Stereoscopic Display through Electro-holography

1. Introduction
As a 2-D image display medium, television has undergone developments ranging from color to high-definition, with the aim being high-resolution, highly realistic visual reproduction. Along with these developments, interest in stereoscopic image displays has grown, and there are growing expectations that stereo television capable of offering a new sense of realism will appear in coming years. At the NHK Science and Technical Research Laboratories, we are conducting research into electro-holography using LCD panels, with the aim of developing an ideal stereoscopic image display system.

Holography is a technology for recording and reconstructing optical information. By holographically recording and reproducing the light from an object (object beam), it is possible to re-create a scene that is identical to the original one. Accordingly, since the conditions of viewing an image reconstructed by holography are the same as those of viewing an object in the natural world, holography can be used to reproduce 3-D images without concern about human visual perceptual functions. Although holography has commonly been used to display stationary stereo images using photographic plates, in recent years more and more research is being done on video playback of stereo images in which electronic devices express hologram display surfaces. In particular, LCDs, which are a type of 2-D spatial modulator, can switch modulation components at video rate, and they have been used for hologram display surfaces for video playback. However, since the minimum pixel pitch of current LCDs is approximately 10 μm, LCDs offer very low resolution compared with the 1,000 lines/mm resolution of the photographic plates used for holograms. In addition, LCDs suffer from other drawbacks, such as the phenomenon of overlapping of conjugate beam at the reconstructed image, and the difficulty with the narrow viewing zone of stereovision. As techniques to overcome these limitations, we have already proposed a conjugate beam elimination method and viewing zone enlargement method. In this study, we applied these improvements to a high-resolution LCD and created a prototype stereoscopic display device that enables binocular stereovision at a distance of 90 cm from the reconstructed image.

2. Hologram Reconstruction using an LCD Panel
A hologram is an image created by recording the interference pattern resulting from the interference between the light beam of an object and a separate light beam that serves as a reference (reference beam). All the wave front information of the object beam is recorded in the interference pattern, so that when the hologram interference pattern is radiated with a light beam identical to that of the reference beam (illumination beam), as shown in Fig. 1, the recorded object beam is reconstructed, forming a virtual image in the position where the object existed. This image is called a “primary image,” and normally it is viewed as a stereoscopic image. However, in the reconstruction of holograms, beam other than the object beam is also generated, such as beam (conjugate beam) that forms a real, “pseudoscopic” image, with the object’s concavities and convexities reversed (conjugate image), and illumination beam that is transmitted through the hologram as it is (transmitted beam). When an interference pattern is displayed on a high-resolution display surface, such as a photographic plate, the object beam, conjugate beam, and transmitted beam can be positioned so that their travel directions are at different angles, as shown in Fig. 1 (a), in order to reduce the obstruction caused by conjugate beam and transmitted beam entering the eye of the observer viewing the primary image. In the case of low-resolution interference pattern display surfaces, the angular differences between the travel directions of the light beams are small, as shown in Fig. 1 (b). This means that the conjugate beam and transmitted beam tend to enter the eye of the observer, obstructing proper image formation. Since the resolution of an LCD panel is close to the situation in Fig. 1 (b), it is necessary to reduce the influence of obstructive beam when LCDs are used for hologram display surfaces.

![Figure 1: Hologram reconstruction](image-url)
Next, we consider the resolution of interference pattern display surfaces and viewing zone of primary images (the shaded region in Fig. 1, referred to as the "viewing zone").

