DAMAGE DETECTION IN COMPOSITE MATERIALS USING PZT ACTUATORS AND SENSORS FOR STRUCTURAL HEALTH MONITORING

by

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ABSTRACT

Structural Health Monitoring (SHM) of bridges, buildings, aircrafts, and spacecraft using a network of sensors has gained popularity over recent years. In this thesis, the use of piezoelectric actuators and sensors is described for detecting damage in a composite panel. The composite panels are fabricated using the Vacuum Assisted Resin Transfer Molding (VARTM) process. The panels are cut into small coupons (254 mm x 25.4 mm) to test various properties of the composite. A piezoelectric actuator is surface mounted on the composite coupon to generate Lamb waves while a surface mounted piezoelectric sensor measures the response. Data is collected from an undamaged composite coupon, and then the process is repeated for a damaged coupon. The existing damage is quantified by comparing the response of the damaged and undamaged composite coupons.

LIST OF ABBREVIATIONS AND SYMBOLS

CFRP	Carbon fiber reinforced polymer
DAQ	Data acquisition
FBG	Fiber Bragg Grating
FEM	Finite element method
GPIB	General purpose interface bus
NDE	Non-destructive evaluation
PZT	Lead zirconate titanate
SHM	Structural health monitoring
VARTM	Vacuum assisted resin transfer molding

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CHAPTER 1: INTRODUCTION

Structural Health Monitoring (SHM) is the monitoring of different structures to determine their health. The main use of SHM is to determine current failures and classify the severity of damage. By detecting and defining the severity of existing damage, SHM can aid in forecasting the remaining duration of a structure's lifespan [1]. It is seen that all load-bearing structures will acquire some type of damage over their lifespan [2]. Such damage can lead to catastrophic and expensive failures [3]. Inspection and repair of damage can cost around 27% of an aircraft's life cycle [4]. SHM has gained popularity over the years in the research community for all of the different approaches used in this damage detection. Cost saving research is currently being done by embedding sensors, which allow for continuous real-time reading. Furthermore, by employing a circumstantial damage based maintenance approach, as opposed to a more traditional approach of time-in-service based maintenance, SHM can provide both safety and cost improvements [1].

Bridges, buildings, ships, aircrafts, and spacecraft are a few examples of structures that use this technique for damage detection [5, 6, 7]. Not only does this damage detection technique save money, but it is used for many different reasons including an increase in safety. Many accidents have happened in the past, such as collapsing of bridges and crashing of airplanes and space shuttles that could have possibly been prevented if this technique of SHM was in place.

Early damage detection is the optimal solution for different classifications of damage. SHM is an evolution of techniques known as non-destructive evaluation (NDE), where external actuators and sensors are tailored to obtain the maximum desired signal while maintaining a safe and non-invasive environment [1,8]. The process begins with setting up a data acquisition system to gather the data, implementing or testing the damage, compiling data to get results, and classification of the damage that has been detected. The data acquisition system setup can vary based on the number, type, and/or location of the sensors and signal transmission/actuation. SHM makes use of fixed actuators and sensors, which cannot be ensured to be non-invasive [1]. By allowing fixed actuators and sensors to be on a structure constantly, its condition can be monitored continuously in order to extract dynamic damage information and prevent service downtime by less human interaction [1]. Damage testing depends not only on the chosen parameters in the data acquisition, but also on the damage expected. Once the solution has been defined, it can be implemented to avoid future extensive damage.

The main material chosen by aerospace, automotive and many other industries to improve their product is carbon fiber reinforced polymer (CFRP) composite. CFRP is being used in the manufacturing of aircrafts, cars, bicycles, etc. This composite has been chosen for its lightweight, high stiffness and strength, and low cost. As compared to metal structures, damage detection in composite materials can be challenging with multiple ply numbers and orientation layups; therefore, early life cycle damage detection is crucial to lengthening a composite structure's life and ensuring ultimate performance [1]. Over the CFRP composite lifetime, fatigue, impact, and environmental effects can cause damage. Thus, damage detection becomes an important research topic to improve the lifespan and performance of the structure.

This thesis is divided up into six chapters. Chapter 1 gives a brief introduction of the thesis topic. Chapter 2 gives a brief overview of different points from multiple sources on the topic of SHM. The chapter also goes into detail on variable setups and detection determinations. In addition, this chapter provides a description of Lamb waves and their use in damage detection. The composite panels are fabricated at the University of Alabama, using the Vacuum Assisted Resin Transfer Molding (VARTM) process. The panels are then cut into small coupons (254 mm x 25.4 mm) to test various properties of the composite. These details are presented in Chapter 3. The experimental setup utilizes a piezoelectric actuator, surface mounted on the composite coupon, to generate Lamb waves while a surface mounted piezoelectric sensor measures the associated response. Details of the damage detection procedure are discussed in Chapter 4. Chapter 5 describes results from the data which are taken from both an undamaged and damaged composite coupon. The specific amount of damage is detected by comparing the response of the damaged and undamaged composite coupons, and calculating the magnitude of the difference between the results. Conclusions and future potential work are presented in Chapter 6.

CHAPTER 2: LITERATURE SURVEY

2.1 Sensing and Actuation methods

Smart material technologies and damage detection are among some of the most commonly researched topics in SHM [4]. Some source of excitation and sensing is needed in all cases of damage detection; however, researchers have different views on what types of excitation or sensing provides the most accurate results. One consistency with the choice of actuation and sensing is that the technique should be non-destructive. Sun et al. developed impedance based techniques which represents non-destructive evaluation methods [9]. Impedance–based techniques have been shown to help with receiving real-time responses and potential problems with temperature changes and boundary conditions [10]. Some other non-destructive techniques being used include scanning laser vibrometer, resonant ultrasound spectroscopy, radiographic, and hydro-ultrasonic [11, 12].

Another method for detecting damage involves the use of sensors where a wide variety of sensor types are being utilized; a few examples are Fiber Bragg Grating (FBG), strain gauges, and Piezoelectric sensors. The advantages of a Fiber Bragg Grating (FBG) sensor is that the sensors are small, lightweight, flexible, and require no electrical connection, which makes them optimal for embedding applications [13-18]. With embedding these sensors, there are a few consequences. FBG sensors, being fragile, could possibly damage the structure while embedding, and it is not possible to know the exact location of the embedded sensor. Further, the wavelength of the reflected light is determined by the period of the Bragg grating which changes when strain is applied to a structure [19]. High frequency ranges are used when using FBG sensors to detect damage [20]. This process works if the sensor is surface mounted or embedded into the structure. Strain gauges are inexpensive, small, and easy to implement.

Strain gauges show a change in resistance when a mechanical stress or strain is applied. Disadvantages of the strain gauges include a low lifespan, limited temperature ranges, and sensitivity; sensitivity being the major disadvantage due to the area which a strain gauge covers. If strain gauges are used on a large structure, a high number of sensors would be needed [2].

Piezoelectric transducers are lightweight, sensitive and very responsive to small amounts of strain producing high amplitude. Piezoelectric transducers can be made from different materials some of which include lead zirconate titanate (PZT), lead titanate, and polyvinylidene fluoride. The advantage of a PZT transducer is that it can be used as an actuator or a sensor. One disadvantage is that these sensors, unlike the FBG sensors, are not flexible. Further research is currently being done to create a PZT sensor that is flexible and smaller in size. If embedding the sensors the temperature levels of the fabrication process will be of importance, to not change the sensors. PZT sensors and actuators were chosen for testing during this research.

Some researchers classify use of sensors and actuators as semi-destructive because of the fact that they must be bonded and removed for testing purposes. Although, with real-world damage detection, one of the benefits of this semi-destructive method is that it allows for continuous remote monitoring for damage [4]. However, this would entail that the sensor be embedded within the structure. Embedding of the sensors reduces the associated testing errors as well as the structure down time. While some researchers suggest that the sensor performance is the same if embedded or not [21], further research is being conducted in order to prove the amount of destruction caused by embedding sensors.

