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Analysis of a PZT Fiber Rosette for Structural Health Monitoring

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Analysis of a PZT Fiber Rosette for Structural Health Monitoring

by

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Abstract

In this project, a lead-zirconate-titanate (PZT) rosette array was developed and applied to Lamb-wave-based structural health monitoring (SHM). Both sensor rosettes and a macro-fiber composite (MFC) actuator were mounted to a composite plate for Lamb wave actuation and sensing demonstration. The piezoelectric properties of PZT allowed for a voltage-controlled actuation, as well as a sensor response that converted mechanical strain to measurable voltage. The PZT sensor rosettes, similar to the strain gage rosettes, were designed and prototyped in the Adaptive Structures Laboratory. Each contained three PZT fibers oriented along the 0°, 45°, and 90° directions, respectively. In order to evaluate the performance of the newly developed PZT rosette system, experiments were conducted by sending Lamb waves of a certain frequency through the plate, comparing the waveform generated by an actuator to that received by the sensor. Experimental data collected from the PZT rosettes showed the expected wave signature and affirmed the ability of the PZT rosette to detect Lamb waves.

Introduction

Lead-zirconate-titanate (PZT) is a piezoelectric material – a transducer of mechanical strain and voltage. The piezoelectric property of PZT allows it to be employed as either a sensor (detecting strain and producing voltage) or an actuator (receiving voltage and producing strain). As a result, the use of PZT fiber in structural health monitoring is on the rise. The location of structural damage with ultrasonic wave propagation is one example, in which the orientation and location of PZT fibers is used in calculating the direction of propagating waves.[1] In this experiment, a Lamb wave propagating in the plane of a solid plate is used. Studies including acoustic source location with macro-fiber composite (MFC) and with metal-core piezoelectric fiber rosettes make use of this guided wave in a solid plate.[2,3]

Fabrication of a novel PZT sensor rosette, performed in the Adaptive Structures Lab, was conducted in conjunction with the experimental setup described here. These sensors are under development by Dr. Gang Wang of UAHuntsville for the purpose of damage detection.[4] A photograph of a sensor rosette in fabrication is shown in Figure 1.

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[1] Kijanka, et al., *Damage location,* 3-4.

[2] Matt, et al., *Macro-fiber composite*, 1489-1493.

[3] Liu, et al., *Metal-core piezoelectric*, 865.

[4] Wang, *Lamb Wave Based Damage Detection*, 1.

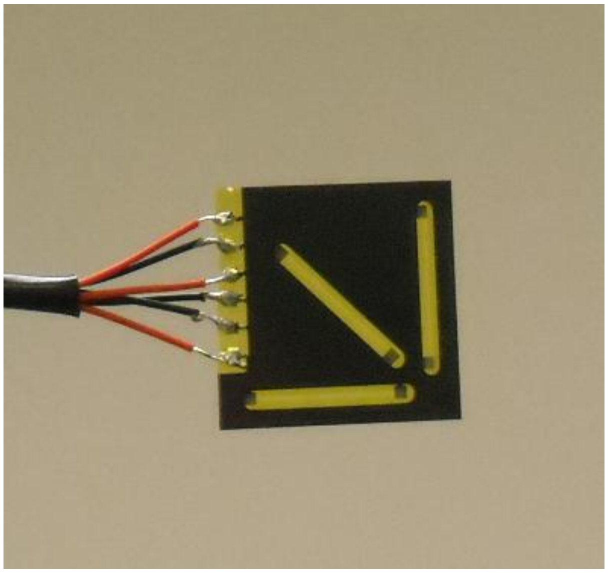

Figure 1: PZT sensor rosette.

This rosette depicted still lacks the three piezoelectric fibers, each 0.8 mm in diameter and 10 mm in length, which were then mounted in the yellow slots. To secure the fibers in place, silver conductive paint was brushed onto the electrodes and a drop of liquid adhesive was applied at the center of the fiber.

