Bone-Crack Detection by Piezoeletric-Electromechanical Impedance Method

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Abstract—**There is a growing interest in the application of smart materials such as piezoelectric in the biomedical field. The work presented in this paper is an attempt to demonstrate the feasibility of bone-crack detection by using piezoelectric-electromechanical impedance (EMI) method, which has the advantages of low cost, portable and simplicity in measurement. A piezoelectric transducer known as PZT (lead zirconate titanate) was used for actuating and sensing simultaneously and as a means of coupling the electrical and mechanical impedance. The basis of this novel method is to monitor variation in the mechanical impedance of a structural element via electrical impedance of a piezoelectric transducer attached to the host structure. In this study, a PZT transducer was used to detect artificially induced cracks in a bone. EMI measurements were carried out using AD5933 evaluation board for frequency range between 0.04 kHz to 100 kHz. The results obtained from the experiment were analyzed by quantifying the damage index using root mean square deviation (RMSD) of the impedance signals before and after cracks were induced in the bone. The results from the study show the feasibility of the piezoelectric-EMI method to effectively detect physical changes in the bone due to the artificially induced cracks.**

Keywords- EMI method, Piezoelectric, Bone Cracks

I. INTRODUCTION

Piezoelectricity was first discovered by Pierre and Jacques Curie in 1880. Monocrystalline materials such as quartz, tourmaline and Rochelle salt are known to generate an electric charge when subjected to mechanical stress know as direct effect and in converse effect they generate mechanical strain resulting from electrical charge.

In the biomedical community, there has been a growing interest to utilize the direct and converse effect of piezoelectric materials. Some researchers have studied the characteristics of bone by using piezoelectric effect [1-3]. LA. Cornejo *et al.* [3] reported that piezoelectric transducers can be used for applications such as medical diagnostic imaging, therapeutic treatments and non-destructive evaluation. Special interest has been associated with the mechanical properties of bone since the condition of bone can be easily determined from its mechanical properties [4]. Knight *et al.* [5] reported that a change in bone mineral density can be associated with a change in the mechanical properties of bone. These altered mechanical properties of the underlying subchondral bone may cause cartilage degeneration and affect the progress of osteoarthritis. In another study, piezoelectric patches were implanted to monitor capsule formation around soft tissue in Sprague-Dawley rats [4].

Compared to other existing smart materials, piezoelectric transducer has the advantages such as structural simplicity, low cost, and high reliability [6-7]. EMI method, which employs piezoelectric transducers, has been reported by many researchers for monitoring damage in civil engineering structures [8-13]. The EMI method uses both direct and converse effect a piezoelectric material simultaneously and changes in mechanical impedance of a structural element via electrical impedance of the piezoelectric transducer (e.g. PZT) attached to the host structure can be monitored through the coupling of the electromechanical impedance response [14].

The work presented in this paper is an attempt to demonstrate the feasibility of bone-crack detection by piezoelectric-EMI method, which has the advantages of low cost, portable and simplicity in measurement. PZT-type piezoelectric transducer was used to detect progression of artificially induced cracks. Results were obtained from series of experiments by comparing the impedance signals before and after each crack progression using the AD5933 evaluation board, which can be used to excite the PZT transducer between frequency range of 0.04 kHz to 100 kHz.

II. METHODOLOGY

Electromechanical Impedance Measurement

The electromechanical impedance response was obtained by applying electrical current to a PZT transducer, which was used to evaluate a bone sample via a medical grade stainless steel needle. The average radius of the needle was approximate 0.35 mm, embedded into the bone which was still in the pristine condition. A PZT patch was cut into a rectangular shape approximately 1 cm width x 1 cm height x 0.05 cm thickness and connected to electrical wires about 0.90 mm diameter. The other end of the wires was connected to the AD5933 evaluation board for measuring electrical impedance as shown in Fig. 1. The AD5933 evaluation board was connected to a laptop to run a software interface used to communicate with the AD5933 impedance chip. The parameters such as start frequency, increment frequency,

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number of increment and resistor value can be selected. The maximum number of increments that the device can sweep across was 511.

Before connecting the PZT to the needle, the resonance frequency of the PZT was determined first by using frequency range from 1 Hz to 100 kHz. For the proposed study, the resonance frequency used was between 20 to 30 kHz. The PZT was then attached to a stainless steel needle already embedded into the bone specimen. Superglue was used to bond the PZT and the needle. The resonance frequency was checked again for verification. The information needed and output data can be retrieved through the AD5933 evaluation board which processed the electromechanical impedance response of bone specimen via the PZT.

