BONE CHARACTERIZATION USING PIEZO-TRANSDUCERS AS BIO-MEDICAL SENSORS

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Short Title: **Bone Characterization using Piezo-Transducers**

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ABSTRACT

This technical note demonstrates the application of piezoelectric ceramic (PZT) transducers for evaluation of structural dynamic parameters of bones. An experimental study conducted on chicken's femur is reported in the paper. The bone is instrumented with two PZT patches, one serving as an actuator and the other as a sensor. The actuator patch is excited by applying a sinusoidal sweep voltage signal, which in turn excites the bone, whose vibrations are picked up by the sensor patch. The gain across the sensor patch as the function of frequency serves as a frequency response function (FRF). Structural dynamic parameters of the bone such as the modal frequencies and the corresponding damping ratios are derived from this FRF. The proposed technique is found to detect changes in the mechanical properties of the bone through changes in the FRF. The proposed technique can be employed in monitoring the healing of critical bones after surgery. It can also aid research related to bone injury, diagnosis of ailments such as osteoporosis and numerous other fields of bio-mechanics.

KEYORDS: Piezo-electric ceramic (PZT); bone; bio-mechanics; injury; frequency response function (FRF).

INTRODUCTION

Bones form the main load carrying structure of the human body and their well being is vital for our functionality. No direct techniques are available to characterize their mechanical properties *in situ*. The mechanical properties undergo changes after an injury and during the healing process. They also change during disease conditions, such as osteoporosis, which shows incidence in the middle aged women and older men, and is a leading cause of functional loss among the elderly. This technical note explores the possibility of miniaturized PZT patches as bio-medical sensors to evaluate structural dynamic characteristics of bones, by employing them as transmitters and receptors of acoustic waves.

Piezoelectric materials belong to the class of the so-called 'smart' materials [1] that is the materials possessing an inherent capability to alter their physical properties in response to an external stimulus. The piezoelectric materials undergo the development of surface charges on the application of a mechanical stress. This 'smart' feature is called the direct effect and is utilized in numerous engineering gadgets, such as accelerometers, strain sensors and pressure transducers, which are employed as sensors. They also exhibit the converse effect that is, undergoing mechanical deformations on the application of an electric field. The converse effect is made use of in actuator related engineering applications such as structural control, robotics and turbo-machinery. Interestingly, bones are also known to exhibit the phenomenon of piezoelectricity [2, 3]. Commercially, the piezoelectric materials are available as ceramics, such as lead zirconate titanate oxide (PZT) or polymers, such as polyvinvylidene fluoride (PVDF).

Fig.1 shows a PZT patch bonded to a slender structure, such as bones, with an alternating electric field E_3 acting along axis '3'. The behaviour of the PZT patch is governed by following relations [4]

$$D_3 = \overline{\varepsilon_{33}^T} E_3 + d_{31} T_1 \tag{1}$$

$$S_1 = \frac{T_1}{\overline{Y^E}} + d_{31} E_3 \tag{2}$$

where S_1 is the strain in direction '1', D_3 the electric displacement, d_{31} the piezoelectric strain coefficient and T_1 the axial stress in direction '1'. $\overline{Y^E} = Y^E(1+\eta j)$ is the complex Young's modulus of elasticity of the PZT patch at constant electric field and $\overline{\varepsilon_{33}^T} = \varepsilon_{33}^T(1-\delta j)$ the complex electric permittivity at constant stress, $j=\sqrt{-1}$ and η and δ denote respectively the mechanical loss factor and the dielectric loss factor of the PZT material. Eq. (1) denotes the direct effect and Eq. (2) the converse effect.

There has been a recent interest in the bio-medical community to utilize the direct and the converse effects of the PZT patches for clinical applications. Bender et al. [5] reported the use of embedded PZT sensors to monitor capsule formation around soft tissue implants. They utilized the implanted PZT patches as impedance transducers to monitor changes occurring in the surrounding tissue. The technique essentially involved measuring electrical impedance across the implanted patches over high frequency range (typically in kHz range) over long periods of time to detect any changes in the mechanical properties of the surrounding medium. Interestingly, their observations were similar to those of Soh and Bhalla [6] who employed the piezo-impedance transducers for monitoring the strength, the damage and the curing of concrete. Special interest has been associated with the mechanical properties of bones [7] since the condition of bones can be easily assessed on the basis of their mechanical properties. Bones undergo slow but continuous restructuring as a normal biological process as well under disease conditions, such as osteoporosis, which is accompanied with loss of bone density, especially near the ends of the bones.

