Distortion Analysis in Holographic Optical Elements

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ABSTRACT

The distortions in digital and analogue HOEs for image projection are estimated with a Shack-Hartmann wavefront sensor. The optical characteristics of the HOEs are compared with those of a spherical mirror. The HOEs show a significant amount of wavefront distortion compared the mirror. Among the HOEs, the digitally recorded one shows more wavefront distortion. Furthermore, the digitally recorded HOE shows also astigmatism that is not shown in the mirror and the analogue HOE. It is considered that the astigmatism is caused digital nature of the HOE as in the reconstructed image from the digital holographic display. The optical characteristics of the analog HOE is much better than that of the digital in the current samples.

1 INTRODUCTION

The image projection in a projection type three-dimensional imaging has often been done on a holographically recorded screen (Holographic screen) because it is not even thinner and lighter than the real optical elements for the screen but also has multi-functional performances. The screen is a digitally or analogically recorded HOE(Holographic Optical Element) having the properties of a spherical mirror and a lens in optically [1]. The first holographic screen for image display has been recorded in 1980th for monocolor [2] and full color version at 1994 [3]. These screens are analog type recorded with a spherical mirror as the object. Instead of the spherical mirror, a long thin slit shape diffuser is used to record the screen with a green laser. In this case, the screen is capable of displaying full color images [4]. In addition to these holographic screens, there have also been the screen with two-dimensional (2-D) grating array and others [5]. Lately, the holographic screen has been recorded digitally. Since the digital recording requires no real mirror or lens, it can theoretically record any size. The origin of the digital recording is the Zebra hologram type stereo hologram [6]. In the SLM(Spatial Light Modulator), a chirp fringe or Fresnel zone pattern that performs the same function as the lens or a spherical mirror is divided into a 2-D array, and each piece is recorded as a hogel(holographic optical element) instead of each view of the Multiview images as in Zebra hologram. Hence, the digitally recorded HOE consists of an array of hogels which will be reconstructed as the chirp fringe or Fresnel zone pattern. The hogel works as a pixel composing the HOE. This means that each hogel is not different from a pixel of an SLM which displays a hologram. Since it has been known that the digital hologram reveals astigmatism. The astigmatism will be stronger as the pixel size increases for the case of DMD [7]. For the case of HOE, the reconstruction condition is somewhat different from DMD because there is not pixel aspect ratio change as in the DMD, but it is still considered that there will be astigmatism due to the digital nature of the hogel. It is also expected that the focused beam has the shape of distorted circle due to non-uniform hogel shapes caused by the accuracy changes in the optical set-up of the recording HOE. The accuracy change can be induced by the device fatigue and ambient condition change for the long-term operation of the laser, scanner and optics in the set-up. The HOE has two natures: One as a hologram and the other as an optical element: As the hologram, diffraction efficiency, angular and spectral selectivity, and as the optical element, PSF (Point spread function), focal length, uniformity and aberrations are the quality parameters. Among these quality parameters, the HOE for the image projection, the diffraction efficiency, PSF(Point spread function), focal length and uniformity. The angular and spectral selectivity may not be important for the monocolor display and the uniformity is also not essential when the screen size is small. Hence the diffraction efficiency and focal characteristics are measured to compare the two HOEs. The optical characteristics includes PSF, astigmatism and other aberrations. For the aberrations, a Shack-Hartmann wavefront sensor [8] is used together with Zernike polynomial to estimate the differences between the digital and analog HOEs as an optical element. The

Shack-Hartmann wavefront sensor together with Zernike polynomial has been frequently used to identify aberrations in the optical elements.

In this paper, the optical characteristics of digital and analogue HOEs for image projection are measured with a shack-Hartmann wavefront sensor. The aberrations are processed by Zernike polynomial.

