INVESTIGATION OF AN IMPROVED TECHNIQUE IN THE FABRICATION OF MULTIPLEX HOLOGRAM

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SYNOPSIS

Multiplex holography is widely used to record live subjects and out door scenes by means of synthesizing a horizontal sequence of strip holograms. This thesis investigates a method of overcoming shadow effects in conventional multiplex holographic systems. The knife edge slit cannot get rid of shadowing effects which results in barriers and blurred images while displaying multiplex hologram.

The method of glass slits, which comes from contact copying hologram, has been investigated and an appropriate slitholder has been designed, manufactured, assembled and tested. When a wide angular incident light projects onto the holographic plate through the slit, the closer the distance between the plate and the slit, the less the shadowing effect we can obtain. Glass slits can reduce the shadowing effect by 90%. Two other kinds of glass slits were investigated, the soft edge slit and fractal slit which can obtain a soft transition from one strip hologram to another while viewing the multiplex hologram.

The technique for displaying multiplex holograms has been studied in this thesis. The relationship between the reduction of distortion and the position of the display light source are discussed. For conventional concepts, collimated white light illuminates a displaying multiplex hologram forms a series of flat invisible slit planes in space in front of the hologram. In this study, curved shape slit planes are calculated by using Fresnel's diffraction equation and the possibility for obtaining the achromatic multiplex hologram are discussed.

CONTENTS

CHAPTER I

INTRODUCTION

1. 1 MULTIPLEX HOLOGRAPHY

One of the most obvious limitations to conventional holography is the difficulty of recording live subjects or out door scenes. Unlike photography which can follow a subject which moves very fast, holography records images coherently, so it needs a very stable arrangement to obtain good quality interference fringes. A coherent light source e.g laser is necessary together with a huge bench for stability. These confine the holography such that holographic recording then can only take place in laboratories.

A method of combination of photography and holography was first developed 25 years ago by T. J. McCrickerd and N. Geoger. This is a rather ingenious way to make a portrait or out door scene hologram. The concept involves using photography first and then storing a series of pictures holographically. It may seem a somewhat complex task, but compared to other techniques which uses pulsed laser, it is certainly an easier method to implement. This method is called multiplex holography.

Multiplex holography is a technique for synthesizing a three dimensional image from sets of two dimensional objects such as a series of photographic images shown on a diffuser screen. Assuming there is a conventional camera which records a natural light illuminated object along a rail. The camera takes one photograph after another by moving a given distance. This series of photographic images are recorded holographically as a horizontal sequence of strip holograms. For an individual strip hologram, it records an appropriate image from one of the photographs. Everywhere (no matter whether top, bottom or middle) on the strip the same image is shown while reconstructing. This means there is no parallax in the vertical direction. In the horizontal direction, however, each strip hologram has its own image. As a result this synthesized hologram has a parallax only in the horizontal direction.

The optical geometry for shooting a multiplex hologram is as simple as that of the split beam transmission hologram. A laser provides a coherent light source. The object beam and reference beam interfere with each other on the emulsion of the holographic plate. However, there are three obvious differences between them. First, the master holographic plate should be masked off by a moving slit for recording the series of images. Secondly, instead of a solid object used for a conventional transmission hologram, the series of photographic images are projected onto a diffuser screen and this image constitutes the object of the multiplex hologram. If a white light transmission multiplex hologram is desired, the second step of transferring the hologram has to be carried out. For the transferring process, a conjugate light source of the original reference light source is required. So the last difference is that a collimated laser reference beam is needed in multiplex holographic geometry.

In the multiplex holographic geometry, which we investigated, the strip hologram was obtained by means of a slit immediately in front of the holographic plate. For the conventional geometry, a knife edge slit was used and a shadowing effect (see fig 1.1) was inevitably in existence. The purpose of this project is to develop a technique to overcome or to reduce the shadowing and diffraction effects. Further theoretical research was carried out to investigate the relationships between the displaying technique and slit planes (invisible) spatially in front of the displaying hologram and the shape of the slit planes.

1. 2 LAYOUT OF THESIS

In chapter 2 the basic theory for a multiplex hologram is introduced and in chapter 3 the history and development of Multiplex Holography is explained. Multiplex holography is a technique which combines photography and holography with each other. This technique also introduces live and out door scenes into holography. A multiplex hologram possesses all the advantages of both photography and holography and can show a three dimensional view of a white light illuminated object. Today, holography has grown in scope to include large-scale holography, living and moving, or computer generated subjects, and the beginnings of colour imaging.

Chapter 4 introduces basic multiplex holographic theory which was developed by Dr. Stephen A. Benton. The general method for making a white light transmission multiplex hologram is explained. Chapter 5 introduces a method for measuring magnification and distortion when the multiplex hologram is displayed with a light source which is identical to the reference beam used for transferring.

Chapter 6 explains a new model slit which is a key element for making a good multiplex hologram. The reduction of the distance between holographic plate and slit has been achieved by using the new slit. This reduction can overcome the shadowing effect which is one of the most difficult problems in conventional multiplex holographic geometry. This reduction also makes it possible to record larger images from a diffuser screen and to cut short the exposure time which ensures a better quality multiplex hologram to be obtained.

Based on the theory of magnification in chapter 5, an investigation of magnification under different displaying conditions is explained in chapter 7. Chapter 8 explains the shape of the slit plane formed in front of the display hologram while a collimated white light is used. For traditional setups, slit plane is flat. However in this study a curved slit plane is calculated

Chapter 9 introduces the equipment used in the experiment and some details about making the glass slit, soft edge and fractal edge slit. The optical system, plate and slit holder system and computer control system and holographic processing system are introduced. Included in chapter 10 are methods of improving the quality of multiplex holograms which are concerned with coherence length, polarization of signal and reference beams, beam ratio, quality and stability of slit and slitholder and so on. Chapter 11 is a conclusion of all the work in this thesis. Discussion is made as to whether the required goals have been achieved, what has been understood and recommendations for future work suggested.

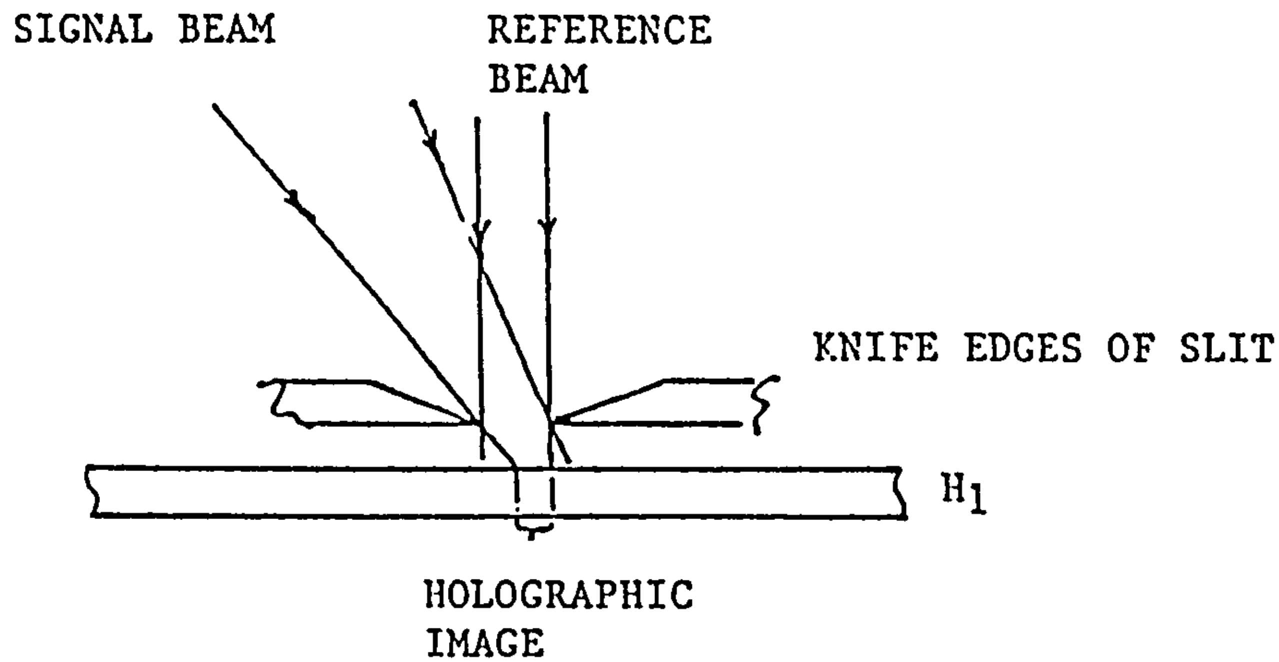


Figure 1. 1

The main reason for producing the shadowing effect

CHAPTER II

BASIC THEORY

2. 1 WAVE

A hologram records the whole information about the wave at each point on a two-dimensional surface. The information includes U_o and ϕ. Here U_o is the amplitude of the wave and ϕ is its phase. A monochromatic wave which arises at some point in space due to a stationary object undergoes amplitude of the form [1-3]

$$U = U_o \sin(\mathbf{k} \cdot \mathbf{r} + \omega t + \alpha_o) \qquad \text{------ (2.1)}$$

where **k** and **r** are the position and propagation vectors respectively, ω is the angular frequency and α_o is initial phase angle. We set $\mathbf{k} \cdot \mathbf{r}$ equal to a constant because we wish to examine waves at a fixed point in space. Thus

$$U = U_o \sin(\omega t + \phi) \qquad \text{------(2.2)}$$

Where the constant phase angle is

$$\phi = \mathbf{k} \cdot \mathbf{r} + \alpha_o$$

Two such harmonic waves of the same frequency, intersecting at a fixed point, may differ in phase by

$$\phi_2 - \phi_1 = \mathbf{k} \cdot (\mathbf{r}_2 - \mathbf{r}_1) + (\alpha_{02} - \alpha_{01})$$

due to a path difference (given by the first term) and initial phase difference (given by the second term). The time variations of the waves at the given point can be expressed by

$$U_1 = U_{01} \sin(\omega t + \phi_1) \qquad \text{------(2.3)}$$
$$U_2 = U_{02} \sin(\omega t + \phi_2) \qquad \text{------(2.4)}$$

By the superposition principle, the resultant electric field U_R at the point is

$$U_R = U_1 + U_2 = U_{01} \sin(\omega t + \phi_1) + U_{02} \sin(\omega t + \phi_2) \qquad \text{------(2.5)}$$

using the trigonometric identity for the sum of two angles and recombining terms,

$$U_R = (U_{01} \cos\phi_1 + U_{02} \cos\phi_2) \sin\omega t + (U_{01} \sin\phi_1 + U_{02} \sin\phi_2) \cos\omega t \qquad \text{------(2.6)}$$

If we picture each of the component waves, Eqs. (2.3) and (2.4), graphically as phasors by plotting magnitude and phase angles and add them (Figure 2.1.a) as if they were vectors, a resultant, or sum, is found with magnitude U_0 and phase ϕ. From Figure 2.1.b the components of the resultant are

$$U_0 \cos\phi = U_{01} \cos\phi_1 + U_{02} \cos\phi_2$$

and

$$U_0 \sin\phi = U_{01} \sin\phi_1 + U_{02} \sin\phi_2$$

In terms of the quantities U_0 and ϕ defined by this graphical technique, Eq. (2.6) becomes

$$U_R = U_0 \cos\phi \sin\omega t + U_0 \sin\phi \cos\omega t$$

or

$$U_R = U_0 \sin(\omega t + \phi) \qquad \text{------(2.7)}$$

The resultant wave U_R is a harmonic wave of the same frequency ω too, with amplitude U_0 and phase ϕ. An expression for U can be obtained from Figure 2-1

$$U_0^2 = U_{01}^2 + U_{02}^2 + 2U_{01} U_{02} \cos(\phi_2 - \phi_1) \qquad \text{------(2.8)}$$

and phase angle

$$\tan \phi = (U_{01} \sin \phi_1 + U_{02} \sin \phi_2) / (U_{01} \cos \phi_1 + U_{02} \cos \phi_2) \quad \text{------(2.9)}$$

From Eqs 2.8 and 2.9, the intensity of this resultant wave depends not only on the intensities of the two individual waves, but also on the phase difference between them. This is the key to holography.

Consider the case of waves focusing a hologram at a point. The wave information, U(x), in the plane of the point is shown in Figure 2-2. U(x) is used to specify the phase information. The '+ ' and '-' regions differ in phase by π. When a holographic plate is placed a the focal plane, a pattern of $|U(x)|^2$ will be recorded as shown in Figure 2-3. [4-6]

If a uniform and coherent reference wave A_o is introduced, then the total amplitude will be

$$U_T = A_o + U(x) \qquad \text{------(2.10)}$$

The pattern is shown in Figure 2-4. A Physical medium would record $|U_T|^2$ as shown in Figure 2-5. It would be possible to shift the phase of the reference beam by π to achieve a recording as shown in Figure 2-6 . The recorded patterns (see Figures 2-5 and 2-6) with a reference beam show the changes of peaks which were affected by reference beam and these two recordings between them contain all the phase and intensity information [7-8]. Either of these patterns can be used to reconstruct the original wave.

2. 2 INTERFERENCE AND COHERENCE

From the equations 2.8 and 2.9, we know that two waves are present at one point and the effect of these waves is NOT simply the sum of the independent effects of each wave. This is called interference which can be extended to three or more waves. The theory of interference is called "coherence theory". Early experimenters found that light derived from a single "point" source and well filtered for monochromacity could be split into two beams which would exhibit interference effects. Such beams were called "coherent". Light from different sources or light which was not wave-length filtered exhibited no interference effects and was called "incoherent"

In some situations even incoherent sources may be utilized in forming the hologram. In those cases where the illumination is derived from a primary incoherent source, the field at the position of the object is partially coherent , thus enabling interference fringes to be formed in the hologram. The main problem of this kind of hologram is that too small portions of the total light incident on the recording medium form interference fringes. In additional, in practice incoherent holography has only been successfully applied to a relatively small number of resolvable point objects. By far the most useful light source for holography is the laser which will be used as the only recording light source in this thesis.

For an interference pattern, the time variations in the wave at the point of measurement obey certain statistical rules. Usually the interference pattern has a spatially non-uniform time average which is identical for all time-averaging intervals greater than

$$\tau_o = 2\pi/\Delta\omega \qquad \text{------(2.11)}$$

The quantity τ_o is the "coherence time". The finite bandwidth of all wave sources leads to restrictions on the interference experiments. The most severe experimental restriction arises from the necessity of matching the path lengths of the two beams to within a distance, l

$$l \ll L_c = c\,\tau_o = 2\pi c/\Delta\omega \qquad \text{------(2.12)}$$

where c is the speed of light. The quantity Lc is called the "coherence length". A path mismatch, l, will cause a phase mismatch between two rays with wavelengths ω and $\omega + \Delta\omega$. This mismatch results in the patterns being misaligned. For forming an interference or holographic pattern, a coherent light source with a long "coherence length" is important and necessary.

2. 3 TECHNIQUES OF HOLOGRAPHY

There are many techniques for making different types of holograms [5]

TABLE 2.1 VARIOUS HOLOGRAPHY TECHNIQUES

Classification	
With respect to techniques	(1) single beam hologram
	(2) split beam hologram
	(3) rainbow hologram
	(4) multiplex hologram
	(5) colour hologram
	(6) transfer hologram
Shape of Object wavefront	(1) Fresnel hologram
	(2) Fraunhofer hologram
	(3) Lensless Fourier-transform hologram
	(4) Image hologram

We are interested in split beam, multiplex and transfer holograms. A Multiplex hologram is obtained by composing a series of two dimensional images into well arranged strip holograms, which are located on a recording plate, by means of holography. A transfer hologram is a technique of recording an image, which is located exactly in the plane of the hologram and projected from another ready made hologram. These techniques and theories will be introduced in Chapter 4 and in the remaining part of this chapter. First we will discuss the geometry of construction and reconstruction of split-beam holography.

