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Optical sensing of sound fields: non-contact, quantitative, and single-shot imaging of sound using high-speed polarization camera

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Imaging of a sound field aids understanding of the actual behavior of the field. That is useful for obtaining acoustical spatial characteristics of transducers, materials and noise sources. For high spatial resolution imaging, optical measurement methods have been used thanks to its contactless nature. This paper presents sound field imaging method based on parallel phase-shifting interferometry, which enables to acquire an instantaneous two-dimensional phase distribution of light. Information of sound field is calculated from the phase of light based on the acousto-optic theory. The system consists of a polarization interferometer and high-speed polarization camera. The number of the measurement points in a single image are 512×512 and the interval between adjacent pixels is 0.22 mm. Therefore, the system can image a sound field with much higher spatial resolution compared with conventional imaging methods such as microphone arrays. The maximum frame rate, which is corresponding to the sampling frequency, is 1.55 M frames per second. This paper contains the principle of optical measurement of sound, the description of the system, and several experimental results including imaging of sound fields generated by transducers and reflection of the sound waves.

1. INTRODUCTION

Imaging of sound aids understanding of the spatial characteristics of a field, material, and environment. The imaging is often conducted by using a microphone array, while there are problems such as the difficulty of achieving high spatial resolution and scattering of the wave due to the presence of the instruments in the measurement field. In contrast, optical methods can overcome such problems owing to its contactless nature.

There are lots of research for applying optical methods to acoustical imaging and measurement. For a sound field in air, those methods are, for example, Schlieren method,[1–4] Shadowgraph method,[1] laser Doppler vibrometry,[5–9] holography,[10–13] and optical wave microphone.[14] Although these methods are well researched, the single-shot and quantitative imaging of a sound field is still under developing.

This paper describes the imaging of a sound field in air by using a high-speed polarization camera[15] and parallel phase-shifting interferometry.[16] Our methods[17,18] can achieve single-shot, quantitative, and high-speed imaging of the field. The brief review of the principles and several imaging results are provided in this paper.

2. METHODS

A. ACOUSTO-OPTIC THEORY

The optical measurement of sound is realized through the acousto-optic effect that is the variation in phase of light caused by the sound.[19] The relation between the refractive index of air and sound pressure is given by

$$n(\boldsymbol{r},t) = n_0 + \frac{n_0 - 1}{\gamma p_0} p(\boldsymbol{r},t), \tag{1}$$

where $\boldsymbol{r} \in \mathbb{R}^3$ is the three-dimensional position vector, t is the time, n_0 and p_0 are the refractive index and pressure under static conditions, γ is the specific heat ratio, and p is the sound pressure. This relation holds when the sound pressure is much smaller than the static pressure. By using the geometrical optics theory, the light that propagates in the sound field can be written as

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}_0(\boldsymbol{r},t)\mathrm{e}^{i(\omega t + \phi(\boldsymbol{r},t))}, \tag{2}$$

where $\boldsymbol{E_0}$ is the complex amplitude vector, ω is the angular frequency of light, and ϕ is the phase term. The phase is given by

$$\phi(\boldsymbol{r},t) = kn_0|\boldsymbol{L}| + k\frac{n_0 - 1}{\gamma p_0}\int_{\boldsymbol{L}(\boldsymbol{r})} p(\boldsymbol{l},t)d\boldsymbol{l}, \tag{3}$$

where k is the wavenumber of light, and $\boldsymbol{L}(\boldsymbol{r})$ is the optical path. The second term of Eq. (3) represents the phase modulation of light due to the sound field. Those equations indicate that the optical measurement of sound can be realized by detecting the phase of light.

