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Optical aberration correction of scanning holographic display

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Abstract

Multiplexed holographic display structures using optical scanning have features that extend the image size or viewing angle of the holographic display through beam steering. This makes the display device relatively free from the performance limits of the SLM(Spatial light modulator), thereby increasing the possibility of the practical use of the holographic display. However, the holographic display optical structure of the beam-steering system that propagates the beam in the off-axis direction necessarily generates optical aberration. In this study, the optical aberration according to the steering of the light wave is measured through the optical simulator and converted into the Zernike polynomial form. The aberration values obtained by this method are reflected in the optical field of the reconstructed hologram image to correct the optical aberration. As a result of the aberration compensation, distortion and image deterioration of the reconstructed holographic image were reduced, which was verified through experiments.

Introduction

The viewing angle of a typical holographic display is determined by the diffraction angle according to the pixel pitch of the SLM, and the size of the reconstructed image is determined by the SLM area. For a holographic display to provide a conventional LCD level viewing angle, it is necessary to develop an SLM with a pixel pitch of a few microns or less and a pixel number of several terapixels. However, since the development of the SLM with the above-mentioned performance is remote, it is difficult to expect the emergence of the holographic display in the near future. Therefore, various multiplexing studies are underway to recognize the performance limit of SLM and to utilize its maximum performance.

The holographic display method of the structure through beam steering has been studied steadily as a system that efficiently utilizes the limited space bandwidth of the SLM [1-4]. However, the holographic display in which beams are steered has various optical aberrations due to the complex optical structure and the feature of reconstructing the holographic image on the off-axis. Such optical aberration negatively affects image quality, causing issues such as distortion and image deterioration of the reproduced image. Therefore, there is a need for an aberration correction method for propagating the modulated light wave from the SLM to the pupils of the user without distortion.

To compensate for this, we measured the wavefront aberration and compensated for it. The measurement of the wavefront aberration was performed by simulating the propagation of the light wave by modeling the holographic display optical structure using an optical simulator called ZEMAX. The wavefront aberration measured through the simulator was fitted to the Zernike function form, which can efficiently analyze the wavefront aberration. The Zernike function is expressed by a combination of arbitrary orthogonal functions of the circular pupil, and a specific optical aberration can be expressed numerically through each term. Therefore, it is possible to predict how the measured wavefront aberration will distort the reconstructed holographic image through the display. The compensation of the wavefront aberration determined through the above process is performed by reflecting the conjugate complex value of the phase function of the wavefront aberration on the complex field of the hologram image to be reproduced.

Determination of wavefront aberration

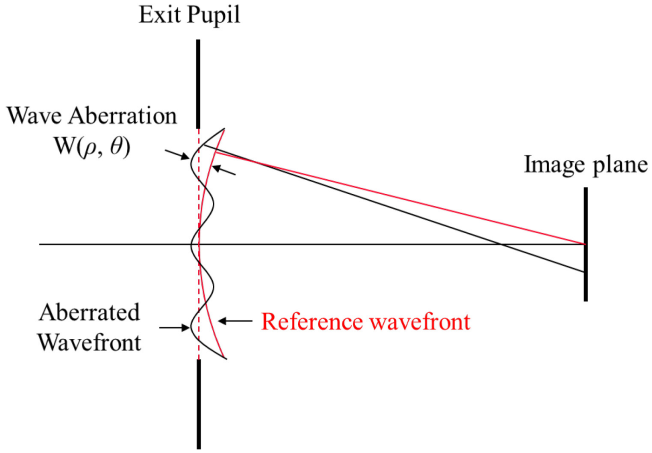


Figure 1. Wave aberration function for a distant object

Wavefront aberration refers to the optical path difference between the reference wavefront that is predicted through paraxial optics at the exit pupil of the optical system and the wavefront that passes through the actual optical system. The aberration analysis through the wavefront is an appropriate method for explaining the aberration that occurs in the imaging region of the holographic display, since the diffraction effect of the optical system can be explained.