Six electrical connections can be seen extending from the sensor, which is composed of plastic with circuits printed such that each fiber is connected to a lead at its two ends. Conventionally, red wires indicate connection to the positive electrode and black to the negative electrode. A diagram of these connections, and the corresponding PZT fibers, can be seen in Figure 2.

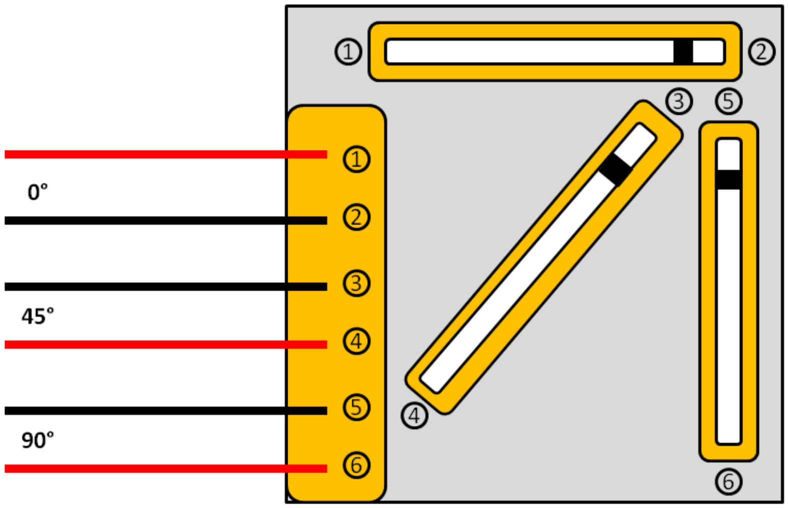

Figure 2: PZT sensor diagram

The negative electrode of each PZT fiber is indicated by a black band in the diagram, applying the convention used by the lab when preparing the fibers. The standard for fiber orientation is also shown in the figure, with the fibers situated along the 0°, 45°, and 90° directions. Following the addition of the PZT fibers and the application of a 3M adhesive to protect them, the sensor would be ready for bonding to a solid surface for testing.

Experimental Setup

The first set of data collected with the PZT sensor array was for the verification of the sensor setup on a composite plate. A commercial MFC transducer, pictured in Figure 3, provided the actuation.

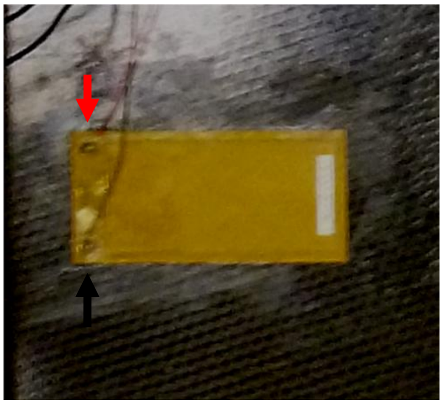

Figure 3: MFC actuator

The two electrical leads are indicated with black and red arrows for negative and positive, respectively. Two sensors, fabricated according to the specifications mentioned in the introductory section, were bonded to the composite surface with M-Bond adhesive. The location of the sensors used in this experiment, labeled as K1 and K2, are indicated in Figure 4.