The size of the viewing zone is an important aspect of a stereoscopic display. Unless both eyes enter into the viewing zone at the same time, binocular stereovision cannot be achieved. The greater the amount of interference, or in other words, the greater the angular difference between the object beam and reference beam, the narrower the fringe spacing of the interference pattern (the higher the spatial frequency). In the case of interference patterns displayed on surfaces having a pixel structure, like LCDs, interference patterns are sampled by pixel period, such that those interference pattern spatial sampling frequency components having a sampling frequency greater than 1/2 are aliasing. This means that when the display surface pixel pitch is determined, the maximum angular difference between object beam and reference beam to prevent interference-pattern aliasing is also fixed. This maximum angular difference, \( \phi \), can be calculated as

\[
\phi = \frac{\lambda}{2p}
\]  

(1)

Here, \( \lambda \) is the light wavelength, and \( p \) is the pixel pitch of the interference pattern display surface. The viewing zone becomes the range of spread of the object beam recorded in the interference pattern. Thus, when the pixel pitch of the display surface is \( p \), the viewing zone is defined by the angular range \( \pm \phi \), measured from the center-line of the reference beam travel direction. For example, for a light wavelength, \( \lambda \), of 632.8 nm (red light), the viewing zone of a photographic plate for holograms having a resolution of 1000 lines/mm (equivalent to a pixel pitch of 0.5 \( \mu \)m) would be \( \pm 36 \degree \). For the same light, the viewing zone with LCDs of pixel pitch 10 \( \mu \)m would be \( \pm 1.8 \degree \). This example illustrates the extremely narrow viewing zone of LCDs.

3. Obstructive Beam Elimination and Viewing Zone Enlargement

3.1 Reconstruction optical system

In the last section, it was shown that increasing the resolution of the interference pattern display surface is effective in enlarging the viewing zone and eliminating obstructive beam. However, it is currently difficult to produce spatial light modulators, such as LCDs, of similar resolution to that of photographic plates for holograms. For this reason, we have proposed techniques that can enlarge the viewing zone and eliminate obstructive beam without increasing the resolution of the display surface.

These techniques feature a reconstruction optical system utilizing a converging lens, as shown in Fig. 2, in order to process the light reconstructed from the hologram in the spatial frequency region. In this optical system, the hologram is positioned in the front focal plane (on the left side of the lens in Fig. 2), such that the light scene at the back focal plane (on the right side of the lens in Fig. 2) is a Fourier transform of the light scene immediately after emerging from the hologram. Thus, by placing a spatial filter at the back focal plane, it is possible to perform processing in the spatial frequency region of the reconstruction light. In this optical system, through the effect of the converging lens, the primary image formed at the position of the original object is reconstructed on the right side of the lens. We refer to this reconstructed image as the "reconstructed image," and it is this image that we are observing here. The viewing zone angle \( \Omega \) for this reconstructed image is given by the following formula.

\[
\Omega = \frac{4d}{pf}
\]  

(2)

Here, \( d \) is the distance between the object and the hologram, while \( f \) is the focal length of the converging lens.

3.2 Eliminating obstructive beam

Here, we describe how to eliminate the transmitted beam and conjugate beam that obstruct the observation of reconstructed images. Plane waves are often used for illuminating beams, and we used plane waves. In the optical system shown in Fig. 2, the transmitted beam forms an image (carrier image) at a single point ("X" in the figure) in the back focal plane. Thus, by placing a tiny light shield plate at this image formation position, the transmitted beam can be easily eliminated.

A technique for eliminating conjugate beam is the single-sideband method. This technique, which is effective for holograms utilizing relatively high-resolution display surfaces, eliminates the conjugate beam components by limiting the reconstructed beam band by half in the spatial frequency region. When creating interference patterns for display on low-resolution display surfaces such as LCDs, it
is not possible to increase the angle between the object beam and reference beam. In this case, the single-sideband method can be effectively applied to the interference pattern created by half-zone-plate processing. Half-zone-plate processing assumes that the object consists of an aggregate of point light sources, and restricts the light spreading from these sources by half, with a surface which passes through the point light sources and includes the travel direction of the reference beam, as shown in Fig. 3 a). When the light reconstructed from the interference pattern resulting from this processing passes through the optical system of Fig. 2, the conjugate beam (hatched part of Fig. 3 b)) and object beam (shaded part of Fig. 3 b)) are spatially separated, and particularly in the rear focal plane, the pass region of the conjugate beam becomes a constant region, irrespective of the point source position. If the pass region of the conjugate beam is blocked at the rear focal plane, the conjugate beam for all the point sources of which the object is constructed can be eliminated. Whereas Fig. 3 shows the recording of the upper half of the light, the lower half of the light can be recorded too. However, in this case, the position of the half-plane mask will be reversed, since the pass range of the conjugate beam will be on the opposite side of the optical axis, as in Fig. 3 b).

