Controlling Speckle and Resolution of Reconstructed Images 
by Vibrating Multimode Optical Fiber with a Cylindrical 
Piezoelectric Transducer in Electro-Holography

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ABSTRACT

To reduce the speckle of reconstructed images in electro-holography, reducing laser coherence is essential. We developed a device to vibrate a multimode optical fiber using a cylindrical piezoelectric transducer to reduce coherence. In addition to speckle, the resolution can be electronically controlled with this device.

1 Introduction

In recent years, research on three-dimensional (3D) display technologies such as virtual reality (VR) and 3D movies has been active. Among them, electro-holography is expected to be an ideal 3D display technology because it satisfies all physiological elements for stereoscopic perception [1]. However, electro-holography has many problems, one of which is speckle. Speckle is a noise caused by interference of light waves reflected by highly coherent light such as a laser light source on a rough surface. Since a laser light source with high coherence is used as reconstruction illumination light in electro-holography, speckle is generated, degrading the quality of reconstructed images. Therefore, reducing speckle is a very important challenge.

There are many kinds of methods to solve this problem, one of which is to reduce the temporal and spatial coherence of a laser light source. This method has the advantage of being easy to apply to other methods because it solves a fundamental problem of speckle generation. Previous studies have investigated using a supercontinuum light source [2] and a random laser light source [3] instead of a laser light source to reduce speckle. The former approach lowers temporal coherence, and the latter lowers spatial coherence. However, a supercontinuum light source has not been put into practical use, and a random laser light source is very expensive, so both are difficult to obtain. In addition, the resolution of reconstructed images is very degraded while speckle is reduced, because it is difficult to control coherence. Another method is to vibrate a multimode optical fiber (MMF) by generating sound with a voice coil [4]. In this method, vibrating an MMF causes it to expand and contract, modulating the phase of light waves and reducing spatial coherence and speckle. However, the use of a voice coil creates a very loud sound when vibrating an MMF. One method that solves this problem is to use a cylindrical piezoelectric transducer (PZT) to vibrate an MMF [5]. A PZT is not as loud as a voice coil because it generates frequencies beyond the human hearing range and is more readily available than a supercontinuum light source and a random laser. However, this method has not been applied to computer-generated holography (CGH).

In this study, we developed a device that can electrically control the coherence of a laser light source with a PZT, making it possible to easily change the speckle and resolution of reconstructed images.

2 Proposed Method

Figs. 1 and 2 and Table 1 show a schematic diagram, a photograph, and the parameters of the proposed device, respectively. The proposed device uses a Fresnel-type holography display system incorporating a 4f optical system [6]. Figs. 1 and 2 show that a laser light source is transmitted to a collimator via a step-indexed MMF coiled around the PZT. The PZT is vibrated by amplifying the output of the signal generator. The laser emitted from the collimator is collimated and expanded by a concave lens (Lens1) and a convex lens (Lens2). f₁ and f₂ represent the focal lengths of Lens1 and Lens2, respectively. The expanded light is irradiated to the reflective spatial light modulator (SLM) and reflected. Light reflected by the SLM passes through a half mirror and two Lens2s to reach an observer. At this time, unwanted light is removed by the barrier.

The MMF is coiled five times around the surface of the PZT in a tight circular shape and bonded with instant adhesive so that the MMF expands and contracts when the PZT is vibrated. Therefore, the spatial modes in the MMF are phase-modulated, which modulates the speckle pattern formed at the output of the MMF and reduces the coherence of the laser.

3 Experiment

The proposed system was constructed, and experiments on speckle and resolution of reconstructed images were conducted to demonstrate its effectiveness.
When vibrating the PZT, the driving frequency of the signal generator was set to 21.4 kHz, which is the resonance frequency, so that the PZT would vibrate most strongly. This experiment was silent because this frequency is above 20 kHz, the maximum audible value for humans. In both experiments, the driving voltage to the PZT was experimented at five different values: 0V, 100V, 200V, 300V, and 400V. Note that the 0V condition indicates no vibration.