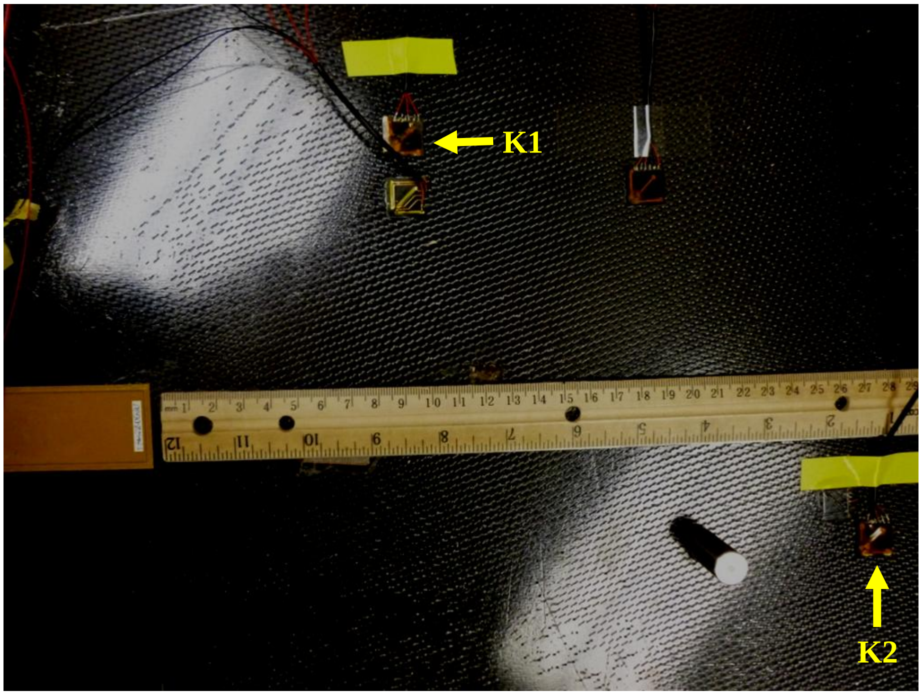

Figure 4: Location of sensors K1 and K2

The MFC can be seen on the left of the photograph, beside a ruler on the plate for scale. Each of the sensors has dimensions of 15x15 mm, and the MFC dimensions of 31.5x66.4 mm. A few other objects attached to the plate, such as other sensors and a metal cylinder, are not relevant to this experiment.

The voltage provided to the MFC was supplied by a National Instruments data acquisition (DAQ) system, controlled from a computer running the National Instruments LabView software package. The voltage was amplified 10 times through a voltage amplifier between the DAQ and the leads of the MFC. A program written in LabView sent the voltage as a five-cycle sine wave, modulated by a Hanning window, with amplitude of 1.0 V and frequency of 200 kHz.[5] Use of the Hanning sine function anticipated data analysis by fast Fourier transform (FFT), for transformation of the data from the time domain to the frequency domain.[6] Data was collected on the input channels of the same DAQ, where the voltage response of each fiber was recorded while stimulating the MFC. For the two sensors, K1 and K2, the data was recorded separately from each of the three fibers. The voltage as a function of time was written to a comma-separated values (CSV) file as the test was running, sampling at a rate of 1 MHz. The waveform was sent from the output channel 200 times in each test, so an averaged value of sensor response could be obtained.

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[5] Cordner, et al., *Hanning Wave VI.*

[6] Harris, *Use of windows for harmonic analysis*, 60-62.

Experimental Results

One trial of time-domain data for the sensor K1 is shown in Figure 5, over a time span of 500 µs with a 1 MHz sampling rate. The plots were generated in MATLAB from the CSV data collected.

