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Trends in Measurement Techniques on Ultrasonic Electronics
超音波エレクトロニクスにおける計測技術の動向

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1. Introduction

Measurement – the act of measuring physical properties that we perform unwittingly – is the common thread which strongly related to all science that supports our daily lives. To achieve quantification of various physical properties, electronic materials that converts one form of energy to another are necessary.

Focusing on electric energy conversion, piezoelectric element is one of the famous solid-state transducers that can support high-frequency, bi-directional energy conversion with excellent efficiency. By using piezoelectric transducers, indirect measurements can be achieved by converting mechanical information into electrical one. Hence, piezoelectric transducers can cover wide range of measurement applications. The scope of piezoelectric transducers can also be utilized for not only solid system but also for liquid and gas systems, for example, temperature[1-6], velocity [7-14], and length [15-19] can be determined by measuring a time-of-flight of ultrasonic sound. Moreover, visualization of distributed components [20-27], structure [28], and defects [29-36] can also be achieved by combining measurement of time-of-flight and inverse problem. Consequently, the field of ultrasonic electronics contributes our industrialized society by providing measurement techniques utilizing the electro- mechanical energy conversion.

In this manuscript, we explain the necessity of measurement techniques to provide some ideas for related applications, by introducing recent studies related to measurement techniques on ultrasonic electronics

Measurement techniques

Application	*Power* *Manipulation* *Imaging*
Instrumentation	*Sensors and actuators* *Transducers*
Materials	*Crystal* *PZT*
Method	*Analysis* *Simulation* *Theory*

Fig. 1 Measurement techniques in ultrasonic electronics

2. Measurement methods

Various measurement methods have been developed for numerous applications. In this section, some recent measurement methods are picked up, and introduced. A visualization method for defect detection in steel billet has been proposed [29-36]. There are conventional methods of non-destructive testing for defect detection in solid. Although pulse echo method is a typical method, ultrasound may be absorbed especially in high-attenuation steel. While pulse echo method uses the pulse wave reflected or scattered by defects, the proposed method is based on time-of-flight of longitudinal wave propagating through the billet. The time-of-flight will increase if a defect exists on the propagation path since the pulse wave diffracts around the defect, so that the propagation path becomes slightly longer. The defect image is extracted using one of computerized tomography. The propagation time increase due to diffraction causes apparent decrease of sound speed at the location of the defect in the reconstructed image. **Figure 2** shows an example visualized image of the defect in a billet. All of five defects were possibly seen in visualized image. Some artifacts were also seen because sound-to-noise ratio was low in high attenuation steel.

3. Material property measurement

Viscosity is one of important material properties in fluid dynamics, and the measurement of viscosity is important factor for designing industrial fluid process such as transportation and mixing up. Especially in recent years, the measurement of very low viscosity (~ 1 mPa·s) has an important role for microscopic fluid process with the development of ink-jet technology. In such a situation, some methods for low-viscosity measurement have been proposed [38-40]. Among these, rotational viscometer

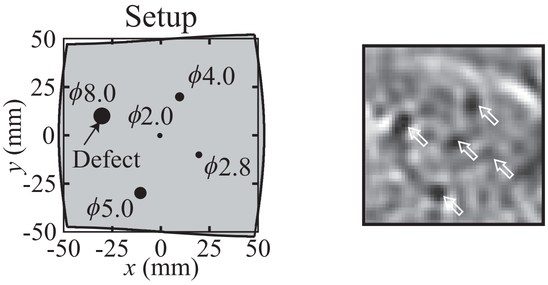

Fig. 2 Experimental result of defect visualization in high attenuation steel billet [35].

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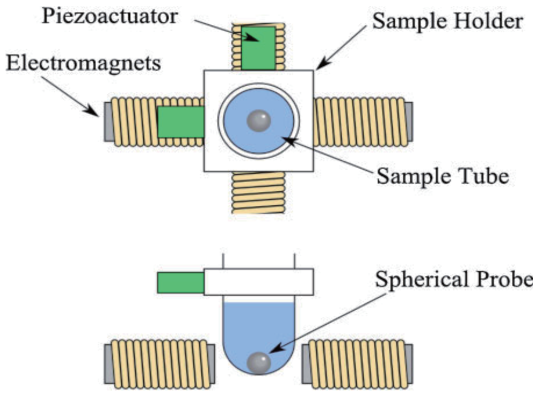

Fig. 3 Ultrasonic vibration system incorporated in electromagnetically spinning viscometer [41].