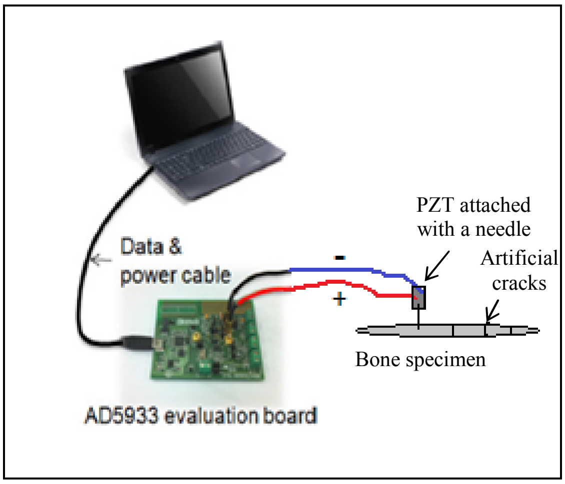

Fig 1. Setup for the experiment Bone-Crack Detection

Fig. 2 shows the EMI measurement flowchart. Before the EMI measurement was performed, the AD5933 program device was registered using start frequency at 20 kHz, increment frequency at 20 Hz, number of frequency sweep was 511 points, resistor value was 200 kΩ and without changing values of other parameters. Then, the gain factor was calculated after the program device was successfully registered. To obtain the impedance data and observe the frequency response plotted in a graph, the single impedance measurement was chosen. Note that the program device and gain factor only need to be calibrated once and the subsequent measurements for the same parameters need not be calibrated again. The resonance frequency or impedance data was collected first for pristine bone condition as a baseline data. New data was collected after the damage or bone crack was artificially created as shown in Fig. 1. The frequency range between 20 to 30 kHz was used during the experiment and the change in frequency response was observed as the crack distance was reduced nearer to the PZT-needle location. The artificial crack formed on the bone was about 0.1 cm in width, 1.5cm in length and the depth about 1 cm in longitudinal direction using a cutter. The steel needle attached with the PZT was embedded at one end of the bone and crack was artificially formed on the bone from 5 cm away and multiple cracks were formed by reducing the crack distance at 1 cm to get 5 data.

To precisely measure the changes in the EMI signals, a statistical technique known as root mean square deviation (RMSD) can be employed to give a quantitative value for the variation of the EMI signals [14]. Eq. 1 shows the formula used to calculate the RMSD value.

$$RMSD = \sqrt{\frac{\sum_{k=1}^{N}[\mathrm{Re}(Z_k)j - \mathrm{Re}(Z_k)i]^2}{\sum_{k=1}^{N}[\mathrm{Re}(Z_k)i]^2}} \quad (1)$$

The reference or baseline signal of PZT impedance is indicated as $(Z_K)i$, and $(Z_K)j$ is the corresponding impedance for each sample crack at k-th measurement point. In general, if the difference between the baseline and the consecutive measurement is large, this will result in a high RMSD value. In this study, the RMSD values were calculated using the real part of the impedance as it is well known to be a better indicator for detecting any structural change when compared to the imaginary part of the impedance [15].

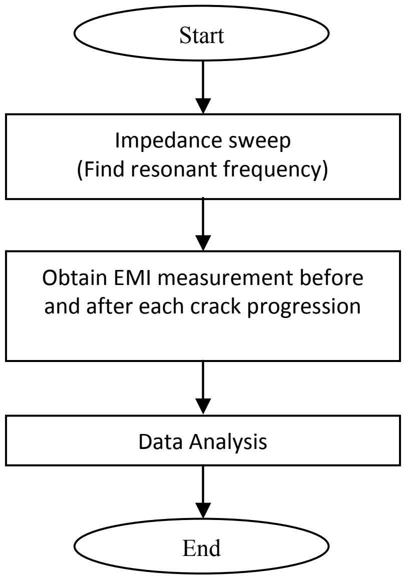

Fig 2. EMI measurement flowchart

III. RESULT AND DISCUSSION

Data Analysis

The data was collected for the frequency of 20 to 30 kHz and the total number of frequency sweep used in this experiment was 511 points. Two types of graphs were plotted in this paper where the data was obtained from the experiment conducted. The first graph was RMSD versus number of cracks and another graph was real impedance vs. frequency. Firstly, pristine bone condition was used as a baseline data or reference point. Then, EMI response due to the first sample of artificial crack induced in the bone were examined. Sample 1 represented 1 crack where the length of the crack from PZT sensor was 5 cm. Then multiple cracks were also induced in the bone which was labeled as sample 2, 3, 4 and 5, respectively, which was formed 3, 2 and 1 cm away from the PZT-needle location. EMI response due to each artificial crack signal was observed and measured. The data was then extracted from the device (AD5933) for the purpose of calculating the RMSD value.

