SCANNING HOLOGRAPHY AND ITS APPLICATIONS

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ABSTRACT

Scanning holography is a brand new concept in holographic optics. We describe various techniques of making scanning holograms and elaborate on the basic principles, relevant mathematics, applications and limitations of scanning holography.

2. INTRODUCTION

The basic idea of holography was originated by Professor Dennis Gabor in 1948. Since the 1960s, with the advent of the laser and off-axis geometry presented by Leith and Upatnicks, holography has been rapidly developed and become a very active field of optics.

As everyone knows, in order to make a hologram with a He-Ne laser, one has to work on a vibration-isolated table. Furthermore, one would need a pulsed laser to make a hologram of a hand or a portrait (except for holographic stereograms, of course). This is common knowledge to every holographer. In order to get a hologram with high quality, one should not only carefully arrange the optical elements on the table, but never change the position of any element during the exposure, including the laser. In most cases, people have to use a big cover or screen on the table to avoid the disturbance from outside aircurrent, because they know they are dealing with things as fine as the wavelength of laser light.

However, people may have never imagined that if one holds holographic plate and object in one hand, a laser in the other, and scans the laser beam across the plate, one will still be able to get a hologram of high quality. This is the so-called scanning hologram. Here we will discuss in detail various aspects of scanning holography and report some interesting results from the experiments we have conducted in this field.

3. PRINCIPLE

A hologram holds the entire three-dimensional information of an object by recording the pattern of interference between a reference beam and an object beam. Therefore, the way in which the interference pattern is constructed and recorded is the key to success in making holograms. In general, in addition to the coherence of light source, it is essential to keep the interference pattern stationary during exposure. If this is true, how are we able to construct stable interference fringes by means of scanning? Apparently there will always be inevitable movement of the light source during exposure. The point is, if we can keep the difference in optical pathlengths between object beam and reference beam unchanged or almost unchanged during the exposure, the fringes may still be considered stable enough. Now let us consider a configuration, as shown in Figure 1, of making a scanning reflection hologram.

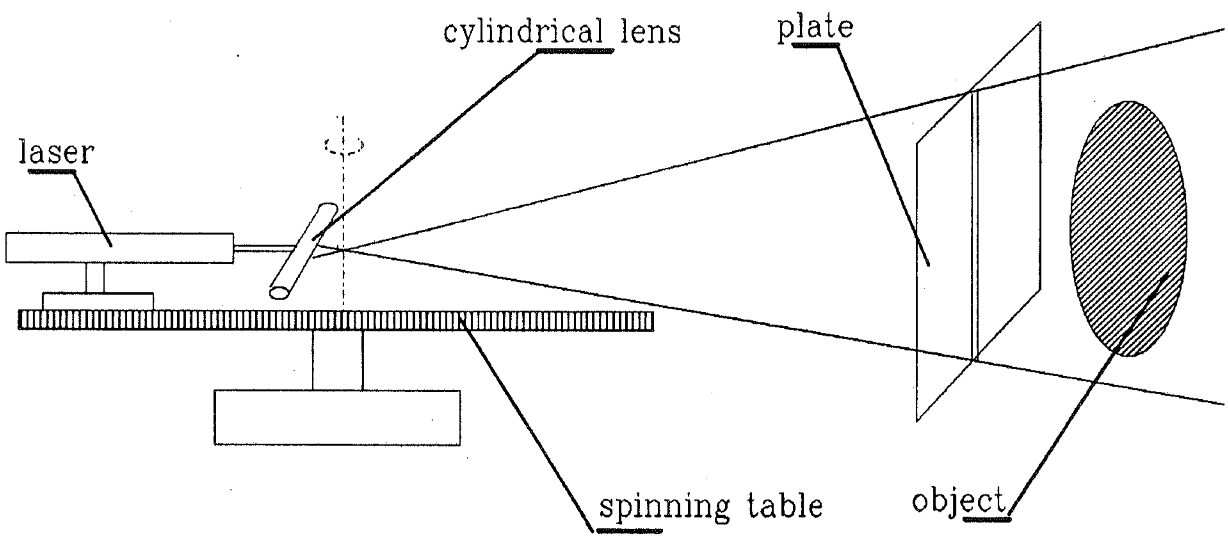

Fig.1 A typical setup used to make scanning reflection hologram

We arrange a laser and a cylindrical lens on a spinning table whose axis passes through the focal point of the lens. When the table is turning, the narrow line beam scans across the holoplate and object simultaneously. This is one of the simplest setups for making scanning reflection hologram. We shall discuss in detail how a hologram like this is made.