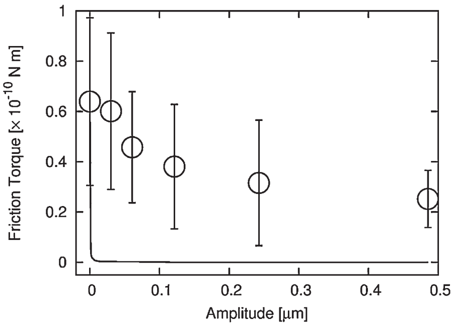

Fig. 4 Relation between amplitude of piezoelectric actuators and friction [41].

is one of the most popular apparatus for viscosity measurement using a rotating probe is put into the fluid.

The method of friction reduction was proposed, in which ultrasonic vibration reduces the friction of spinning viscometer, as shown in **Fig. 3** [41]. Spherical probe is electromagnetically spinning, and piezoelectric actuator vibrates the sample tube. As shown in **Fig. 4**, the friction torque was reduced with the increase of the amplitude of the piezoelectric actuators. With help of ultrasonic friction torque reduction, it was expected that the accuracy of very low-viscosity measurement (in 1 mPa·s order) to be improved from 10 to 3 %.

4. Optical measurement under high-intensity ultrasonic field

The size of acoustic cavitation bubbles is an important parameter in sonochemistry. The size of cavitation bubbles generated by high-intensity ultrasound in liquid oscillates in the ultrasonic field, so that the size distribution of the bubbles and surrounding ultrasonic field are both required to be measured. However, under extremely high intensity ultrasound, probe microphone are possibly damaged by cavitation bubbles. In addition, the insertion of microphones in the liquid itself may disturb the sound field. Therefore, noncontact methods to measure the size of cavitation bubbles and the sound field are required. Since small particles like microbubbles diffract laser light depending on their size, the observation of diffraction pattern will give us the particle size information. The principle is applied to laser diffraction particle size analyzer. Therefore, the size distribution and its fluctuation by ultrasonic field can be measured by using laser diffraction. **Figure 5** shows the measurement system recently reported [42-43]. The bubble size distribution and its fluctuation were measured using laser diffraction pattern. In addition, stroboscopic imaging system was also setup for verification. **Figure 6** shows the fluctuations of the volume-based mean size of bubbles measured by the proposed method and stroboscopic imaging. The results roughly agreed with each other. This research was followed by the measurement of ultrasonic field using almost the same optical system [44]. In the future, it is expected that the acoustic cavitation bubble size and ultrasonic field are simultaneously measured.

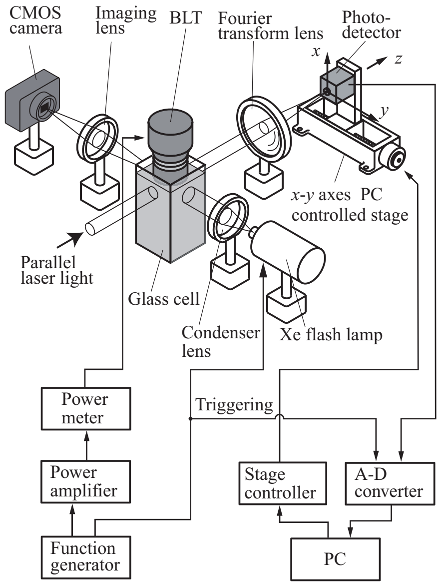

Fig. 5 Measurement setup of microbubble. [42]

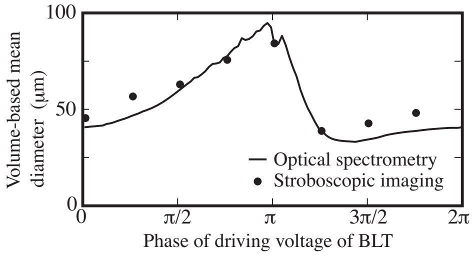

Fig. 6 One-cycle fluctuation of the volume-based mean diameter [42].

5. Piezoelectric sensors

Surface acoustic wave (SAW) device is one of electro-mechanical devices, and SAW devices has been widely used in recent electronic circuits for communication. On the other hand, electro-mechanical devices, not limited to SAW devices, convert electrical signal to mechanical vibration, and vice versa. Thus, electro-mechanical devices can act as sensor for mechanical phenomena. SAW sensors are one of piezoelectric sensors. The SAW sensor consists of a pair of IDTs and a delay line between these IDTs. Since the precision of such a sensor largely relies on quality factor of resonance, reducing mechanical loss is one of important problems. Ball SAW sensors were developed in order to improve the precision by using roundtrip of SAW [45-46]. As shown in **Fig. 7**, an IDT is set on the surface of a quartz crystal ball. When the aperture (width of IDT) is appropriate, naturally collimated SAW is generated and propagates multiple times along the equator. The quartz crystal ball was coated with sol-gel SiO_x film sensitive to moisture. During the multiple roundtrip propagation, the SAW interacts with moisture with help of the SiO_x film. This resulted in the sensitivity of 0.2 nmol/mol to moisture. It is comparable to the most sensitive commercially available moisture sensor.