2. 4 SPLIT-BEAM HOLOGRAPHY

For split-beam holography the beam is to split into two parts (see Figure

2.7). Only one beam is allowed to interact with the object. When the object beam and reference beam overlap and fall with different angles of incidence on a recording medium, a hologram will be recorded. The plane is located within the recording medium and it is usually called the hologram plane " H ". When the hologram is reconstructed by a duplicate or conjugate of the reference beam after processing, part of the reconstruction beam continues undeflected. However, part of the reconstructed beam forms a continuation of the object beam which produces a virtual image of the object and another beam in a third direction also contains object information and forms a real image. If the object wave $U_o = A_o e^{i\phi_o}$ and the reference wave $U_R = A_r e^{i\phi_r}$, where A is the amplitude and ϕ is the phase of the waves, the combination effect will be [9]

$$U = U_o + U_r = e^{i\phi r}(A_o e^{-i(\phi r-\phi o)} + A_r) \qquad \text{-------(2.13)}$$

and the intensity recorded by the film placed at the hologram plane H is

$$I = | A |^2 = U U^* =[A_o^2 + A_r^2 + A_o A_r e^{i(\phi r-\phi o)} + A_o A_r e^{-i(\phi r-\phi o)}] \qquad \text{-------(2.14)}$$

where the superscript asterisk indicates complex conjugation.

If the hologram has been processed and placed at its original place and if it is illuminated by a conjugate reference light source, an image will be formed of the original object at the object plane. The amplitude of transmission from the hologram is

$$U' = IU_R = A_r e^{i\phi r}[A_o^2 + A_r^2 + A_o A_r e^{i(\phi r-\phi o)} + A_o A_r e^{-i(\phi r-\phi o)}] \qquad \text{------(2.15)}$$

By comparison with Eq.(1.13), then

$$U' = A_r^2[U + (A_o^2/ A_r + A_o^{-i(\phi o-\phi r)})e^{i\phi r}] \qquad \text{------(2.16)}$$

There are three terms in Eq.(2.16) which may be interpreted as follows: The first term represents the zero-order diffraction, the second is the first-order virtual image diffraction and the third is the first-order real image [10] as shown in Figure 2.8. Figure 2.9 shows virtual and real three-dimensional hologram images respectively.

If the reconstructing beam is a conjugate coherent source of the recording beam (collimated laser beam for example), a real image will be projected onto the original object plane [11]. If the reconstructed real image is used as an object and allowed to interfere with another coherent beam, which is split from the same source, and used as reference beam, a transfer image hologram will be recorded. This hologram can be reconstructed using white light. This is usually called a white light illuminated transfer hologram or transfer hologram.

2. 5 RAINBOW HOLOGRAM

The rainbow hologram uses a technique of producing hologram images by reconstructing their image using a simple inexpensive white light source (compared with laser light), high-intensity desk lamps or even sunlight. This type of hologram is capable of producing brighter and more colourful holographic images. Since these types of hologram images are observed through the transmitted light field, they are called white light transmission holograms [9, 10] to distinguish them from white light reflection holograms [14].

A ready made split beam hologram is reconstructed with very small hologram apertures. In other words, it is possible to reconstruct the entire hologram image when the aperture is reduced to a narrow slit, as shown in Figure 2.10. [15]

When recording a rainbow hologram, we illuminate the ready made hologram called master or primary hologram H_1 with the same laser light as its recording. Insert another holographic plate H_2 between H_1 and its real image. To obtain a better rainbow hologram image, it is recommended that H_2 be located near the hologram image plane. A slit now is placed between H_1

and H_2 very close to h_1 and introducing another reference beam evenly spread over H_2, then, a rainbow hologram will be recorded.

In order to see the effect of a narrow aperture or slit, we first reconstruct the hologram image from the rainbow hologram H_2 by a conjugate divergent coherent source, as shown in Figure 2.11. Because the narrow slit used for the rainbow holographic construction acts as a slit object, a real slit image will be reconstructed down-stream from the rainbow hologram H_2. Looking through the slit image, we would expect to see a virtual hologram image behind the holographic plate H_2. If the holographic plate H_2 is inserted behind the real image reconstructed from H_1 during H_2 construction, a real image can be viewed through the slit image by using the reconstruction process.

In view of the holographic magnification which will be introduced in chapter 5, we see that the location of the real slit image as a function of wavelength reconstruction, the slit image appears to be located higher and closer to H_2 and the width of the slit image is also wider with increasing wavelength. The same effect applies to the hologram image seen through the slit image, that is for a longer wavelength illumination, the holographic image appears to be larger and closer to the holographic plate H_2.

Now, if H_2 is illuminated by a conjugate divergent white light source, as shown in Figure 2.11, the hologram slit images, resulting from the different wavelengths of the white light source, will disperse into rainbow colours in the real slit image space. The holographic image of the object will take on the same rainbow effect behind the hologram. If we transversely view this image through the smeared slit image, the hologram image is observed in a series of rainbow colours one at a time. In other words, if the image is viewed through the red coloured smeared slit image, we will see a red coloured holographic image, If we observe a smaller green holographic image then we must have viewed through a green coloured smeared slit image.

While viewing the rainbow hologram, if an observer moves his or her head transversely up and down against the smeared slit image, the "over" or the

"under" of the hologram object image will not be observed. Vertical parallax is lost with this type of hologram. However the full horizontal parallax is retained, providing a right to left perspective view for binocular stereopsis and motion parallax. Therefore, the sensation of a three dimensional scene is preserved.

2. 6 BINOCULAR PARALLAX

The depth perception is obtained due to each eye having the simultaneous impression of two dissimilar images of the same object. This depth perception is called binocular parallax. [15]

An observer looks at the point M as shown in Figure 2.13. Let the centres of the crystalline lenses be o_1 and o_2. We draw straight lines m_1 a md m_2 on the retinas. Now we define that two points p_1, p_2 on the retinas as shown in Figure 2.13 are at corresponding positions when

$$\angle p_1 o_1 m_1 = \angle p_2 o_2 m_2 \qquad \text{------(2.17)}$$

If the light comes from point P and forms its image at points p_1 and p_2, the binocular parallax disappears for the point P for which it forms equidistant or equiangular images on each retina.

However, a point Q as shown in Figure 2.13 will never focus at corresponding positions. Thus binocular parallax is perceived and the difference in distance is recognized.

Consider the discrepancy η from the standard convergence angle. It is given as:

$$\eta = \theta_1 - \theta_2 = \alpha - \beta \qquad \text{------(2.18)}$$

Let the distances to points M and Q be denoted by a_M and a_Q, respectively, and define

$$a_Q - a_M = \delta \qquad \text{------(2.19)}$$

Then we obtain, assuming $\delta \ll a_M$ and L equals the length of arc between two eyes,

$$\eta = \alpha - \beta = L/a_M - L/a_Q \cong L\delta/a_M^2 \qquad \text{------(2.20)}$$

For a pair of healthy eyes, the threshold of η for perceiving binocular parallax is 10". The minimum detectable difference in the viewing distance, therefore, is

$\delta_{min} = 0.8$ mm for $a_M = 1$ m

$\delta_{min} = 8$ cm for $a_M = 10$ m

$\delta_{min} = 8$ m for $a_M = 100$ m

For medium viewing distance, binocular parallax information is the most important clue for depth perception.

Suppose we observe an object while shielding one eye. If the viewing position is held fixed, accommodation will be the only effective clue for depth perception. However, if displacement of the viewing position is permitted, we can make use of an effect arising due to various directions. This effect is called movement parallax[13]. The movement parallax is extremely important for viewing multiplex hologram when the viewer moves his/her head from the left side of the hologram to the right side.

2. 7 PRINCIPLE OF MULTIPLEX HOLOGRAM

The Multiplex hologram is the result of a hybrid form of holography, which combines many techniques such as cinematography, split beam holography, rainbow holography (or transfer holography). Even when displaying with white illuminating source, it also borrows from the techniques of binocular parallax and movement parallax.

making a multiplex hologram, which will be introduced in details in chapter(3, 4, and 9), is a three-step process. In general, the first step consists of making a series of photographs of a subject. The resulting photographs record the camera motion or subject motion from a three-dimensional horizontal viewpoint.

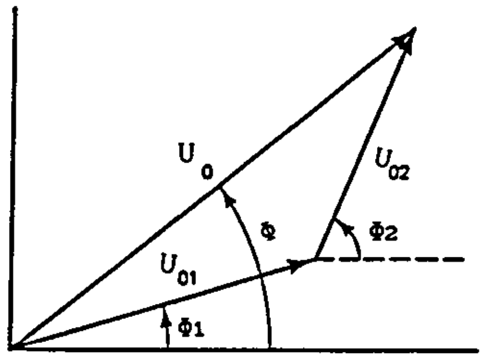
The second step of the process is the holographical recording of the photographs one by one. The beam of the coherent light source is split into two beams. One illuminates the photograph and project the image onto an image screen. The other (reference beam) is collimated to illuminate the holographic plate H_1 uniformly. A small aperture slit is introduced between the image screen and holographic plate. The distance between the slit and the plate is often less than 1 mm. Both object and reference light overlap each other and are recorded by a strip hologram. For the next image, the slit is moved to its adjacent position of the strip hologram.

The third step, like making a rainbow hologram, is transferring the hologram H_1 made in the second step onto a holographic plate H_2. H_2 is located at the exact place of image screen. The ready made hologram H_1 is located at its original place.The conjugate reference light illuminates H_1 and the real images are projected onto H_2. Another coherent light beam illuminates H_2 as a reference light and the real images are recorded holographically on the final or display holographic plate H_2. Each individual strip hologram brings its own information on H_2. A composed and image overlapped multiplex hologram is obtained.

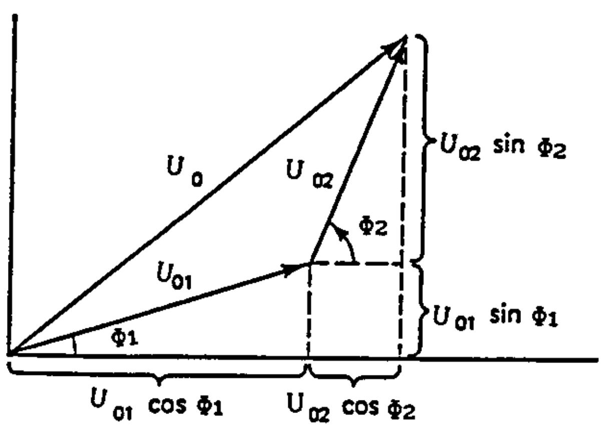
For a reconstruction multiplex hologram which is illuminated by a collimated white light, the slit images are not flat as introduced in some articles. More details will be given in chapter 8. For simplification we call them slit plane well arranged slits images rather than a single slit image for rainbow holograms. (see Figure 2. 14). A viewer can obtain a three dimensional image while each eye looks through appropriate slit images (caused by binocular parallax). While he moves from left to right he perceives the panorama of photographic recording. Because the narrow slit used for the multiplex holographic construction acts as a slit plane object, the image information is transferred onto H_2. When we reconstruct the hologram image from the multiplex hologram H_2 by a conjugate coherent collimated source, a real slit plane image will be reconstructed in front of H_2. Looking through a different slit image, the viewer perceives monochromatic virtual or real images.

If H_2 is illuminated by a conjugate white light source the hologram slit planes, resulting from the different wavelengths of the white light source, will disperse in the real slit image space. The real slit image plane is also a function of wavelength reconstruction. If the hologram images are viewed horizontally, a three-dimensional synthetic image can be obtained. If the viewer transversely observes the holographic image, the vertical parallax is totally lost. The colour of the hologram image depends on what colour slit plane the viewer looks through.

The colour of the hologram image, the spatial location and the magnification of multiplex hologram will be discussed in detail in chapter 5, 7 and 8.



(a)



(b)

Figure 2. 1

phase diagrams for two harmonic waves (a) Adding two harmonic waves. (b) Phase components.