Figure 2 shows the geometry of the optical arrangement for making reflection scanning holograms. During scanning, point source S is shifted to S'. To simplify discussion, we let the displacement be Δs, and divide it into components Δx, Δy and Δz in three mutually perpendicular dirctions. Let point O on the object and point P on the holoplate be under illumination from S at the same time. Since the width of the scanning light beam is quite narrow, we simply consider S, O and P to be in the same plane, e.g. the yz plane in Figure 2. This is the most sensitive case. We set the initial position of S to be the origin, so the coordinates for O and P are $(0, y_2, z_2)$ and $(0, y_1, d)$, where d is the distance between S and the holoplate. Let l be distance between S and O, l' between S' and O, r between S and P, r' between S' and P. We are going to describe mathematically the criteria of recording scanning hologram in x, y, z directions separately.

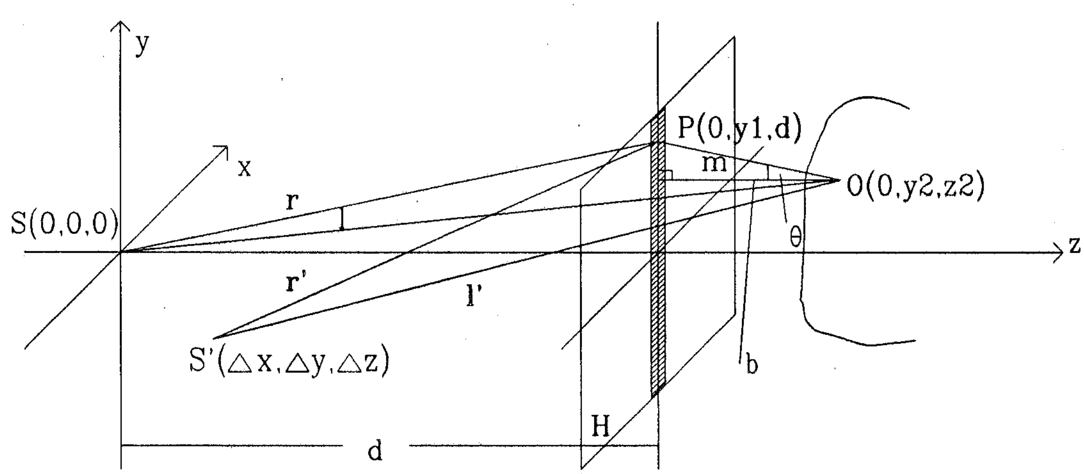

Fig.2 Conditions of recording scanning hologram in X, Y, Z directions

I. X-direction:

Assume the displacement of light source is only in x direction. In this case, $\Delta y = \Delta z = 0$. The line beam is extended in y direction and the scan is in the xz plane. The hatched narrow strip is the region illuminated by the scanning beam. If the point source S is shifted by Δx to S' during scanning over O and P, the pathlength of the reference beam is changed from l+m to l'+m, and r to r' for the object beam. If the difference in the pathlengths between the reference beam and object beam is so small that it can be ignored, e.g. smaller than $\lambda/8$, then the interference fringes are stable enough to be recorded on holographic plates just like ordinary holograms.

Here we should emphasize that the width of the line beam is very narrow and exposure is considered finished for any point on the plate after the line beam scans past it.

In fact, as Figure 2 shows, we have the difference of the pathlengths between reference and object beams before scanning as

$$\Delta L = l + m - r \tag{1}$$

and the difference during scanning

$$\Delta L' = l' + m - r' \tag{2}$$

Therefore, the condition for making scanning hologram to be recorded is

$$\Delta = |\Delta L' - \Delta L| \le \frac{\lambda}{8} \tag{3}$$

where Δ is the absolute value of the variation of the pathlength difference. Obviously, from Figure 2, we have:

$$l = \sqrt{y_2^2 + z_2^2};\ l' = \sqrt{\Delta x^2 + l^2};\ r = \sqrt{y_1^2 + d^2};\ r' = \sqrt{\Delta x^2 + r^2} \tag{4}$$