2 HOE sample preparations

For the comparison, two HOE samples for each of digital and analog are recorded on silver halide and photopolymer photoplates, respectively, to use the one with better performance for the measurement. For the case of the photopolymer, the photopolymer film is laminated on a glass plate. A spherical mirror as the object is used for the analog and a piece of the diffraction pattern, displayed on a SLM for the digital. The piece of the pattern is focused on the surface of the photoplate and recorded as a hogel as in Zebra hologram. The recording set-ups for analog and digital HOEs are shown in Fig. 1(a) and (b), respectively. In Fig. 1(a), a green laser beam of wavelength of 532 nm, which optical axis is aligned with that of the spherical mirror is expanded to illuminate the surface of the spherical mirror through the photopolymer photoplate. The illuminating beam and the converging beam reflected from the spherical mirror works as the reference and the object beams, respectively. The focal length of the HOE is defined as the distance between the photopolymer photoplate and the focused point of the reflected beam. In Fig. 1(b), each piece of the hologram fringe pattern is displayed on the SLM and imaged as a point to the surface of the silver-halide photoplate. Each hogel is recorded within the area of 0.9 mm X 0.5 mm by shifting the photoplate by a x-y translator. The focal point of the digital HOE is defined by the recorded pattern. Fig. 1 indicates that the recording time of the digital is much more than that of the analog. The HOEs have approximately the size of 5 inch.

3 Measurement set-up for focal spot

For the measurement of the focal spot characteristics of the HOEs, the set-ups shown in Fig. 2 are used. Fig. 2(a) shows the set-up for analog HOE and 2(b) for the digital. Since the analog HOE recorded by making the surfaces of the HOE and the spherical mirror in parallel, a collimated laser beam of wavelength 532 nm is normally incident to the HOE surface through a half mirror. The reflected beam from the HOE is reflected again by the half mirror. The focused beam intensity is measured to estimate the diffraction efficiency. For the current samples, the efficiency is slightly more than 17%. The focused beam size is around 0.6 mm and no astigmatism is appeared as shown in the right side of images in Fig. 2(a). The beams before and after the focal beam have no visible shape changes. The focal length of the HOE is given as 440 mm. Since the focal length of the spherical mirror is 480 mm, the focal length of the HOE is reasonable. The problem in this measurement is the low diffraction efficiency. Due to the low efficiency, the majority of the reflected beam from the HOE is the collimated beam of the incident beam. This collimated beam is overlapped with the converging beam. This overlapping will cause problem in the wavefront distortion measurement. For the digital HOE, the reference beam is incident to the photoplate with the incident angle of 45˚. And the object beam and the reference beam are crossed to each other with 38˚ crossing angle. This is why the measurement set-up in Fig. 2(b) shows that the HOE is aligned to 45˚ with the collimated laser beam of wavelength 532 nm. The converging beam is appeared around 38˚ from the incident beam. This beam changes its shape as the vertically elongated at 295mm and horizontally elongated at 325 mm. This beam shape changes indicate the presence of astigmatism. The least circle of confusion focal spot is appeared at 310 mm and its size is more than 2 mm in diameter and the diffraction efficiency is less than 15 %. The beam shape is near a circle but it is slightly elongated to 45˚. The presence of the astigmatism is probably caused by both the digital nature of the hogel and the off-axis nature of the converging beam. Since the object beam is around 7 ˚ (45˚ - 38˚) off -axis from the normal direction of the HOE surface. This means that the recorded pattern on the HOE is slightly distorted. This will cause that the vertical and horizontal focusing appear at different distances. In Fig. 4, the composition of the digital HOE is shown. The light spot is a hogel. The HOE of the size 50 mm x 50 mm is consisted of 55 X 100 hogels.