When a PZT transducer is used as an actuator, an electrical charge is produced when mechanical stress is experienced [22]. PZT actuators transmit the Lamb waves. The details of this Lamb wave such as frequency, voltage amplitude, number of cycles, and pulse shape are still being investigated. Low frequencies are more sensitive to damage detection. In SHM, low power is often a requirement; with this requirement low voltage amplitude is often chosen. The number of cycles and pulse shape are varied. The commonly observed shapes are hanning and sine at 3-5 cycles. For the work presented in this thesis, a five cycle hanning and a three cycle sine were chosen.

2.2 Lamb Waves

Many researchers have used a Lamb wave methodology for detecting damage. Lamb waves are elastic waves and a reliable non-destructive way of detecting damage in structures. By using Lamb waves, various types of damage (internal and surface) can be detected. Horace Lamb described and analyzed Lamb waves and showed that Lamb waves can move freely through a solid plate with free boundaries due to elastic perturbation [23]. Based on different parameters of the Lamb wave, the identification of damage becomes straightforward. Lamb waves can vary in pulse shape, frequency, amplitude, and number of cycles. Researchers have taken different approaches to determine which of these gives the best results for damage detection applications. Kessler has shown damage detection results for 15 kHz and 3.5 cycles which were seen to be an optimal form of actuation. Similarly, frequencies less than 50 kHz were shown to be particularly sensitive by Diamanti and Soutis [4]. Lamb waves are capable of traveling long or short distances and through thick or thin plates [24].

There are two fundamental modes that can be generated with Lamb waves. These modes are seen to be either symmetric (S_0) or anti-symmetric (A_0). The sensitivity of damage is seen to give better responses at certain frequencies and modes. It is noticed that frequencies below 50 kHz, Lamb mode A_0 is generated with a smaller wavelength than A_0 modes, making it more accurate in detecting damage. The following are two methods used to perform the analysis of damage detection: 1) the pulse-echo method and 2) the pitch and catch method. The pulse-echo method consists of one transmitter that generates the waves and also captures the reflected waves from the boundaries of the plate [25]. Guo and Cawley have performed research using pulse-echo testing. This testing shows using this method only reflections from the ends of the specimen will be seen if no defects are present [13]. In the pulse-echo method, the arrival time of the response wave is of importance. The pitch and catch method consists of an actuator transmitting a signal and another sensor receiving the signal on the opposite end. This method is dependent on changes in amplitude and time of flight [1].

2.3 Types of Damage

Damage detection can be described as a change in a structure's properties depending on the amount of damage. Damage is detected using multiple approaches, including passive, active, or combination of both. In research presented in this thesis, a passive approach is used with surface mounted sensors transmitting Lamb waves.

Different types of damage have been investigated. Delamination has been one of the ways that has been vastly researched [26]. Delamination can be created by applying a high-temperature mold wax between any two layers during the fabrication process [11]. Kessler presented a comparison of different types of damage, comparing undamaged, matrix-cracked, delamination (by a cut of a knife in the mid-plane) and drilling a hole [23,27]. Takeda investigated damage which was performed by using a drop weight impact at various energy levels [28]. Other damages such as stiffeners [29] and holes are also being investigated.

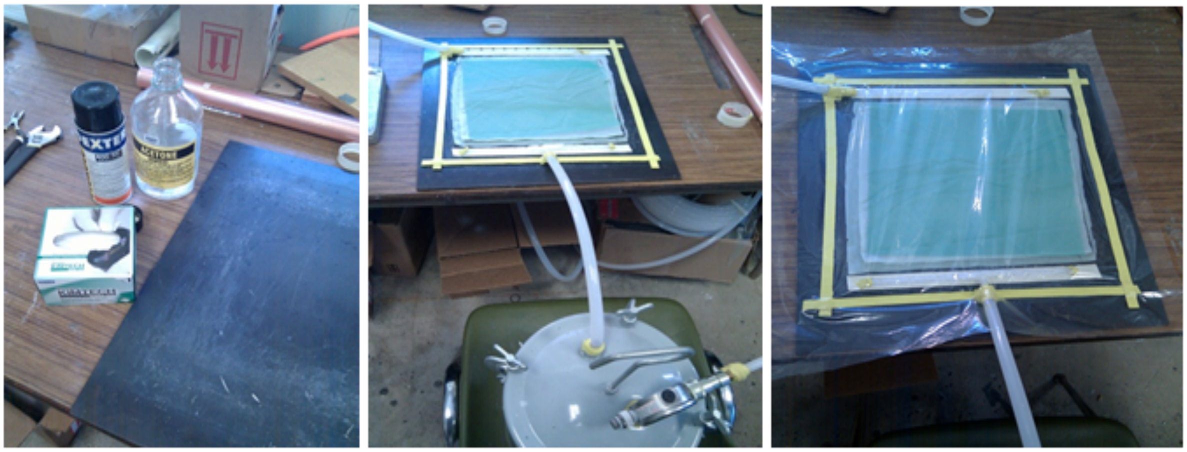
With most of the previously described sources of damage, verification of the amount of delamination after completion of the fabrication process is an issue. This can be resolved by taking an X-radiograph, using die-penetrant of the damaged specimens [23]. The X-radiograph reveals information about inner components such as sensors, manufacturing defects, and possibly damage. For this work, since there was not a way to verify damage within the composite, visual damage by drilling a hole was used.

In addition to studying different types of damages, different types of structures other than carbon fiber are being researched and tested. For example, aluminum [30,31], concrete [7], and other structures are tested for damage as well. This is representative of the different structures which could be used for damage detection applications.

CHAPTER 3: COMPOSITE PANEL FABRICATION

There are a variety of methods available for fabrication of the composite laminates including resin transfer molding (RTM), compression molding, and filament winding. In this work, vacuum assisted resin transfer molding (VARTM), a variation of RTM, was used to fabricate the composite panels. In the VARTM process, a premixed liquid thermoset resin is injected into the dry fiber under vacuum, the resin being later cured at high temperatures [32]. This process was chosen because of multiple advantages, including low manufacturing cost, room temperature processing of resin, and improved quality due to better wet-out [33]. The VARTM process is used for applications in airplanes, space shuttles, automobiles, and many more industrial structures.

For this specific process, IM7 sized unidirectional and surface treated carbon fiber was utilized to prepare the composite panels. Carbon fiber is used in many applications due to the strength and stiffness of the material [28] and resin has improved the properties used in electrical, mechanical, and thermal [34]. The IM7 carbon fibers were cut in a 304.8 mm x 304.8 mm square, in which sixteen plies were needed for the desired panel. These plies were placed on top of one another in the same fiber direction, with a zero degree orientation. To help with the resin flow, a sheet of fabric was put under the fiber cutouts with a distribution mesh sheet and fabric sheet placed on top. This combination was placed on a metal plate that had been pre-cleaned with acetone and coated with a non-stick release coating. Plastic tubing was used around the edges to allow an inlet for the resin and an outlet for excess collected resin. The outlet side, which collected excess resin, was connected to a pressure gauge for monitoring when complete vacuum was achieved. Vacuum bagging was laid over the metal plate, tubing, and fiber setup and was bonded using tacky tape. Figure 1 shows the surface preparation and the complete setup, including vacuum bagging and inlet and outlet tubing.

