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Distributed Wireless PZT Fiber Composite Sensor System Development and Demonstration: Sensor Design and Fabrication

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Distributed Wireless PZT Fiber Composite Sensor System Development and Demonstration:

Sensor Design and Fabrication

by

Markus Rex Murdy

An Honors Capstone

submitted in partial fulfillment of the requirements

for the Honors Diploma

to

The Honors College

of

The University of Alabama in Huntsville

May 1, 2015

Honors Capstone Director: Dr. Gang Wang

Assistant Professor of Mechanical and Aerospace Engineering

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Student Date

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Director Date

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Department Chair Date

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Honors College Dean Date

Table of Contents

Abstract

The purpose of this UAH Honors Capstone Project developed a wireless piezoelectric (PZT) fiber composite sensor to provide distributed sensing capability to measure structural deformed shapes. Modern PZT fiber composite sensors have the potential to substantially reduce cost, size, and weight, and provide accurate deflection measurement when compared to the current state of the art, the distributed fiber optic Bragg grating (FBG) system. Prototype PZT fiber sensors were fabricated in the UAH Adaptive Structures Laboratory. Tests near a representative beam's resonance frequency validated the manufacturing process with proper sensor performance.

Chapter 1: Background

Introduction

Piezoelectric materials have been widely used as actuators and sensors in structural health monitoring (SHM) applications because of their electro-mechanical coupling property. Such applications include surface-mount sensors to measure physical movement or strain by directly bonding or embedding piezoelectric thin sheets onto the structure. Piezoelectric ceramics, e.g., lead zirconium titanate (PZT), are perhaps the most popular piezoelectric materials for actuation/sensing purposes[1]. A PZT composite, such as Macro-fiber-composite from Smart Material Corp., overcomes the brittle nature of ceramics and offers high performance, durability, and flexibility in SHM applications[2].

Composite materials are finding broader application in aerospace structures due to benefits such as superior stiffness and light weight relative to conventional materials. These new materials have yet to endure the test of time through an entire product life cycle, as compared to well understood conventional metallic materials. Additionally, policy decisions to extend the operational lifespans of current aerospace vehicles well beyond initial design requirements are becoming increasingly common. Continuous health monitoring over the lifespan of the structures is needed in order to fully optimize these material options for the next generation of vehicles.

This research serves to complete the requirements of the Honors Capstone Project for the Honors College at the University of Alabama in Huntsville (UAH). Modern PZT fibers can be

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[1] "Lead Zirconate Titanate Materials", http://www.morgantechnicalceramics.com/materials/lead-zirconate-titanate-pzt

[2] "PZT Fiber Backgroung", http://www.smart-material.com/PZTFiber-product-main.html

fabricated to monitor the strains and stresses in materials, such as composite wings and rotor blades. This project validated the manufacturing process currently used, to understand where advances can be made. Items for improvement were listed for a future student, possibly under the Research Experience for Undergraduates program.

Application

The focus of this Honors Capstone Project was the design and development of a method for distributing single axis PZT sensors along a body. The PZT sensor transfers deflection into a voltage, which can then be correlated to the strain in the material. All natural materials have some piezoelectric characteristics. Most do not produce voltages high enough to be of practical use in test data acquisition. This project makes use of a particular ceramic material that does produce voltages capable of being useful for engineering analysis. The ceramic cylinder by itself tends to be brittle. Casting the sensor protects it from fracture and provides a larger surface area for handling. There are many applications for this type of sensor, specifically, the rotating blade of a helicopter. Many helicopters use some sort of fiber reinforced matrix or metallic composites in their rotor blades. As the defense landscape changes, composite materials are utilized past their initial design lifespan. Taking measurements from sensors distributed along the line of action of the blade allow for structural health monitoring of the blade as it goes through its operational routine. Structural health monitoring is the key to understanding how these structures change over time, and as might be arrived at by the name, allows the research team to understand the relative health of the material and structure. SHM might be able to warn of blades stressed past their operational limits during an evasive maneuver. This knowledge allows the blades to be replaced before they fail, saving lives and increasing capability.