This technical note focuses on evaluating the dynamic mechanical properties of bones, such as modal frequencies and the associated damping factors, using a pair of PZT patches. Recently, Christopoulou et al. [8] reported the measurement of modal damping of bones of adult female Wistar rats using accelerometers. However, compared to accelerometers, the PZT patches have several advantages, such as low-cost, negligible weight and wide bandwidth. The most striking feature of PZT patches is their miniaturized appearance and the ability to be permanently implanted in bone-like structures. Additionally, the PZT transducers are also not likely to alter the subject's dynamic properties by their own added mass.

EXPERIMENTAL DETAILS

Fig. 2 shows the experimental bone, a fresh femur of a chicken, 12.5cm long. Two PZT patches, 10x10x0.3mm in size, conforming to grade PIC 151 [9], were bonded near the two ends of the bone, using standard araldite epoxy adhesive. The bone was placed on foam to simulate 'free-free' boundary conditions, for the ease of experimentation. While one PZT patch acted as actuator, the other acted as sensor. The actuator patch was excited by applying a sinusoidal voltage signal of amplitude 5V by means of a function generator FG-702C (μ-TEC Electronic Measuring Instruments). The excitation frequency was varied from 0.5 kHz to 20 kHz. Due to converse effect, the excited patch transmitted acoustic waves in the bone. The resulting vibrations were picked up by the PZT sensor patch, which, on account of the direct piezoelectric effect, developed alternating voltage signals across its terminals, which were measured by the Agilent 34411A digital multimeter. Measurements were made at each frequency in the range of interest. A plot of voltage gain (voltage sensed by the sensor patch divided by the voltage applied across the actuator) as a function of frequency served as a FRF and provided a means for determining the dynamic mechanical properties of the test bone.

ANALYSIS AND RESULTS

The experimental condition of the bone placed on foam was close to 'free-free' condition. Considering axial vibrations, the natural frequencies of the bone are given by [10]

$$f_n = \frac{(2n-1)}{4l}\sqrt{\frac{E}{\rho}} \tag{3}$$

where E represents the Young's modulus of the bone, ρ the density, n the mode number and l the distance of the nodal point (here the centre of the PZT actuator patch) measured from the end of the bone. Substituting E = 20GPa, ρ = 2000 kg/m^3 [11] and l = 0.1m, the first two natural frequencies result as 7.91 kHz and 23.72 kHz respectively. Fig. 3 shows a plot of the gain across the sensor PZT patch as a function of frequency. In this plot, the resonant frequencies appear as points of peak gain across the PZT sensor patch. The first two modal frequencies can be identified as 4.95 kHz and 14.3 kHz from the figure. Other minor peaks are also observed in the figure, which can be attributed to the flexural or the coupled axial-flexural vibrations, since the PZT actuator patch, bonded on the surface, induced flexural vibrations also. The difference between the analytical and experimental first frequency suggests the large variability associated with the values of E and ρ used in the theoretical computations. The results show that theoretical computations are not very reliable for bone like materials.

Another useful information that can be obtained from the FRF is the modal damping associated with bone. Modal damping has been shown as a potential diagnostic tool by Christopoulou et al. [8] in detecting bone related ailments. In this study, the modal damping was determined using the half power band method [12] as 0.04 for the first resonance peak, which is typically of the order reported earlier [8] using accelerometer. The present approach, on the other hand, is much straight forward since the requirements for the hardware and the sensors are minimal.

In order to investigate the feasibility of detecting changes in the mechanical properties of the bones, the test bone was allowed to dry for a period of one week. After one week, a small incision was also made located in between the actuator-sensor pair using a knife. Fig. 4 shows the FRF of the bone after these changes and compares with that of the pristine bone. Distinct differences between the two FRFs can be easily observed from the figure. The drying of the bone caused increase in Young's modulus and reduction of bone density (due to moisture loss). The incision, on the other hand, caused reduction of the bone stiffness locally. Observing from Fig. 4, the overall effect has been that of increase in the natural frequencies. This can be explained, using Eq. (3), that the uniform increase of Young's modulus and the uniform decrease of density throughout the bone, had greater influence than small incision, which reduced stiffness of the bone locally. Further, the damping ratio (corresponding to the first mode) was found to reduce from the pristine value of 0.04 to a final value 0.035 (a reduction of 12.5%), thereby highlighting the fact that drying is accompanied by such reduction. The results clearly show the potential of the proposed technique in detecting mechanical changes in the bone.