Put these into Δ and we get

$$|\sqrt{\Delta x^2 + l^2} - \sqrt{\Delta x^2 + r^2} - l + r| \le \frac{\lambda}{8} \tag{5}$$

Since $\Delta x << l$ and $\Delta x << r$, approximation gives

$$\left|\frac{1}{2}\frac{\Delta x^2}{l} - \frac{1}{2}\frac{\Delta x^2}{r}\right| \le \frac{\lambda}{8} \tag{6}$$

or

$$\left|\frac{(r-l)\Delta x^2}{rl}\right| \le \frac{\lambda}{4} \tag{7}$$

Let $r \cdot l \approx d^2$ and $b \approx |r - l|$ be the distance between object and plate, we arrive at

$$|\Delta x| \leq \frac{d}{2}\sqrt{\frac{\lambda}{b}} \tag{8}$$

This inequality implies that:

1. In most cases, it can be easily satisfied with properly selected d and b.
2. High quality scanning holograms may be made only if this equation is satisfied.
3. In the special case of $b \to 0$, Δx will go to ∞. That is, if the object has little depth and is close enough to the plate, for instance, coins attached to a plate, we can perfectly record holograms in whatever way we want, even with both the laser and the plate held by hand. Here we temporarily do not consider the problems that might occur in abberration or read-out of holographic information.

II. Y-direction:

When displacement of S is only in y direction, we have $\Delta x = \Delta z = 0$. Similar to the x-direction, we have the equations

$$l' = \sqrt{(y_2 - \Delta y)^2 + z_2^2} \approx \sqrt{y_2^2 + z_2^2 - 2\Delta y y_2} = \sqrt{l^2 - 2y_2\Delta y} \approx l - \frac{y_2 \Delta y}{l} \tag{9}$$

$$r' = \sqrt{(y_1 - \Delta y)^2 + z_2^2} \approx \sqrt{y_2^2 + z_2^2 - 2\Delta y y_1} = \sqrt{r^2 - 2y_1\Delta y} \approx r - \frac{y_1 \Delta y}{r} \tag{10}$$

In the above equations we have omitted terms including $(\Delta y)^2$ since Δy is very small in comparison with z_2 and d. Therefore we have the absolute value of the variation of pathlength difference as

$$\begin{aligned} \Delta &= |(l'-l) - (r'-r)| \\ &= |(\sqrt{(l^2 - 2y_2\Delta y)} - l) - (r - \sqrt{(r^2 - 2y_1\Delta y)})| \\ &\approx |\Delta y(\frac{y_1}{r} - \frac{y_2}{l})| \\ &= |\frac{\Delta y(ly_1 - ry_2)}{rl}| \end{aligned} \tag{11}$$

Substitute this into Equation (3) and we get

$$\Delta = |\frac{\Delta y(ly_1 - ry_2)}{rl}| \leq \frac{\lambda}{8} \tag{12}$$

or

$$\begin{aligned} |\Delta y| &\leq \frac{\lambda}{8}\frac{rl}{|ly_1 - ry_2|} \\ &\approx \frac{\lambda}{8}\frac{d}{b\tan\theta} \end{aligned} \tag{13}$$

Therefore

$$|\Delta y| \leq \frac{d\lambda}{8\, b \tan\theta_{max}} \tag{14}$$

where θ_{max} is the maximum view angle in y-direction and b is the distance between the object and the plate.

III. Z-direction:

Let $\Delta x=\Delta y=0$ in Figure 2, it is not difficult to arrive at the following equation, therefore

$$l'=\sqrt{y_2^2+(z_2-\Delta z)^2}\approx\sqrt{l^2-2z_2\Delta z}\approx l-\frac{z_2\Delta z}{l} \qquad (15)$$

$$r'=\sqrt{y_1^2+(d-\Delta Z)^2}\approx\sqrt{r^2-2d\Delta z}\approx r-\frac{d\Delta z}{r} \qquad (16)$$

in z direction we have the variation Δ of pathlength difference between object beam and reference beam during scanning. The variation of pathlength difference in z direction is:

$$\Delta=|(l'-l)-(r'-r)|=|\Delta z\frac{(ld-rz_2)}{lr}| \qquad (17)$$

Use our criterion (3), and we have

$$\Delta=|\Delta z\frac{ld-rz_2}{lr}|\leq\frac{\lambda}{8} \qquad (18)$$

or

$$|\Delta z|\leq\frac{\lambda}{8}\frac{lr}{|ld-rz_2|}\approx\frac{\lambda}{8}\frac{d^2}{d(d-z_2)} \qquad (19)$$

or

$$|\Delta z|\leq\frac{\lambda}{8}\frac{d}{b} \qquad (20)$$

Up to now we have obtained the conditions which have to be satisfied for successfully recording a scanning hologram: inequalities (8), (14) and (20). From these we have the following conclusions:

