Direct recording of holograms by a CCD target and numerical reconstruction

U. Schnars and W. Jüptner

The principle of recording holograms directly on a CCD target is described. A real image of the object is reconstructed from the digitally sampled hologram by means of numerical methods.

Key words: Digital holography, numerical reconstruction, charge-coupled devices.

In this Note a method is described that uses a charge-coupled device detector (CCD) as a holographic recording medium. The resolution of a CCD is ~100 lines/mm, which is one order of magnitude less than standard film materials. For this reason the maximum angle between the reference wave and the object wave has to be in the range of a few degrees.[1] Only small objects at a large distance from the hologram (CCD target) can be recorded. However, using CCD's for recording holograms is advantageous because video frequencies are available and no chemical or physical developing is necessary. Reconstruction can be performed by digital image processing.

In the early days of holography, some research was done in the field of television transmission of holograms.[2] The holograms were performed directly on the photosensitive layer of a TV camera tube, and the interference signal was transmitted through the television channel. A replicate of the original hologram was written on a transparent surface at the receiving station. The transmitted hologram was reconstructed optically from this replicate. The hologram was recorded optoelectronically and reconstructed optically. There are also a few examples for reconstructing objects from their holograms with mathematical methods.[3–5] In these examples an optically enlarged part of a conventionally recorded in-line-hologram is used for reconstruction. In this Note, the mathematical reconstruction is done directly with the digitally sampled Fresnel hologram from the CCD. No apparatus for enlarging the hologram is necessary. The method is demonstrated in the case of off-axis holography with diffusely reflecting objects.

Figure 1(a) shows the recording geometry. A plane reference wave and the diffusely reflected object wave are interfering at the surface of a photosensitive medium. In optical holography the object wave can be reconstructed by illumination of the processed hologram with a plane wave, similar to that used in the process of recording. Looking through the hologram, one notices a virtual image of the object at the position of the original object [Fig. 1(b)]. If a screen is placed at a distance d behind the hologram, a real image is formed.

Mathematically the amplitude and phase distribution in the plane of the real image can be found by the Fresnel–Kirchhoff integral. If a plane wave illuminates the hologram located in the plane $z = 0$, with an amplitude transmittance $t(x, y)$, the Fresnel–Kirchhoff integral results in the complex amplitude $\Gamma(\xi, \eta)$ in the plane of the real image:[6]

$$\begin{aligned}\Gamma(\xi, \eta) = \frac{ia}{\lambda d} \exp\left[-i \frac{\pi}{\lambda d} (\xi^2 + \eta^2)\right] \\ \times \iint_{(x,y)} t(x, y) \exp\left[-i \frac{\pi}{\lambda d} (x^2 + y^2)\right] \\ \times \exp\left[+i \frac{2\pi}{\lambda d} (x\xi + y\eta)\right] \mathrm{d}x\mathrm{d}y. \qquad (1)\end{aligned}$$

a is the amplitude of the incident wave. It should be pointed out that Eq. (1) is an approximation of the exact formula. This Fresnel approximation is valid if the following condition is fulfilled:[6]

$$d^3 \gg \frac{\pi}{4\lambda} [(\xi - x)^2 + (\eta - y)^2]^2. \qquad (2)$$

The authors are with the Bremen Institute for Applied Beam Technology, Klagenfurter Strasse 2, Bremen 28359, Germany.

Received 8 February 1993; revised manuscript received 6 July 1993.
0003-6935/94/020179-03$06.00/0.

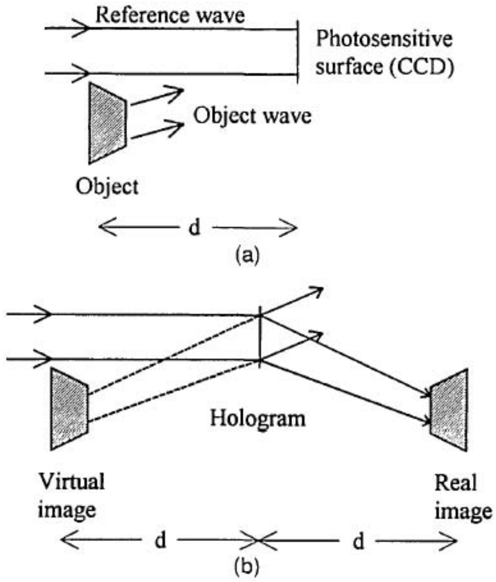

Fig. 1. Off-axis holography with a plane reference wave: (a) recording, (b) reconstruction.

In inequality (2) the maximum possible value of $(\xi - x)^2$ and $(\eta - y)^2$ must be considered. For $\lambda = 600$ nm and typical hologram dimensions of $(\xi - x)_{\max} = (\eta - y)_{\max} = 0.5$ cm, d must be larger than 15 cm.