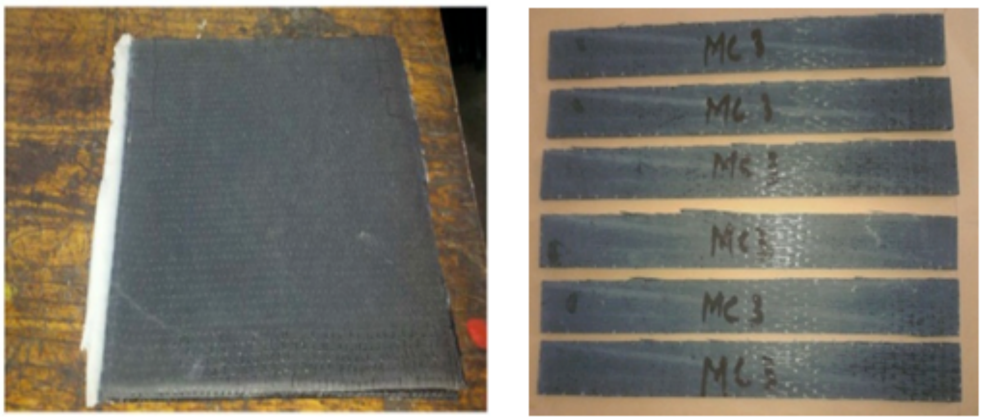


(a) **(b)** **(c)**

Figure 1: Carbon Fiber Composite Setup

(a) Surface mold preparation, (b) Lay-up and resin infusion set-up, (c) Complete set-up with vacuum bagging

Debulking is a process where the vacuum pulls out all of the air from the composite fabrication setup; this process was allowed one hour to obtain a complete vacuum seal. While a complete vacuum seal was being achieved, the resin mixture was prepared by using SC780 resin, a two part epoxy, at a four-to-one ratio. Once the debulk process was complete, the resin could be infused by allowing the vacuum to pull the resin mixture over and into the fiber layup. This allowed for a uniform flow through the composites, while excess resin was trapped by the resin catch. The resin was left for 1.5 hours to allow for complete infusion over and into the fibers. The vacuum pump was disconnected and the composite setup left for twenty-four hours at room temperature for a green cure. Then, the panel of carbon fiber, with infused resin, was removed from the metal plate and fabric. The carbon fiber panel was cured in the oven at 71 °C for six hours, followed by a temperature increase to 104 °C for 2 hours [35]. The resulting composite panel was 304.8 mm x 304.8 mm x 5.08 mm. This panel was cut into 254 mm x 25.4 mm coupons for damage testing with the outer frame used for moisture testing. This same process was used to make similar panels with multiple orientations. However, test results from only one orientation are discussed in this thesis.



(a) **(b)**

Figure 2: Final Carbon Fiber Composite

(a) Final 304.8 mm x 304.8 mm x 5.08 mm panel, (b) Resulting coupons for testing.

CHAPTER 4: EXPERIMENTAL SETUP

The experimental setup was established to obtain all necessary damage detection testing results. This set-up makes use of a National Instruments LabVIEW program. A program was created to control the waveform type, frequency, amplitude, burst count, and burst rate per run for easier and more consistent utilization. This is required to synchronize the actuation and data acquisition. This particular program allows for synchronization of a waveform generator with a data acquisition (DAQ) card. With a general experimental setup in place, changes in the LabVIEW program allow for corresponding changes in the Lamb wave. On the front panel of the LabVIEW program are specific knobs that can be used for changes based upon what signal is desired for generation. Also on this front panel is a display for real time results in graphical or tabular form. Some features that can be seen for convenience are file name and a stop button. These can be done in different ways, but for convenience were placed on the front panel. Figure 3 shows an example of the front panel and what specifically can be controlled. Figure 4 shows the block diagram and flow path of components from LabVIEW front panel.

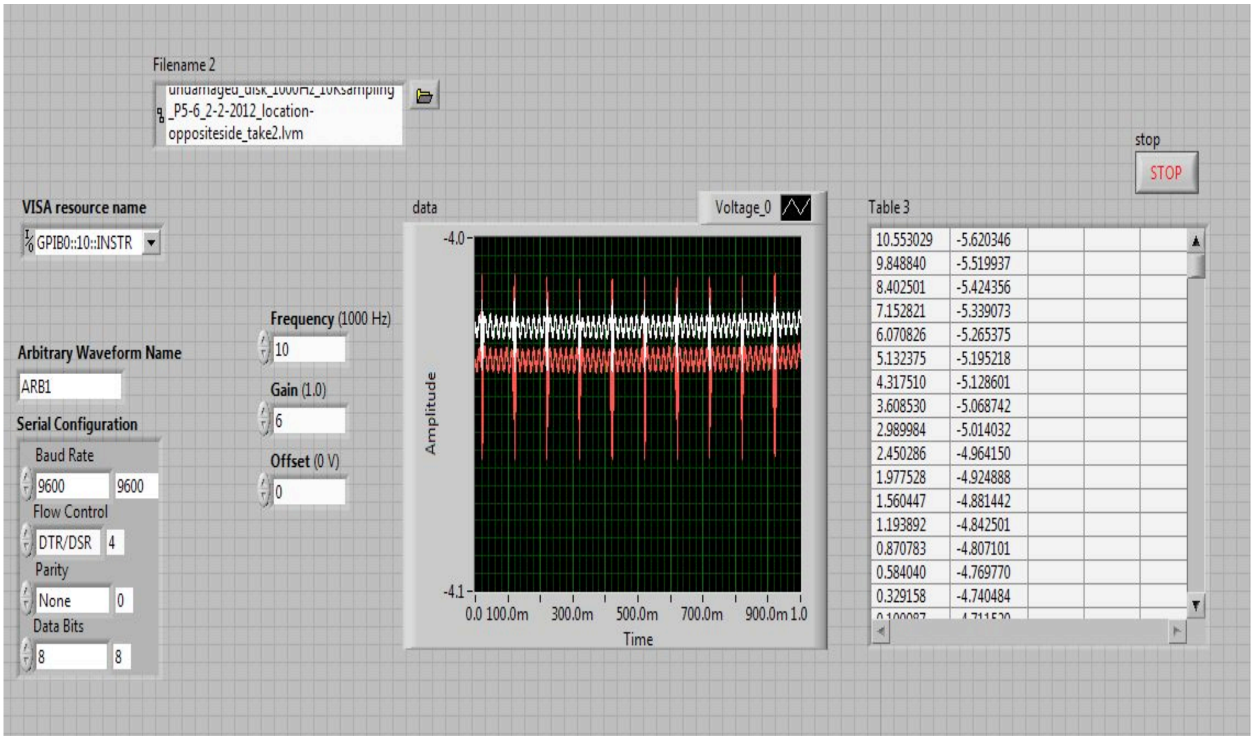


Figure 3: Front panel of LabVIEW code for controlling the waveform generator.