CONCLUSIONS

This technical note has presented a simple technique, utilizing a pair of piezo-patches as bio-sensors, for evaluation of the mechanical properties of the bones. Simple hardware and sensors, such as miniaturized PZT patches, a function generator and multimeter, which are all low-cost and commercially available, have been utilized. By monitoring the measured parameters, that are the modal frequencies and the modal damping, changes in the mechanical properties of bones can be easily detected. Hence, they could possibly aid in detecting abnormal conditions, such as osteoporosis, in which case, modal frequencies are likely to drop and damping increase. In addition, this technique can also be used to monitor the healing of fractured bones or condition of the critical bones during the post surgery period. This paper is primarily focused on proof-of-concept of the proposed technique. Further studies need to be undertaken for determining the feasibility of implantation of the sensors and their long-term performance.

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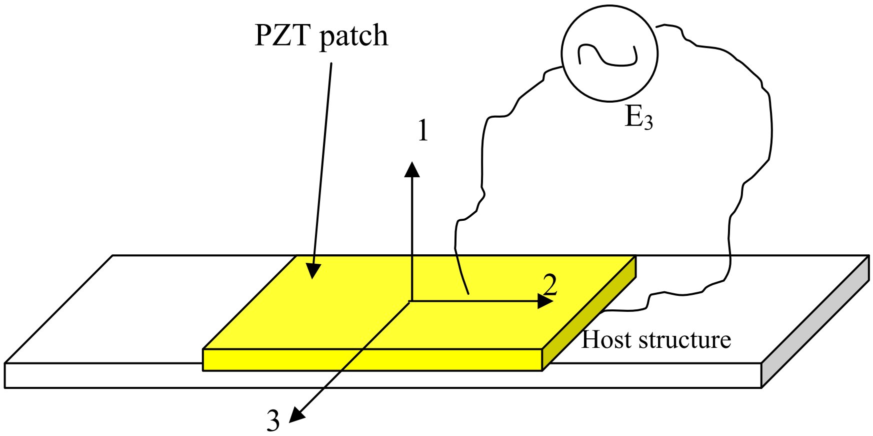

Fig. 1 A PZT patch bonded to a 1D slender structure.

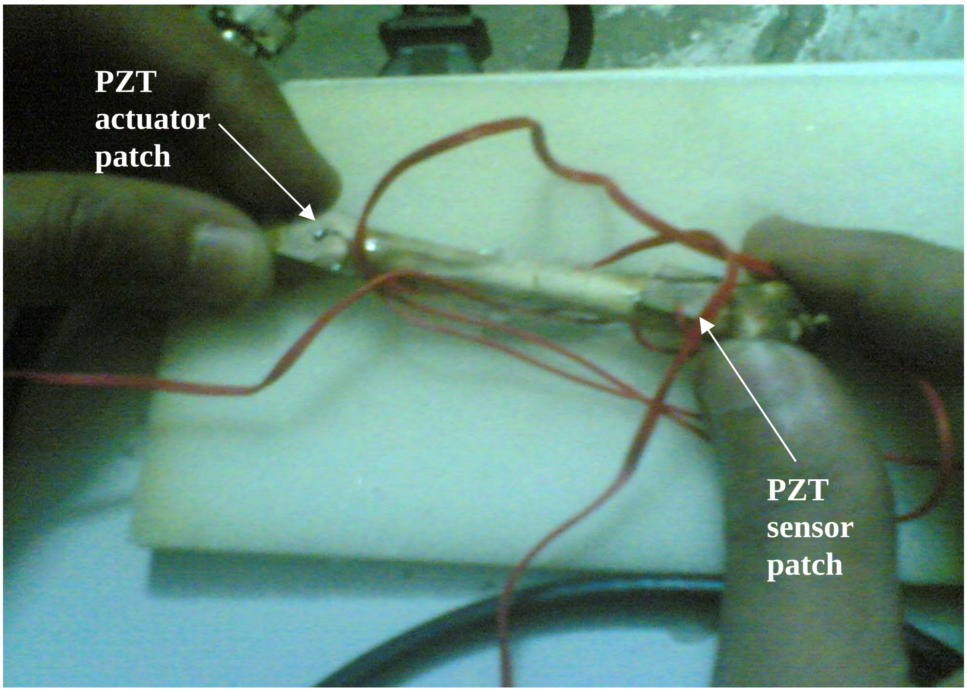

Fig. 2 Chicken femur instrumented with PZT actuator-sensor pair.