WAVES AND IMAGES

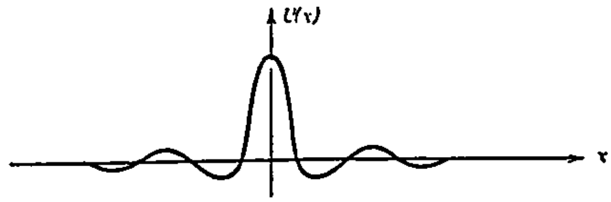


Figure 2. 2

Recording the wavefront as an actual wavefront

WAVES AND IMAGES

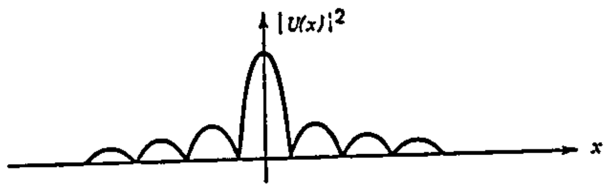


Figure 2. 3

Following the square-law detected wavefront $|U(x)|^2$

WAVES AND IMAGES

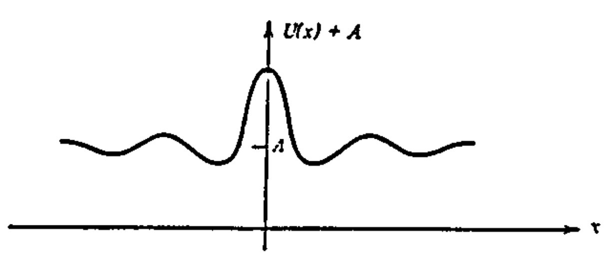


Figure 2. 4

U(x) plus a strong coherent reference wave A

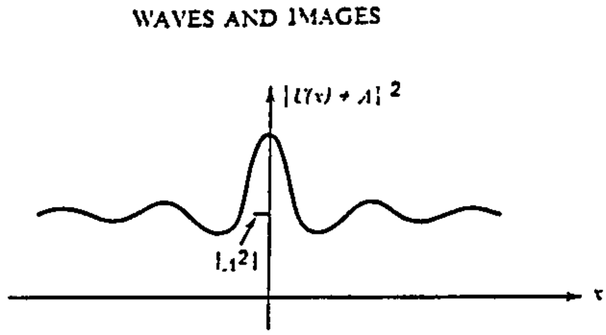


Figure 2. 5

The square-law detected wavefront, $|U(x) + A|^2$

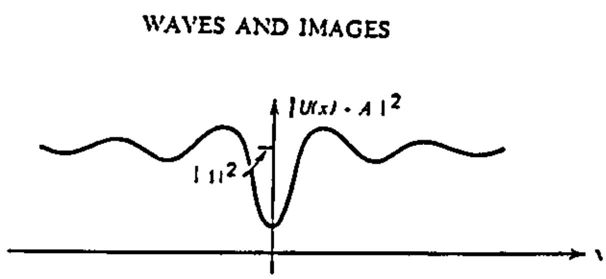


Figure 2. 6

The spare-law detected wavefront, $|U(x) - A|^2$

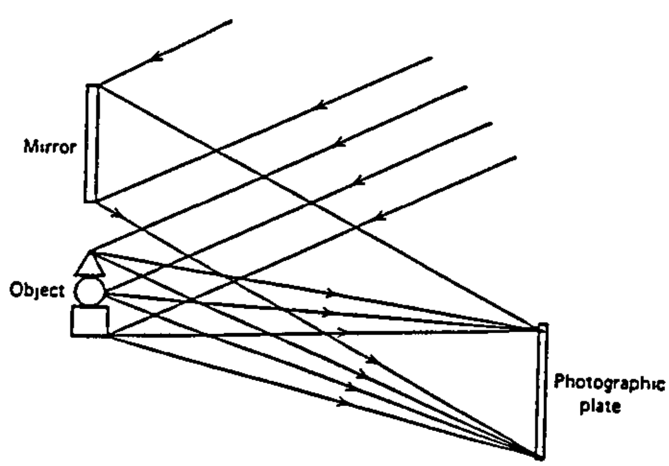


Figure 2. 7

A typical hologram formation setup of the split-beam method

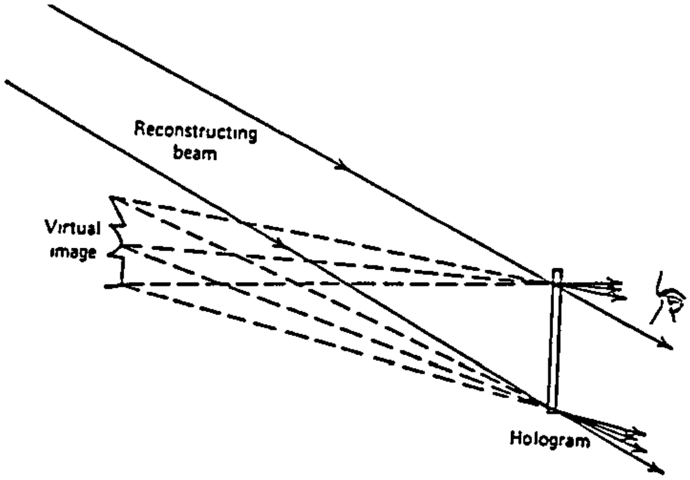


Figure 2. 8

Reconstruction of the object wavefront using the hologram shown in Figure 2.7

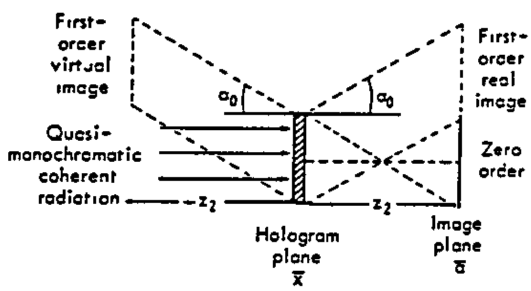


Figure 2. 9

First order images reconstructed from a hologram

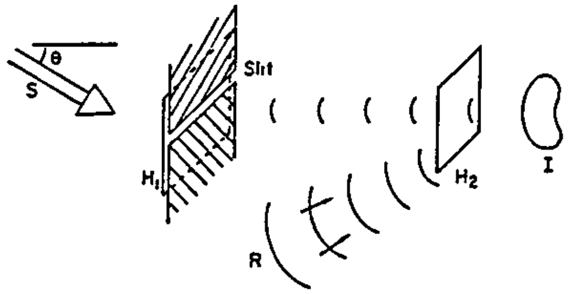


Figure 2. 10

Rainbow holographic recording. S, conjugate coherent illumination; H_1, primary hologram; R, convergent reference beam; H_2, holographic plate; I real hologram image

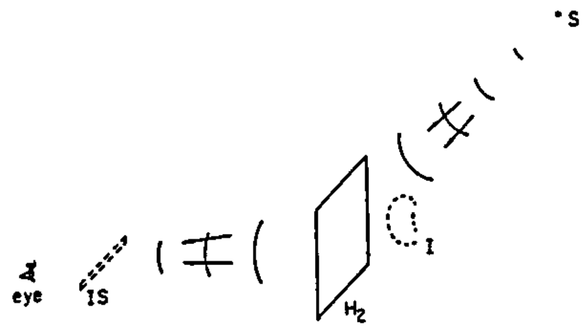


Figure 2. 11

Hologram image reconstruction by a coherent source. IS, slit image; H_2, rainbow hologram; I, hologram image; S, monochromatic point source

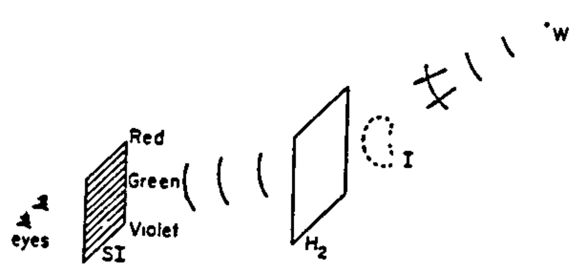


Figure 2. 12

Rainbow hologram reconstruction with white-light source. SI, smeared slit image; H_2, rainbow hologram; I, hologram image; W, divergent white-light source

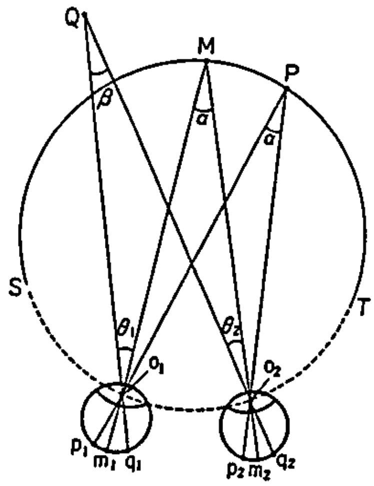


Figure 2. 13 Binocular parallax

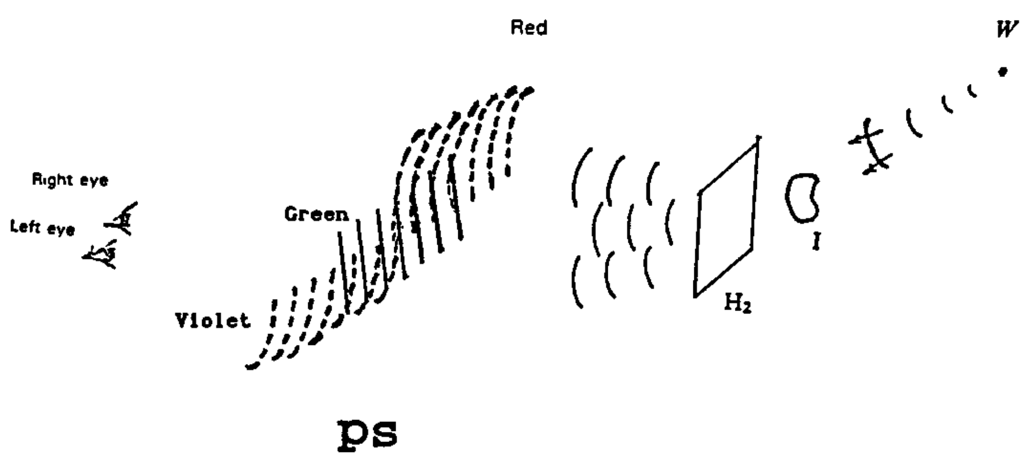


Figure 2. 14

Multiplex hologram reconstruction with white-light source. PS, slit plane images; H_2 multiplex hologram; I, hologram image; W, divergent white-light source

CHAPTER III

MULTIPLEX HOLOGRAPHY

Nearly all multiplex holograms have to be prepared in two steps. First, a sequence of photographs is taken with the object illuminated in natural light. Secondly, one should record the photograph images holographically by projecting the photograph with coherent light. Multiplex holography is gradually developed from full aperture (fly's eye lens) horizontal parallax only to alcove, cylindrical and planar white light transmission multiplex hologram and recently developed computer generated multiplex holograms. The images have also been improved. Twenty five years ago, this kind of hologram offered dim, speckled, jump images that were hard to see, while today the viewer can enjoy bright and clear images that are beginning to look as solid and realistic as those from true holograms.

3. 1 MULTIPLEX HOLOGRAPHY

The human visual system naturally perceives a scene as being three dimensional if the multiplex hologram or multiple two dimensional images such as stereoscope are appropriately presented. [17] Multiplex holography is a technique for synthesizing a composite hologram from a sequence of incoherently recorded two dimensional photographs. [18]

A multiplex hologram is composed of many successively arranged narrow strip holograms. The images on the strip holograms come from a series of photographs which were taken using a conventional camera. The camera records these photographs at equal distance each along a rail from left to right in front of a white light illuminated subject. Each of the photograph images is recorded holographically on a corresponding strip hologram. So the images of two adjacent strip holograms a have little difference and it changes one by one gradually over the whole plate. When it is reconstructed, a viewer whose left eye watches at the first strip, for example, and right eye watches at the sixth strip hologram, gets slightly different images usually called stereo pair; the impression of depth comes from the brain's interpretation of these differences.[19] The interpretation of those differences results in the depth perception of stereoscopic perception. When a viewer moves from left to right, he may obtain a stereo panorama view coinciding with the perspective view of the camera. So that is why the multiplex hologram can produce a stereographic view from two dimensional images.

One of the obvious distinctions of a multiplex hologram from other kinds of holograms is the elimination of vertical parallax. Since the hologram is redundant in its information storage, it becomes possible to prepare holograms which satisfy the large angle requirement only in the horizontal direction, hence preserving parallax and the three dimensional panoramic view in that direction only. [20] Following this concept, the multiplex hologram has only horizontal parallax but no vertical parallax. However, this is not too great a disadvantage when the viewer normally moves his head from side to side and not up and down. [21]

3. 2 FULL PARALLAX MULTIPLEX HOLOGRAM

In 1908, G. Lippmann [22] proposed the use of an array of small spherical lenses or a "fly eye's lens to first gather a range of perspective views onto a single photo-emulsion, and then retro-project them to synthesize a three dimensional image in the space of the original object. [23] Borrowing this idea, R. V. Pole (1967) described his method of obtaining a hologram of three dimensional objects illuminated in white light. First an object is photographed through a fly's eye lens. If this photograph is projected through the same lens it yields a real 3-D image of the object directly. If coherent light is used for the projection, this image can be used as an object of a hologram. In fact, this hologram is a stereogram consisting of n individual images ($n >> 2$).

This kind of hologram has full parallax and shows the full three dimensional image in the same way as an ordinary hologram. However, the small sized lenses (fly's eye lens) and the large inactive area between lenses make the image appear fuzzy as if the object were viewed through the rather small sized lenses or apertures. Conflicting demands on the size of the lenses and the optical design limitations of a single refracting surface limit the quality of the three dimensional image.

Similarly another method for making a full parallax hologram was developed by J. T. McCrickerd and N. George [24] in 1968. It needs two steps. In the first step, a sequence of ordinary photographs is taken and the object is also illuminated in white light. Each photograph is taken from a different segment of a reference plane. (This kind of photograph seems to be a big photograph film used in an old style photographic studio. A photograph occupies only a part of the whole film). The whole photograph provides a panorama view of stereoscopic record. In the second step a Fourier transform hologram of each photograph is recorded on the corresponding segment of a hologram plate which is placed in the reference plane. Compared with fly's eye, this method can make the component photographs much larger and illuminate the effect caused by dead space between adjacent lenses as mentioned above.

These kind of multiplex holograms need a coherent light source for reconstruction and the images are not clear and bright. However, these methods opened the door of holographic laboratories and brought white light illuminated objects into holography.

3. 3 HORIZONTAL PARALLAX ONLY MULTIPLEX HOLOGRAM

The large number of sequential photographs needed for full parallax holographic stereograms and the complexity of their printing has limited its wider use. The informational economies of restricting the parallax to horizontal parallax only were first recognized in holography in 1968 and its practical economies were soon explored in holographic stereography. Since viewers generally move across a horizontal surface to enjoy motion parallax and the eyes are separated horizontally to capture slightly differing perspectives, very little of the viewing experience is lost by completely eliminating the vertical parallax.

In 1968 D. J. Debitetto, [21] , described a technique by using a conventional strip hologram which reduces the bandwidth required for holographic data transmission by eliminating vertical parallax. Since the hologram is redundant in its information storage, it becomes possible to prepare holograms which satisfy the large angle requirement only in the horizontal direction, hence preserving parallax and the three dimensional panoramic view in that direction only.

The first application of this technique was done by D. J. Debitetto [25] himself. He placed holographic film directly behind in close contact with a stationary horizontal slit. The objects used were 2 three inch high figures on a small rotatable table. Each strip of holographic film recorded one position of the figures with coherent light. While reconstructing, it was like a holographic motion picture.

He also applied this technique in 1969 [18]. In his experiment, a series of *n* ordinary two dimensional photographs of a three dimensional subject were taken sequentially from a series of equally spaced positions along a horizontal line. These photographs are then sequentially projected onto a translucent screen at the image plane by using collimated coherent light. A holographic plate is exposed through a horizontally movable vertical slit directly in front of the plate and a diverging coherent reference light is also provided.

Debitetto's technique introduced a slit in his optical geometry and eliminated the vertical parallax. The elimination of vertical parallax does not impair the vivid impression of image depth and solidity. Especially the second method of photography and holography being carried out separately provided possibilities for obtaining an alcove or cylindrical multiplex hologram and a planar multiplex hologram with a larger viewing angle (bigger than full aperture multiplex hologram). Conventional transmission hologram requires coherent light sources for their reconstruction.

3. 4 WHITE LIGHT TRANSMISSION MULTIPLEX HOLOGRAM

For exhibiting many holograms, it is not economical to use a laser, however, it is natural and easy to use a white light source. Laser illumination needs at least a powerful laser and other complex equipment. A white light source is very easy to obtain, install and adjust. A diverging white light source, a spot light with vertical filament, is often used for displaying white light transmission holograms. The holograms introduced above can be only displayed by using a coherent light source. So some methods for making white light transmission multiplex holograms were explored by holographers and the pioneer was Dr. Stephen A. Benton. [26-27]

There are three steps for making white light transmission multiplex holograms. The first two steps are the same as for the second application of Debitetto's technique. The only difference in Benton's geometry is that collimated reference light is used to substitute the diverging light source. The third step is to transfer the composite image from the master hologram to a holographic plate which is placed in the image plane. During transferring, the composite image is projected by the conjugate reference light. [28]

Compared to other types of multiplex holograms. this technique has four advantages. First, a white light source is needed for reconstruction. Secondly, the image is clear, continuous and realistic. Thirdly, the technique is simple. Finally, the image has less distortion. So this thesis investigates developments of the multiplex system based only on this model. The detailed layout for Benton's geometry will be introduced in chapter 4 and chapter 8.

3. 5 ACHROMATIC MULTIPLEX HOLOGRAM

Achromatic [29], or black and white, stereogram images are desirable because of the increased reality and sense of solidity they offer. When shooting a master hologram, compared with the method introduced in the previous section, the holographic plate is tipped at the "achromatic angle" α with the diffuser screen. The illumination of the composite master hologram with the conjugate of the reference beam produces a synthetic horizontal parallax only with the real image focused in the plane of the diffuser screen, where a second holographic plate is exposed with a collimated reference beam, vertically inclined at the angle of θ_R corresponding to the angle α. The relationships between θ_R and α is

$$\tan \alpha = \sin \theta_R$$

While reconstructing with a white light source, all the wavelengths simultaneously produce co-linear real images of each slit and if they are long enough, an eye at any one position sees a single perspective view in so wide a range of colours as to render it achromatic.

3. 6 OTHER TYPES OF MULTIPLEX HOLOGRAMS

The multiexposure multiplex hologram was first developed by Sopori [30] in 1971. A multiple exposure hologram consisting of superpositions of holograms of successive individual views is made from a sequence of photographs. The horizontal parallax is obtained by means of changing the angle of the signal light. This method gives the exact registration of the views. The relative displacements of various parts of the object are reproduced in reconstruction.