The problem with this method of eliminating conjugate beam is that half-zone-plate processing cuts the object beam spread by half, and thus the viewing zone is also reduced by half. To address this problem, we proposed a technique for restoring the viewing zone to its original value, and verified its effectiveness in a prototype test. The technique works by splitting the light in two, creating interference patterns from each of the two parts, and then combining the object beam reproduced by applying the single-sideband method to each of the interference patterns. This technique was not used with the prototype device of this study. Instead, a simplified device was used in which half-zone-plate processing was performed; i.e., the spread of the object beam was limited in the vertical direction. By using this method, conjugate beam was eliminated without narrowing the viewing zone in the horizontal direction, which is necessary for achieving stereovision.

3.3 Viewing zone enlargement using high-order diffraction beam

To enlarge viewing zone without reducing pixel pitch, we explain a technique for reconstructing the object beam from the aliasing of interference patterns obtained using high-order diffraction beam. To simplify this discussion, however, we limit ourselves to enlargement in one direction (horizontal), although vertical enlargement can be achieved in the same way. When creating a hologram, if the angular difference between object beam and reference beam satisfies the conditions of the formula given below, the obtained interference pattern will have a high-pass spatial frequency, consisting of aliasing corresponding to a display surface having a pixel pitch of \( p \).

\[
(2n-1) \phi_m < \phi_o, \theta_R \leq (2n+1) \phi_m \quad (n=..., -1, 0, 1, ...)
\]

Here, \( \phi_o \) and \( \phi_R \) represent the angles of incidence of the object beam and reference beam on the hologram surface, while \( \phi_m \) represents the angular difference obtained from Equation (1). The aliasing of the interference pattern obtained from the conditions of Equation (3) is referred to as the \( n \)th aliasing. The case of \( n=0 \) represents an interference pattern without aliasing. Figure 4 is a graphical representation of Equation (3).
When reconstructing a hologram, high-order diffraction occurs as a result of the pixel structure of the interference pattern display surface. Through this high-order diffraction beam, the reconstructed image, conjugate image and carrier image, are formed repeatedly, as shown in Fig. 5, within the surfaces perpendicular to each of the optical axes. The repetition period is $f/p$. The reconstructed image obtained from the m-order diffraction beam (m-order reconstructed beam) is referred to as the m-order reconstructed image.

The 0-order reconstructed image, from the interference pattern having no aliasing, is formed at the object position, and this image is normally observed as a stereoscopic image. On the other hand, the 0-order reconstructed image from aliasing is formed at a different position. For example, the 0-order reconstructed image from the kth aliasing is formed at a distance of $k \times f/p$ from the object position. However, the k-order reconstructed image is formed at a distance of only $k \times d$ from the object position, which corresponds to the object position. Thus, from the kth aliasing, the k-order reconstructed image is formed at a position corresponding to the object position. The path of the beam constituting the k-order reconstructed image (k-order reconstructed beam) is different from that of the 0th-order reconstruction beam from the interference pattern without the aliasing. Thus, by using this high-order diffraction beam, the viewing zone angle can be enlarged beyond the value of $\alpha$ given in Equation (2).

Figure 6 shows an image of the enlarged viewing zone. The figure represents a hologram having a viewing zone angle double that of an ordinary hologram. It was achieved by combining 0-order reconstruction beam from an interference pattern with no aliasing (equivalent to a normal holography), and 1-order reconstructed beam from a 1st aliasing interference pattern. In this way, the pass bands of high-order diffraction beam at the back focal plane do not overlap for each order of interference, and line up equidistantly. Accordingly, by positioning a spatial filter in front of the pass range for necessary orders of interference, regarded as an aperture, only the diffraction beam for specified orders of interference will be extracted.