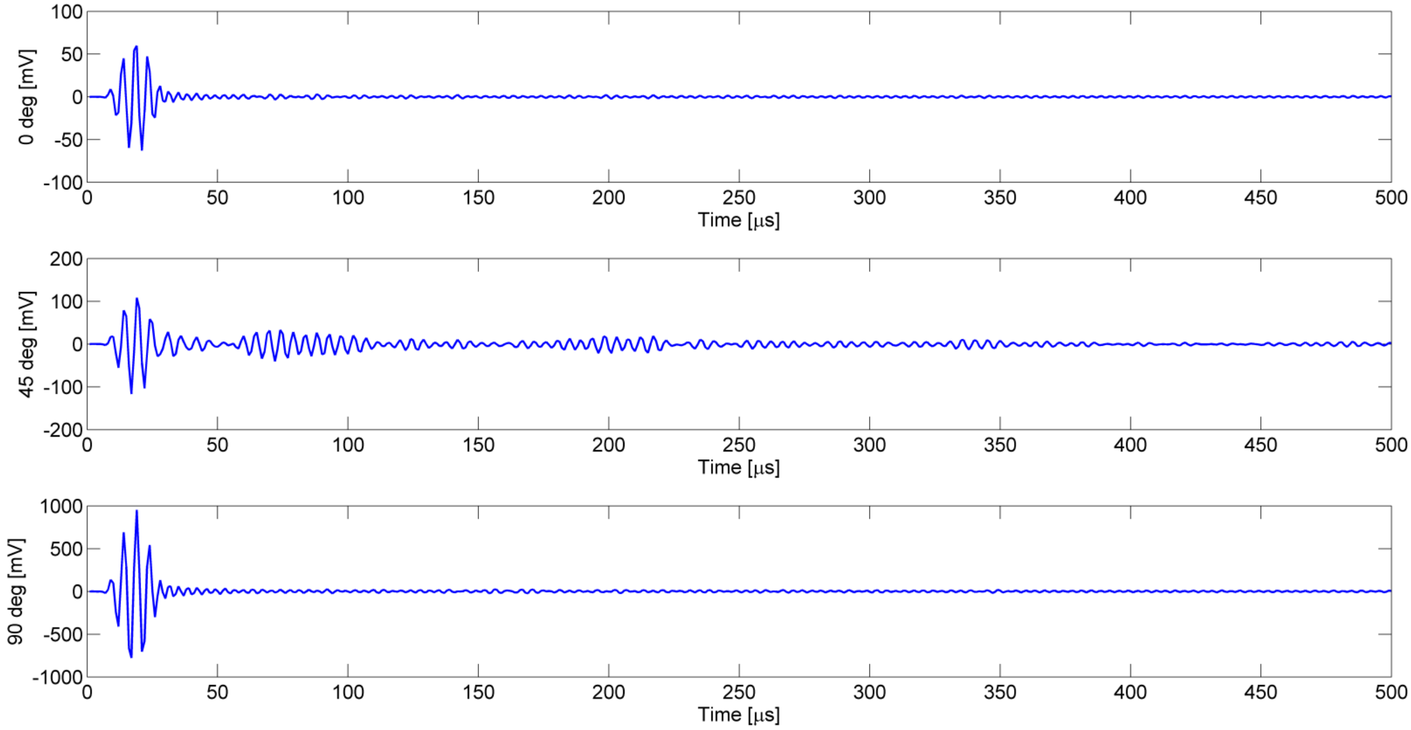

Figure 5: K1 sensor data

The response of interest can be seen in the first 50 µs, the five-cycle wave emitted by the MFC actuator. Farther forward in time, other responses can be seen due to reflections of the original wave off the plate boundaries or irregularities, which could later be used in damage localization.[7] The amplitude of oscillations is important in this data, as it would be used in determining the

[7] Kijanka, et al., *Damage location*, 6-11.

direction of the propagating Lamb wave.[8] It can be seen in the figure that the 90° fiber generated the response of greatest amplitude, about 1000 mV, and the 0° fiber that of lowest amplitude, about 60 mV.

The corresponding data for one trial with the sensor K2 is shown in Figure 6.