The rotating blade case is a difficult environment to take active measurements. The rotating blades, the target region, do not have enough extra volume to store the large data acquisition equipment needed for test flights. Figure 1 shows the a concept flowchart from the companion Honors Capstone project to this effort, a project to design a wireless communication suite that can transmit the data collected by these PZT fibers, in the rotating blade frame, to the stationary airframe cabin. Ethan Hopping is conducting this research. There will be a small data conditioning board placed near the sensors. This conditioning board will wireless transmit the signal back to a larger data acquisition and storage system.

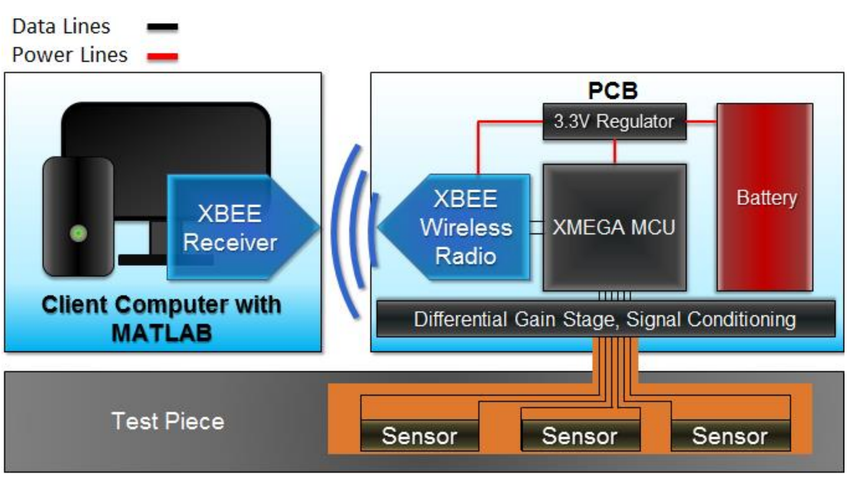

Figure 1: Wireless Communications Design

Chapter 2: Current Work

Concept

The concept for the distributed sensors is constructed in such a way to be applicable to several target SHM areas of interest. Each sensor would be cast in a small mold. This mold contains a fixture to hold the PZT, a path for the positive and negative wire connections, and a bond land to facilitate easy attachment to the target material. Features would be incorporated to the side of the mold facing the slipstream to reduce the aerodynamic effect created by the sensor's presence on the blade. The mold could utilize additive manufacturing technology to create different shapes optimized for these design features. Figure 2 shows the concept CAD drawing. If it is found that the current state of the art with regards to additive manufacturing materials cannot support these designs, traditional machining techniques and materials could be examined.

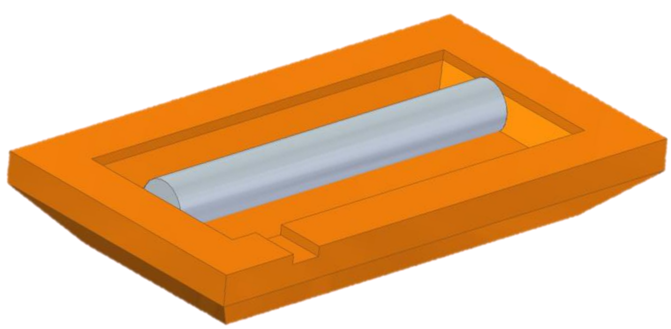

Figure 2: Concept PZT Fiber Sensor and Mold

Sensor density is an important parameter for test data collection. There has been some discussion as to what would be appropriate parameters to set for this sensor. It is expected that sensors would be spaced much closer together for a flight test campaign than for operational use. Effective structural health monitoring can be accomplished with a lower sensor density after an initial characterization test campaign. In summary, sensor density should be defined by the application.

