3P5-13

Piezoelectric polarization induced by oblique ultrasound irradiation in biological tissues

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1. Introduction

Piezoelectricity is defined in inorganic single crystals without a center of symmetry. The definition has expanded to include inorganic polycrystalline or organic materials. Not only piezoelectric polymers such as polyvinylidene fluoride (PVDF) and polylactic acid (PLA) but also fibrous biological tissues such as bone and tendon exhibit piezoelectric properties.[1] In polycrystalline materials, piezoelectric polarization results from the summation of electric dipole moments in each quasicrystal region within the material. Therefore, the piezoelectricity is strongly affected by its crystalline or the orientation of polymers.

In fibrous biological tissues of locomotor organs, the orientation of collagen fibers is deemed to be an important factor in their mechanical strength. Piezoelectricity has the potential to be a physical property that evaluates the fiber orientation of tissues, and thus assessing it may lead to a diagnosis of the "quality" of the locomotor organs.

In recent years, we have demonstrated a unique ultrasonic method to evaluate piezoelectric polarization named the acoustically stimulated electromagnetic (ASEM) method.[2,3] In this method, acoustic pressure of ultrasonic pulses induces electric polarization through piezoelectricity of the object. The alternating electric field of the piezoelectric polarization is detected with a capacitive antenna. The anisotropy of piezoelectric polarization was observed in tendon, skeletal muscle, and aortic wall, and the major non-shear term of piezoelectric tensor was confirmed to be d_{33}, with polarization occurring along the fibrous direction.[4] The ASEM method allows non-invasive piezoelectric measurements and is expected to be applied to diagnostics using bio-piezoelectric properties.

However, in fibrous biological tissues, the shear term d_{14} of piezoelectric tensor is reported to be fundamental and approximately one order of magnitude larger than non-shear terms.[1,5] The purpose of this work is to detect the ASEM response due to the shear term by irradiating oblique ultrasound. In this paper, we report experimental results for PVDF and PLA films with different piezoelectric tensor, and for bone.

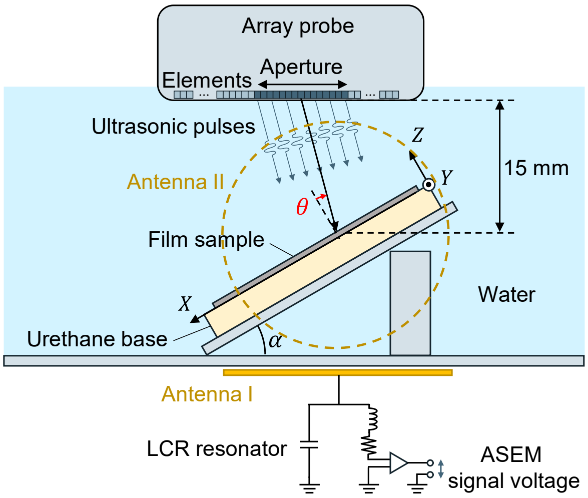

Fig. 1 Schematic illustration of the measurement setup. The antenna I and II are used for the PVDF and PLA measurements, respectively.

2. Experimental Setup

PVDF and PLA films (thickness of 0.13 mm and 0.02 mm, respectively) were attached to a urethane base angled at α (**Fig. 1**). For polarized PVDF with the thickness direction as the 3-axis, the macroscopic piezoelectric tensor follows C_{2v} symmetry.[6] Piezoelectric polarization corresponding to a non-shear term, d_{33}, is expected to occur perpendicular to the film surface (along the Z-axis shown in Fig. 1) when the ultrasound is irradiated perpendicularly to the surface. On the other hand, the symmetry of uniaxially stretched (L-type) PLA is D_{∞},[6] where the piezoelectric tensor has only shear terms d_{14} and $d_{25} = -d_{14}$ (the stretched direction is defined as the 3-axis). Piezoelectric polarization corresponding to the shear term, d_{14}, is expected to occur along a direction perpendicular to the stretched direction in the film surface (along the Y-axis). The samples were submerged in a water tank filled with deionized water. Ultrasonic pulses (center frequency: 6 MHz, 6-dB bandwidth: 3 MHz) were irradiated to the samples using a linear array probe. The incident angle θ to the film surface is controlled by the beam steering accomplished by adding delays to the transmit timing. A metal plate antenna (circular plate, radius of 15 mm) was installed out of the water tank. The antenna was