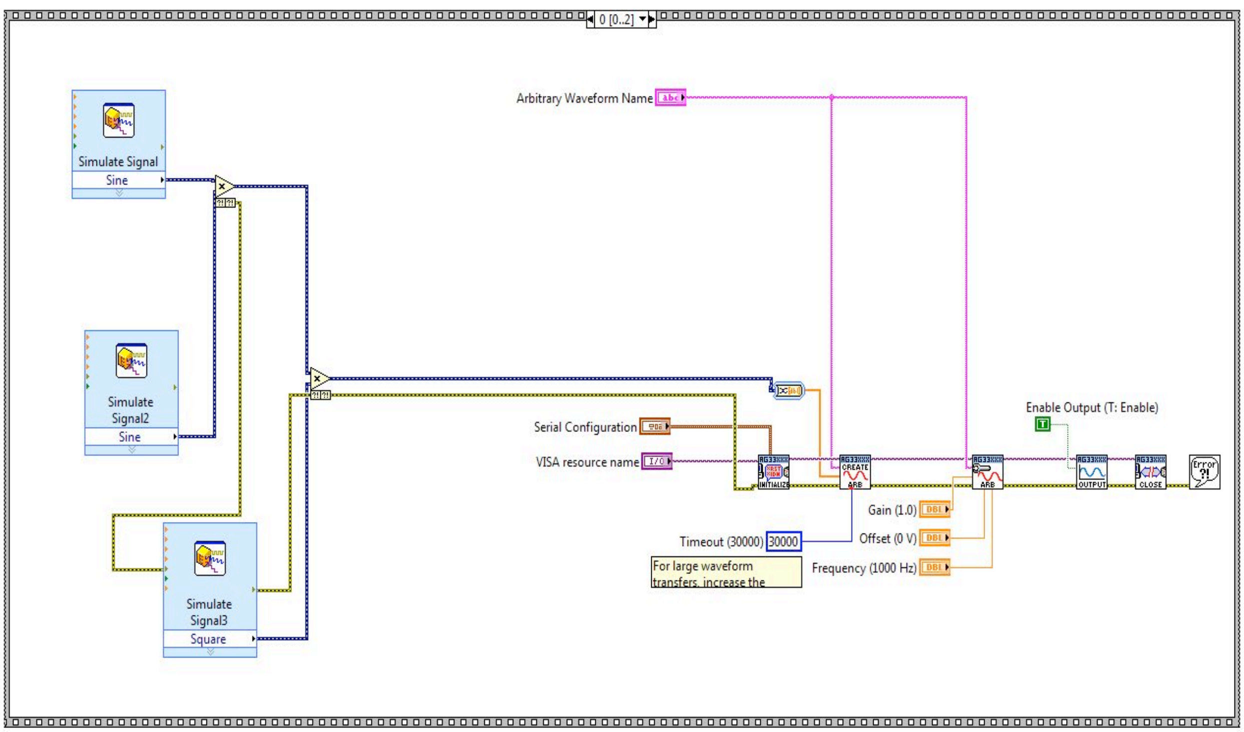


Figure 4: Block diagram of LabVIEW code for controlling the waveform generator.

Specifically, some of the different excitations tested were a five-cycle sine burst at 100 Hz and five-cycle tone burst (hanning burst) at 1000 Hz. Different variations of excitations were used during this work, the five-cycle sine burst and the five-cycle hanning were the most commonly used. With the LabVIEW program in place, a general purpose interface bus (GPIB) cable was used to connect the waveform generator to the computer, allowing communication between the two pieces of hardware. An Agilent 33120A arbitrary waveform generator was used to generate the sine tone burst. This waveform generator along with an A-301HS piezo amplifier was used to excite the PZT actuator. The PZT actuator was surface mounted on the composite coupon that produced Lamb waves which were received by a surface mounted sensor. The actuator was mounted on one end of the coupon while the sensor was mounted on the opposite end. The sensor response was routed through a connector box, then observed and recorded by a DAQ card with a sampling rate of 100 kHz. This DAQ card was interfaced with the LabVIEW program which allowed for real-time data collection and observation. A schematic of the experimental setup is shown in Figure 5.

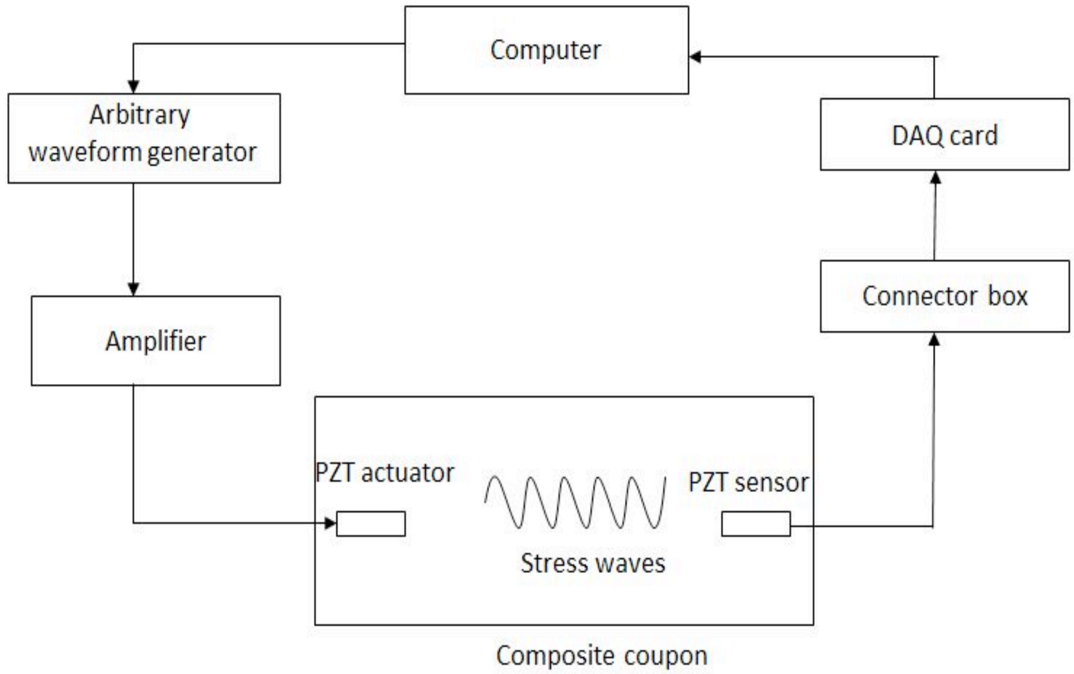
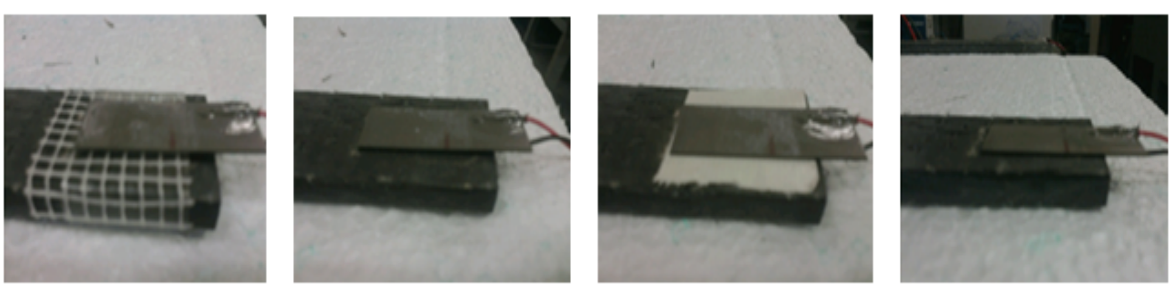


Figure 5: Data acquisition system

Multiple surface bonding techniques were used in determining the optimal solution to provide the most consistent results, while minimizing the error, when compared to the excitation input. In addition, the desired bond would also be reusable, repeatable, cover a maximum amount of surface area, provide the optimal response, and minimize costs. Four different types of bonding were compared as shown below in Figure 6. The first bonding technique, shown in Figure 6(a), depicts a layer of tape and mesh wrapped around the test coupon, which allowed for reusing the same PZT actuator for repeated testing. This coupon covered over half of the actuator surface and minimized associated costs. The output was similar to the input but voltage damping was observed. The second bonding technique, shown in Figure 6(b), tested the use of tacky tape as a potential solution. This technique was extremely cost effective but was not as repeatable as other solutions. Also, the tape's thickness limited the actuator and coupon contact. These particular issues were observed in the way of high error between the input and output data. Double sided tape was tested as the third bonding technique and is shown in Figure 6(c). The tape was applied to the top of the coupon while the actuator was attached to the opposite side of the tape. This method allowed for the actuator to be reused for multiple tests and the sensor also covered over half of the actuator surface. This particular bonding technique was also cost efficient. The output was the most similar to its input providing the minimum amount of error. Finally, silver paste was tested as a bonding technique and is shown in Figure 6(d). This method allowed for good surface contact but was not reusable. However, the silver paste provided a bond such that very few vibrations were observed in the output.