An alcove hologram [31-32] needs a sequence of photographs which are taken from a constant distance centred at the object by either rotating the camera around the object or rotating the object around itself with the camera fixed. Each frame is imaged in the vertical plane on the hologram film. However, in the horizontal plane, a cylindrical lens brings all the signal light leaving the projector to a line focus a contiguous series of vertical strip holograms is then recorded of successive movie frames, covering the full range of views of the original subject, with a reference beam incident from below. After processing, the film is wrapped around a plexiglass half cylinder for viewing. When it is illuminated by a point white light source, several viewers can move and enjoy a three dimensional image within the space of the alcove. Instead of photographs, computer-graphic 2-D images rendered through idealized anamorphic optical systems permit penetration of the hologram plane without 3-D distortions. [33-34]

Making a cylindrical multiplex hologram [35] involves the same procedures as alcove's but more photographs and strip holograms. When the film is wrapped around a transparent cylinder and illuminated with white light, the observers move around the cylinder and obtain a progression of perspective views and an impression of a three dimensional image floating in the centre of the cylinder. The best known of the images is Cross and Brazier's "Kiss II" in which Ms. Brazier winks and blows a kiss as the viewer moves by.

Because both alcove and cylindrical multiplex holograms' images seen from any one point are actually a composite of many nearby perspective views, the spatial image becomes seriously distorted away from the hologram centre. [36] When observers move close to or away from the hologram, the form of the observed image is expanded or contracted in the vertical direction, and distorted in the shape of a trapezoid, because part of the image is observed in different colours. [37]

The development of Multiplex holography over the past twenty-five years has responded to the obvious challenges of photographic imaging, biomedical imaging and computer generated imaging. At the beginning of the research, multiplex hologram offered dim, speckled, jumpy images that were hard to see. While today we are enjoying bright and clear images that are beginning to look as solid and realistic as those from true holograms. Many types of multiplex holograms [38] have been widely applied in many areas, such as computer generated, electronic microscope, X-ray images [39] and body scans [40]. A solid technique base has been built for this work. However, there are many new questions ready to be explored, and new gaps in the technique for making multiplex hologram to be filled. In this thesis, a technique for overcoming shadowing and diffraction effects are investigated and a theory developed for the shape of the slit plane has been carried out.

CHAPTER IV

GEOMETRY OF A WHITE LIGHT TRANSMISSION MULTIPLEX HOLOGRAM

In this chapter a geometry for producing multiplex holograms is introduced. This technique was pioneered by Dr. Stephen Benton at Polaroid Corporation, Massachusetts, U. S. A.

A three dimensional object, illuminated in white or natural light as shown in fig (4. 1), is photographed through a pin registering camera or cine-camera for the accuracy of recording the master hologram H_1^*. A series (100-150) according to the necessity of the size of H_1, angular size of the image and the viewing over distances which are going to be introduced in chapter 7) of photographs is generated by moving the camera passing the object from left to right along a rail. Since the final hologram H_2^{**} is flat not curved or located on a circle, the first step of taking photographs must be located in a plane. If not, the final hologram would show funny or non-coincident images. So the camera should keep its orientation fixed and take each photograph for the same distance. The photographs should be taken in an accurately planned way. Careful attention must be paid to all parameters from the lighting and lens used when filming the object to the playback configuration and light source. [41]

The photographs of perspective views are then projected onto a diffusing screen with a laser light fig (4. 2). The first pin registering frame taken from the far left end for example, its image projected onto the screen (two dimensional image) is recorded on the first strip of holographic plate which is masked by a slit. This plate is located on the other side of the diffusing screen. For holographic recording, a collimated beam from the same laser is introduced as a reference light falling onto the same strip of the holographic plate. After the first exposure, the film is advanced one frame, the slit moves the same distance as its width and then this adjacent holographic strip is exposed. In this way the "project plate" H_1 is sequentially built up from successive perspective views.

Now, the master multiplex hologram can be reconstructed only under the same wavelength of laser light as the recording one. If a white-light viewing multiplex hologram is wanted, however, a procedure of transferring the images from master hologram H_1 to the transfer hologram H_2 must be carried out. The term "transfer hologram" is taken to mean a hologram that is made by using the real image from another hologram as the object, with the plates separated. Holograms made with the two plates close together or in contact are referred to as "copies".

The H_1 is located at its original place after processing and is illuminated with a collimated conjugate beam of the recording reference light and forms real images exactly on the plane of a diffuser screen. It is important to use the collimated laser as the recording reference source because it can form the real image easily and accurately. Those images are coming from the strip holograms, with each strip bringing its own information to the plane. The whole information forms the panorama view which was recorded by the camera. Instead of the diffuser screen, another holographic plate is located in that plane, usually being called transfer hologram H_2. Diverging or collimated reference light coming from the same laser is introduced to H_2 for transfer recording. No matter whether diverging or collimated reference light is used, the angle and the distance (from the light source to the centre of H_2) should be identical to the illuminating light for displaying. The relationships between the displaying light and reference light for transferring are quite complicated and will be discussed in chapter 7. After processing H_2, a full aperture transmission transfer hologram is obtained which can easily be reconstructed, in almost any light, but especially well if a vertical filament lamp is used. [42]

Why can a person get stereo views from the multiplex hologram? This is due to the human eyes being separated and viewing objects from slightly different azimuths or viewing angles. This results in a horizontal displacement of the far and near images in relation to each other, between the left and right eye. The disparity of images formed on the retinas is obvious. The image formed on the left retina is the just reversal of that formed on the right retina. These messages are sent to the brain and the brain performs a congruent area processing operation on the terminal disparity differences of near and far points. Those differences result in and give the impression of the depth perception or stereoscopic perception. [43]

While the transfer hologram H_2 is illuminated with a white light source from the back of H_2, the viewer gets a stereo image by looking with each eye through different slit(s), which are forming in space in front of H_2. The whole perspective view may be seen when moving from left to right. It can be easily imagined that if the illuminating light for displaying is coming from the back of H_2, it will occupy a very big space. In other words, if the light source is coming from the front of H_2, the displaying place can be saved and it brings more convenience.

From the introduction given above, the slit is a key element of the apparatus for making a multiplex hologram. The quality of the slit is especially important in obtaining good results for this kind of hologram. In this study, a way of improving slits is investigated and discussed and several methods of displaying the hologram and variations of slit planes under different illuminating light sources are also discussed.

* H_1 is usually called a master hologram and sometime also a called holographic plate.

** H_2 has four names: transfer hologram, final hologram, displaying plate and displaying hologram depending on its uses.

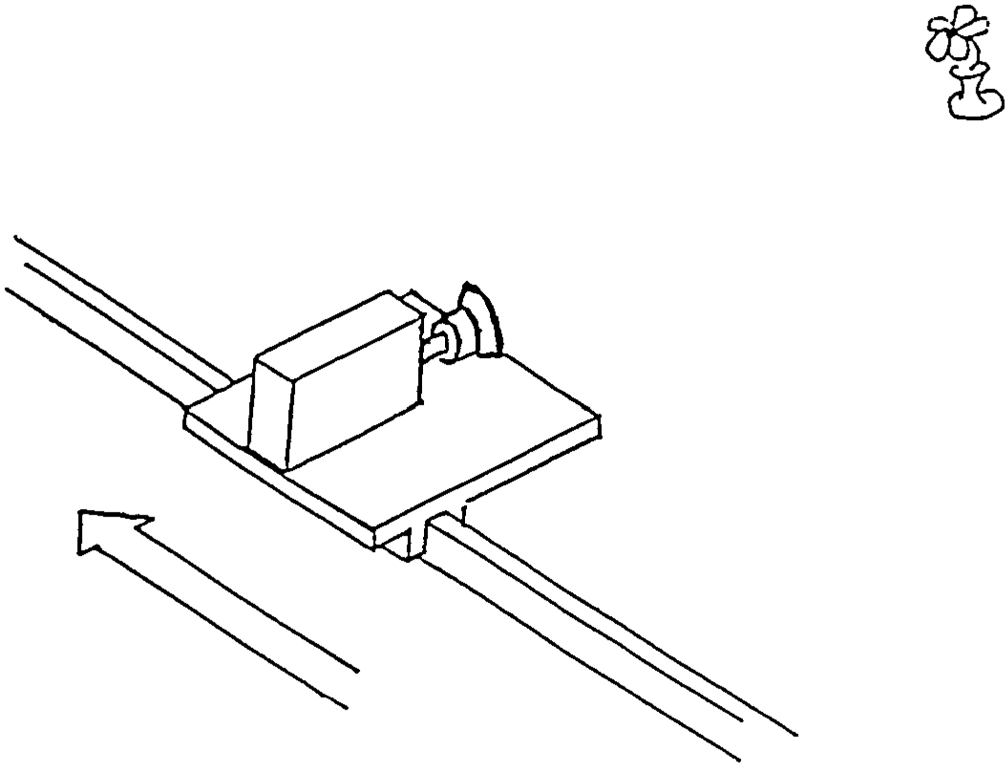


Figure 4. 1

The camera is taking photographs along a rail and the subject is illuminated with white light

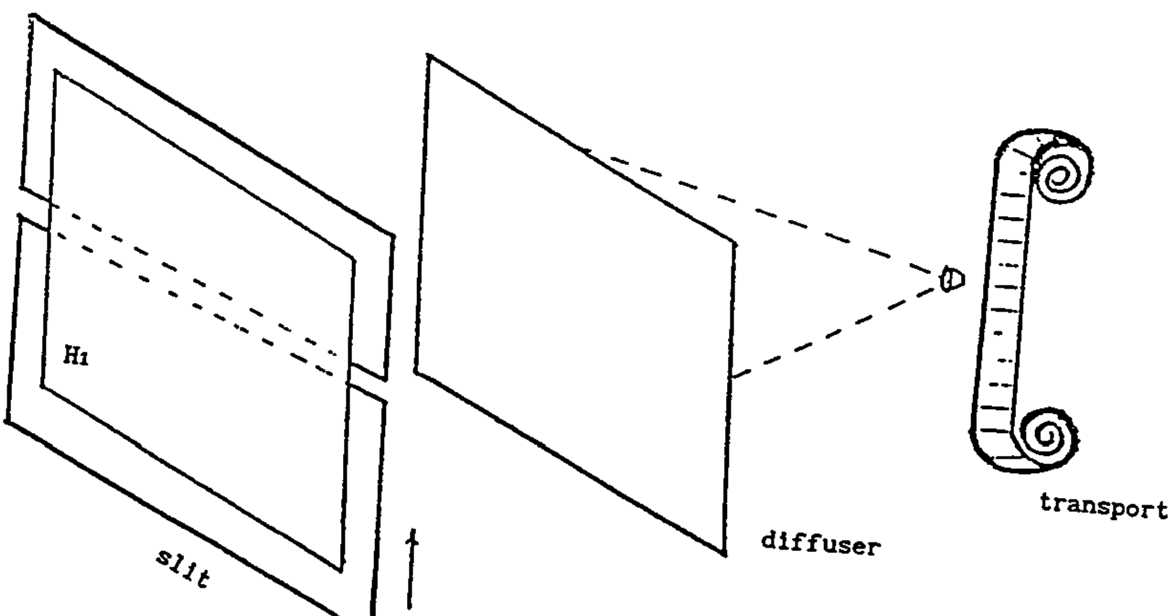


Figure 4. 2

The photograph is projected onto the diffuser screen and the image is recorded by a strip holographic plate

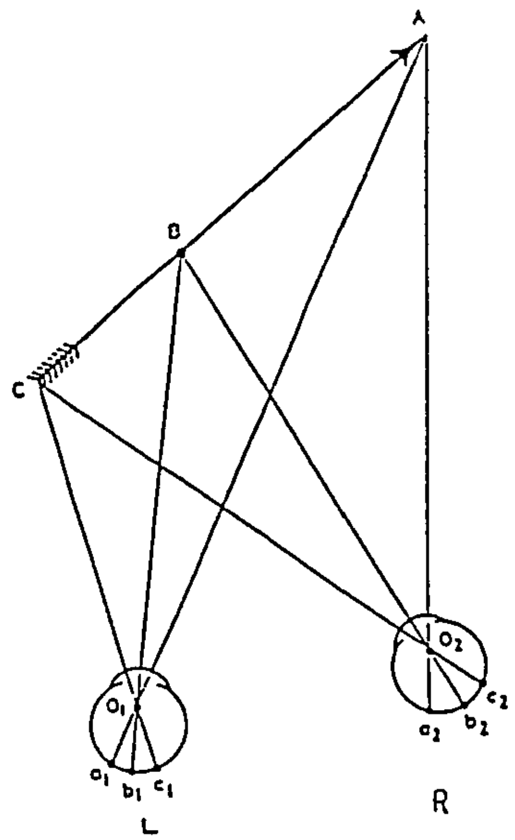


Figure 4. 3

The opposite images formed on the retinas and eye-brain uses a number of clues to perceive stereo view.

CHAPTER V

MAGNIFICATION AND DISTORTION OF MULTIPLEX HOLOGRAM

Before introducing magnification and distortion, some basic concepts relating to them should be described.

5. 1 VIEWING DISTANCE

The viewing distance for seeing a hologram is the same as for seeing a photograph. When watching a bigger hologram, the viewer would stand a little bit further away from the plate in order to get the panoramic view. If a viewer hopes to see a small hologram in detail, he has to move closer to the plate. Thus, the size of the displaying plate is fixed and then the general range of viewing distance is fixed, too. The viewing distance is defined as the normal distance for viewing a certain sized hologram. Different sizes of hologram need different viewing distances. In the table below, a list of commonly used sizes of hologram and the appropriate viewing distances are given:

plate size (cm^2)	viewing distance (cm)
2.5 * 2.5	15 --- 30
5 * 7.6	20 --- 35
7.6 * 10	25 --- 45
10 * 15	30 --- 50
15 * 20	40 --- 60
20 * 25	50 --- 75
30 * 40	65 --- 95

This table only gives some general relationship between the size and distance for normal eyes. It may vary depending on the visual ability. If the size of the hologram plate is chosen, 20*25 cm^2 for example, the viewing distance can be determined, according to the table, as between 50 to 75 cm. The viewing distance is an important parameter for displaying a hologram. While calculating the magnification of the image, this parameter is also used.

5. 2 SLIT PLANE

In the geometry of a multiplex system, the diffuser screen is used for recording the master hologram. While transferring, H_2 takes the place of the diffuser screen. H_2 records all the information from H_1 including a series of well arranged slits. If the illuminating light is the same as the reference light for transferring (no matter whether a point source or a collimated source is used) and coming from the same angle (45° for example) and distance, the series of slits will be formed on the plane where H_1 was.

From the geometry of a multiplex hologram, the distance from the slit plane to H_2 is the same as the distance from H_1 to H_2 and also the same as the distance from H_1 to the diffuser screen*. The plane of the diffuser screen is called input plane. From the introduction given above it is assumed that the distance between the slit plane and the input plane is a key parameter for recording H_1, transferring H_2 and displaying. Many discussions about the slit plane and its property will be introduced later.

(*In a conventional multiplex system, the distances described above are the same, but for viewing an out of plane or behind plane image, the distance between H_1 and H_2 may be variable.)

5. 3 IMAGE PLANE

An obvious difference between the hologram and a photograph is that the former can give viewer a stereo perspective. Usually the image of the hologram offers an impression of the image either out of or behind the holographic plate, or some parts out and some parts behind (often called cross) the hologram plate. For a hologram one cannot simply say that the hologram plate is the image plane as in the case of a photograph.

Since the multiplex hologram offers an image with certain depth, the image can not be formed on a single plane. So the image plane is defined as a plane on which an image of a certain point of the whole object is expected due to the synthesized parallax.

5. 4 MAGNIFICATION AND DISTORTION

A multiplex hologram has horizontal parallax only and it is composed of more than one hundred strip holograms. When it is reconstructed, the hologram may exhibit an anamorphic imagery. Because of the elimination of the vertical parallax from the multiplex hologram, the vertical magnification is unity. In the horizontal direction, however, there is the lateral magnification related to the parameters in the above three subsections.