4 Wavefront distortion measurement

For the measurement of the wavefront distortion and optical aberrations, a Shack-Hartmann wavefront sensor is used and its response is used to find Zernike coefficients to estimate the aberrations. The measurement of the wavefront distortion has been done by locating a microlens array at near the near the focusing point of the reflected beam from the HOE. The microlens array is consisted of 75 X 52 microlens of having a square shape with 0.3 mm in its each. The focal length of each microlens is 2 mm and a CMOS detector is located at the microlens focal plane. The detector has 6,000 x 4,000 resolution and each pixel has the size of 3.89μm x 3.89μm. Hence each microlens covers approximately 77 x 77 pixels. The detector size is 234 mm x 156 mm. Hence the microlens should be located at the place where the cross section of the converging beam has the detector size to cover the surface of the HOE covered by the incident beam. The typical image from the detector is shown in Fig. 4. The image is the 75 X 45 array of light spots. Each spot has a position within a cell with the 77 x 77 pixels. However, 67 X 43 points are processed to minimize the effects imposed by the surrounding restrictions of installing the microlens array above the detector. With the light spot image as shown in Fig. 4, the light spot deviation from the center of each cell is plotted in Fig. 5. Since the center of each cell corresponds to the center of its front micro lens in the microlens array, the deviation corresponds to the wavefront distortion. Hence Fig. 5 shows the comparisons of the wavefront distortions in the spherical mirror for Fig. 6(a), in the analogue HOE recorded with this mirror for Fig. 5(b) and in the digital HOE for Fig. 5(c). The images are consisted of concentric circles. Each circle from the center represents 0 to one wave length (λ), λ to 2λ, 2λ to 3λ, and so on as in the Fresnel zone pattern. Hence the number of circles in each image and the size of each circle represent the focusing power of each element. As shown in Fig. 5, the spherical mirror has more clear circles and more circle like circles than others though the diameter of each circle is slightly bigger than that of the analog HOE. This size difference is probably caused by their focal length difference, since the converging angle of the short focal length beam will be bigger than the long one. Hence the number of cells having each wavelength differences will be smaller. The circles numbers are 11 for the mirror, 6 to 8 for the analog HOE and 5 for the digital HOE. And the circle sizes are the biggest among the three. This is why the focal spot size of the digital HOE is bigger than those of others and its shape is not a circle. For the analog HOE, the number of circles and clearness of the circles are more and better than those of the digital HOE. However, the effects of the incident beam are shown in edges of the image as specified by broken rectangular shape boxes. As closer to the edges, the effect of the collimated beam becomes stronger. Added on the effect, the cell size may not be enough to cover all the phase distortion because the focused beams are no longer within its corresponding cell but its adjacent cells. In Fig. 6, the total aberration in each element calculated with Zernike polynomial is compared. The pattern shapes of the spherical mirror (a) and the analog HOE (b) are very similar but the digital HOE (c) is different from them. This will be caused by the astigmatism in the digital HOE.

5 CONCLUSIONS

The optical characteristics of a spherical mirror, analogue HOE from the mirror and the digital HOE are measured a measurement set-up, a Shack-Hartmann sensor and Zernike polynomial. These measurements inform that the analog HOE's characteristics are close to the those of the spherical mirror but the digital HOE has much differences from them. The digital HOE has astigmatism and bigger focal spot. The diffraction efficiency is also smaller than the analog though they are recorded to different photoplates.

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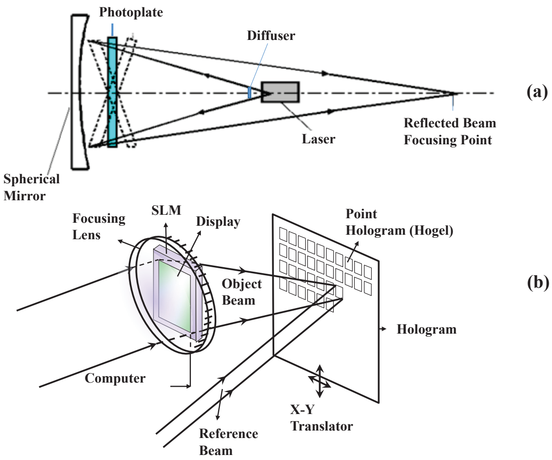