B. OPTICAL SYSTEM

Figure 1 illustrates the optical components of the measurement system. The system consists of the Fizeau type polarization interferometer[20] and the high-speed polarization camera.[15] The line

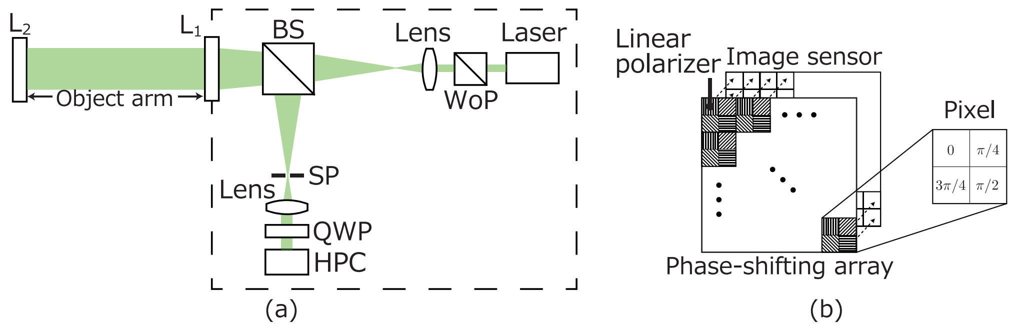

Figure 1: The schematic of the optical system. (a) The Fizeau type polarization interferometer. The dashed line indicates the case of the interferometer. WoP: Wollaston prism, BS: beam splitter, L1 and L2: lenses to transmit and reflect lights, QWP: quarter wave plate, and HPC: high-speed polarization camera. The sound field between L1 and L2 is measured. (b) The high-speed polarization camera. The phase-shifted array device is mounted on the image sensor. The single pixel is consists of four linear polarizers and four photo detectors. The numbers in the pixel indicate the orientations of the linear polarizers. The single phase value is calculated from the four values of each photo detector.

integrated sound pressure between L_1 and L_2 is measured by the system. The detected value by the single photodetector is proportional to the intensity of the interfered light that can be written as

$$I(\theta) = E_0(1 + \cos(\varDelta\phi + 2\theta)), \tag{4}$$

where $\varDelta\phi$ is the phase difference between the object light and reference light, and θ is the orientation of the linear polarizer. The object light means the light that propagates through the object arm and reflected by the lens L_2, and the reference light means the light reflected by the lens L_1. Therefore, the phase described in Eq. (3) is included in $\varDelta\phi$. The single-shot acquisition of the phase difference from the trigonometric function is achieved by using the parallel phase-shifting technique[16] that is realized by the pixelated phase-shifting array device as shown in Fig. 1(b). The phase difference can be retrieved by using the four intensities in a single pixel as

$$\varDelta\phi = \mathrm{Arg}\left[\sum_{k=1}^{4} I\left(\theta_k\right) \mathrm{e}^{-i2\theta_k}\right], \tag{5}$$

where $\mathrm{Arg}[z]$ denotes the principal value of complex argument of z, $i = \sqrt{-1}$, θ_k is the orientation of the k-th polarizer, and $2\theta_k$ means the phase retardation due to the k-th polarizer. In our system, $\theta_1 = 0$, $\theta_2 = \pi/4$, $\theta_3 = \pi/2$, and $\theta_4 = 3\pi/4$.

3. EXPERIMENTS

A. SETUP

Table 1 shows the experimental conditions. Two types of transducers were used as sound sources. The frame rate equals to the sampling frequency, the exposure time is the integral duration of the image sensor, and image resolution is the data points in a single image. Since the

Table 1: Experimental conditions.

Sound source	Transducer	Ultrasonic transducer MURATA MA40S4S	Two-way loudspeaker DENON SC-A11SG
	Waveform	Sinusoidal	Sinusoidal
	Frequency	40000 Hz	2000 Hz, 8000 Hz, 15000 Hz
Camera	Frame rate	7000 fps	7000 fps
	Exposure time	1/101000 s	1/40000 s
	Image resolution	512 × 512	512 × 512
	Image size	100 mm × 100 mm	100 mm × 100 mm