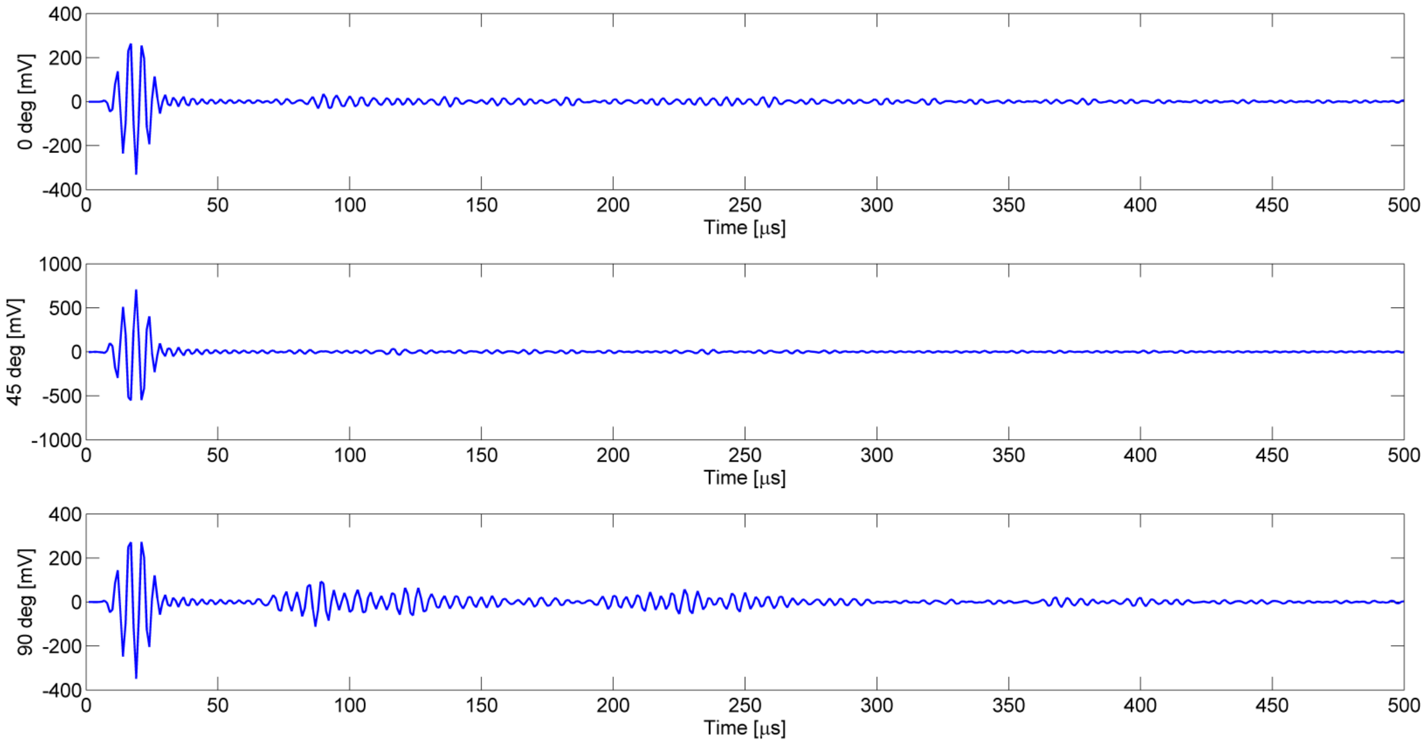

Figure 6: K2 sensor data

The response for K2 also shows the expected five-cycle wave, with some reflections most evident in the 90° direction. Differences in the amplitudes and reflections compared to the K1 data were anticipated, since their different locations on the composite plate should change how the Lamb wave travels to the various fibers.

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[8] Liu, et al., *Metal-core piezoelectric*, 71-873.

Another analysis of interest with the sensor data is the confirmation of the Lamb wave frequency, which was actuated at 200 kHz. The data was transformed to the frequency domain with a MATLAB implementation of the FFT. The FFT is plotted in Figure 7 for the sensor K1.