1) The farther the distance between the point source and the plate, the less sensitive the holographic interference fringes are to the movement of light source, and therefore the easier to record scanning hologram; vice versa.

2) The smaller the shift of the point source during scanning, the deeper the depth of field may be recorded.

3) Since the scan is in the xz plane, the position of the light source is the easiest to be changed in x-direction. But fortunately the limitation on source shift is the least strict in this direction, which is easy to see in inequality (8).

4) Here we should emphasize that it is only during scan that (8)(14)(20) are to be satisfied simultaneously. In fact, "during scan" implies that it is the short time interval during which the line beam moves across a distance of its width. The narrower the width, the shorter this time interval.

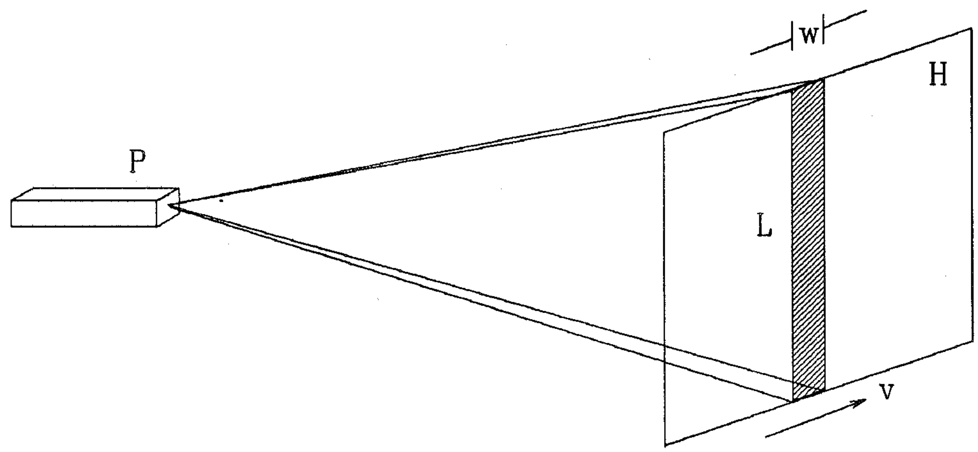

Fig. 3 Scanning hologram recording

Now let us move on to the exposure of scanning holography. We will use an example to illustrate the exposure characteristics of scanning hologram, as shown in Figure 3. This is the most straightforward approach to recording a scanning hologram.

The exposure E on unit area on the plate is

$$E = \frac{P}{Lw}t \tag{21}$$

where P is the power of the laser, L and w are the length and width of the scanning line beam respectively, t is the exposure time. Here we have ignored the energy loss in optical elements and the contribution of the object beam. It is easy to see that scanning speed v is related to the other parameters as

$$v = \frac{w}{t} \tag{22}$$

so

$$E = \frac{P}{Lv}, \quad t = \frac{EA}{P} \tag{23}$$

where A = Lw is the area of illumination.

Obviously, from Equation (23), exposure is independent of the width of the line beam and the area of the plate. This is very important and is quite different from common holography. First of all, the exposure depends only upon output of laser, length of the scanning beam and speed of scanning. The faster the scan, the shorter the exposure time; for any laser power, plate and beam length, proper scanning speed can be calculated from Equation (23). Exposure time is proportional to the cross-sectional area of beam. With fixed beam length L, we can control its width w so that exposure time can be reduced to the order of 10^{-3}s or lower -- so that CW lasers can be used to make portrait holograms which used to be possible only with pulsed lasers [Ref.1,2]. Secondly, since exposure is independent of the size of the plate, it is not difficult to imagine that we may make extraordinarily large format holograms with the scanning technique.