The magnification and distortion discussed here are under the conditions: 1. the geometrical optics is the same as that described in section 3. 1; 2. other sources of magnification have been removed; 3. a correct viewing point is taken; 4. the wavelength and radius of curvature of the reconstructing beam are identical with those of the reference beam for transferring.

If a, b, c, are the distances from the viewing plane to the input plane, to the image plane and to the slit plane respectively as shown in fig. (5. 1). An equation of the horizontal magnification can be obtained as: [44]

$$M_h = \frac{a (b - c)}{b (a - c)} \qquad \text{----- (5. 1)}$$

From the equation two important things are revealed: one is if C=0 then there is no magnification or the lateral magnification is unity. That means the viewer is watching the hologram at the slit plane and he can not see any magnification or distortion in the horizontal direction (as to multiplex hologram, the distortion is the reciprocal of the lateral magnification). So that if the distance between the input plane and the slit plane (a - c) is appropriately arranged, the magnification or distortion can be minimized.

Another case is that if $M_h > 1$ then for normal conditions, b is bigger than a. That means the image of the multiplex hologram can be formed behind the input plane which shows a deeper depth perspective view to the viewer. If the parameters a, b and c are arranged properly, an out of or behind the input plane image can be obtained and the lateral magnification can be well controlled.

Though there are some other cases which can adjust the magnification such as a=b and $b \rightarrow \infty$ and so on, they are not useful for making multiplex holograms. Some other parameters about the displaying and transferring, which also result in the magnifications, will be discussed and some concepts introduced above are mentioned and used mainly in chapter 7.

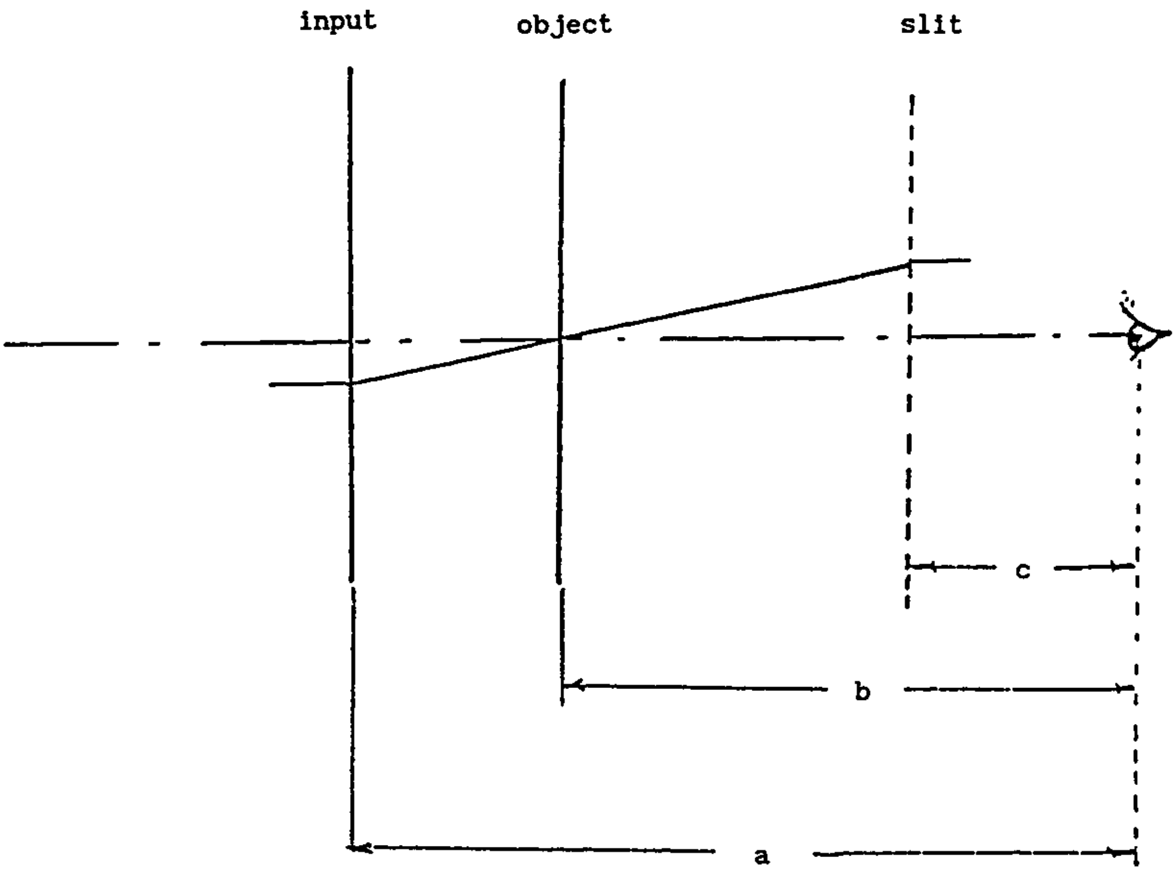


Figure 5. 1

a, b, c, represent the distances from viewer to the input plane, to the object plane and the slit plane, respectively

CHAPTER VI

SLIT IN MULTIPLEX HOLOGRAPHIC GEOMETRY

6. 1 INTRODUCTION

An obvious difference between a common hologram and a multiplex hologram is that the multiplex hologram is synthesized by many strip holograms usually comprising more than one hundred. As discussed in chapter 2 and 4, each of the strip holograms records a two dimensional image viewed from certain view point with respect to the object. A slit used as a mask moves along the holographic plate and lets the incident and reference light come through whilst preventing unnecessary light falling onto the plate. The quality of the multiplex hologram depends not only on the laser, bench, optical geometry, beam ratio etc, but also on the quality of the slit.

The shape of the slit is usually a long narrow rectangular (in this study its dimensions are 2 * 300 mm^2), the middle of which is blank to allow the incident and reference light to come through and to shoot the strip hologram. Outside the slit all other parts are blocked preventing any light from falling onto the plate. The slit is located close to the master hologram H_1(about 1 mm).

An ideal slit permits all the useful light to come through and gets rid of unnecessary light. The dimensions of the strip hologram are exactly the same as that of the slit. In conventional multiplex system, the minimum distance between the slit and holographic plate is 1 mm. It is a big gap compared to the 2 mm width of the slit. The object light from the diffuser screen comes through the slit with a large angle. This light falls not only on the strip hologram, but also on some area behind the slit and this part of light is unnecessary. The area, which unnecessary light reaches, is called the shadowing area. This area decreases the information for transferring and impairs the effect of displaying. This phenomenon is usually called the shadowing effect which is one of the major problems with which this study deals.

Within the conventional multiplex hologram system, it is very difficult to minimize the shadowing effect because the steel-made slit may scratch the emulsion surface of the holographic plate if the distance between the slit and the plate is less than 1 mm. In this study, a different style slit, a glass-slit, is investigated and its advantages compared to the steel slit is also discussed.

6. 2 <u>CONSIDERATION FOR IMPROVING THE CONVENTIONAL SLIT GEOMETRY</u>

For the conventional geometry, the slit used for exposing the master hologram is made from two ground steel knife edges from which the minimum distance to the hologram plate is about 1 mm, please see fig (6. 1). As shown in fig (6. 2), if a smaller shadowing area is wanted, the distance between the diffuser and holographic plate should be relatively longer or the size of the image has to be reduced. This is the least a holographer wants. The other factor has been considered for minimizing the shadowing effect - reducing the distance between the slit and holographic plate.

Consider an ideal model for a slit. The slit is able to contact or nearly contact the holographic plate, for overcoming the shadowing effect, and move up and down freely without scratching the emulsion surface. The distance between the diffuser screen and the holographic plate can be chosen according to the necessity of recording. The size of the image on the diffuser screen is no longer limited by the shadowing effect and the diffraction effect is minimized. In practice, the conditions above are very difficult to achieve.

For the conventional geometry, it is very difficult to get the slit as close as possible to the holographic plate due to the accuracy of machining. If the slit of steel knife edges contacts the holographic plate or if it is as close as 0.2 mm, it is very difficult to control the slit moving up or down along the holographic plate without scratching the surface of the emulsion film. While mounting the holographic plate, it is so easy to bend or tilt the plate a little bit that scratching may be inevitable.

Considering the geometry introduced in chapter 4, if there is a little overlapping when recording the master hologram that means the moving distance of the slit after each shooting is smaller than the width of the slit. This may cause some other difficulties. The overlapping part which was shot twice is overexposed. This can result in a rapid reduction of diffraction efficiency in this part. While transferring this part it can not contribute much information to the whole image. In additional, the transfer hologram also records the slits and the overlapping parts from H_1. When reconstructing the transfer hologram, the slits and the overlapping parts will form a plane or planes in front of the hologram. The slit(s) are like windows through which the viewer can see the images. The overlapping parts, however, are like barriers preventing the viewer from looking through and giving the viewer an uncomfortable view. Furthermore, whilst recording the master hologram, if the slit moves from the bottom to the top of the holographic plate, the incident light from a point of the diffuser screen (on the top or at the bottom for example) the incident angle, which causes the variation of the width of shadowing area, changes during the recording procedure and the width of the overlapping region is different for each strip holograms.

It is very difficult to change the shape of the metal slit. It is hard to imagine that the metal slit can be made as a gradually darkened slit (e.g. laterally changing from the middle part to the edges from transparent to grey and from grey to dark). Such a slit is usually called a soft edge slit. Furthermore, it is impossible to make a metal slit with some pattern in it. A fractal slit, for example, will be introduced later. These new kinds of slits have their own advantages for overcoming the shadowing effect.

By using the conventional slit geometry, the shadowing effect can not be overcome efficiently. The overexposure on shadowing area results in a high reduction of diffraction efficiency. So when transferring the image from the master hologram H_1 to the transfer hologram H_2, the image information, coming from larger shadowing areas, will be much weaker than those from areas which have smaller shadowing areas. When displaying a hologram with a heavy shadowing effect, the image shows an uneven brightness (usually getting weaker while reaching both ends) to the viewer when he moves from left to right. The conventional slit geometry is powerless to get rid of the shadowing effect. So seeking an ideal slit(s) is a task of top priority.

In practice, a slit should not only achieve or approach an ideal slit, but it should also possess some other advantages. For example: the slit should be easy to manufacture, requiring minimal, inexpensive manufacturing skills. It should require a commonly used material and should change its pattern or shape easily. It should also be easily fixed and unfixed. All of these advantages have been possessed by a new model slit -- the soft edge glass slit.

6. 3 A NEW MODEL SLIT -- THE GLASS SLIT

A glass slit indicates a slit which is based on a piece of glass whose shape is also rectangular. In this study it was made by means of exposing a piece of rectangular holographic plate on which a deliberately pre-made mask is located to leave this part unexposed. Further details will be introduced in the chapter entitled 'Apparatus'. Two pieces of very smooth and thin (about 0.1 to 0.2 mm in thickness) tapes are inserted, which are fixed at the two shorter ends of the glass slit, between the glass slit and the holographic plate H_1, for keeping the distance between them. The slit itself does not contact H_1 but the tapes do. The slit moves up and down while keeping its distance and always being parallel even under the condition where the holographic plate is a little bit bent or tilted in the process of mounting. So the slit can move along H_1 without scratching its emulsion surface.

Though the distance between the glass slit and H_1 has been reduced, the shadowing effect can be decreased within certain range. The size of the image on the diffuser and the distance between H_1 and the diffuser screen can be selected within a large range and a better quality master hologram may be obtained. Whereas the edges of the slit are still sharp, it can not limit the shadow area to a minimum and the diffraction effect can not be controlled effectively. So further improvements on the glass slit are carried out and a new model glass slit, the soft edge slit, is designed.

6. 4 SOFT EDGE SLIT

A slit, whose middle part is transparent with two symmetric very narrow parts separately located along the longer edges of the slit varies from clear to grey and then to dark towards the edges and is called a soft edge slit. The transitional parts are called grey spaces. In the experiment, the dimensions of the middle part is 300*1.8 mm^2 and each of the grey space is 300*0.2 mm^2.

The edge softness enables one to overcome the shadowing and diffraction effects by means of some overlapping on the border of two adjacent strip holograms. The overlapping can be achieved by making the moving distance of the slit after each shooting smaller than the width of the soft edge slit including the two grey spaces.

By using a sharp edge slit no matter whether steel knife edge or glass sharp edges are used, the overlapping part would receive double exposure. The over exposure may result in the reduction of the diffraction efficiency or crippled information. So the information sent from the overlapping part is weak during transferring. While transferring, the transfer hologram also records the information of slits and overlapping parts which can be reconstructed in front of the final hologram when displaying. Because of the overexposure the overlapping parts were much darker than the central part of the strip hologram. When viewing the hologram, they are like barriers and give the viewer an uncomfortable feeling.

If the grey spaces are getting darker evenly and the half transparent part is exactly in the middle of them and the width of the overlapping part is just the same as one of the width of grey spaces, the exposure quantity of both the transparent part of the slit and the overlapping part are the same. Therefore the overlapping areas do receive double exposure. For the first exposure, the information of the image sent from the overlapping part(s) is getting weaker and weaker with the grey space becoming darker and darker. For the next exposure, the original grey space is replaced by the other with the opposite way of various shading which compensates the first exposure. At the overlapping area, a gradually weakened information is sent to the transfer hologram while transferring with a gradually and softly enhanced information of the image next to it. Because the quantity of the exposure of the overlapping area is the same as that of the transparent part, instead of seeing the barriers, the viewer can get one view transmitting to another softly while his eye crosses the boundary of the two slits.

In section 6.1, it has been mentioned that the incident light which comes from different places can cause the shadowing effect. However from the point of recording useful information, when the slit moves along the holographic plate from the top to the bottom the incident angle, which is from the bottom of the diffuser screen for example, will change all the way during recording. So there is a certain area of the strip hologram that the incident light from the bottom of the diffuser cannot reach but from the top of the diffuser can if the slit is a sharp edge one. Some useful information is lost.

If looking through the details of the soft edge slit geometry; please see figs (6. 2) and (6. 3), the slit is on the top of the master holographic plate for the first exposure, the area a_2 records information coming from the area of the image from which the signal light can reach a_2 and the light is softened in different range according to the incident angle. Light, which comes from the bottom of the diffuser for example, has the biggest incident angle. During the next exposure, the light coming from that area reaches a_2 and is also softened but in an opposite way caused by using the other soft edge, in addition, the light coming from the bottom of the image can reach a_2, with different image and a slightly different incident angle. a_3, a_4, a_5 ......,and a_n may be deduced by analogy. Soft transmitting the image and making up the insufficient exposure of regions with respect to another are the two main advantages of the soft edge slit.

The soft edge slit is also able to reduce the diffraction effect. Because there is not an obvious line between the transparent and opaque regions. The diffraction effect of both the reference light and signal light has been greatly reduced though its effect is much less than the shadowing effect.

The glass soft edge slit can reduce and keep that distance between the slit and H_1 and make up the difference of the light intensities between the transparent part and the overlapping part. While displaying, the barriers in front of H_2 have been removed and the sudden jump of the image has disappeared. The other advantages of the glass soft edge slit such as manufacturing, fix and so on will be introduced in detail in chapter 9 experimental apparatus.

6. 5 FRACTAL EDGE SLIT

The fractal edged slit is similar to the soft edge slit but instead of the grey parts the fractal edged slit uses fractal patterns in those areas. Generally the fractal is a broken comb form, here however, we describe it as a pattern (see fig. 6. 4). This pattern looks like a bush or some cypresses with their needles branching out along both edges. This pattern offers a natural and comfortable sense perception and can be easily accepted by most viewers. In fact the slit possesses the same functions as that of the soft edge slit. The fractal patterns can be designed by computer and then copied onto a piece of holographic plate. Since the researching time is limited, this slit will not be discussed further.