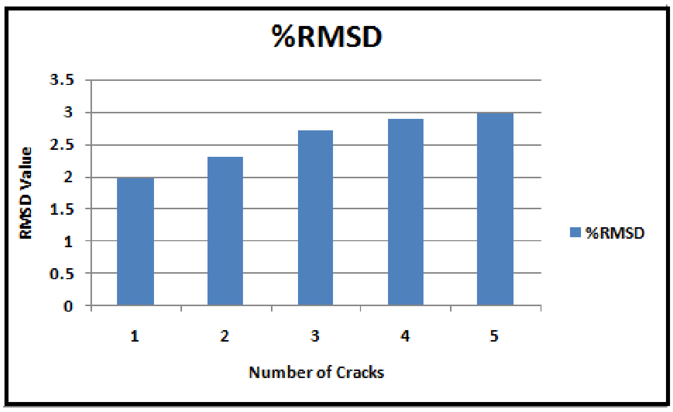

Fig 3. RMSD versus Number of Cracks

Fig. 3 shows the percentage of RMSD vs number of cracks graph for all 5 samples of artificial cracks . It can be seen that the lowest RMSD value was produced from sample 1 with 1.98%. Sample 2 gives 2.29%. Sample 3 produces 2.70% while sample 4 gives 2.89%. Highest RMSD value is shown by sample 5 with 2.98%. Sample 1 represents the lowest RMSD value because it was formed further from the PZT-needle location whereas sample 5 shows highest RMSD value because the artificial cracks was the nearest to the PZT-needle location.

Apart from the distance of crack to the PZT-needle location, another parameter that can be considered was number of cracks created in the bone. From the RMSD graph, it can be seen that as number of artificial cracks increased, the percentage of RMSD value was also increased. It was observed that sample 1 gives lowest RMSD percentage because the PZT has detected only one artificial crack in the bone. Highest RMSD value was produced by sample 5, because the PZT has detected all five artificial cracks in the bone. It can be said that higher results means more cracks have been identified. This shows that if samples of artificial cracks are gradually increased in the bone, the RMSD value shall show increasing value, which can be interpreted as deterioration of health condition in the bone.

Fig. 4 shows the real impedance value versus frequency for the 5 samples of artificial cracks. The frequency ranges from 20 to 30 kHz. It can also be seen that once the number of cracks increased the results show increment value of the real impedance and resonant frequency. At each sample of crack, the impedance signatures were recorded and compared with the pristine bone signals. It is observed that impedance is directly proportional with the resonant frequency. All samples show the linearity response. Therefore, it can be said that there is a good match between the theoretical and the practical results. The practical results confirm that the electrical impedance of the PZT increases as the mechanical impedance of the bone increases.

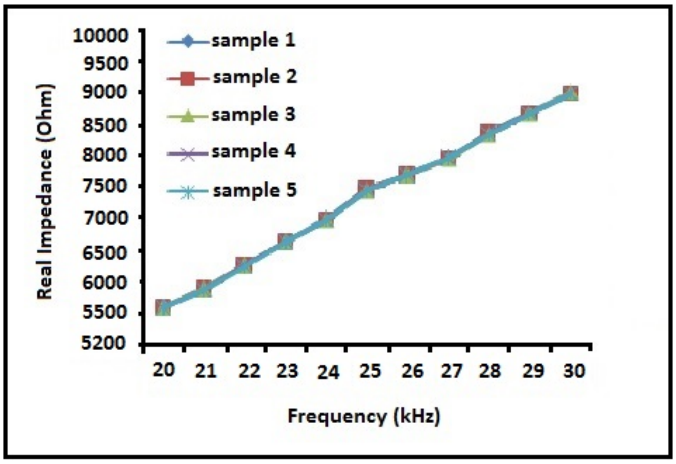

Fig 4. Real impedance vs Frequency

IV. CONCLUSION

This paper presented a study to detect bone-crack progression by using piezoelectric-EMI method. From the experimental results, it was observed that as the number of cracks increased, the percentage of RMSD value was also increased. As the distance of cracks were closer or near to the PZT-needle location, the sensitivity of the PZT was higher which contributed to higher value of RMSD. RMSD value shows higher value when the bone has more cracks.

All sample of cracks represented by sample 1 to sample 5 show that the real impedance directly proportional to the frequency. As frequency increases the amount of impedance also increases.

In addition, it can be concluded that piezoelectric materials in particular the PZT used in this study, is capable to effectively detect physical changes in the bone due to the artificially induced cracks. The proposed EMI measurement setup as introduced in this paper has the advantages of low cost, portable and simplicity in measurement. This may be useful in biomedical field to check on whether the bone is in good condition or not.

ACKNOWLEDGEMENT

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