Prototype Sensor Fabrication

The Adaptive Structures Laboratory at UAH's Technology Hall supported initial prototype fabrication. Two prototypes were produced to validate that the manufacturing process could produce sensors with a noted piezoelectric effect. These sensors were tested on a scale beam with a lab table top oscillator introducing frequencies ranges from below to above the resonance frequency. The following section includes details concerning the fabrication of individual sensors

Shim

The backbone of the sensor is a 0.025 inch thick aluminum shim. The shim is cut from a roll to a useful size of 4 millimeters wide and 20 millimeters long. This shim is secured to the fabrication table with double sided tape. It is necessary to isolate this shim from the electrically active PZT fiber. Isolation is accomplished by using a thin clear PVC film. The film is cut to closely mimic the footprint of the backbone shim, taking care to cover the entire shim. Double sided tape is again used to secure the PVC film to the shim. The buildup is now ready to add the PZT fiber.

PZT Fiber

A PZT fiber is placed on the PVC, roughly equidistance from either end of the shim. The fiber is positioned using a tweezer to reduce human finger oil contamination. Next, the wires are added to the assembly. This project used coated thin gauge wire. The coating needs to be removed from both ends of a strand to be used. Two wires are used, one at each end of the PZT fiber. Small right-angle kinks are made to the wire strand ends. Figure 3 shows a lead wire with the kink in it being placed on fiber assembly. It is optimal to have 3 millimeters of contact surface between the PZT fiber and the wire strand. The wires need to be positioned such that each fiber tip is at the wire kink. Next, the fiber and wire are secured together with a small drip of conductive silver paint. This step takes a bit of patience; less paint at this step enables more flexibility later in the process. The assembly needs just enough paint to hold everything together. Too much paint will make the final sensor too large. The assembly is left for 2 hours to allow the silver paint to dry. After this period has elapsed, and if the paint is dry, the assembly is coated with a thin film of cyanoacrylate, or superglue. The superglue coating holds all the different components together securely, but is not bulky. At this point, the assembly is left overnight to cure.

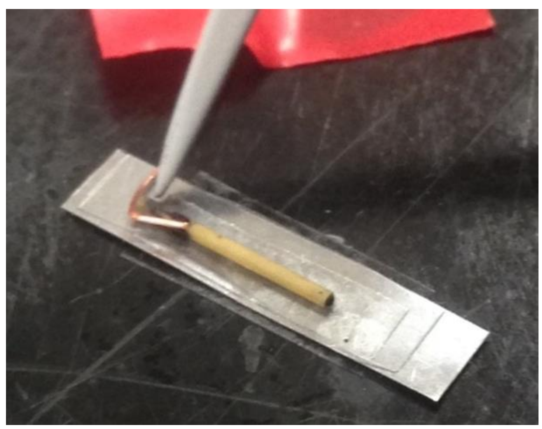

Figure 3: Placing a Lead Wire on PZT Fiber Sensor Assembly

Casting

The final step in the sensor fabrication process is the casting process. As mentioned earlier, the PZT fiber is brittle, and casting it in this material improves the fiber longevity without negatively impacting sensor performance. Polyester is used as the casting material. The polyester used for this effort was a two part mixture, roughly 60% resin and 40% hardener.

Small molds have been CNC machined from wax to hold the polyester and sensor while the assembly cures. Two PZT sensor assemblies are accommodated within each mold. The sensor assembly is slid into the mold vertically on its long side. To keep sensor components aligned properly, tape the wire leads to a structure above the mold. Figure 4 shows the PZT fibers in the casting mold. This could be a box or other lab piece. Roughly 1.4 grams of polyester, of the ratio mentioned earlier, is prepared, to be mixed for about 10 minutes. With the mold and sensors prepared, the polyester is poured through the mold. It is important to make sure the sensors stay straight in the mold, and that the polyester covers all parts of the sensor. The polyester needs to be left for 48 hours to fully cure. It is prudent to check the molds after about 3 hours to ensure sensor alignment is still straight inside the mold.