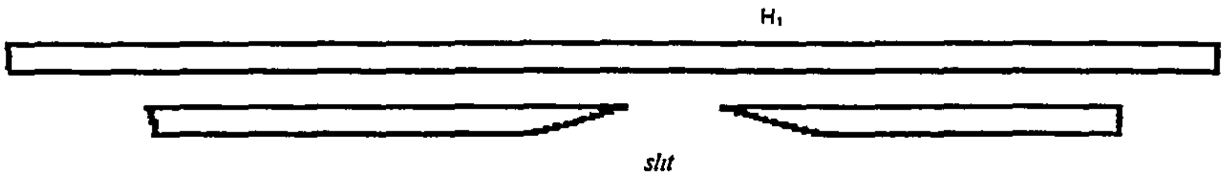


Figure 6. 1

The slit is located immediately above the holographic plate

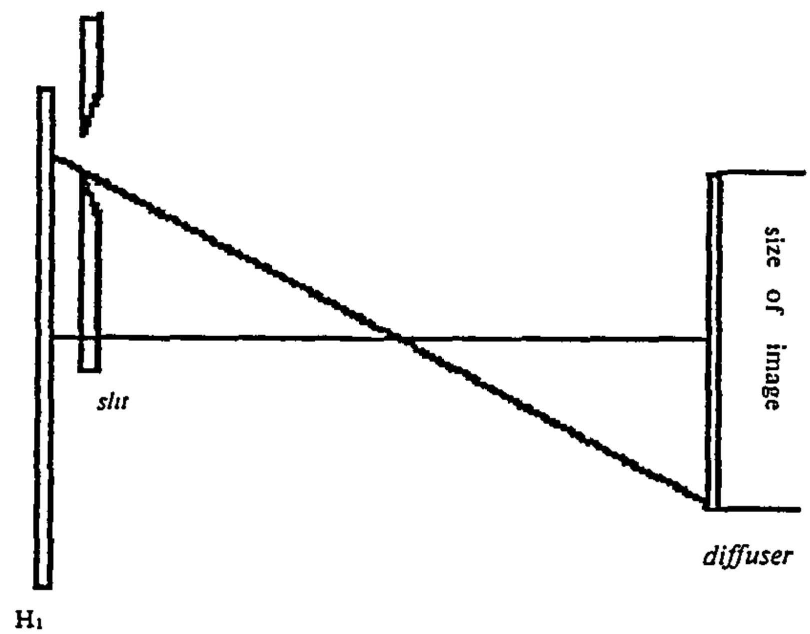


Figure 6. 2

The shadowing effect is caused by the different angles of the incident light

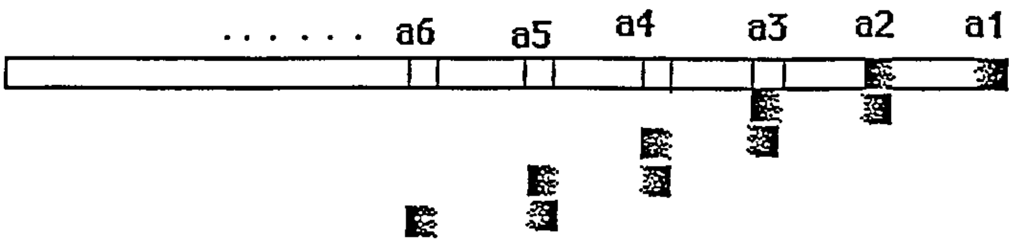


Figure 6. 3

Soft edges can make up for the shortcomings caused by gaps of overlap. A soft transit from one image to another can be obtained

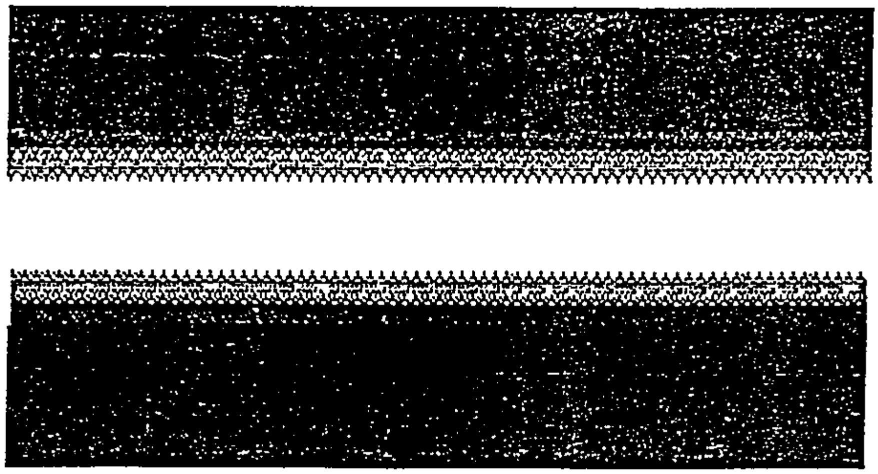


Figure 6. 4

A fractal edge slit can be designed by computer

CHAPTER VII

DISPLAY TECHNIQUES AND SLITS

Displaying a multiplex, no matter what kind of illuminating light is used, the viewer enables to see the image or perspective views only through slit(s) or a series of slit plane(s), which are invisible and formed in space in front of the displaying hologram. Looking through different slit(s) or slit plane(s), the viewer can get not only different perspective views, but also different colours (if it is a full aperture white light transmission multiplex hologram). The slit plane is like a coloured window through which the object can be viewed. So the quality of the slit is extremely important for the showing of the multiplex hologram. The discussions below about the slit or slit plane represent the different perspective views and colours of the object(s).

7. 1 DISPLAYING LIGHT SOURCE AFFECTING THE SLIT PLANE

It is natural and easy to display a hologram by using a white light source. Usually a spot light of a vertical filament lamp is used which is very good for reconstructing the transmission transfer multiplex hologram. When transferring the image from the master multiplex hologram H_1 to the transfer hologram H_2 the reference light may be a collimated or a diverging laser light. This makes things quite different for the reconstruction. So the discussion will be divided into 4 parts:

A. collimated laser reference light and collimated white displaying light
B. collimated laser reference light and diverging laser displaying light
C. collimated laser reference light and diverging white displaying light
D. diverging laser reference light and diverging white displaying light

The hologram plate is a holographic lens and the lens and image are not usually on a straight line (due to the effect of the holoprism). The focal length of the lens depends on the colour of the light: the longer the wavelength the less the focal length. [45] For simplifying the discussion, if the displaying light is coming from the same place as the reference light for transferring, no matter whether collimated or diverging light is used, the light will be regarded as coaxial light. Changing the position of the displaying light sources in the discussion later is also considered as near axis light. Thus, a coordinate is set up with its origin at the centre of the holographic plate and some symmetric points are chosen as the coordinates.

Before starting the discussion, there are some data, which often appear in the description and calculations, and these should be given: the discussion below is based on the sharp edged slit so the width of the slit is W_s = 2 mm. The wavelength of the laser light for recording and transferring is L_g= 514 nm. The size of the master hologram H_1 is 30 * 40 cm^2. The size of the transfer hologram or display hologram H_2 is 20 * 25 cm^2. The distance between H_1 and H_2 for transferring or from H_1 to the diffuser screen L_1=32.5 cm. These data are going to be described in detail later.

7. 1. 1 COLLIMATED LASER REFERENCE LIGHT AND COLLIMATED WHITE DISPLAYING LIGHT

The geometry for transferring a hologram has been introduced in chapter 4. One thing that has to be mentioned here is that the transfer hologram H_2 records not only the image coming from the master multiplex hologram H_1, but also the information of a series of well arranged slits from H_1 as well. When displaying, H_2 offers both an image (like a focus image hologram) and the slit plane (s) formed in space in front of H_2.

If the reconstructing light has the same wavelength as the reference light 514 nm for transferring, the incident angle is 45° fig (7. 1). Then a slit plane is formed at the place

$$m \lambda = d_m (\sin \alpha \pm \sin \beta) \qquad ------ \quad (7.\ 1)$$

In equation (7.1), m is the diffraction order, λ is the wavelength of the laser light 514 nm, d is the pitch between two adjacent interference fringes (after transferring and processing d is a constant), α is the angle of the incident light and β is the diffraction angle of the projected light or output light.

If H_2 is illuminated by a collimated white light and the range of its wavelength is from 400 nm to 700 nm, the incoming light of each wavelength is also in accordance with the equation. Thus:

$$m \ \lambda' = d_m \ (\sin \alpha' \pm \sin \beta') \qquad \text{------} \quad (7.\ 2)$$

λ' is the wavelength variable from 400 to 700 nm and β' is the appropriate project angle. Now by using equation (7. 1) in (7. 2) to eliminate the constants one obtains:

$$\sin \beta' = \sin \alpha' - \frac{\lambda'}{\lambda} (\sin \alpha \pm \sin \beta) \qquad \text{------} \quad (7.\ 3)$$

From equation (7.3) one sees that if the incident light is coming through the same area of H_2 with the same incident angle. For different wavelengths, different projection angles are obtained. In another words, different wavelengths form different slit planes. Because many properties can be deduced from the location of the slit plane(s), in this chapter, the centre stands for the slit plane. See fig (7.1), from H_2, two small spots are chosen with the coordinates of (0, 10, 0) and (0,-10, 0) and the incident angle has been given as 45°:

$$\lambda = \lambda' = 514 \ \text{Å}$$

$$\alpha = \alpha' = 45^{\circ}$$

$$\text{and} \qquad \beta = \arctan \left(\frac{10}{32.5} \right) = 17.10^{\circ}$$

Using the results in equation (7. 3) and choosing ten equally spaced wavelengths with intervals between 400 nm and 700nm. The ten slit planes formed by the various wavelengths are shown clearly in table (7. 1) and graph (7. 1). In table (7. 1), D represents the distance from the centre of one coloured slit plane to the displaying plate H_2.

From graph (7. 1), it can be very easily seen that the centres of the slit planes deviate from the Z axis. It is desirable to work out the distances between slit planes and H_2 as it is very important for determining the positions of the slit planes.

Normally the illuminating light is on the top of the display hologram, the incident angles to the symmetric points along X axis is identical. So the displacements of slit planes only happen in Y and Z directions but X direction.

Now randomly choosing a slit centre, see graph (7. 2), from which, a vertical line to H_2 is drawn and the intersection point on Y axis is P. Assuming m and n are the distances between the top and the bottom of H_2 to the point P (or between two symmetric coordinates to the point P) and the two project angles have been worked out as β' and β''. [β' is defined as the project angle coming from the points above the origin (0, 0, 0) and β'' is below that point. Further, the distance from the top to the bottom coordinators is L, then a formula for determining the distance between the slit plane center of any colour to H_2 can be deducted:

$$L = m + n \quad ; \quad \tan\beta' = m / D \quad \text{and} \quad \tan\beta'' = n / D$$

$$\tan\beta' + \tan\beta'' = (m + n) / D = L / D$$

thus;

$$D = L / (\tan|\beta'| + \tan|\beta''|) \qquad ------ (7.\ 4)$$

In some special cases, such as $\beta' < 0$ or $\beta'' > 0$

$$D = L / (\tan|\beta'| - \tan|\beta''|) \qquad ------ (7.\ 5)$$

For red light, with a wavelength of 700 nm, for example, one obtains:

$$\beta' = \arcsin [\sin \alpha' - \lambda' (\sin \alpha \pm \sin\beta) / \lambda]$$
$$= \arcsin [\sin 45^\circ - 700 (\sin 45^\circ - \sin 17.10^\circ) / 514]$$
$$= \arcsin (0.1446)$$
$$= 8.31^\circ$$

and using formula (7. 3) again:

$$\beta'' = \arcsin [\sin \alpha' - \lambda' (\sin \alpha + \sin \beta) / \lambda]$$
$$= - 41.02^\circ$$

Now working out the distance between the centre of the red slit plane to H_2; if the length from top to bottom of the holographic plate L= 20 cm, then from Eq (7.4)

$$D = L / (\tan | \beta' | + \tan | \beta'' |)$$
$$= 20 / (\tan | 8.31^\circ | + \tan | - 41\ 02^\circ |)$$
$$= 19.69 \text{ cm}$$

The distance of the centre of the red slit plane deviates from the z axis by D_d and is given by

$$D_d = L / 2 - D * \tan (\beta')$$
$$= 7.12 \text{ cm}$$

That means that the centre of the red slit plane is 7.12 cm away from the z axis but only in the direction of the y axis with no displacement in the x direction. Because the illuminating light is exactly head on (H_2) and for the symmetric points the incident angles are the same, there is no displacement of the slit plane centres in x direction. In other words, the deviation D_d is only in Y direction.

Using the same method, a series of data are worked out and from the table and graph (7. 1), the following is deduced:

1. Different wavelengths form different slit planes.

2. Each slit plane has its own centre which is different from the centres of all the other slit planes.

3. The centres deviate from the central axis of the holographic plate, so that the viewing field is larger than the one illuminated by laser light.

4. Nearly all centres are located along a line which is tilted 35° with respect to the horizontal plane.

5. The distances between the slit planes to H_2 are variable. The red (700 nm) slit plane is closest to the H_2 and the violet (400 nm) is the one farthest away from H_2.

6. Magnifications for different slits can be obtained by using Eq. 5.1. For red colour slit if a=50 cm, b=55 cm and c=a-D=30.31 cm, then M_r=1.14. Similarly, the magnification of the violet slit plane is M_v=1.02.

7. Different magnification means that the red image, by looking through red slit plane, looks bigger and closer to H_2. Whereas the violet image is small and far from H_2.

8. Different colours of image can be seen whilst looking through differently coloured slit or slit plane .

9. Changing the viewing distance, the viewer may get different stereoscopic effects because the slits he is looking through have changed.

10. The longest distance (along the Z axis) between the two slit planes is formed by violet light and red light with 20.38 cm.

11. The illuminating light falling in the lateral direction is symmetric. There is no displacement of the slit plane centres along x axis. This case is suitable for any kind of light source (except one which is moving along the x axis). So this case will not be mentioned any more in the discussions below.

Using collimated laser light as the reference light for transferring the image from the master hologram to the transfer hologram is not very difficult, because many holographic laboratories are equipped with collimated mirrors and collimated lenses. For displaying, however, the laser is too expensive and needs many and diverse devices and even the collimated white light will cost much to display each hologram. Furthermore there are many technical problems when exhibiting such as space for illuminating, distances from light source to the plate with the correct angle. If it is possible to use a white light point source instead of the collimated one for illuminating the white light transmission transfer multiplex hologram, this simplifies things considerably.

Now a point light source, a spot-light, is used to illuminate the white light transmission multiplex hologram. Is it able to display a good and sharp image? How big is its magnification? In the next two sections all these things will be discussed.

7. 1. 2 COLLIMATED LASER REFERENCE LIGHT AND DIVERGING LASER DISPLAYING LIGHT

Before discussing the diverging white displaying light, a simpler case should be described here, for which a diverging laser (the wavelength is the same as the reference light for transferring) displaying light is used and which is fixed at the exact centre of the collimated white displaying light. Assuming its coordinates are (0, 60, 60) cm, and the angle is 45° between the incident light (from the centre of the light source to the centre of the displaying plate) and the horizontal plane. Although the wavelength is the same, the incident angle is variable with the different heights of the display hologram. As shown in fig. (7. 2), the incident angle is smaller at the top of the hologram plate and bigger at the bottom. The diverging light source has a different angle of incidence at every point. It is impractical to work out the contribution to the slit planes from every point on the displaying plate H_2. So some special points are chosen to present the characteristics of the diverging light source.

The whole length of the H_2 in the vertical direction is divided into twenty equal parts and twenty points are chosen along the Y axis (0, 10, 0), (0, 9, 0), ... (0, 1, 0), (0, -1, 0), ... (0, -10, 0). Using equation (7. 3)

$$\sin\beta' = \sin\alpha' - \frac{\lambda'}{\lambda} (\sin\alpha \pm \sin\beta)$$

a series of data, listed in table (7. 2), and a relevant graph (7 3) can be obtained.

