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Acoustically induced electric and magnetic polarization and its sensing applications

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1. Introduction

Ultrasound measurement is widely used in medical and industrial fields. Academic societies related to ultrasound techniques go far beyond the field of physics and are dispersed among societies in various fields such as medicine, steel industry, and civil engineering. The improvements in measurement techniques for specific targets are being promoted daily. The reasons why ultrasound techniques are used in such a wide range of practical settings may be due to the fact that (1) noninvasive evaluation is possible for many objects through which light does not penetrate and (2) real-time waveform acquisition is easily performed in the radio frequency (RF) range. However, since ordinary ultrasound measurements acquire the reflection/ transmission coefficients or velocity of ultrasound, their use is mainly limited to the evaluation of mechanical properties and geometric anomalies --- that is, the electrical and magnetic properties of matters are not probed.

Over the past decade, we have pursued a unique method to probe the electromagnetic properties of matters through ultrasound waves (acoustically stimulated electromagnetic (ASEM) method) [1-3]. In general, elastic waves do not directly couple with electrical and magnetic properties. However, elastic modulation can often provide the time modulation of electric and magnetic polarization of an object through electro- or magneto-mechanical coupling. It follows that an alternating dipolar field can be generated from the object to the surrounding environment by acoustic stimulation (**Fig. 1**).

We have focused on this new measurement scheme, which has not been available before, and have been studying electric and magnetic polarization induced by ultrasound waves. First, we revealed that ultrasound can electrically polarize not only conventional piezoelectric materials, but also biological tissues such as bone, tendon, and aortic wall [2]. Second, we showed that ultrasound can modulate the magnetic polarization (magnetization) of ferromagnetic materials, resulting in magnetic imaging and hysteresis measurements via ultrasound stimulation [3].

In this plenary talk, I will present (i) the measurement concept based on acoustically induced polarization, (ii) what we can measure at present, and (iii) the prospects for its sensing applications.

2. Measurement concept

Piezoelectric materials are discussed here, but similar discussion can be made for piezomagnetic and ferromagnetic materials as well. Electrostriction (magnetostriction) is phenomenologically equivalent to piezoelectricity (piezomagnetism) in the linear response regime, and we make no distinction between them for the purpose of this discussion [4].

In strict definition, piezoelectricity is limited to single crystals of inorganic materials that do not have a center of symmetry. Later, this concept of piezoelectricity was extended to polycrystals, organic materials [5], and even biological tissues [6]. In the case of polycrystals, piezoelectric polarization can be attributed to the sum $\bar{p} = \sum_n p_n$ of the electric dipole moments, p_n , occurring in partially crystalline regions within the material.

Let me begin with the electromechanical linear response, $P_{\mathrm{ac}} = d_{\mathrm{loc}} T_{\mathrm{ac}}$, where P_{ac} and T_{ac} are the acoustically induced electric polarization and acoustic stress, respectively, and d_{loc} is the local piezoelectric constant in the acoustically excited volume, V. The polarization, $P_{\mathrm{ac}}(t) = \overline{p(t)}/V$, is temporally modulated when stress, T_{ac}, is applied locally by ultrasound irradiation. The alternating electric dipolar field, $\boldsymbol{E}_{\mathrm{dip}}(t)$, is then emitted to the surrounding environment. The dipolar field is detected, for instance, by a resonant capacitive antenna.

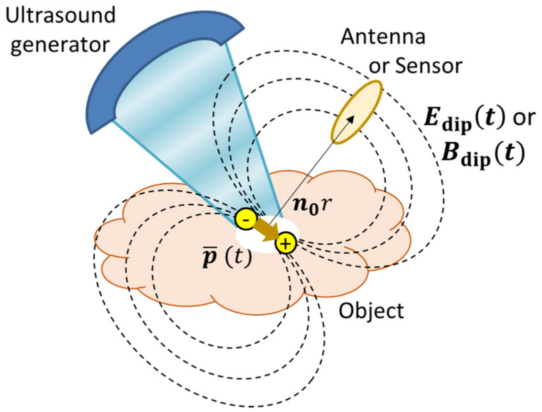

Fig.1 Schematic representation of the ASEM method.