4. SCANNING HOLOGRAPHY

I. Classification

Scanning holography may be divided into two categories according to the scanning method being used: line scanning and dot scanning. For line scanning, a narrow line beam is used for scanning. In dot scanning, a light dot is scanned in two dimensions, like electron beam scanning the TV screen.

In line scanning, the beam can either turn around an axis or move along a line parallel to or tilted from the plate. For the former, the reference beam has a spherical wavefront. For the latter, the reference beam is equivalent to a plane or cylindrical beam. Of course, any deviation during turning or moving will produce deformation or aberration in reconstructed images.

Scanning involves relative movement between light source and plate. Thus one may turn or move either the beam or the plate. They are equivalent.

For a certain special purpose one may also use more than one line or dot for scanning to attain special results.

II. View angle

The view angle is a major concern in scanning holography. Because a scanning hologram consists of innumerable subholograms, the final view angle is limited by those of the subholograms. The view angle is larger in the direction parallel to the scanning line than that perpendicular to the line.

In the viewing plane, we assume that the width of the line beam on the object and the plate are w' and w repectively, as shown in Fig.4. D and b are distances from the viewing plane and the plate to the the object.

It is not difficult to find out the minimum distance D from which we can see the whole object whose dimension is *a*:

$$D = \frac{ab}{w'+w} \tag{24}$$

Refer to Figure 4, the relation between viewing distance R and the dimension of viewing region F is given by Equation (25)

$$F = a(\frac{R}{D} - 1) \tag{25}$$

According to Equation (24), since L is usually by far larger than w, D would be much smaller if we do a vertical scan with horizontal line beam, which means we will have a much wider horizontal view angle.

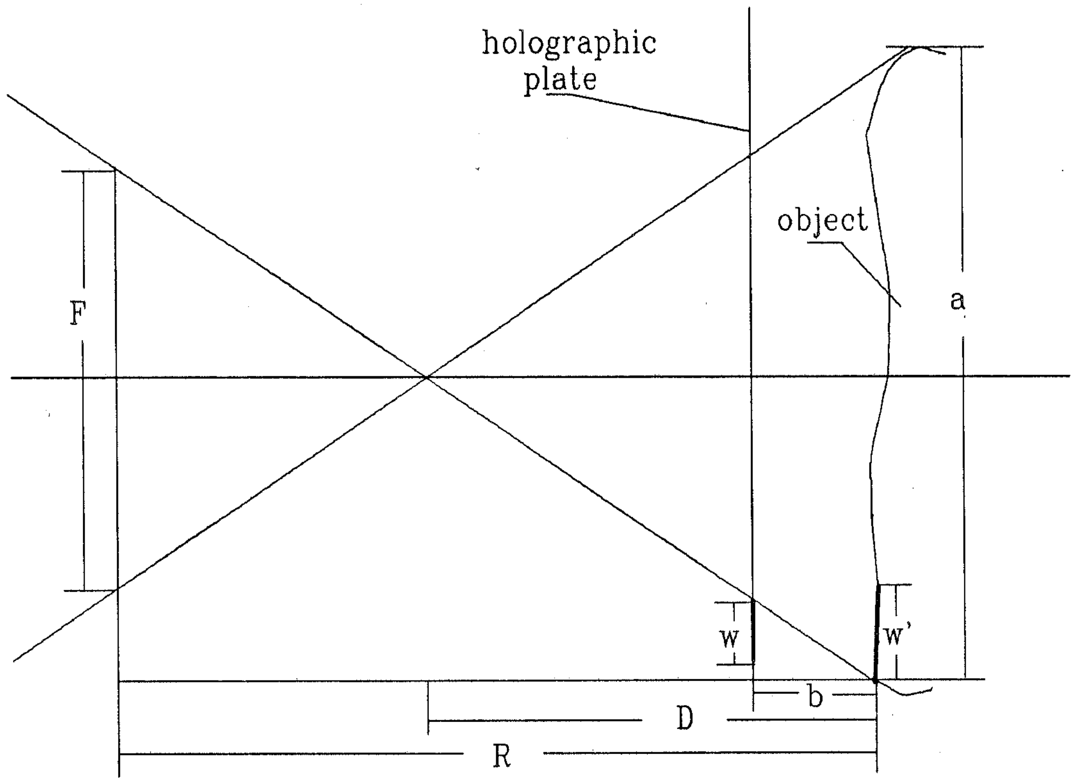

Fig. 4 View angle and view region

III. Application of Scanning Holography

By using scanning technique one can make various kinds of holograms: reflection holograms, transmission holograms, double-exposure holograms, one-step, two-step rainbow holograms, color reflection holograms, etc. It can substitute popular CW laser holography in many situations.