From the table and the graph some analysis are given below:

1. Though the illuminating wavelength is the same as the reference light for transferring, the diverging light makes the slit plane further away, compared with collimated laser illuminating light, from the displaying plate H_2.

2. For the symmetric points, the projection angles are different because of the different angle of incidence.

3. For the symmetric points, their intersection points or the centres of slit planes are different too, the farthest is located 41.46 cm away from H_2 and getting closer with the reduction of the symmetric coordinates.

4. The distance between the slit plane and H_2 is a function of the coordinates along the Y axis or a function of the angles of incidence.

5. Nearly all the centres of the slit planes are off the Z axis, but the smaller the numerical values of the coordinates are, the closer the centres are located to the Z axis

6. The largest magnification for diverging illuminating laser light is M_d = 1.022. Using laser light to illuminate a multiplex hologram has a rather small distortion.

7. 1. 3 COLLIMATED LASER REFERENCE LIGHT AND DIVERGING WHITE DISPLAYING LIGHT

In 7.1.1 and 7.1.2, the situations of the collimated white and diverging laser illuminating light sources have been discussed. From the discussion above, we have understood that for the collimated white light, the distances between the slit planes and the displaying plate or, going a step further, the magnifications are functions of the incident wavelengths, For the diverging laser light, the magnifications are a function of the incident angles. For the diverging white illuminated light, however, the magnifications should be functions of both the incident wavelengths and angles of incidence. So that in equation (7. 3)

$$\sin \beta' = \sin \alpha' - \frac{\lambda'}{\lambda} (\sin \alpha \pm \sin \beta)$$

α' and λ' represent the variables of the incident angles and wavelengths. β is changed with the variation of coordinates.

If all the conditions are the same as for the diverging laser illuminating source except for given wavelength, the table (7. 3) and graph (7. 4) can be obtained and the characteristics of the diverging white light illumination are listed below:

1. By using the diverging white displaying light, the distance between the slit planes formed by different wavelengths to the displaying plate H_2 are longer than those correspondence planes obtained by using collimated white light illumination.

2. The distance (along the Z axis) between the farthest (400nm or violet light formed) slit plane and the closest(700nm or red light formed) plane is longer than that one which is created by a collimated white light source.

3. Nearly all the centres of the slit planes are off the Z axis. Even the green (514nm) slit plane too.

4. Since the laser light used is 514 nm, the centre of the green slit plane deviates from the Z axis by only 0.36 cm. For the centres of the violet and red slit planes the deviations are larger than 8 cm

5. Every slit plane centre roughly aligns a line which is around 30 degree but not 35 degree mentioned in 7.1.1. This line is an very important parameter when making an achromatic multiples hologram if the displaying source is a diverging white light

6. The biggest magnification is produced by red light at the coordinate (0, ±10, 0) and $M_r = 1.1$. This is smaller than that produced by collimated white light illumination. When $D \geq 50$ cm, the magnification is zero because the viewer just stands at a slit plane.

7. 1. 4 DIVERGING LASER REFERENCE LIGHT AND DIVERGING WHITE DISPLAYING LIGHT

During transferring, if a diverging laser reference light is used to take the place of the collimated reference light the interference fringes of every point on the display hologram H_2 are different from those obtained by using a collimated reference light (as discussed in the previous subsections). Assuming the diverging white light source for illumination is located at the same place as the diverging laser light source for transferring and their diverging angles are identical. In spite of the different interference fringes, the discussions here should be the same as for a collimated reference laser light for transferring and a collimated white light for illumination. For displaying this kind of multiplex hologram, a correct light source and an accurate position for illumination is very important.

In this section, the displaying light sources and some phenomena, such as the slit planes formed by different wavelength, the spatial positions of the slit planes, magnifications and so on have been considered. All of these discussions are based on the fact that the position of illuminating light source must be identical to that of the reference light source used for transferring the hologram. In many cases, the illuminating light can not come from the exact position of the reference light. What will happen to the image? How big is the magnification or distortion that it can show? Can it be tolerable? In which way can the magnification be compensated. In the next section these problems will be discussed.

7. 2 MOVEMENT OF THE DISPLAYING LIGHT

Usually the illuminating light is on the top of the display hologram or at the bottom. It is not necessary to worry about the displaying light moving parallel with the hologram plate. The cases discussed here are under the conditions of the central line of the multiplex hologram in vertical direction and the illuminating source is in the same plane. In this section, the things considered are the light source moving forward and backward (illuminating angle changed) or keeping the incident angle but the illuminating distance is changed.

7. 2. 1 ILLUMINATING DISTANCE

A change of the illuminating distance is often encountered in practice when displaying a hologram, especially during an exhibition. The displaying room is not big or high enough or the ceiling is too high and it is very difficult to put the light source at the exact place where the reference light source was. Assuming a diverging white light illuminating source is used and the incident angle of 45° is kept, see the fig (7. 3), the light source is at the coordinates of (0, 40, 40), (0. 50, 50), (0, 70, 70) and (0, 80, 80). For the wavelengths only the two extreme colours are chosen, 700 nm and 400 nm. Since many discussions about the changes of the slit planes caused by the variations of the different points on the display hologram H_2 have been done, the top (0, 10, 0) and the bottom (0, -10, 0) points along the Y axis are studied and the formula used still is Eq (7. 3).

$$\sin \beta' = \sin \alpha' - \frac{\lambda'}{\lambda} (\sin \alpha \pm \sin \beta)$$

If the illuminating source is located at the coordinates (0, 40, 40) cm, the incident angles of the illuminating source can be worked out: for the top point of the displaying hologram, the incident angle is

$$\alpha ' = \arc\tan\left(\frac{30}{40}\right) = 36.87^{\circ}$$

and for the bottom:

$$\alpha '' = \arc\tan\left(\frac{50}{40}\right) = 51.34^{\circ}$$

Using these data of the illuminating source at the coordinates (0,60,60); $\alpha = 45^{\circ}$ and $\beta = 17.10^{\circ}$, for the wavelength of 700 nm, the projection angle on the top, $\beta '$ is:

$$\beta ' = \arc\sin\left[\sin\alpha ' - \frac{700}{514}(\sin\alpha - \sin\beta)\right]$$

$$= \arc\sin\left[\sin 36.87 - 1.3619(\sin 45^{\circ} - \sin 17.10^{\circ})\right]$$

$$= 2.15^{\circ}$$

and the projection angle at the bottom $\beta ''$ is:

$$\beta '' = \text{are}\sin\left[\sin 51.34^{\circ} - 1.3619(\sin 45^{\circ} + \sin 17.10^{\circ})\right]$$

$$= -35.63^{\circ}$$

Using the same methods the project angles for wavelength of 400 nm can be obtained. $\beta ' = 16.17^{\circ}$ and $\beta '' = 0.1^{\circ}$. Applying formula (7. 4)

$$D = L / (\tan|\beta '| + \tan|\beta ''|)$$

the distances from the slit planes to H_2 can be worked out. For the red slit plane, Dr = 22.77 cm and the violet slit plane, Dv = 69.39 cm and all the other visible coloured slit planes are in between these two slit planes. All other calculations of the other coordinates, at which the illuminating light comes from, are shown in table (7. 4). From this table, some results can be inferred.

1. The closer the distance between the light source and H_2, the further the slit planes are moving away from H_2.

2. The distance between the slit planes are getting closer and closer when the light source is moving away from H_2.

3. If moving the light source forward too much, (0, 30, 30) for example, the centres of the red slit planes are above the top line of H_2 and the centres of the violet slit planes are beyond the bottom line of H_2.

4. In the table, the biggest magnification is produced by red slit plane with M_r = 1.11. The smallest, due to the violet slit plane, is M_v = 1. This indicates that there is distortion when a viewer looks through a violet slit plane.

5. The magnification produced by the diverging light source is in all directions. Changes in the shape of the image can not help to minimize the magnification discussed in chapter 5.

6. From the analysis 1, one infers that if the light source is located close to H_2, the magnification will be reduced. So the magnification or distortion can be compensated by adjusting the light source properly.

7. 2. 2 ILLUMINATING ANGLE

Changing the angle for illuminating the hologram is often encountered while displaying. Usually the room for displaying is not big enough and the illuminating light has to be moved forward or even backward in some cases along the ceiling. That means the light source (moving in Y, Z plane) keeps the distance in Y orientation but not along the Z axis. As shown in fig (7. 4), if the coordinates of the light source are chosen as (0, 60, 40), (0, 60, 50) ------ (0, 60, 80) and using the formulas in subsection 7. 2. 1, the table (7. 5) can be obtained.

The results of changing the illuminating angle are quite different from those of changing the illuminating distance. One obtains:

1. The closer the light source is moving towards H_2, the further the red slit planes are moving away from H_2.

2. The distances between the slit planes are getting smaller when the light source is moving towards H_2.

3. If the light source is moved forward too much, the centres of the violet slit planes are located beyond the bottom line of H_2.

4. If the light source is moved backward too much, the centres of the red slit planes are above the top line of H_2.

5. In the table, the smallest magnification, produced by violet slit plane, it is $M_v = 1$. The biggest, due to the red slit plane, is $M_r = 1.13$ which is obtained form the light source situated at the coordinate (0, 60, 80).

6. From the analysis 1, one infers that if the light source is getting closer to H_2, then the magnification will be reduced so that the magnification or distortion can also be compensated by adjusting the light source properly.

All the discussions given above are based on the assumption that the other light sources affecting the image and the magnification have all been removed. Since the stray light sources may come from anywhere, it is too difficult to include all the factors in our analysis. If the displaying light source is much stronger and coming from the place not too far from the original source of the reference beam for transferring, all the distortion and chromatic dispersion can be tolerated or neglected.

It is worth investigating, what sort and shape of slit plane can be formed in space in front of H_2 while reconstructing. Is it a flat one, or a curved one, paralleled to H_2, tilted with a certain angle? In the next chapter, the answers to these questions will be given.

7. 3 VIEWING OVER DISTANCE

The viewing over distance is defined as the biggest distance of viewing from the very left end where the image can just be seen to the far right end and for a given viewing distance. These two distances should not be confused with each other. The viewing distance is the distance from the viewer to the displaying plate H_2. This distance is vertical to H_2. The viewing over distance, however, is a lateral distance which is parallel to H_2. For simplifying the discussions, the conditions of both the reference and displaying light source are used for the collimated laser light.

As shown in fig (7. 5), D_v is the viewing distance, L_1 is the distance between the slit plane and H_2, L_{H1} is the length of the master hologram H_1, L_{H2} is the length of H_2, and D_{vo} is the viewing over distance. From the simple geometric relationships shown in the fig (7. 5) a formula can be deducted:

$$D_{vo} = L_{H2} + D_v \frac{L_{H1} - L_{H2}}{L_1} \qquad (7.\ 6)$$

If the conditions are as given before: $L_{H1} = 40$ cm, $L_{H2} = 25$ cm, $L_1 = 32.5$ cm, then the viewing over distance is only a function of the viewing distance:

$$D_{vo} = 25 + 0.46\ D_v \qquad (7.\ 7)$$

If the viewing distance is 40 cm, then from formula (7. 7) the viewing over distance is 43.3 cm and for a viewing distance of 50 cm, the viewing over distance is 48 cm. That means, if the viewer stands further away from H_2, he may get longer viewing over distance.

7. 4 <u>ANGULAR SIZE OF IMAGE</u>

When a viewer is moving along a viewing over line from left to right, he can get a different perspective view of an object. The variable ratio of the perspective angle of the object (image) is defined as the angular size of the image. Looking through the slit plane to see an image is somewhat like seeing an object through a window. The further the viewer is away from the window, the smaller the angle by which he can see the object. So the angular size of the image is a function of the viewing distance.

As described before, the slit plane is formed in space in front of the displaying plate H_2. It has the same effect as a window. Thus,

$$\alpha^* = \arc\tan \frac{D_{vo}}{D_v - D_i} \quad ------ (7.\ 8)$$

α^* is the angular size of the image , D_v and D_{vo} are the same as in the subsection above and D_i is the distance from image plane to the displaying plate H_2. Inserting formula (7. 6) into (7. 8), one obtains

$$\alpha^* = \arc\tan \left\{\frac{L_{H2} + 2\ D_v\ [\ (\ L_{H1} - L_{H2})\ /\ 2\ L_i\ ]}{D_v - D_i}\right\} \quad ---- (7.\ 9)$$

In practice, D_v = 50 cm, L_{H1} = 40 cm, L_{H2} = 25 cm, L_i = 32.5 cm and assuming that D_i = -5 cm. Then:

$$\alpha^* = \arc\tan \frac{25 + 100 * 0.23}{55} = 41.11^\circ$$

So under the conditions as given above, a viewer can get the angular size of 41°. This is the angular range of the viewer who looks around an object.

7. 5 QUANTITY OF STRIP HOLOGRAMS

The quantity of the strip holograms is given by how many times the slit has to be moved while forming the master multiplex hologram. It seems very easy to be determined. It is related to many factors: the width of the slit, viewing distance, viewing over distance, normal distance of the human eyes and so on.

As discussed many times in the previous subsections, if the displaying plate H_2 is illuminated by a collimated laser light of 514 nm, the slit plane will be formed in the space at exactly the distance, where the master hologram H_1 was located in front of H_2. Therefore there is no magnification of the width of the slit at all. For diverging white light, however, this distance changes not only with the variation of the wavelengths, but also with the angles of the incident light. From the results in table (7. 3) and considering the wavelength of 514 nm in the white light, the distance between the slit plane and H_2 changes from 32.5 cm to 41.56 cm. The magnification is 1.28 and the width of the slit at that distance has changed from 2 mm to 2.56 mm.

If a viewer stands 50 cm away from H_2 and the width of the slit is 3.1 mm the viewing over distance is 48 cm. When the viewer moves from left to right, he will look through about 150 slits. That means when making the master hologram H_1, at least 150 strip holograms should be shot.

What will happen when the viewer keeps his head stationary? What can he see? How big is the depth perception he can get? If he has the normal distance between his eyes (6.5 cm), he must get two different views by looking through two different slits 21 slits apart from each other. But how big are the differences between these two images?

The camera moves along a rail by passing the object with its orientation fixed. For each shoot, the camera moves one centimetre (or longer depending on how big the object is), then the camera moves a total of 150 cm. Assuming that the camera's recording angle F is 60°, then (60° / 150 frames) the two adjacent frames have 0.4° difference. Thus 21 frames of 21 slits will have 8.4° difference which is just like putting one of the fingers in front of an observer's nose at the distance of full arm length and alternatively shielding one of his eyes. Two different sides of the finger can be seen by using a different eye. Though the finger is much smaller than the image in a multiplex hologram, the depth perception for this angle is big enough to give the viewer a stereo view and when the viewer is moving along the viewing over line, he will enjoy a stereo panorama of the object with 60° perspective view.

Incidentally, the distance between the camera and the object is introduced while the photographs are shooting. As shown in fig (7. 6), the moving distance of the camera along the rail is D_s and the recording angle of the camera is F which varies for different cameras. It is very easy to infer that the distance between the object and the rail is:

$$D_q = \frac{D_s}{2 \tan (F / 2)} \qquad \text{------} \quad (7.\ 10)$$

Using this formula for the example given above the shortest distance of D_q is

$$D_q = 150 / 2 \tan 30^\circ = 129.9 \text{ cm}$$

7. 6 TRANSFERRING DISTANCE

Transferring distance is the distance between the master hologram H_1 and the final hologram H_2. This distance has been met many times in some descriptions and calculations. It often shows on some formula and graphs. However, why was it picked in this study and what determines this distance or 32.5 cm, called L_1? The explanation will be given below.