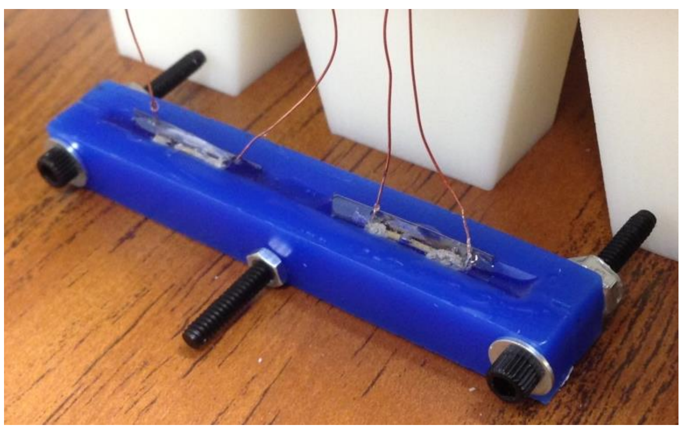

Figure 4: PZT fibers in casting molds

The sensor assembly is now ready to be prepared for the target surface. The screws holding the molds together are removed to allow the separation of each mold wall from the polyester casting. While more stable than before, the sensor is still quite flexible and care should be taken to avoid snapping the PZT fiber through the process of removing the mold walls. The polyester casting, which currently holds two PZT sensors, is cut at the center point, in between the sensors. The wire leads for each sensor can be easily broken off the sensor, bend them as little as possible. Figure 5 shows the fiber after casting. The bottom of the individual PZT fiber sensor is prepared for bonding to the target material by lightly scoring the bottom of

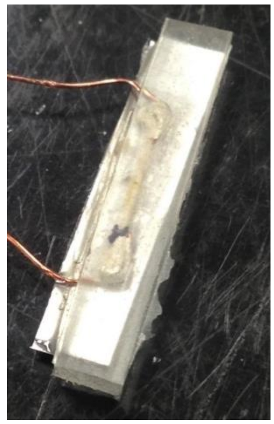

Figure 5: PZT Fiber after Casting

the sensor. An E-Xacto knife can be used for this process. The goal behind scoring the surface is to increase the available area to bond to the target material. The actual bond between the PZT sensor and the target material can be accomplished with a range of adhesives. This effort used superglue. Different applications, especially ones where high temperatures are expected should investigate an adhesive that retains its properties in the test environment.

Testing

The PZT sensor is now ready for testing. The laboratory table top oscillator in the Adaptive Structures Laboratory was used for this experiment. A PZT sensor was fixed to a beam near the clamping point, and another PZT fiber was fixed near the cantilevered end of the beam. Figure 6 shows two PZT fibers on a beam in the oscillator. To demonstrate the PZT properties of these sensors, the beam was shaken vertically at different frequencies. A bluff body was added to the cantilevered end to exaggerate the signal coming from the PZT fiber

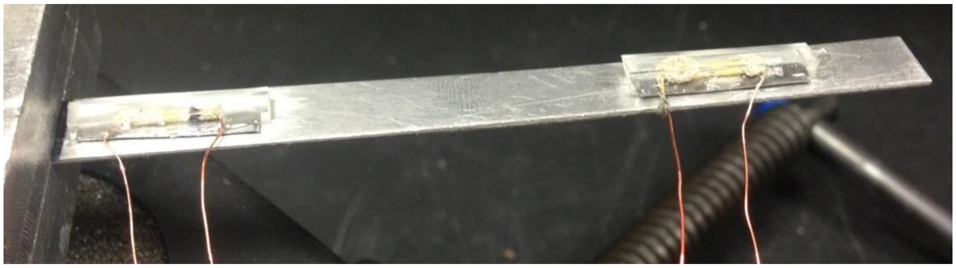

Figure 6: PZT Fibers on Test Piece

sensor. The resonance of the beam was estimated to be near 27 Hz. An increase in signal amplitude, representative of what should be seen as resonance is approached, was observed as the frequency was dropped from 35 Hz to 27Hz and as it was increased from 20Hz to 27 Hz. Figure 7 shows the increased amplitude as frequency approaches resonance. This proved the manufacturing process was successful.