Since all the output power from the laser can be concentrated into a narrow line or even a small dot, the light intensity on the plate will increase tens or hundreds of times, which implies that exposure time may be reduced to a tenth or a hundredth of usual exposure time or even less. Therefore it is especially useful in making holograms with low sensitivity material, e.g. DCG, photopolymer, etc. Some experiments that are impossible in common holography could be accomplished, for instance, making hologram of a hand with He-Ne laser, portrait hologram with Argon laser, even the largest reflection hologram in the world. Theorectically, the size of a scanning reflection hologram is only limited by the size of the film available and the method of holding the film. Extra large cylindrical reflection hologram can also be made with the light beam rotating through 360°.

In a special case, scanning method may be combined with the HOE which T. H. Jeong suggested [Ref.3] to attain true color reflection hologram. In holographic interferometry, it is possible to use scanning technique to measure deformation of large machine tools on the site without the help of vibration-isolated table or pulsed lasers. In dentistry, scanning method could be used to take hologram of teeth and gum.

By encoding the scan, it is possible to use scanning in information storage and read-out for special purposes, e.g. security protection, etc.

IV. The Limitation of Scanning Holography

1) The main problem of scanning holography is its limited view angle. It is more serious in transmission hologram or in the case where there is a large distance between object and plate. Sometimes one can only see part of the object while looking at different parts of a transmission hologram. This phenomenon is very interesting and may be useful in some situations. But in most cases a wide view angle is desired. Increasing the width and number of line beams will improve the results. We hope to solve this problem in future experiments.

2) In order to obtain a narrow line beam for scanning it is often necessary to use cylindrical lenses or a combination of cylindrical and spherical lenses. Usually a spherical wave or plane wave is easily available and is used for reconstruction. If there is difference between recording and reconstructing wavefronts, aberration will occur in reconstructed image. It does not matter for the purpose of display. But in holographic interferometry it may give rise to additional fringes sometimes. So it is necessary to design special optical scanning systems to provide ideal wavefront. In dot scanning, if we have one galvanometric mirror oscillating with variable frequency in two perpendicular directions, the entire wavefront will be spherical.

EXPERIMENTS

We have made reflection holograms of stationary or live objects using He-Ne lasers. Their quality is as good as common holograms.

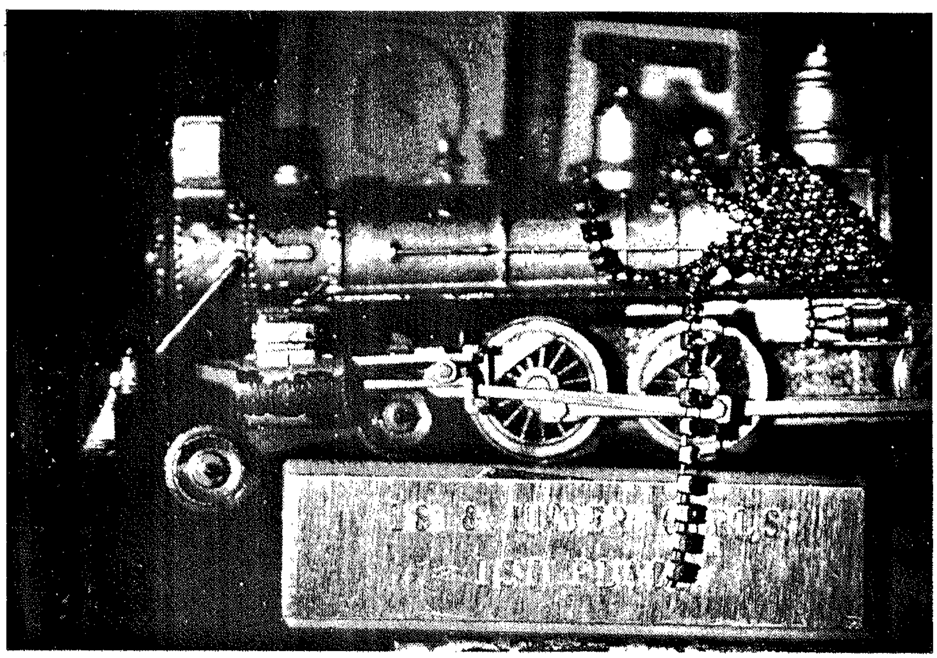

Fig. 5 A reconstructed image from a reflection line-scanning hologram

Figure 5 shows a reconstructed image from a hologram made with line-scanning method. The setup is illustrated in Figure 1.