3.1 Speckle
This section describes an experiment to confirm that speckle is reduced when the drive voltage to the PZT is increased in the proposed device.

The Utah teapot shown in Fig. 3 was used as the virtual object to be displayed. The teapot was placed 100 mm behind the hologram plane with a horizontal size of 10 mm and a vertical size of 5 mm, as shown in Fig. 4. Note that the point-filling method [7] was used as the object light calculation in electro-holography, and the point light source was placed using the ray-tracing method [8]. Fig. 5 shows reconstructed images at each drive voltage to the PZT and enlarged images with the center of the reconstructed images cut into a square. From these reconstructed images, it can be confirmed that the speckle in the reconstructed images reduces as the drive voltage to the PZT is increased. In addition, it can be seen that the outline of the teapot blurs as the drive voltage is increased.

To quantitatively evaluate speckle, the following speckle contrast $C$ is used.

$$C = \frac{\sigma_I}{\langle I \rangle}$$

$\sigma_I$ is the standard deviation of luminance and $\langle I \rangle$ is the mean luminance. A smaller value of speckle contrast indicates less speckle. The area where speckle contrast is measured is the right image shown in Fig. 5. Fig. 6 shows a graph of speckle contrast at each drive voltage to the PZT, where the horizontal axis is the drive voltage to the PZT and the vertical axis is the speckle contrast. Table 2 and Fig. 6 show that speckle contrast decreases as the drive voltage to the PZT is increased. When comparing 0V, which is the state of no vibration, to 400V, the maximum value in this experiment, speckle contrast was reduced by about 43%.
3.2 Resolution

This section describes an experiment to confirm that resolution degrades when the drive voltage to PZT is increased in the proposed device.

The resolution chart shown in Fig. 7 was used as the virtual object to be displayed. As with the teapot, the resolution chart was placed 100 mm behind the hologram plane. When a gap between the bars can be observed, the length of the gap indicates that the resolution is guaranteed. Figs. 8 and 9 show reconstructed images and a graph of the observable gap of the resolution chart at each drive voltage to the PZT, respectively. As shown in the figures, at 0V, 100V, and 200V, a gap can be observed from 0.04 mm, while at 300V, a gap can be observed from 0.08 mm. In addition, at 400V, a gap of 0.10 mm can be observed.

4 Discussion

When comparing speckle contrast in the proposed device with that in the previous study, in which the MMF is vibrated by sound generated with a voice coil [4], speckle contrast is reduced by a maximum of about 53% in the previous study and 43% in the proposed device. The reason for the higher speckle reduction in the previous study is thought to be that the vibration amplitude of the voice coil is considerably larger than that of the PZT, so the coherence of a laser is greatly reduced. However, the proposed device did not generate loud noise, which was a problem in the previous study.

From Figs. 5 and 8, the reconstructed images are blurred by increasing the voltage. This can be attributed to the fact that vibrating the MMF reduces the coherence, resulting in a lower directivity of the laser. Also, when comparing (a), (b), and (c) in Fig. 8, a gap can be observed from the same length at 0.04 mm. The reason for this is thought to be that at 0V in (a), the speckle is quite visible, making it difficult to observe the gap at 0.02 mm.

When comparing the experimental results of speckle and resolution, we confirmed that increasing the drive voltage to the PZT reduces speckle and degrades resolution, while decreasing the voltage increases speckle and improves resolution. Therefore, speckle and resolution can be controlled and easily changed depending on the degree to which either speckle or resolution of a reconstructed image should or should not be prioritized.
5 Conclusions
In this study, we developed a holographic display system that can electrically control laser coherence by vibrating the MMF using a PZT in electro-holography. We confirmed through two experiments that increasing the driving voltage to the PZT reduces speckle and degrades resolution in reconstructed images. By increasing the voltage, the speckle was reduced by up to about 43% in the speckle experiment, and in the resolution experiment, a gap of 0.04 to 0.10 mm could be confirmed. Therefore, the speckle and resolution of reconstructed images can be easily controlled by varying the voltage in this system.

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References