The intensity in the real image can be calculated from Eq. (1) by taking the modulus and squaring:

$$I(\xi, \eta) = |\Gamma(\xi, \eta)|^2. \tag{3}$$

The function $\Gamma(\xi, \eta)$ can be digitized if the hologram transmission $t(x, y)$ is sampled on a rectangular raster of $N \times N$ matrix points, with steps Δx and Δy along the coordinates. ξ and η are replaced by $r\Delta\xi$ and $s\Delta\eta$, where r and s are integers. In this case the discrete representation of Eq. (1) is given by the following equation:[7]

$$\begin{aligned}\Gamma(r, s) = {} & \exp\left[-i \frac{\pi}{\lambda d} (r^2\Delta\xi^2 + s^2\Delta\eta^2)\right] \\ & \times \sum_{k=0}^{N-1} \sum_{l=0}^{N-1} t(k, l)\exp\left[-i \frac{\pi}{\lambda d} (k^2\Delta x^2 + l^2\Delta y^2)\right] \\ & \times \exp\left[i2\pi\left(\frac{kr}{N} + \frac{ls}{N}\right)\right].\end{aligned} \tag{4}$$

$\Gamma(r, s)$ is a matrix of $N \times N$ points that describes the amplitude and phase distribution of the real image. $\Delta\xi$ and $\Delta\eta$ are the pixel sizes in the reconstructed image. If only the intensity distribution according to Eq. (3) is of interest, the phase factor before the summation can be neglected. From the numerical standpoint, Eq. (4) is a representation of the Fresnel approximation in terms of a discrete Fourier transformation. This is an important fact, because the standard algorithms for a fast Fourier transformation can then be applied.

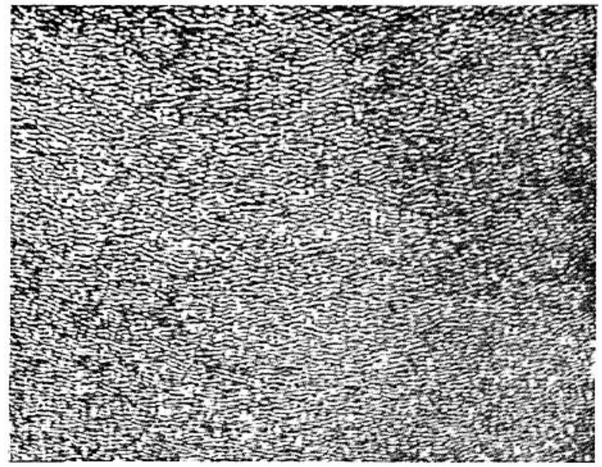

Fig. 2. Digitally sampled off-axis hologram.

In the experimental investigations a CCD array is placed at the position of the photosensitive surface (see Fig. 1). The CCD array consists of 1024 × 1024 light-sensitive pixels. The pixel area is 6.8 μm × 6.8 μm. The camera electronics produces a digital video output signal containing 256 gray levels per pixel. For computation the hologram is stored in a digital image processing system. The object in this experiment was a cube with a side length of 11 mm, which was placed at a distance of 1 m from the target. A helium–neon laser was used as a light source.

Figure 2 shows a part of a digitally sampled hologram. The original dimensions of the whole hologram were 7 mm × 7 mm, which are the dimensions of the CCD chip. The numerical reconstruction

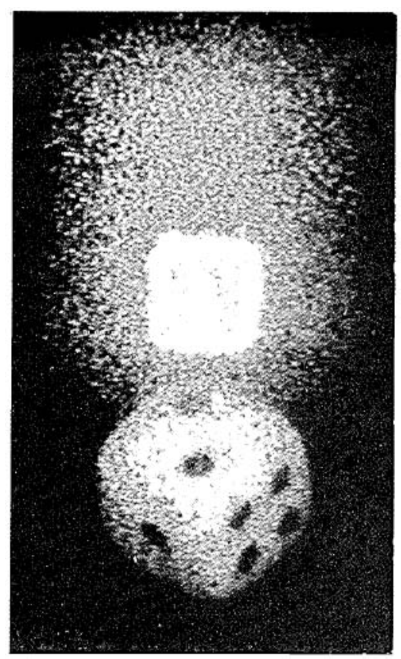

Fig. 3. Numerical reconstruction.

according to Eqs. (3) and (4) is demonstrated in Fig. 3. A real image of the cube together with the undiffracted reference wave are noticeable. Because of the off-axis geometry, these two parts of the real image are separated. Furthermore, a speckle appearance on the reconstructed cube is noticeable. It is a result of the interaction between coherent light and the rough surface of the object. This speckle structure is the same as it would be in optical reconstruction with the same numerical aperture.

This experiment demonstrates that CCD cameras are in principle suitable as recording media for holograms. The applicability of CCD's is still limited to small objects at a large distance from the target because of the low spatial resolution. Future CCD chips, with higher resolutions, will improve the quality of the image. However, even today, promising applications of the method are possible, for example, in the field of holographic interferometry.

References

1. W. Jüptner, "Holographic techniques," in *Sensors and Sensory Systems for Advanced Robots,* P. Dario, ed., Vol. 43 of the NATO Advanced Science Institutes Series (Springer, New York, 1988), pp. 273–293.
2. R. J. Collier, C. B. Burckhardt, and L. H. Lin, *Optical Holography* (Academic, New York, 1971), Chap. 20.2, p. 573.
3. M. A. Kronrod, L. P. Yaroslavski, and N. S. Merzlyakov, "Computer synthesis of transparency holograms," Sov. Phys. Tech. Phys. **17,** 329–332 (1972).
4. M. A. Kronrod, N. S. Merzlyakov, and L. P. Yaroslavski, "Reconstruction of holograms with a computer," Sov. Phys. Tech. Phys. **17,** 333–334 (1972).
5. L. Onural and P. D. Scott, "Digital decoding of in-line holograms," Opt. Eng. **26,** 1124–1132 (1987).
6. P. Das, *Lasers and Optical Engineering* (Springer, New York, 1991), Chap. 2.4, p. 81.
7. L. P. Yaroslavskii and N. S. Merzlyakov, *Methods of Digital Holography* (Consultants Bureau, New York, 1980), Chap. 1, pp. 9–15.