Figure 6 shows a configuration of the dot-scanning method. By using two galvanometric mirrors which oscillate in perpendicular and horizontal directions, the dot scans over the full plate and the object. The scanning lines can be invisible if only the scanning lines are close enough; the quality of the reconstructed image is also as fine as line-scanning.

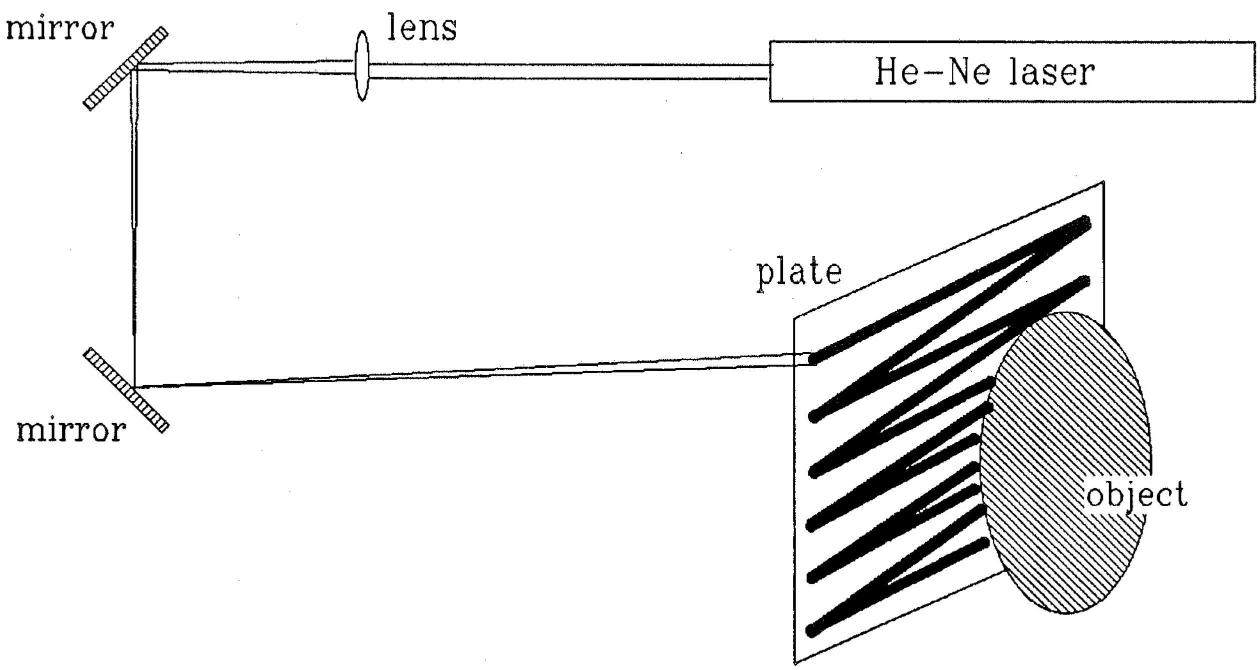

Fig. 6 Dot-scanning setup

Figure 7 shows another reconstructed image from a line-scanning hologram made by a 50mW He-Ne laser. The hand is clearly shown.

In order to prove that the condition for recording a scanning hologram can be easily satisfied, a reflection hologram can be made with one of the authors holding the plate and object in his hand while another holds a laser and scans at them freely. It is very interesting and the hologram is fairly good.

Figure 8 is a double-exposure hologram made with scanning method. The interference fringes are obvious on the deformed object.

6. CONCLUSION

Scanning holography is a new concept and we have only done some preliminary work. There are many more things that we can try to improve and perfect this technique so that it will become useful and practical.