4. Prototype Device

Figure 7 is a diagram of the prototype stereoscopic display device we constructed. This device was made out of two holographic units. One unit reproduces 0-order reconstructed beam from interference patterns with no aliasing, while the other unit reproduces 1-order reconstructed beam from interference patterns of the 1st alias component. These beams are half-mirror combined, to double the viewing zone. For the spatial filters 1 and 2 placed at the back focal plane of the lens of each unit, the areas that halve the pass range of each of the 0-order and 1-order diffracted beam components in the vertical direction function as apertures. The pass range is halved using the single-sideband method to eliminate conjugate beam. This method eliminates transmitted beam at the same time. In this way, only the high-order reconstructed beam is extracted, while obstructive beam is removed.

Table 1 shows the specifications for the LCD for displaying interference patterns. This LCD is of extremely high definition (pixel pitch: 10 μm; pixel number: 3840×2048) and is of the type used in Super Hi-Vision projectors. The viewing zone angle obtainable with this LCD device, as calculated by Equation (2), is $3.6^\circ$, for $d = f$, and $\lambda$ taken as 632.8 nm. Accordingly, when an image of size 18 mm is reconstructed, the viewing zone width would be 6.5 cm, approximately the distance between a person’s eyes, and the distance from the reconstructed image (observation distance) would be 1.3 m. If with this
display device, the previously described viewing zone enlargement technique is applied to this LCD, the viewing zone angle would theoretically be 7.2°, corresponding to a pixel pitch of 5 μm, and the observation distance would be 66 cm.

We created an object made up of three planar letters N, H and K, having a size of 18 mm horizontally and 6 mm vertically. The distance to the hologram surface was set at 52 cm for H, and 48 cm for N and K. The hologram was calculated using the Fresnel-Kirchoff diffraction approximation formula in the Fresnel region. This assumes that the reference beam is a plane wave (wavelength: 632.8 nm) that is vertically incident to the hologram plane. The hologram calculation included half-zone-plate processing for eliminating conjugate beam. The hologram was expressed in 256 gray levels. To make effective use of the LCD's dynamic range, a random phase was applied to each point light source of the object. A laser beam with the same conditions as those of the reference beam was used as the illumination beam for reconstruction.

A photograph of the reconstructed image is shown in Fig. 8. Figure 8 (a) and (b) represent the image seen from two different positions within the viewing zone (left and right sides). The overall image size is 18 mm × 6 mm, with the letter H formed 4 cm behind N and K. The focal point of the photograph is at the letters N and K. The figure indicates that the proper image corresponding to the viewing position was reconstructed, with reduced obstruction from the conjugate beam. Using the viewing zone enlargement technique with this display device, we secured a viewing zone of 6.5 cm, within which the viewer can perceive the hologram with both eyes as a stereoscopic image, at an observation distance of approximately 90 cm. It is thought that observation distance is greater than the theoretical value (66 cm) because with the object position set here, the entire hologram could not be fully displayed on the LCD, so that the scatter of the reconstruction laser was narrower than the theoretical value.

5. Conclusion

We are trying to develop a stereoscopic display using electronic holography technology and have investigated techniques for conjugate beam elimination and viewing zone enlargement. We produced a prototype device in which these techniques are applied to high-definition LCD panels. Using this device and applying half-zone-plate processing in the vertical direction, we were able to eliminate conjugate beam obstruction without sacrificing horizontal viewing zone. Also, by combining 0-order reconstructed beam and 1-order reconstructed beam, the viewing zone was doubled relative to that of normal holography, and the reconstructed images could be viewed in binocular stereovision at a distance of approximately 90 cm. The prototype device has a viewing zone corresponding to a hologram display surface with a pixel pitch of several μm. However, the use of higher order aliasing and high-order reconstructed beam would enable the viewing zone to be enlarged even further. Accordingly, we showed that in electro-holography systems utilizing display elements such as LCD panels, even at a pixel pitch of several μm, it is possible to achieve binocular stereovision. In future studies, we plan to investigate pick-up-display systems which can be taken real objects.

(Tomoyuki MISHINA, Makoto OKUI, Fumio OKANO)