Figure 7 shows the voltage output for all of the above mentioned bonding techniques. Ultimately, the double sided tape technique was chosen for bonding the senor and actuator because of its repeatability, low cost, and small error.



(a) **(b)** **(c)** **(d)**

Figure 6: Sensor Bonding Setup

(a) Mesh and Tape (b) Tacky Tape (c) Double Sided Tape (d) Silver Paste

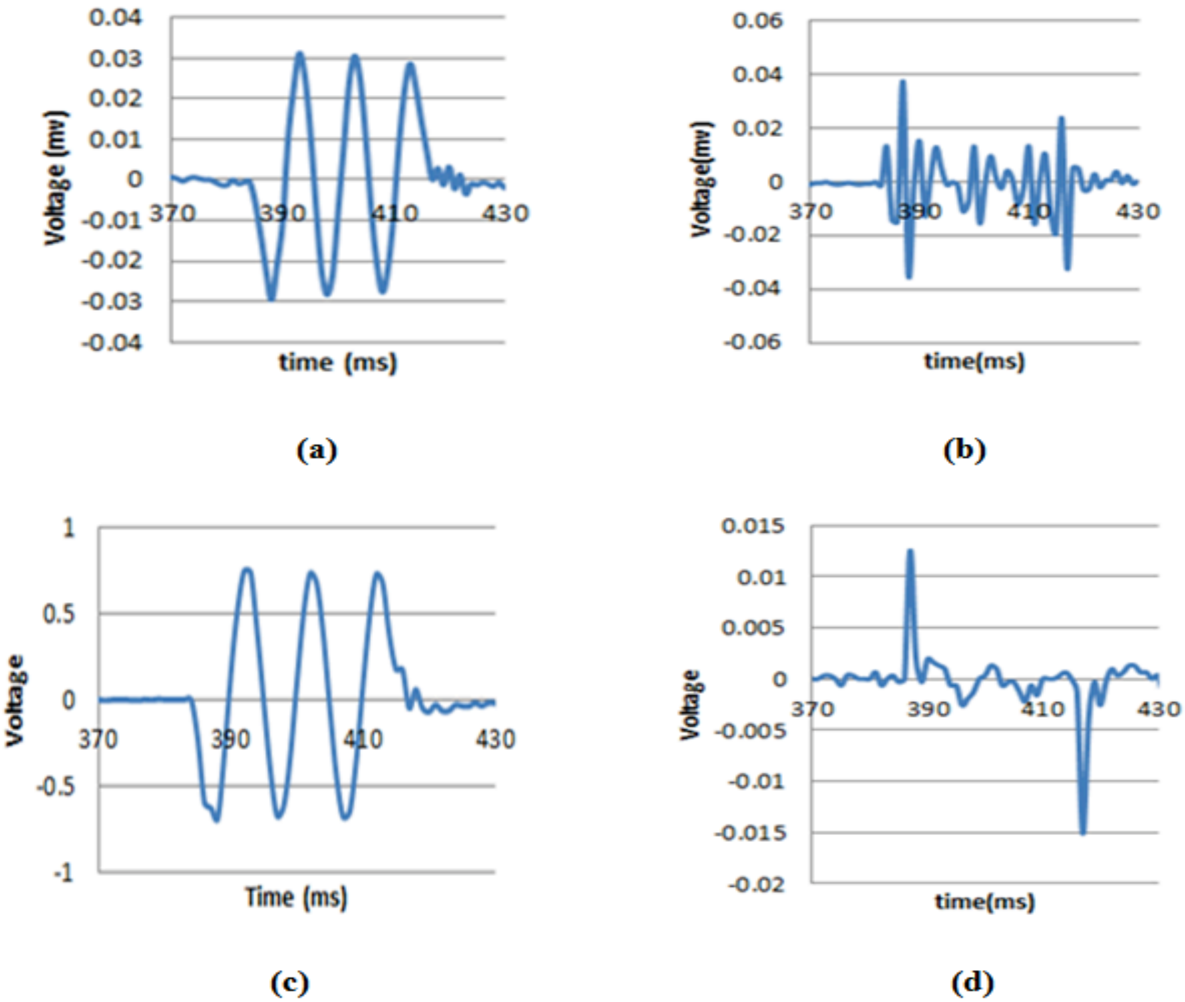


Figure 7: Sensor Bonding Output

(a) Mesh and Tape (b) Tacky Tape (c) Double Sided Tape (d) Silver Paste

CHAPTER 5: DEVICE TESTING

The results presented in this thesis are based on testing performed on a coupon (254 mm x 25.4 mm) which was cut from the composite panel fabricated using the VARTM method, as described in Chapter 3, and using the experimental setup described in Chapter 4. On a 254 mm x 25.4 mm composite coupon, two surface mounted PZT devices were utilized. One PZT was used as a sensor while the other was used as an actuator. In this test, the actuator was located at the free end of the coupon and the surface mounted PZT sensor was located 60 mm from the opposite end of the coupon. The coupon was placed on styrofoam to simulate the free-free condition. Figure 8 shows an illustration of this setup.

The PZT actuator was originally chosen based on the natural frequency of the coupon which is approximately 300 Hz. In addition, research supports choosing this PZT actuator due to the fact that damage is more easily detected and frequencies similar to those of the structure [25]. Lower frequency PZTs were chosen also because the optical interrogator system has a sampling rate of only 10 Hz. PZT actuators of 350 Hz resonant frequency and ±0.28 block force and PZT actuators of 7500 Hz resonant frequency and ±0.28 block force purchased from Piezo systems were used for this work.

Further, to understand the effect of processing across a single panel, multiple coupons from the same panel were prepared and tested. Figure 10 shows that there is a greater magnitude of difference across the panel than what was observed in the panel-to-panel comparison. This difference is again attributed to the variation in resin flows across the carbon fiber and how it is absorbed.

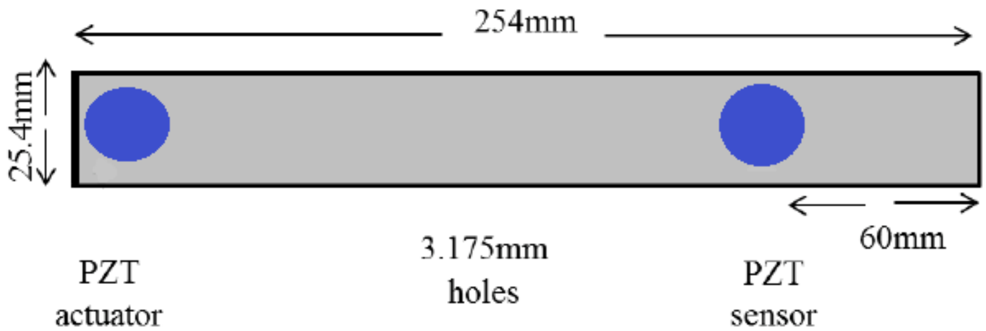


Figure 8: PZT sensor and actuator setup

5.1 Repeatability Testing

The ability to repeat any given test is important for all research applications, including that of damage detection. With the VARTM process, multiple composite panels were prepared for this research. In order to test the repeatability of the VARTM process, coupons from many panels were cut and prepared for testing as explained earlier. Results from these tests were completed to see how comparable one panel is to another. This process was also performed using the damage detection method but simply comparing all undamaged coupons. Figure 9 shows a comparison of the output from an undamaged coupon with another undamaged coupon. These coupons are selected from the same location on different panels. This proves that there is a difference, however, very small in magnitude between the two panels fabricated using the same process. With the VARTM method of fabrication, the potential cause for difference is the way the resin flows across the carbon fiber and how it is absorbed. This is not as consistent and repeatable as with some other fabrication processes, but the VARTM process is more cost efficient for research purposes.