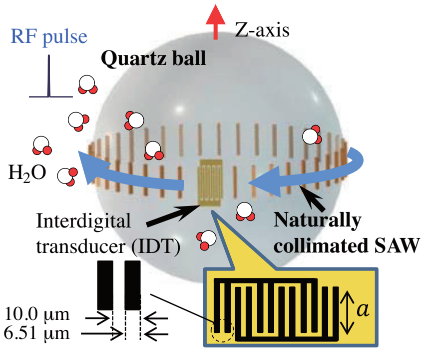

Fig. 7 Ball surface acoustic wave sensor [45].

6. Underwater observation and wireless communications

Japan is a country that is surrounded by the sea. To prevent maritime disasters, ocean bottom seismometers (OBSs) are constructed for monitoring and mitigating earthquake and tsunami disasters (**Fig. 8**) [47]. Recently, these OBSs are utilized for not only environmental monitoring but also for monitoring of marine ecosystem. Because OBSs have three sensitivity axes, the sound of fin whale can be localized on the basis of the incident orientation estimated with a single OBS and the time difference of multipath arrival of sound pressure data from a hydrophone (**Fig. 9**). Hence, OBSs can be utilized for real-time monitoring of the presence of baleen whales around Japan.

Underwater acoustic (UWA) communication is also an important technique to support maritime observations. However, UWA communication is still challenging owing to the characteristics of the UWA channel – large delay and Doppler spreads. Moreover, the physical space and the battery power of the communication platform are usually limited. To cope with these problems, several techniques have been proposed, based on signal processing, array processing, and combination of thereof. For example, a new signal processing technique (orthogonal signal division multiplexing; OSDM) has been found to achieve good communication quality even in large delay-spread channels (**Fig. 10**) [48, 49]. Moreover, several sea-experiments using a combination of signal and array processing techniques have been carried out [50]. By utilizing these wireless communication techniques, it is expected that underwater sensor network that utilize UWA communication will be constructed, and utilized for maritime explorations.

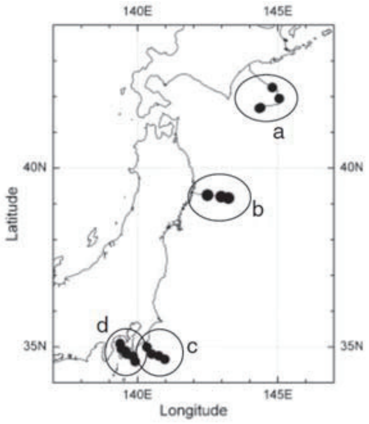

Fig. 8 Locations of the cabled seismic observatories [47].

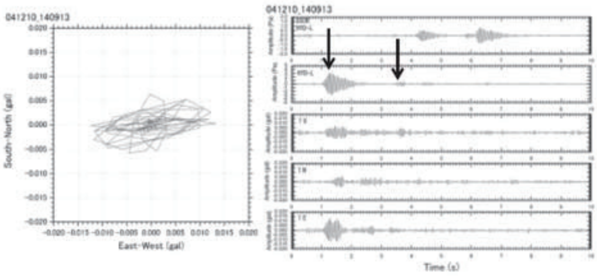

Fig. 9 Observed particle velocity and sound in ocean [47].

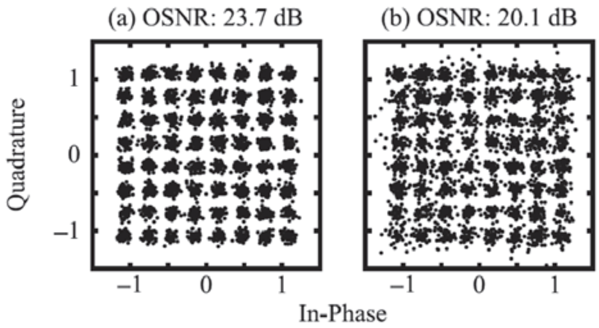

Fig. 10 Example of constellation plot obtained in the experiment [49]

7. Summary

In this manuscript, several recent researches related to measurement technologies in ultrasonic electronics were reviewed within the author's sight. After all, most ultrasonic applications are supported by measurement techniques, and the authors believe that the development in measurement techniques will lead to the advance in whole ultrasonic electronics.

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