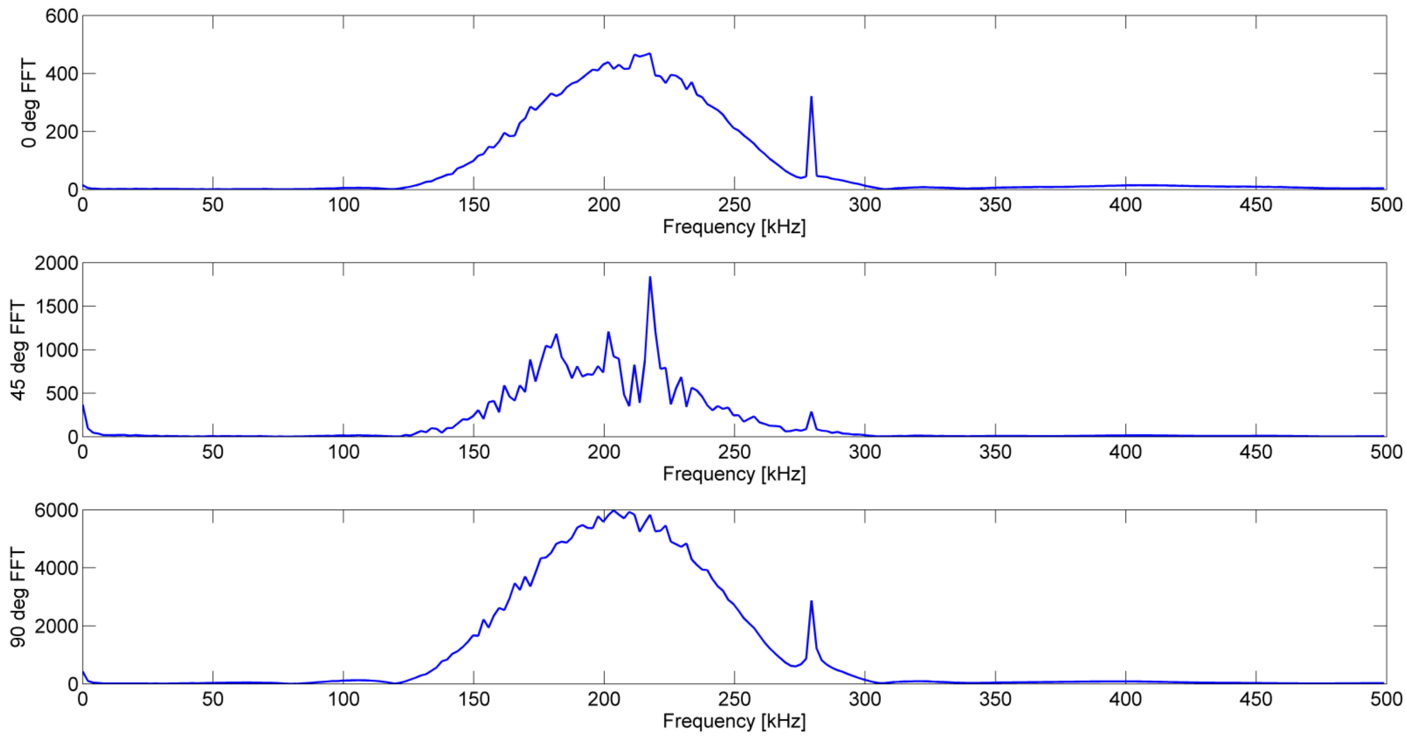

Figure 7: FFT of K1 sensor data

The peak frequency for the FFT should show at the actuation value of 200 kHz to indicate the sensor is responding at a rate that can record the Lamb wave strain. The number seems slightly higher than 200 kHz in the figure, but for a single wave this indicates that the strain changes measured were indeed due to the actuation. The corresponding FFT for the sensor K2 is plotted in Figure 8.