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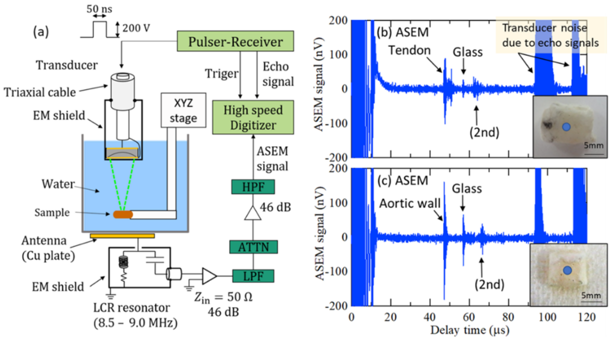

Fig.2 (a) Block diagram of the ASEM measurement system. Typical time traces of ASEM signals of (b) tendon and (c) aortic wall [2].

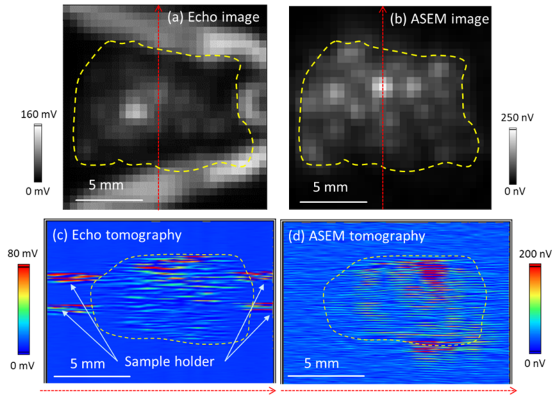

Fig.3 Imaging of the tendon sample. Lateral images of (a) echo and (b) ASEM signals. Tomographic images (B-mode) of (c) echo and (d) ASEM signals [2].

In the case of magnetism, $P_{\rm ac}$ and $d_{\rm loc}$ can be regarded as the magnetization and local piezomagnetic constant, respectively, and $\bar{p}(t)$ is the sum of magnetic dipole moments in the acoustically excited volume. The magnetic dipolar field, $\boldsymbol{B}_{\rm dip}(t)$, due to acoustically induced magnetization is detected by a resonant loop antenna.

3. Acoustically induced electric polarization in biological tissues

A typical setup for measuring acoustically induced electric polarization is shown in **Fig. 2**(a). An appropriate distance between the sample and transducer (70 mm) allows us to separate the pulsed ASEM response from the EM noise generated by the transducer temporally. The acoustically induced dipolar field, $\boldsymbol{E}_{\rm dip}$, is detected by a resonant capacitive antenna tuned to the frequency of the ultrasound waves (8-10 MHz). Because the ASEM response is generated at half the echo delay time, the signal observed at 47 µs is identified as the target ASEM response of the samples (Fig. 2(b) and 2(c)). Spatial images are obtained by scanning ultrasound focused beam (**Fig. 3**). Induced polarization has been clearly observed in Achilles tendon, aortic wall, aortic valve, and bone, whereas it is small in adipose and myocardium tissues, indicating that fibrous tissues exhibit electromechanical coupling [2]. In addition, it has been shown that the alignment of collagen fibers can produce significant anisotropy in acoustically induced polarization. The ASEM method thus provides a powerful tool for exploring biopiezoelectricity, even in living tissue, and may be allowed to pursue clinical applications such as the diagnosis of organ fibrosis and bone quality.

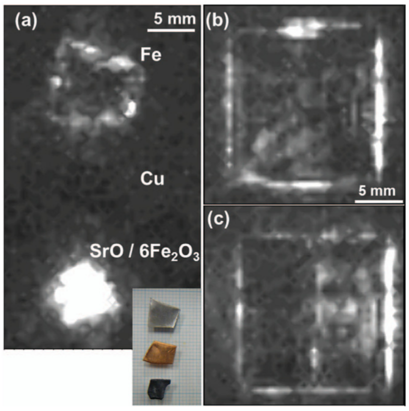

Fig.4 (a) Magnetically selective ultrasound imaging using the ASEM response for pure iron and copper foils and a flake of ferrite. ASEM images of the iron foil (b) before and (c) after folding [3].

4. Acoustically induced magnetic polarization in ferromagnetic materials

Magnetically selective ultrasound imaging has been performed by using the ASEM response (**Fig. 4**). Along with a clear signal from the ferrite, a weak signal along the sample edges of the pure iron foil was also observed. Because net magnetization is not expected in pure iron, we assume that the signal arises from the aligned magnetic domains caused by the distortion resulting from the cutting of the iron foil. When a distortion is applied by folding the foil in the middle, the signals are observed along the folded line (Fig. 3(c)) [3]. This finding provided valuable hints for the nondestructive evaluation of residual stress in steel [7].

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