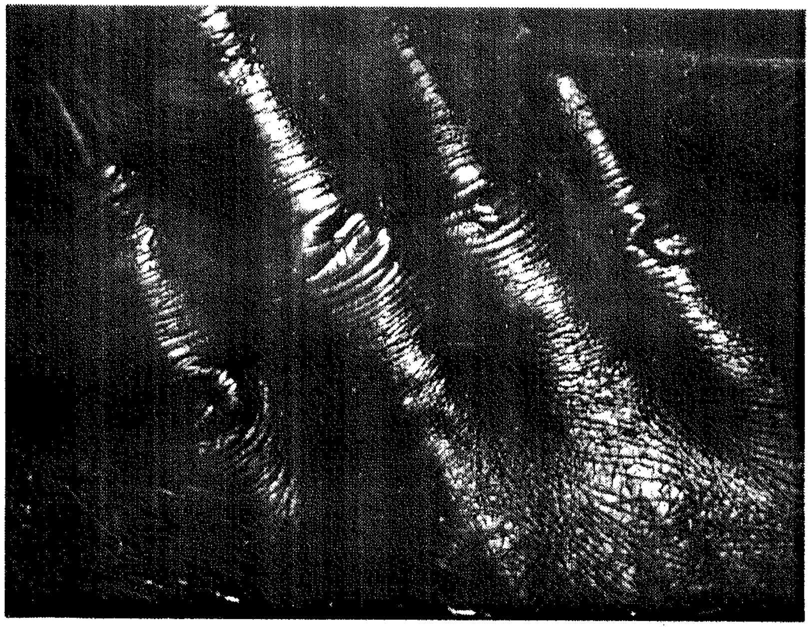

Fig. 7 A reconstructed image of a hand made by 50 mw He-Ne laser

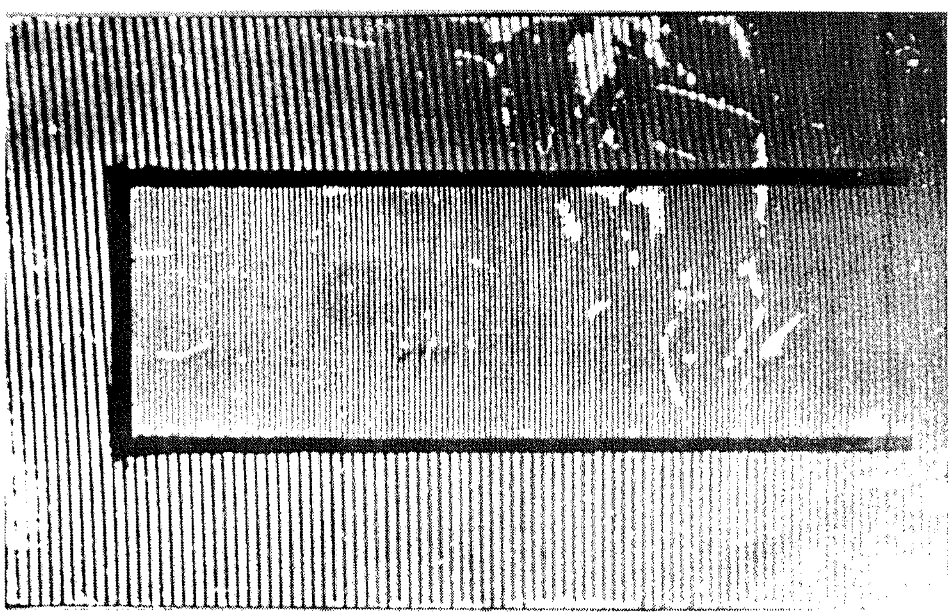

Fig. 8 A reconstruction image of a double-exposure hologram

7. REFERENCES

[1] H. Bjelkhagen, Holographic Portraits; Transmission Master Making and Reflection Copying Technique, Proceedings of the International Symposium on Display Holography, Vol.1, pp.49-54, 1982.

[2] M. Benyon, J. Webster, Pulsed Holographic Art Practice, S.P.I.E. Proceedings, Vol. 615, pp.36-42, 1986.

[3] T. H. Jeong, E. Wesly, Progress in True-Color Holography, S.P.I.E. Proceedings, Vol. 1212, pp.183-189, 1990.