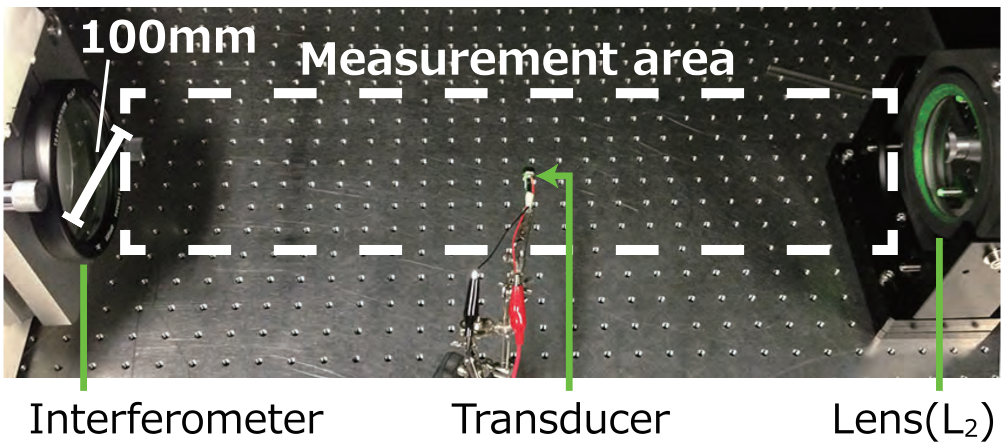

Figure 2: Photo of the experimental arrangement.

image resolution decreases as the frame rate increases, the frame rate was determined so as to use the maximum image resolution of the camera. The length between adjacent pixels is 0.22 mm. Figure 2 shows the photo of the experiments. The object light was emitted from the interferometer, propagated to right, was reflected by the lens, propagated to left, and was back into the interferometer. The laser of 532 nm wavelength and 70 mW power was used. The high-speed polarization camera, CRYSTA PI-1P made by Photron Ltd., was used. The optical components were mounted on the vibration isolation table.

B. PROCESSING

Since the obtained phase by Eq. (5) includes not only the acoustical term but also background phase, slow fluctuation due to flow and thermal source in an experimental room, and random noise; an appropriated signal processing is necessary for extracting only the acoustical information. The sound sources of the experiments were only pure tone sound wave; the band pass filters whose center frequencies were same as the frequencies of the input signals and bandwidth was 100 Hz were applied to every pixel.

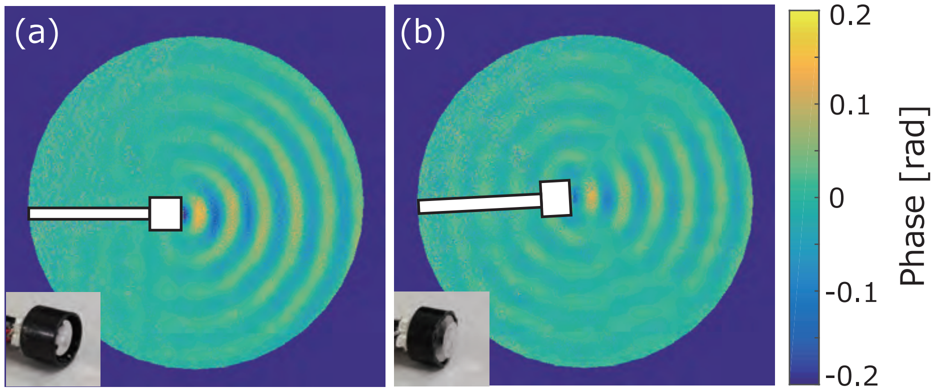

Figure 3: The imaging results of the sound field generated by the ultrasonic transducers and the photos of the each transducer. (left) The diaphragm is covered by a plastic tube. (right) The diaphragm is not covered by a plastic tube. The transducers are placed at the center of the images. The white painted areas are corresponding to the position of the transducers and supported rods.