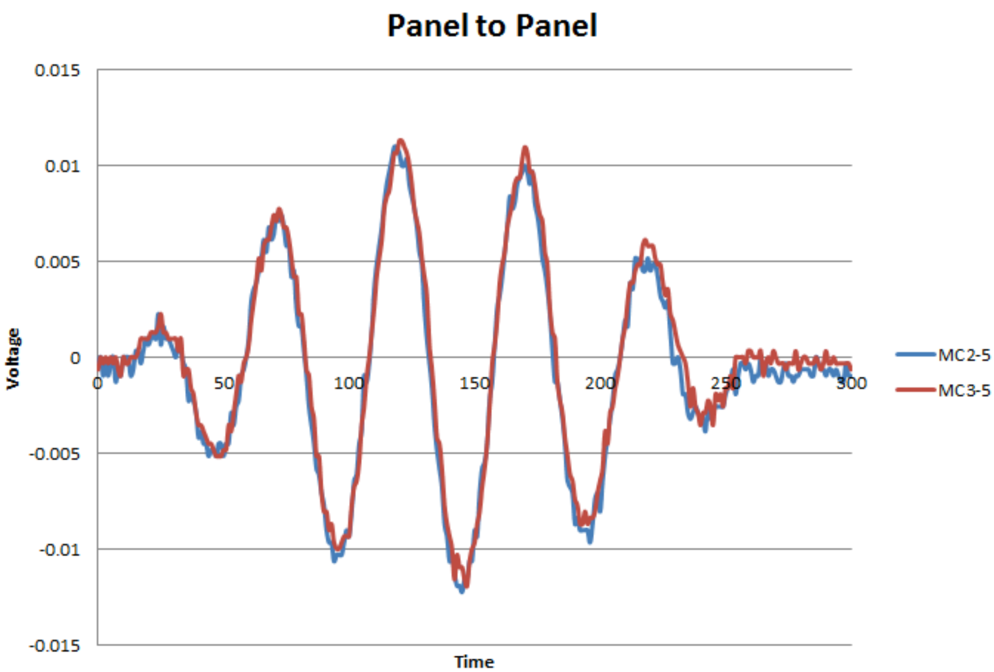


Figure 9: Comparison Panel to Panel

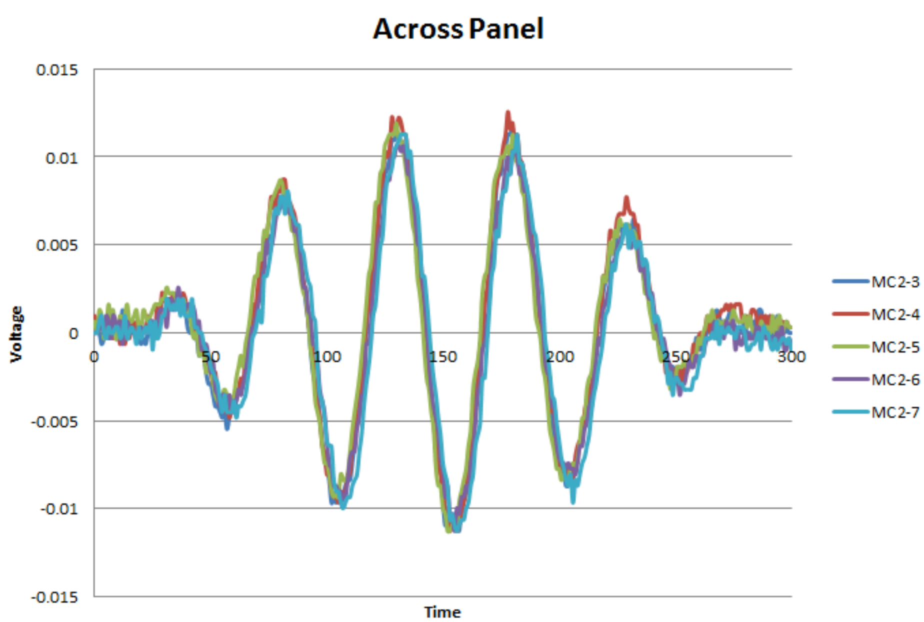


Figure 10: Comparison Across a Panel

Environmental changes also present a concern for repeatability of results. This is a concern primarily when sensors are not embedded in the coupon, which is the best for on-site damage detection. With the sensors being surface mounted, they are more susceptible to environmental changes. This testing was performed by taking measurements on different days of the week. Shown below, in Figure 11, are results obtained from four different test days for comparison. From all of the results shown, the most optimal choice for repeatability is using one coupon and performing the entire testing on the same day.

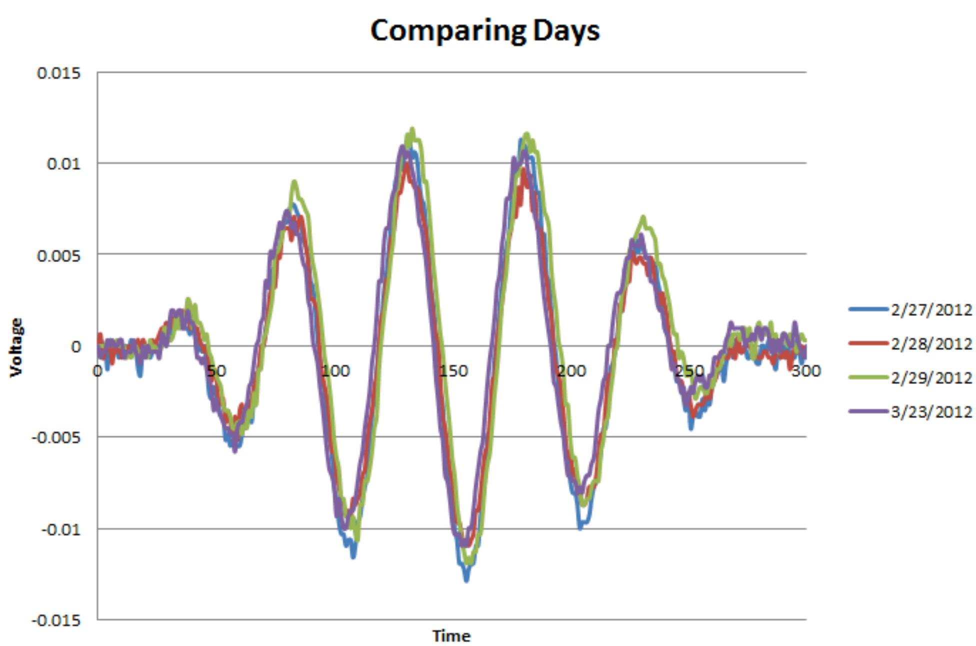


Figure 11: Day to Day Comparison

5.2 Hanning five cycle sine burst

A five cycle hanning burst, with a center frequency of 1000 Hz, was used for actuation purposes. A PZT actuator was surface mounted at one end of a coupon and a PZT sensor was surface mounted 60 mm from the opposite end, as shown in Figure 12. The sensor was placed this distance from the end to avoid excessive reflections from the free edge.

