint-Pierre et al. and Giurgiuțiu et al. focused on observing the piezoelectric resonance. The method described in this dissertation is also able to detect broken sensors as well as delaminated sensors, while the previous work only focused on sensor debonding. The influence of damage on the diagnostic values is also documented, and the unhealthy sensors are still detectable. Structural damage was not included in the previous research. This research notes the first time sensor diagnostics has been used with a completely digital prototype.

7.3 Future Work and Recommendations

As seen in Chapters 4 and 6, an upgrade to the DSP-based impedance method prototype presented in the Chapter 2 already exists. In addition to the new single board prototype, the impedance damage detection algorithm has also been implemented on a microcontroller platform. The ultimate goal of all these hardware configurations is to develop an autonomous prototype with power requirements equivalent to the power generated with energy harvesting circuitry. As Chapter 4 reveals, if adequate thermal gradients are available, energy harvesting can be effectively used to sustain limited operation of an impedance SHM prototype. However, the power dissipation must be greatly reduced for vibration-based energy harvesting to become a viable option.

Eventually, with the knowledge gained from these prototypes, new impedance-based hardware can be custom designed with components specific to the project. All this research leads to the eventual goal of having a completely autonomous, impedance-based SHM system contained on a single chip. The next step will be to use a microcontroller or DSP in a custom printed circuit board (PCB) design. With a PCB containing only the components necessary for
operation, as opposed to the unnecessary features of an evaluation board, the operational power should be greatly reduced. Once the PCB design is complete, work can begin on integration of the impedance hardware, including all the local excitation and computing, energy harvesting circuitry, and wireless communications, into a single chip. To incorporate all of these complex components into one functional chip, very-large-scale integration (VLSI) design will be utilized. VLSI allows for analysis and design of very dense and complicated electronic integrated circuits.

Along with the development of an autonomous VLSI chip, emphasis will be placed on obtaining a highly robust structural interrogation scheme. While the impedance method is very sensitive in detecting localized damage on a structure, limitations often prevent the method from accurately identifying damage location and severity. Combining impedance techniques with other damage detection schemes will provide the most realistic chance of developing a structural health monitoring and damage prognosis system accurate enough to be trusted for use on critical structures. Of particular interest for a combined detection system are guided wave or Lamb wave techniques (reviewed by Raghavan and Cesnik 2007b). An envisioned damage detection system might utilize the impedance method to actively search for the presence of damage. The sensitivity of the impedance method to even incipient damage lends itself quite well to revealing any damage. Lamb wave techniques might then be used to pinpoint the exact location of any structural deformity and determine the severity of any damage. The added advantage of impedance and Lamb wave techniques is that they both utilize the same piezoceramic sensors. In an implemented system, once certain PZTs detect damage with the impedance method, the exact same sensors could then be used to locate the damage with Lamb waves. These piezoelectric sensors could also be used to passively listen for impacts or structural damage with acoustic emissions. With a SHM system developed on a VLSI chip, complex signal processing techniques from multiple methods and advanced feature extraction algorithms can enhance the damage detection capabilities of the autonomous smart sensor.

Utilizing standard, professionally cut piezoelectric patches is one area to improve the sensor diagnostics model developed in Chapter 5. All the PZTs used for the study were cut by hand. While great care was taken to ensure that each patch was the same size and capacitance, there were still small variations seen between each of the sensors. Using standard piezoelectric patch sizes should actually decrease the width of the healthy sensor susceptibility range at each temperature. The method would then be even more sensitive to low levels of sensor breakage or
delamination. Also, a larger number of sensors, both healthy and damaged, should be used in the study to increase the statistical precision of the model.

For adapting sensor diagnostics to digital hardware, the most important area of future work is finding a way to distinguish between sensor breakage and sensor debonding. All of the features able to be observed by the hardware must be carefully investigated for their sensitivity to sensor breakage or delamination. A structure with an increased number of sensors, as discussed above, will help in this task. The final sensor diagnostics method should also be automated similar to the detection of damaged sensors in Chapter 5.
References


Appendix A: Figures for Sensor Diagnostics Model
Figure A.1. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 15 °C.
Figure A.2. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 20 °C.
Figure A.3. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 25 °C.
Figure A.4. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 30 °C.
Figure A.5. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 35 °C.
Figure A.6. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 40 °C.
Figure A.7. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 45 °C.
Figure A.8. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 50 °C.
Figure A.9. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 55 °C.
Figure A.10. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 60 °C.
Figure A.11. Susceptance is shown for PZTs A (a), B (b), C (c), AA (d), CC (e), and all five sensors (f) at 65 °C.
Vita

Benjamin L. Grisso was born on March 9, 1980 to Kenneth and Suzanne Grisso in Warsaw, Indiana. Ben was raised in Grandville, Michigan and graduated from Grandville High School in June of 1998. In the fall of 1998, he started pursuing his undergraduate degree from Michigan Technological University. Ben graduated Summa Cum Laude from Michigan Tech with a Bachelor of Science degree in Mechanical Engineering in May of 2002. Deciding to continue his mechanical engineering education, he started graduate studies at Virginia Polytechnic Institute and University in August of 2002. In May of 2003, he was offered a Graduate Research Assistant in the Center for Intelligent Material Systems and Structures (CIMSS). His research focused on using the impedance method for structural health monitoring to detect damage in composites and constructing a self-contained wireless system prototype utilizing the impedance method. After completion of his Masters of Science degree at Virginia Tech on August 31, 2004, Ben continued working in CIMSS towards his Doctorate of Philosophy in Mechanical Engineering under the support of a National Science Foundation grant. His research was focused on developing autonomous hardware for the impedance method. After completion of his Ph.D. in the fall of 2007, Ben will work as a postdoctoral researcher in CIMSS focusing on combining the impedance method with other structural health monitoring techniques for the development of robust, autonomous damage detection systems.

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