Since the measurement of the wavefront aberration is conducted to measure the phase of the wave, it is necessary to observe and analyze the interference pattern through an interferometer. However, the interferometer is a very sophisticated device, requiring complex and precise placement of multiple optical elements. In addition, since the measurable wavefront width is limited by the aperture size of the interferometer, it is difficult to measure the characteristics of the large optical device.

In this paper, the optical structure to be set up is modeled using an optical simulator and the wavefront aberration is determined through ray tracing. Through this method, wave aberration is predicted by numerical calculation by a computer without complicated measurement equipment and utilized as compensation data. The first step is modeling the optical system as shown below to measure the wavefront aberration generated in the optical system.

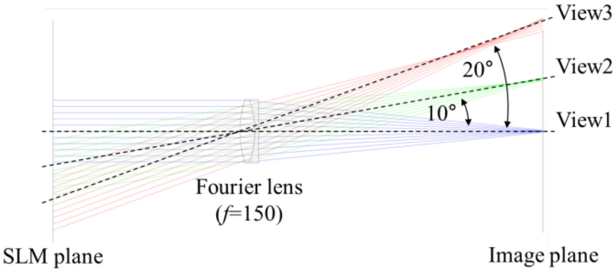


Figure 2. Optical layout using optical simulator

The optical system of the figure is designed to determine the optical aberration value according to the beam-steering direction in the holographic display structure using the temporal multiplexing method. In detail, the beam deflected by the diffraction grating is modulated in the SLM and then converged on the back focal plane of the lens through the Fourier lens to reconstruct the hologram image. Therefore, aberrations, such as coma, astigmatism, curvature of the image field, and distortion, occur in the structure where the beam is incident on the lens off-axis through optical scanning.

Wavefront fitting using Zernike function

The wavefront aberration determined through the above procedure can be expressed by the OPD function $W(\rho, \theta)$. In this, ρ is a radial coordinate ranging from 0 to 1 and θ is azimuthal components ranging from 0 to 2π.

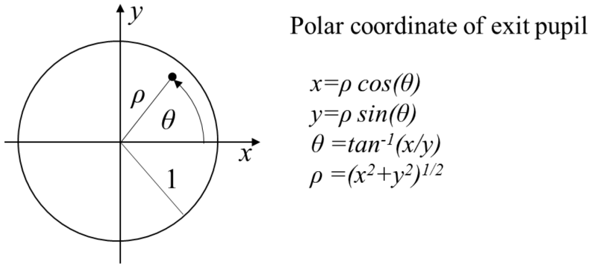


Figure 3. Normalized pupil coordinate system

The Zernike function is an orthogonal function on the unit circle defined by the polar coordinate system and is a suitable method for visualizing the wavefront aberration in the pupil of the optical system. The obtained OPD function $W(\rho, \theta)$ is expressed through the Zernike function so that the distortion tendency of the image due to the specific aberration represented by each polynomial term can be determined. This is expressed by a combination of the coefficient Cnm and the Zernike function Z_n^m, in which $W(\rho, \theta)$ represents various aberrations through the following equation [5]

$$W(\rho,\theta) = \sum_{i=0}^{\infty} C_{nm} Z_n^m(\rho,\theta) \tag{1}$$

The Zernike function is a functional form of the radial and azimuthal and is split into two, as shown in

$$Z_n^m(\rho,\theta) = \begin{cases} N_n^m R_n^{|m|}(\rho)\cos m\theta & for \quad m \geq 0 \\ -N_n^m R_n^{|m|}(\rho)\sin m\theta & for \quad m < 0 \end{cases} \tag{2}$$

Here, the normalization factor N_n^m is obtained by

$$N_n^m = \sqrt{\frac{2(n+1)}{1+\delta_{m0}}} \tag{3}$$

The radial polynomial $R_n^{|m|}$ can be obtained from

$$R_n^{|m|}(\rho) = \sum_{s=0}^{(n-|m|)/2} \frac{(-1)^s (n-s)!}{s![0.5(n+|m|)-s]![0.5(n-|m|)-s]!}\rho^{n-2s} \tag{4}$$

The following is the Zernike function representing the aberration according to the beam-steering angle obtained through the optical simulation.