Fig. 1 Analog (a) and digital (b) HOE recording set-ups

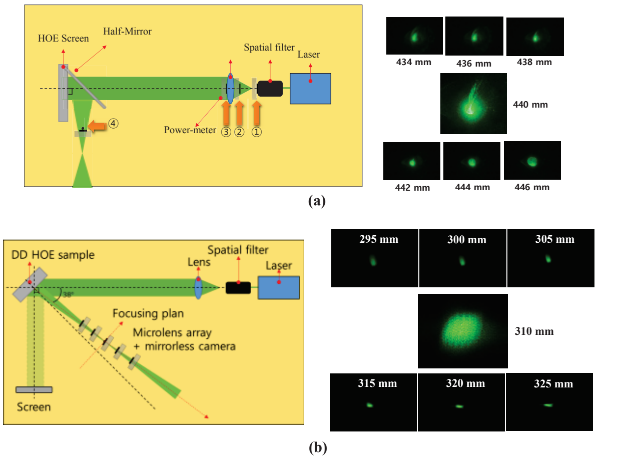

Fig. 2. Measurement set-ups for analogue (a) and digital (b) HOEs

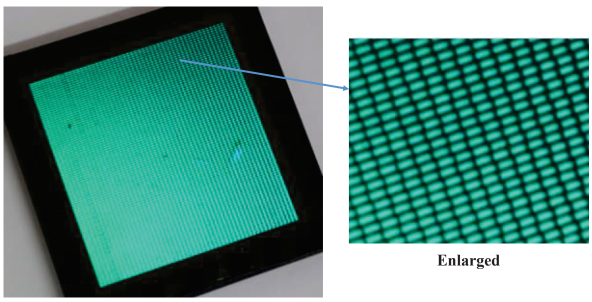

Fig. 3. Hogel array in digital HOE

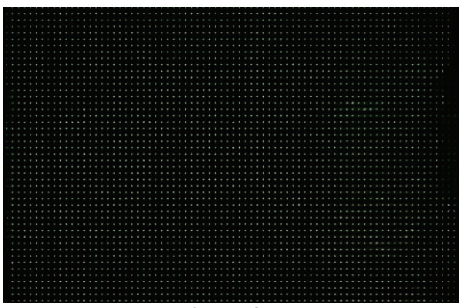

Fig. 4. Light spot array from Shack-Hartmann wavefront sensor

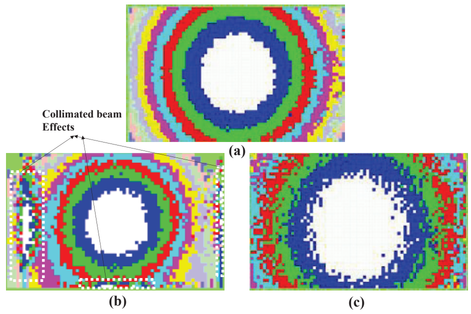

Fig. 5. Light spot deviation from the center of each cell for spherical mirror (a), analogue HOE (b) and digital HOE (c)

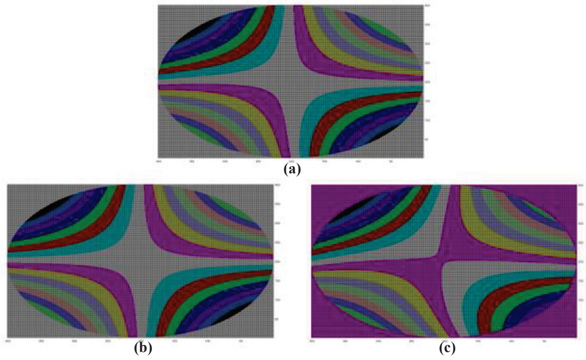

Fig. 6. Aberrations in spherical mirror (a), analogue HOE (b) and digital HOE (c) obtained with Zernike Polynomials.