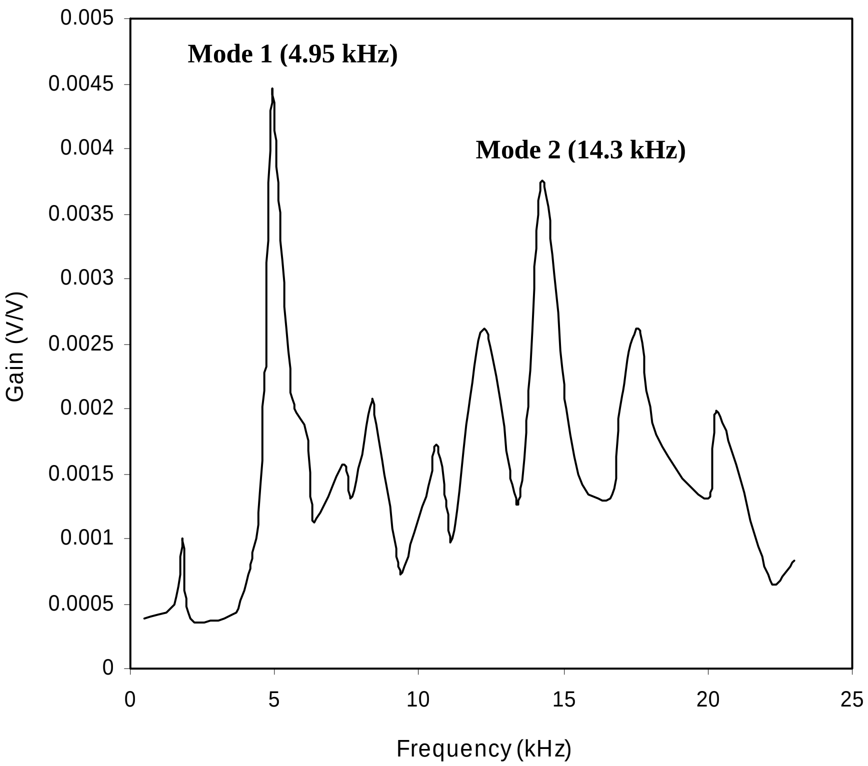

Fig. 3 A plot of gain vs frequency measured across PZT sensor patch.

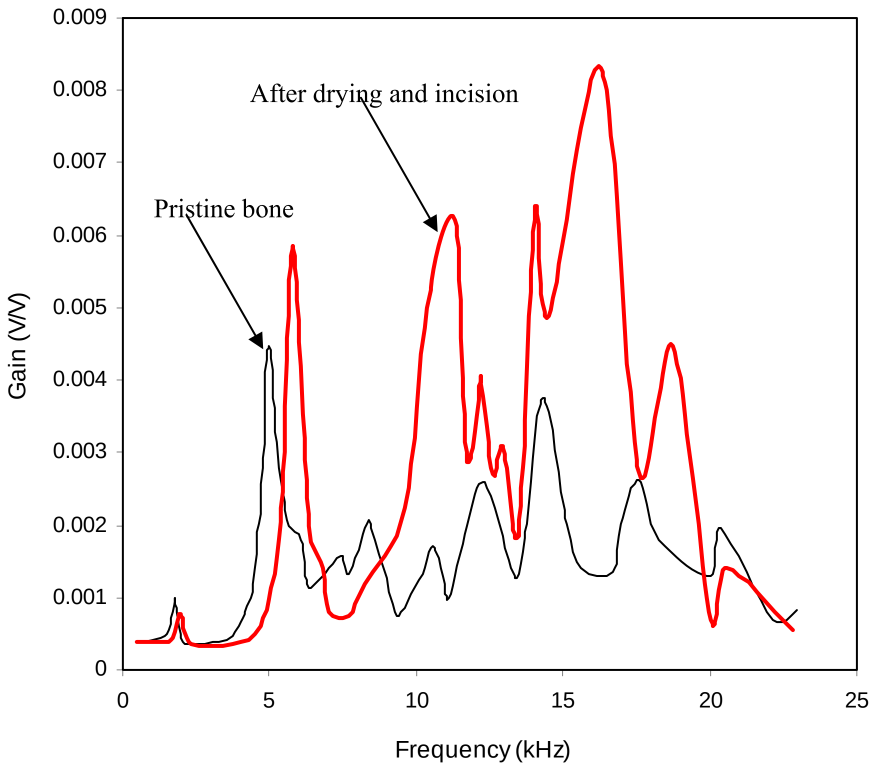

Fig. 4 FRF after change in condition of bone.