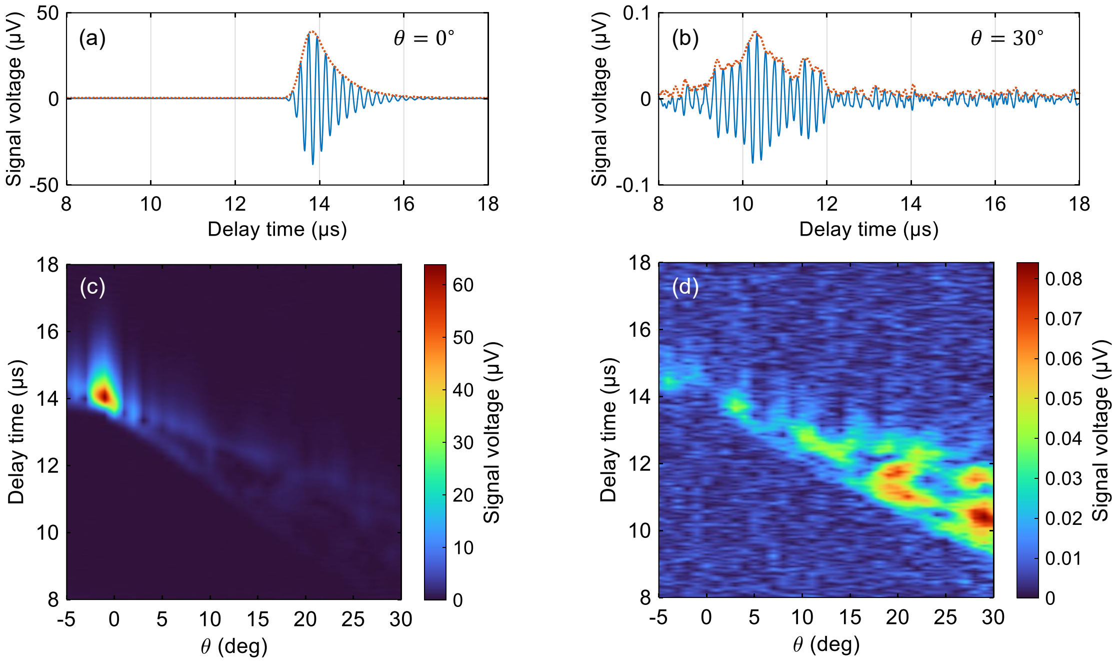

Fig. 2 Time traces of (a) the PVDF sample at $\theta = 0°$ and (b) PLA sample at $\theta = 30°$. The dashed curves indicate the envelopes of the time traces. Color maps of the signal amplitude, plotted in delay time versus angle θ for (c) PVDF and (d) PLA samples.

coupled with an LCR resonator (center frequency: 5 MHz, 6-dB bandwidth: 1 MHz). The ASEM signal was amplified and averaged over pulses in a digitizer.

3. Results and discussion

Figures 2(a) and 2(b) show typical time traces of the ASEM signal. The signal amplitude of the envelope is plotted in delay time versus angle θ (Figs. 2(c) and 2(d)). In the PVDF sample, the signal amplitude was maximized when ultrasonic pulses were irradiated perpendicularly to the surface ($\theta \simeq 0°$) (Fig. 2(c)). Piezoelectric polarization thus occurs through the d_{33} term. In the PLA sample, the signal amplitude exhibited the maximum at $\theta \simeq 30°$ rather than $\theta \simeq 0°$. It indicates that polarization is induced by oblique ultrasound irradiation through the shear term. Interestingly, we observe a tendency for the signal amplitude to oscillate as θ increases. This feature can be interpreted by the constructive condition in the process of converting the obliquely irradiating longitudinal waves into shear waves on the sample. The constructive condition is simply expected to be $\lambda_L = n\lambda_S \sin\theta$, where λ_L and λ_S are the wavelength of longitudinal waves in water and shear waves in the sample, respectively, and n is a positive odd integer. Using the corresponding velocities, $v_L = 1500$ m/s and $v_S = 950$ m/s,[7] the constructive condition was estimated to be about $32°$ for $n = 3$ ($\theta = \sin^{-1}(v_L/nv_S)$). This result strongly supports the generation of shear waves and the associated shear-induced polarization.

Cortical bone samples were also measured. Similar results were obtained, but the situation was suggested to be more complex. The detailed discussion will be presented in the symposium.

4. Conclusion

We demonstrated the detection of shear-induced polarization by oblique ultrasound irradiation through the ASEM method.

Acknowledgment

This work was supported by JSPS Grants-in-Aid, Grant Number JP20H04500. One of the authors (Y. S.) was supported by JST SPRING, Grant Number JPMJSP2116.

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