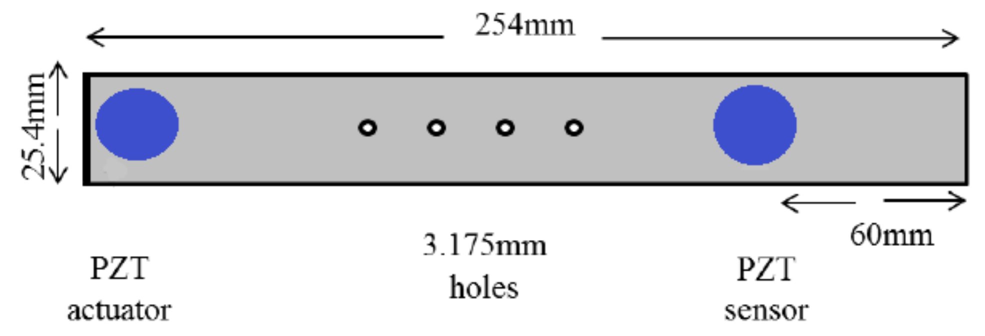


Figure 12: Circular PZT Hole Setup on Composite

A circular PZT actuator, with center frequency 7.3 kHz, measuring 12.7 mm in diameter and with 0.38 mm thickness was chosen for the preliminary test to detect the presence of damage. The damage was introduced by drilling holes of varying diameters at the center of a test coupon. Tests were performed on an undamaged coupon to obtain a baseline for reference. Holes with the following diameters were introduced into the coupon: 1.58 mm, 1.98 mm, and 3.175 mm. The resulting data was recorded after each increase in hole size. The results from this test are shown in Figure 13. These results show that as the damage was increased, the amount of difference also increased. The difference was seen in the amplitude of the cycle. In this damage case, a phase shift or post cycle ringing was not noticed. Either of these would have been additional verification of damage detection.

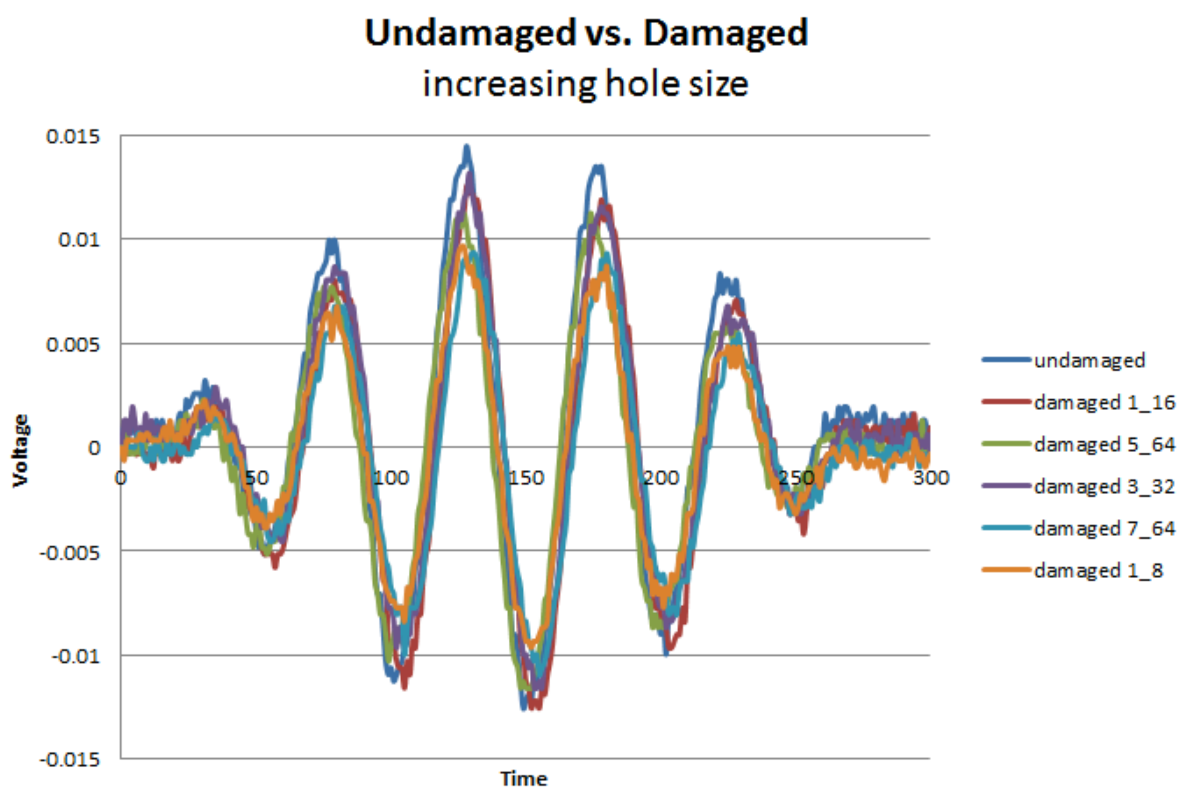


Figure 13: Hanning Five Cycle, Varying Hole Size

5.3 Three cycle sine burst

The PZT chosen for a three cycle sine burst test had a 350 Hz resonant frequency and a rectangular shape (38.1 mm × 12.7 mm × 2.54 mm). This PZT was chosen because of size limitations and the natural frequency (300 Hz) of the composite coupon fabricated, as detailed in Chapter 3. The setup of the PZT senor and actuator remained the same as previously shown in Figure 8. The undamaged case was tested using this method to get a baseline for comparison. The source of damage for this particular damage detection experiment was chosen to be a hole. The hole was located in the center of the coupon, as shown in Figure 14.

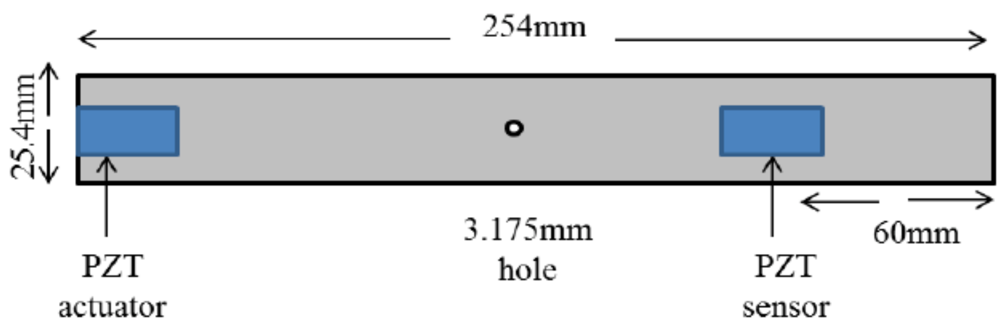


Figure 14: Rectangular PZT Hole Setup on Composite

The initial damage was introduced by drilling a hole, 1.58 mm in diameter, into the composite coupon. In order to determine if an increased hole size would correspond to an increase in detected damage, the hole shape was increasingly changed. The data for each damaged case is compared to the baseline, as shown in Figure 15. It was observed that the amplitude of the response signal increases as the damage, or hole size, was increased. This observed difference proves that damage can be detected.