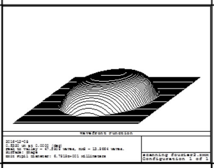
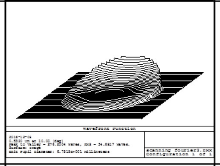
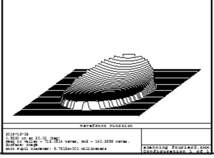
Scanning angle	Wavefront map	Wavefront error (Zernike polynomials)
0°		Field curvature, Defocus -61.86757261 Spherical Aberration -19.97965329
10°		Tilt y 154.35544423 Field curvature, Defocus -19.93303358 Astigmatism 0° or 90° -17.47601034 Coma y 59.04959705 Spherical Aberration -17.97421961
20°		Tilt y 336.78760044 Field curvature, Defocus 111.01610559 Astigmatism 0° or 90° -71.95053744 Coma y 130.33644155 Spherical Aberration -10.23586980 Secondary Astigamatism x -5.86388193

Figure 4. Wavefront error at each view point

By reconstructing the conjugate complex value of the wavefront aberration $W(\rho, \theta)$ obtained through the above simulation on the complex field of the calculated hologram image and by reconstructing it in the holographic display, it is possible to reconstruct the aberration-corrected hologram image. The following figure is a wavefront map modeling the wavefront aberration at view point 3 and the wavefront aberration with a conjugate complex value.

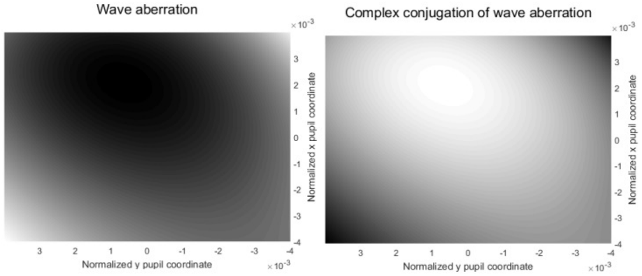


Figure 5. Wave aberration at view point 3: (a) wave aberration, (b) conjugate complex of wavefront aberration

Aberration compensation using SLM

It is possible to correct the optical aberration by compensating for the wavefront through a device capable of controlling the phase. In this case, the phase Φ is defined as follows:

$$\Phi = 2\pi \cdot OPL / \lambda \tag{5}$$

where λ is the wavelength of light and *OPL* is the optical path length, which is given by the following:

$$OPL = n \cdot z \tag{6}$$

where *n* is the refractive index of the medium located in the propagation direction and *z* is the physical travel distance. Thus, phase correction is possible by converting the refractive index of the medium located on the light path or by changing the physical distance over which the light travels. The SLM device used for optical modulation in a holographic display converts the refractive index of the beam propagation path by converting the alignment of the liquid crystal according to the voltage applied to each pixel. Therefore, it is possible to compensate for the wavefront aberration determined by the simulator, since phase control through voltage control is possible.

Experiments

Experiments were conducted to confirm that the determination and compensation of the wavefront aberration through the optical simulation were performed properly. The following is the optical structure for this.