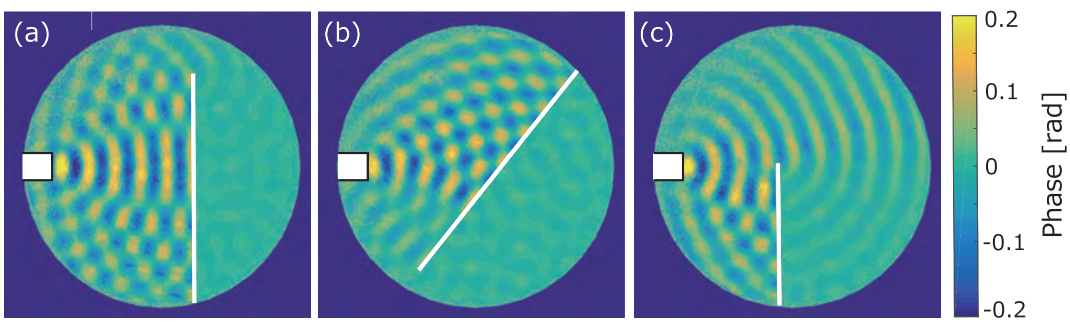

Figure 4: The imaging results of the reflection and diffraction of the sound waves generated by the ultrasonic transducers. The white lines are the thin metal plates for yielding the reflection and diffraction of the waves.

C. RESULTS

Figure 3 shows the images of the radiated sound fields by the ultrasonic transducers. The diaphragm of the transducer in Fig. 3(a) was covered by a plastic tube, while that in Fig. 3(b) was not covered. The spherical wavefront is well visualized in both images. In Fig. 3(a), the amplitude of the forward direction is higher than the that of the backward direction. In contrast, the sound wave spreads to all directions in the case of the non-covered diaphragm. This can be interpreted as the plastic tube strengthens the forward radiation.

The imaging of the reflection and diffraction of the 40 kHz sound wave are depicted in Fig. 4. The ultrasonic transducer covered by the plastic tube was used. A thin metal plate was used for yielding the reflection and diffraction. The interferometric patterns are captured. As a result of the constructed interference, the amplitudes of the interference fields become larger than that of the

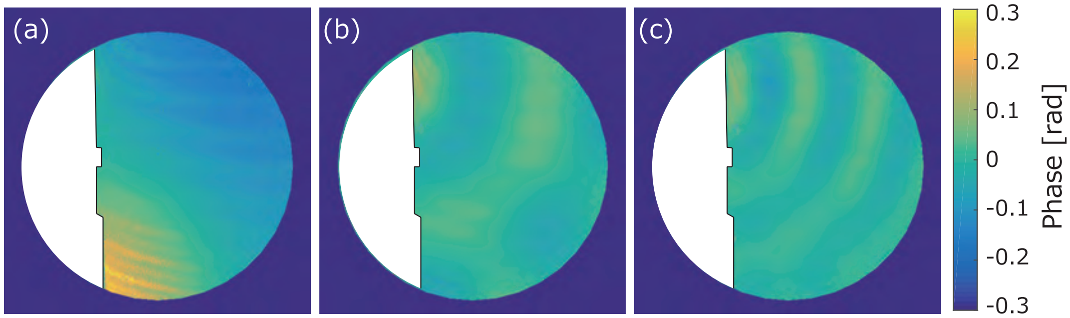

Figure 5: The imaging results of the emitted sound waves by the two-way loudspeaker. The white painted areas are corresponding to the position of the loudspeaker.

only incident wave as Fig. 3(a).

Figure 5 shows the sound fields generated by the two-way loudspeaker. It can be seen that the sound wave of 2 kHz is emitted from the woofer, that of 15 kHz does from the tweeter, and that of 8 kHz does from both. Note that the horizontal fringe pattern appeared in the left image was caused by an implementation error of the optical system.

4. CONCLUSION

This paper described the optical imaging of sound fields by using the high-speed polarization camera and parallel phase-shifting interferometry. The notable advantages of the proposed method include contactless, single-shot, and quantitative nature. The effectiveness of the method was confirmed by the experiments. The spatial information of the sound fields was easily understandable by the high spatial resolution images of the fields. Future work should evaluate the characteristics of the method and apply to various acoustical problems. Moreover, applicability and effectiveness of recently proposed signal processing methods[21–24] should be investigated.

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