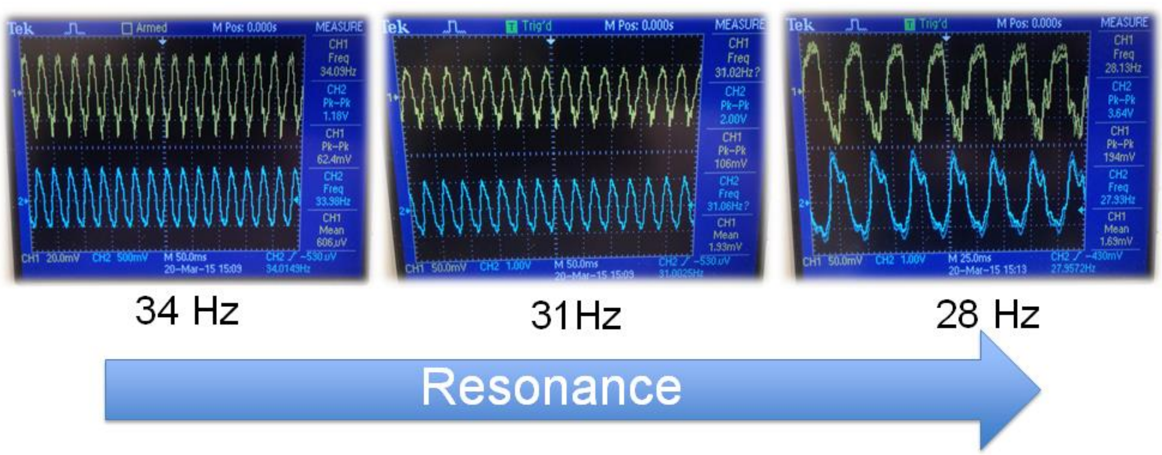

Figure 7: Observed Resonance Tendencies in Prototype PZT Fiber

Chapter 3: Future Work

This research work is exciting and has several potential next steps. This section defines potential actions to be taken by the next undergraduate research student.

Specific Areas of Possible Improvements

Wire Trace Protection

To develop these sensors in a deployed configuration, the wire traces from each PZT sensor to the DAQ should be shielded from the environment, without a large drag penalty on the target object. Stronger wire should be used to avoid snapping the leads.

Mold Design

The mold to protect the PZT fibers in-situ should include a method of holding the fiber in place during the casting process, such as supports at either end of the fiber. This would enable a more reliable manufacturing process. Additionally, the mold should have provisions for the wire traces to leave the mold at a common location.

Lab Testing

To allow for testing of longer beams, the lab shaker used to oscillate the beam near resonance frequencies should be repositioned such that the test article extends past the lab counter's edge. This will allow the beam tip to move through its entire oscillation range.

Distributed Sensors

To validate the distributed sensor concept, a beam should be tested with 3 sensors spaced along the long axis. Higher strains will be seen near the root of the beam. This particular area of the beam might be of more interest from a structural health monitoring standpoint.

Rotating Reference Frame

A final test to validate the concept should put a beam with several PZTs, roughly 4, placed along a beam and attached to a fan or other rotating device and observe the strains induced through different RPM settings.

Chapter 4: Closing Comments

Conclusion

This research effort was accomplished to satisfy the requirements of the Honors Capstone Project. This research effort proved the validity of the manufacturing process for PZT fibers at UAH. The PZT fibers are capable sensors, but their small size can prove challenging to fabricate. Opportunities for future work are also suggested in this report. These fiber sensors could be distributed along a wing or rotor blade for composites structural health monitoring applications.

Acknowledgements

Dr. Gang Wang was the research director and mentor to the author and Ethan Hopping. His patience, passion for the topic area, and interest in students' success was very motivating. William Wilkerson is the Dean of the Honors College, a major project support and a champion of student research on campus. Felix Ewere, one of the doctoral students of the Adaptive Structures Lab, was crucial in bringing the Honors Capstone Project students up to speed on PZT development and UAH practices. The continued support from the University of Alabama in Huntsville, College of Engineering, and the Honors College administration for student hardware focused research is a critical element to ensuring the university's continued relevance in the undergraduate academic landscape. Soli Deo Gloria.