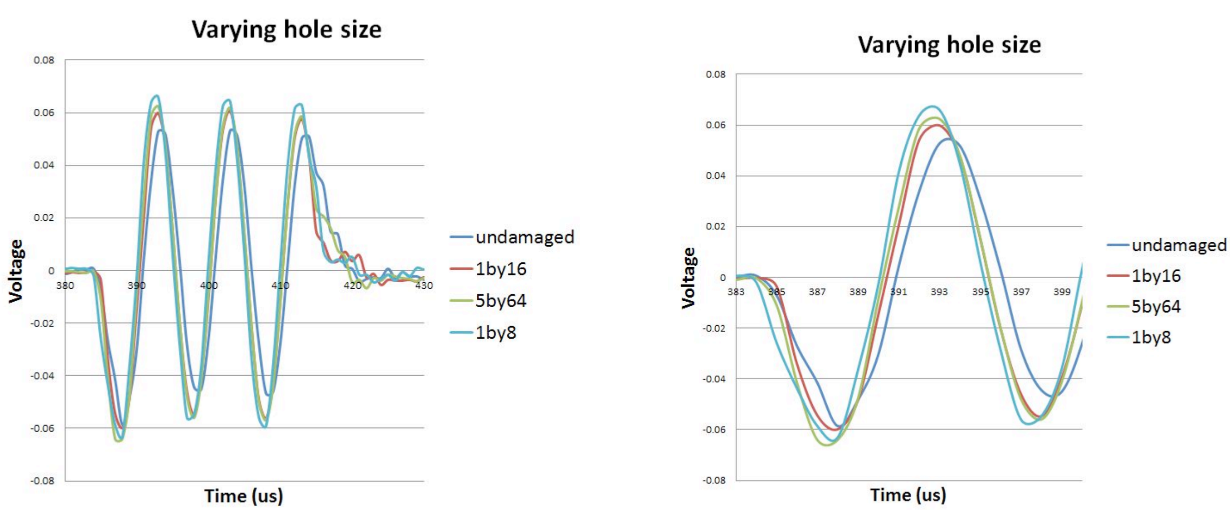


Figure 15: Varying Hole Size

In addition to the size increase in one particular spot, it was also of interest to test the damage across the coupon when multiple sources of damage were introduced. In this case, multiple holes were used as multiple damage sources. The initial damage was also introduced by drilling a hole, 3.175 mm, into the composite coupon. The variation of holes from one to four holes, 20 mm apart, is shown below in Figure 16. The undamaged case was again tested using the method discussed above to get a baseline for comparison. The data for each damaged case is compared to the baseline, as shown in Figure 17. As expected, similar results were seen from the previous test with one varying sized hole. It was observed that the amplitude of the response signal increased as the amount of damage was increased. Also, it was seen that with damage of this magnitude at the end of the sine burst, there are more non-uniform vibrations. The differences in magnitude show a difference which has proven to be a damage detecting factor. Also, in this damage case a slight phase shift and post cycle ringing was detected. Both of these provide additional damage detection verification.

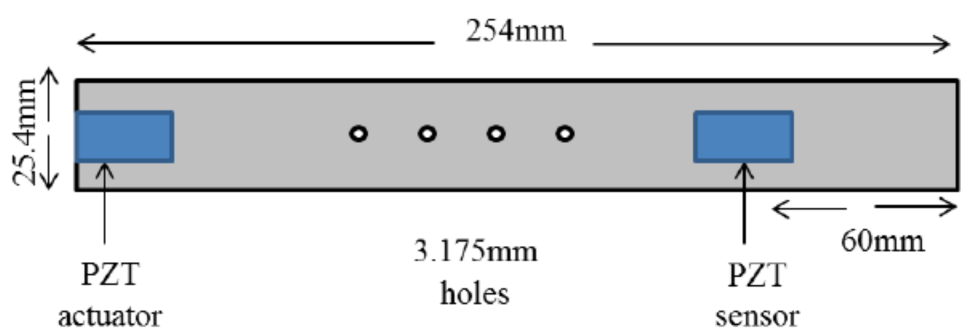


Figure 16: Rectangular PZT Multiple Holes Setup on Composite

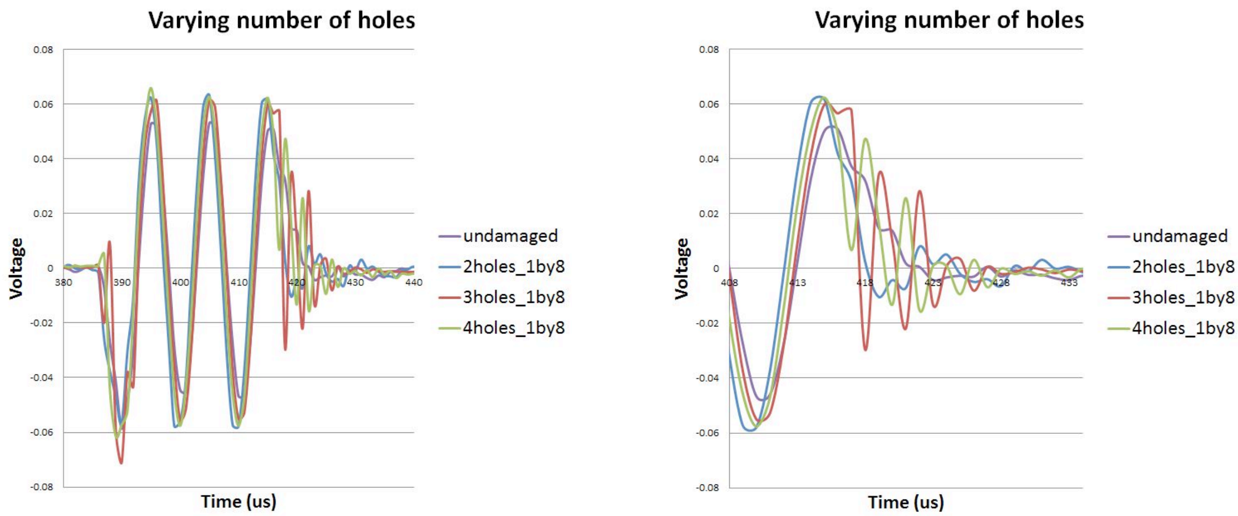


Figure 17: Three Cycle Sine, Varying Number of Holes

CHAPTER 6: CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

Structural health monitoring allows for structures to be continuously monitored for any potential damage. With this monitoring system in place, maintenance will only be needed once damage has been detected. This will effectively eliminate any unnecessary maintenance performed on structures and ultimately decrease associated costs. In this thesis, the VARTM process was used for the fabrication of composite panels. It was observed that this procedure produced a good quality composite at a low cost. The VARTM procedure also allows for variation of the orientation of the composite. Repeatability tests along with testing of sensor bonding were performed on various coupons cut from a big panel. The testing results suggest that a constant temperature and environmental changes do not have a dramatic effect on the damage. For the testing of damage detection, a PZT actuator and a PZT sensor were used. Undamaged coupons and damaged coupons were compared for purposes of testing damage detection. The PZT actuator and PZT sensor were surface mounted to the coupon using double-sided tape. Different excitations of Lamb waves were varied using LabVIEW software to set input parameters and for synchronization of data acquisition. In addition to the change in excitation, there was also a change in the amount of damage. The comparison of undamaged and damaged coupons' response signal showed an increase in amplitude. It is seen that as the damage increased, the amount of difference also increases. In addition, a ringing pattern was noticed in the response signal due to reflections. In conclusion, this damage detection technique was proved successful.

6.2 Future Work

Realistic applications, the sensor would need to be embedded. With this application, research and testing on embedding of the sensor and its associated response would need to be explored further. In addition, a more reliable source of actuation would need to be further investigated. The ability to detect damage of a smaller magnitude would also be increased by embedding the sensor. It has been seen that with higher frequencies, the accuracy of detection of smaller damage is increased. Additional areas that could be investigated include optimization of sensor placement and modeling of PZT actuators and sensors using a finite element method to compare the experimental and modeling results.

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APPENDIX A: CONFERENCE CONTRIBUTIONS

A list of conference proceedings and presentations:

M. Spiegel, A. Nagabhushana, S.Roy, S. L.Burkett and S. Kotru, *Structural Health Monitoring of Composite Materials using PZT Actuators and Sensors,* presented at the MINT Annual Meeting, Center for Materials for Information Technology, October, 2011, The University of Alabama, Tuscaloosa, Alabama, United States.

A. Nagabhushana, M. Spiegel, S. Adu, N. Hayes, D. Paul, K. Trivedi, B. Fairbee, H. Zheng, A.Gerrity, S. Kotru, S. Roy, M. Barkey, S.L. Burkett, *Numerical analysis for structural health monitoring of a damaged composite panel using PZT actuators and sensors*, Smart Structures and Materials – Non destructive evaluation and health monitoring, March 11-14, 2012, San Diego, CA, United States, SPIE.