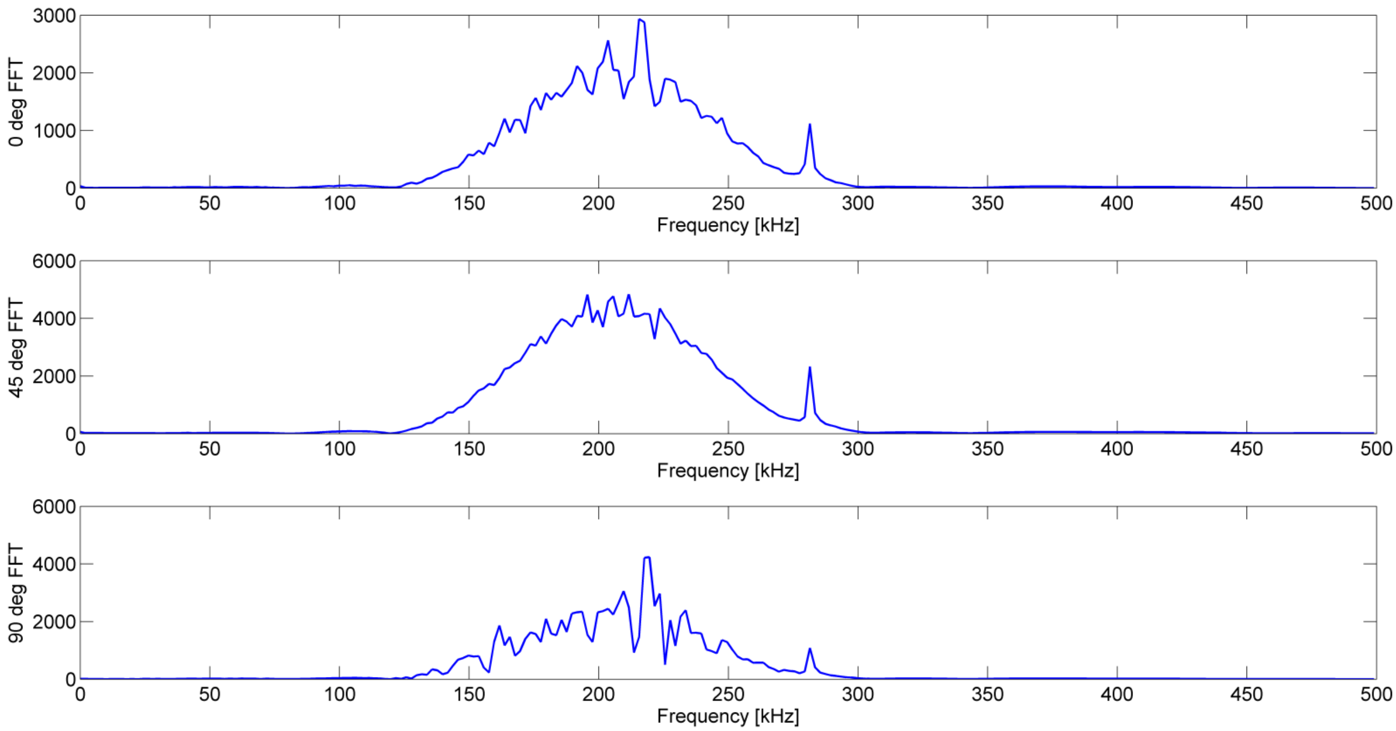

Figure 8: FFT of K2 sensor data

The peak expected to be at 200 kHz can be seen in the figure, indicating reception of the Lamb wave at the K2 location. To obtain better definition on the FFT analysis, the 200 kHz frequency could be further isolated. Prevention of certain sources of noise, possibly by conducting the experiment in a vacuum chamber, may be one method for improving the results of the frequency analysis.

Conclusion

The PZT sensor system mounted on a composite plate demonstrated the ability to detect Lamb waves from an actuation source. Strain produced by a MFC transducer was shown to be transmitted to each of two PZT fiber rosettes, containing fibers along the 0°, 45°, and 90° directions. A five-cycle sine wave, modulated by a Hanning window, was used for the actuation.

This same waveform was repeated in the response of both PZT sensor rosettes, as shown in the collected voltage data. A fast Fourier transform (FFT) was performed to determine the frequency domain information of each sensor signal, which matched the actuation frequency. Further use of the PZT rosette system could involve localization of damage to the plate, once the reflective wave signatures have been characterized. In summary, the piezoelectric rosettes considered in this project are ready to be utilized in structural health experiments involving Lamb wave detection.

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