Figure 6. Experimental setup

The experimental setup was a Fourier holographic display structure, in which the light modulated through SLM was reconstructed in the back focal plane using a Fourier lens with a focal length of 200mm. A laser with a wavelength of 532nm was used as an input light source, and SLM was constructed using a phase-only SLM with a pixel pitch of 8um. To assume a steered beam direction, such as an optical simulation, the lens was moved and rotated as shown in figure 5. The input image $U(u, v, w)$ to be reconstructed in the holographic display was calculated as a complex field $H(x, y)$ by the following equation.

$$H(x, y) = \frac{1}{j\lambda f}\iiint U(u, v, w) e^{j\varphi(u,v,w)} e^{j\frac{\pi w}{\lambda f^2}(x^2+y^2)} e^{j\frac{2\pi}{\lambda f}(xu+yv)} dudvdw \tag{7}$$

Here, $\varphi(u, v, w)$ is a random phase, f is the focal length of the Fourier lens, and λ is the wavelength of the input light source. The complex field obtained by compensating for the wavefront aberration can be obtained by multiplying the complex field $H(x, y)$ calculated in equation 7 (above) by the conjugate complex value of the wavefront aberration $W(\rho, \theta)$.

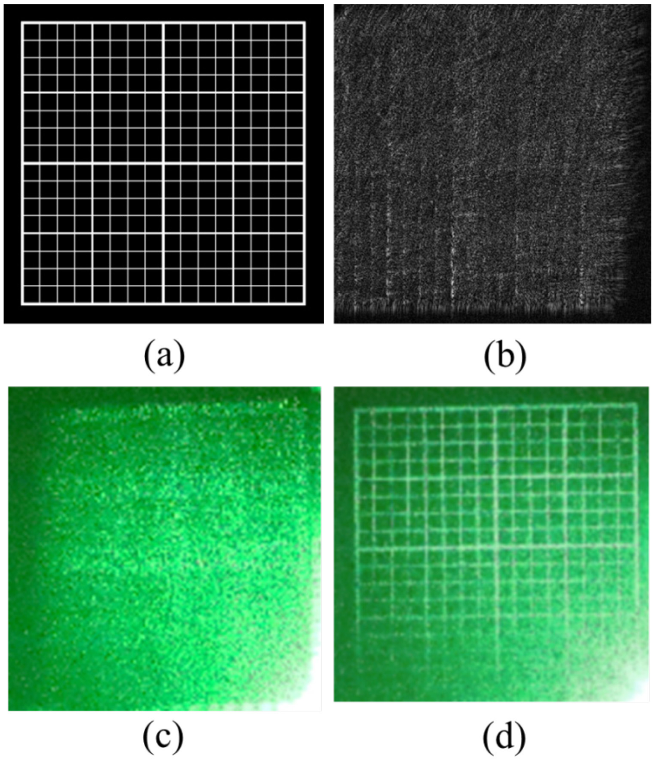

(a) (b)
(c) (d)

Figure 7. (a) Input image, (b) reconstructed image through optical simulation, (c) reconstructed image through experiments, (d) reconstructed image by correcting the aberration

Figure 7 is a reconstructed holographic image when the observer pupil is located at view point 3. (A) is an input image to be reconstructed at view point 3, and (b) is an image reconstructed through simulation when the aberration of view point 3 determined through optical simulation is reflected in the image of (a). (C) is reconstructed through the actual optical setup, and similar imaging characteristics can be confirmed through comparison with the simulation results in (b). Therefore, it can be confirmed that the method of determining the wavefront aberration through optical simulation is effective through experiments. When comparing (c) with (d), we can confirm that the image of (d) has relatively reduced optical aberration and image quality deterioration, and the image close to the original image is reconstructed. It was found that the aberration compensation using the SLM was also performed properly.

Results

We measured and compensated for the optical aberration caused by the optical structure that propagates the beam off-axis in the temporal multiplexing holographic display using beam steering. In the optical aberration measurement, optical aberration is determined through optical simulation, and a method for interpreting the optical aberration is proposed. The determined optical aberration is reflected in the complex field to be reconstructed in the holographic display, so that it is experimentally confirmed that distortion and image degradation of the reconstructed image are reduced.

Acknowledgment

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