Some data have been given at the beginning of this section such as: viewing distance, image plane, magnification and so on. But there is no explanation of L_1. Now one method, for choosing L_1, is introduced and started from the optical geometry of recording and transferring multiplex hologram. If the full size of the image projected on the diffuser screen is 20 * 25 cm^2 and the size of the master hologram is 30 * 40 cm^2; in vertical direction (Y axis) length of diffuser L_{DF} = 25 cm and length of master hologram L_{H1} = 40 cm. Having been introduced in chapter 6, while making master hologram H_1, a slit moves up and down as a mask in front of H_1 to record a series of strip holograms which have to record all the information coming from the whole diffuser screen.

It is assumed that the centres of both H_1 and diffuser screen coincide with each other and that the slit is on the top of H_2. If the distance between the slit and H_1 is D_G and the width of the slit is 2 mm, it can be seen that the light from the bottom of the diffuser screen can not reach certain areas of the emulsion of the strip hologram.

One method to reduce the shadowing area is to increase the distance from H_1 to the diffuser screen L_1, please see fig (7. 7) i.e. To reduce the incident angle α' of the light coming from the bottom of the diffuser screen. From the fig (7. 7) and fig (7. 8), a formula can be obtained

$$\tan \alpha' = \frac{D_G}{D_s} \qquad \text{------ (7. 11)}$$

D_s is the width of the shadow falling onto the holographic plate and preventing the incident light from coming through. Only the extreme case is considered: The slit is on top of the holographic plate and the light is coming from the bottom of the diffuser (for all other cases, the shadowing areas are smaller than the extreme one) and the distance between the master hologram and the diffuser is L_1. In this case another formula can be deduced.

$$\tan \alpha' = \frac{2 L_1}{L_{H1} + L_{DF}} \qquad \text{------ (7. 12)}$$

If let $(L_{H1} + L_{DF}) / 2$ equals a constant C and inserting formula (7. 11) into (7. 12) then:

$$D_s = \frac{(L_{H1} + L_{DF})\, D_C}{2 L_1} = C * \frac{D_C}{L_1} \qquad (7.\ 13)$$

From formula (7. 13), the longer the L_1, the smaller the width of the shadow or the shadowing area. Appropriately adjusting the distance between the diffuser screen and the holographic plate can help to reduce the shadowing effect. Please see the examples below: if L_1 = 32.5 cm , D_C = 1 mm following formula (7. 13) D_s is 1 mm. For a conventional steel-made slit, the width of the slit is 2 mm. It is desirable that the width of the appropriate strip hologram be 2 mm. However from the calculation above, the shadowing area (D_s = 1 mm) is half of the whole strip hologram. Changing the data L_1 =160 cm and keeping D_C = 1 mm , then Ds is about 0.2 mm. The shadowing area is 10% of the whole strip hologram. Extending, L_D, the distance between the diffuser screen and the holographic plate may bring some problems. A huge holographic bench is needed. According to our layout, a 4.5 * 6 m^2 holographic bench is needed. The signal light coming from the diffuser screen has travelled a long distance and the intensity of that light has been reduced to a rather weak level for which the exposure time is much longer than that of L_1 = 32.5 cm. For a long exposure time, the stability of the bench and the laser should be taken into account. Experience tells us that a stable bench, a stable laser and quiet surroundings are necessary for shooting a good quality hologram. So extending the distance between the diffuser screen and the holographic plate is not a good method for reducing the shadowing effect. Fortunately there is another factor D_C that can help reduce this effect.

If the distance between the slit and holographic plate can be minimized to less than 0.2 mm while keeping L_1 = 32.5 cm. The result is better than the previous example with L_1 = 160 and D_s = 0.2 or less. It has been introduced in section 6. 2, the glass slit can reduce this distance to 0.2 mm or less. So in this way, the bench need not be very big and the exposure time is quite short. It is a very efficient method to reduce the shadowing effect. For shooting the master hologram and for the transferring process, L_1 was chosen as 32.5 cm.

For the conventional optical geometry, the distance between the master hologram and the diffuser screen is the same as the distance of transferring. Though different tasks may need variable transferring distances, the value used here is still a very important reference point for making a multiplex hologram.

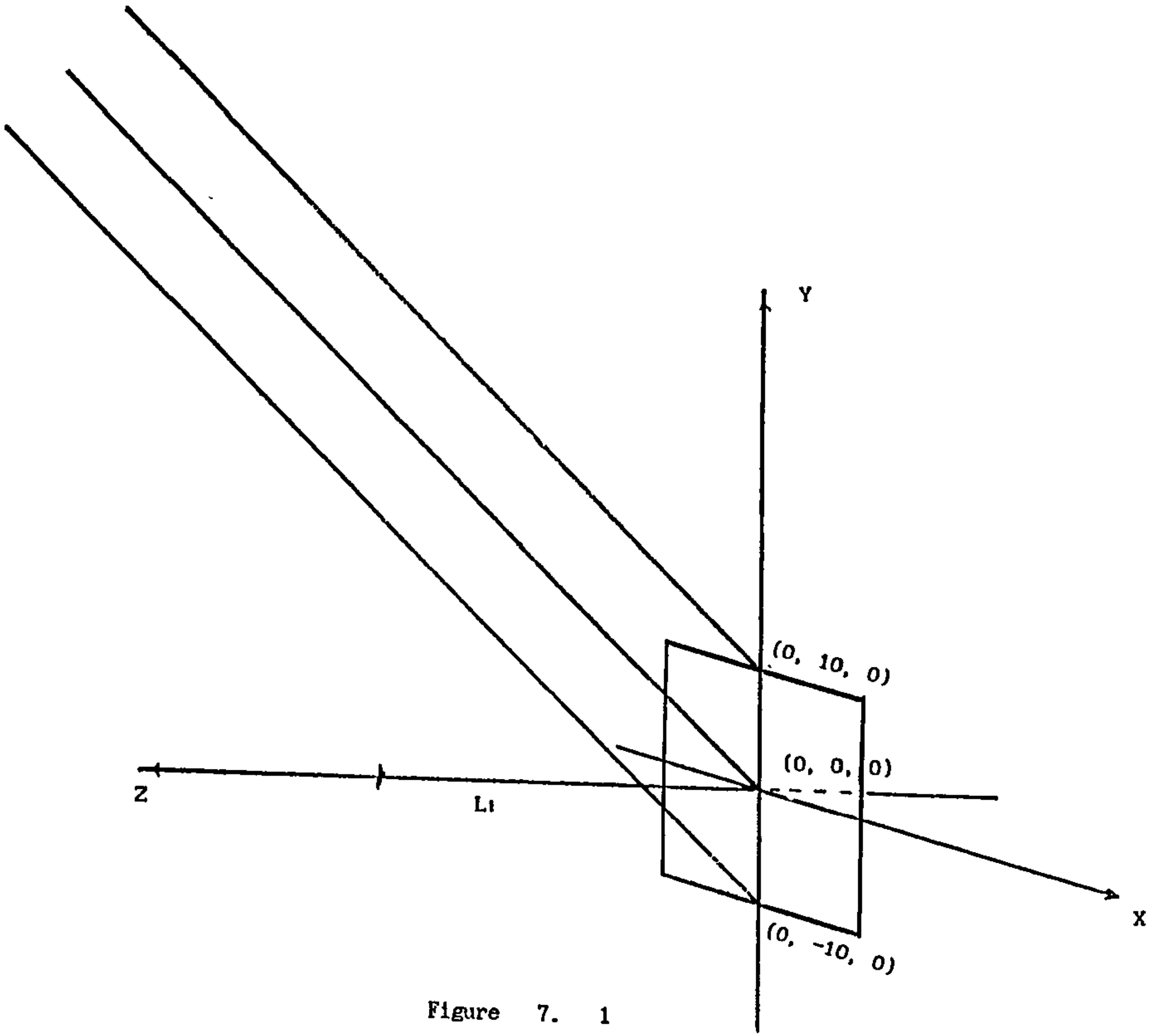


Figure 7. 1

A collimated white light source illuminates H2 with the incident angle of 45°. The origin of the coordinates is set at the centre of the displaying hologram

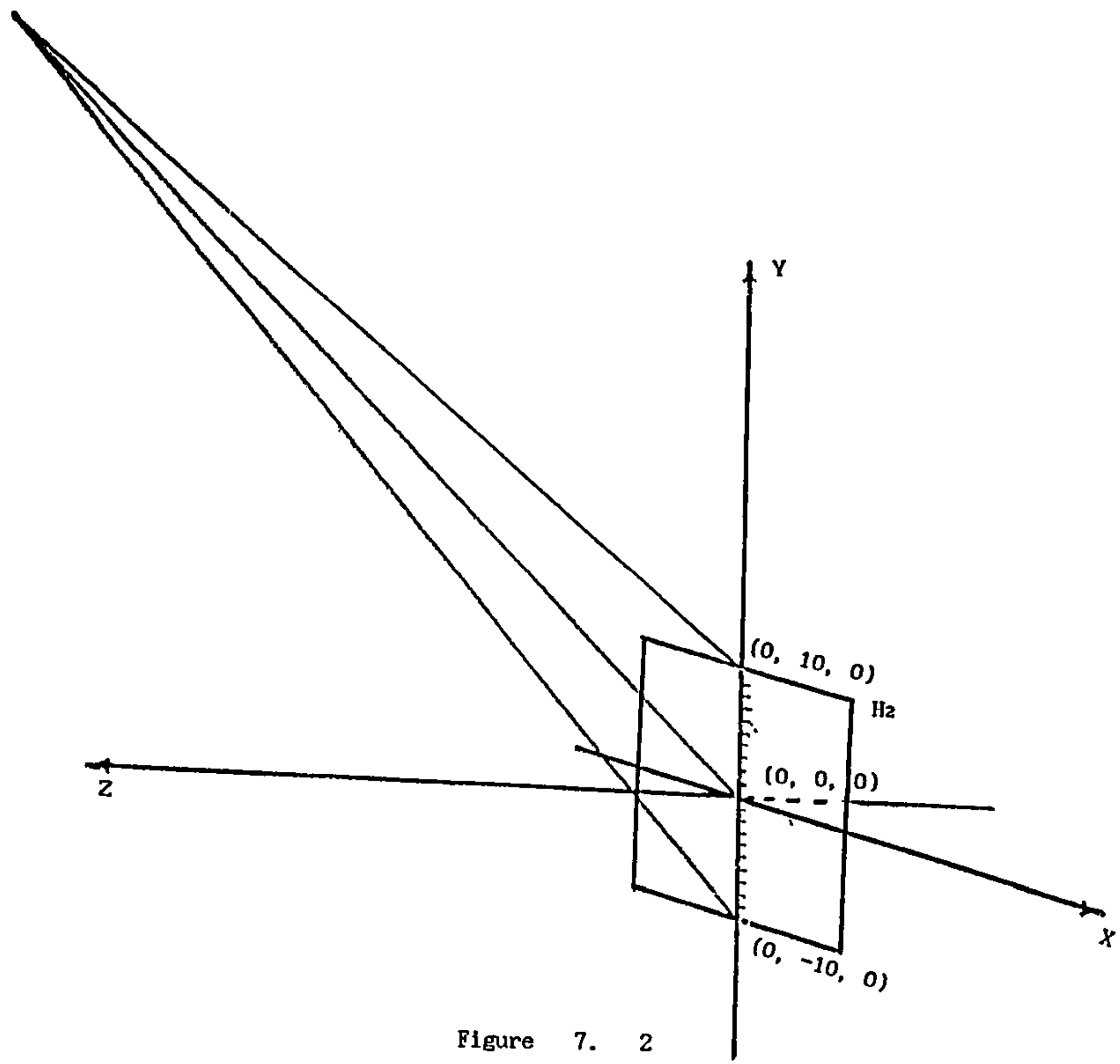


Figure 7. 2

A diverging laser light source is illuminating H_2 and the incident angle changes with the coordinates along Y axis

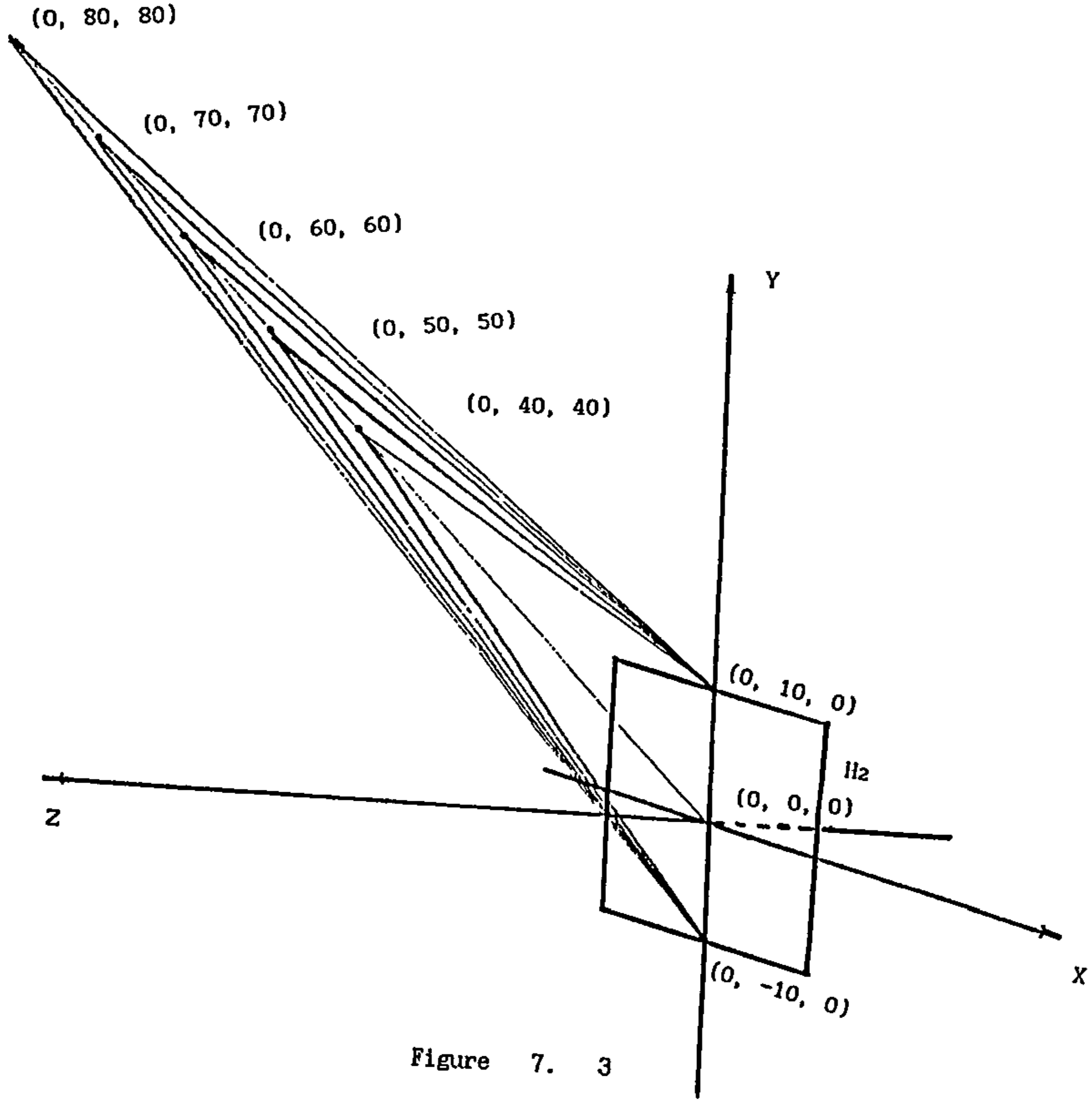


Figure 7. 3

A diverging white light source illuminates H2 with the same incident angle but different distances

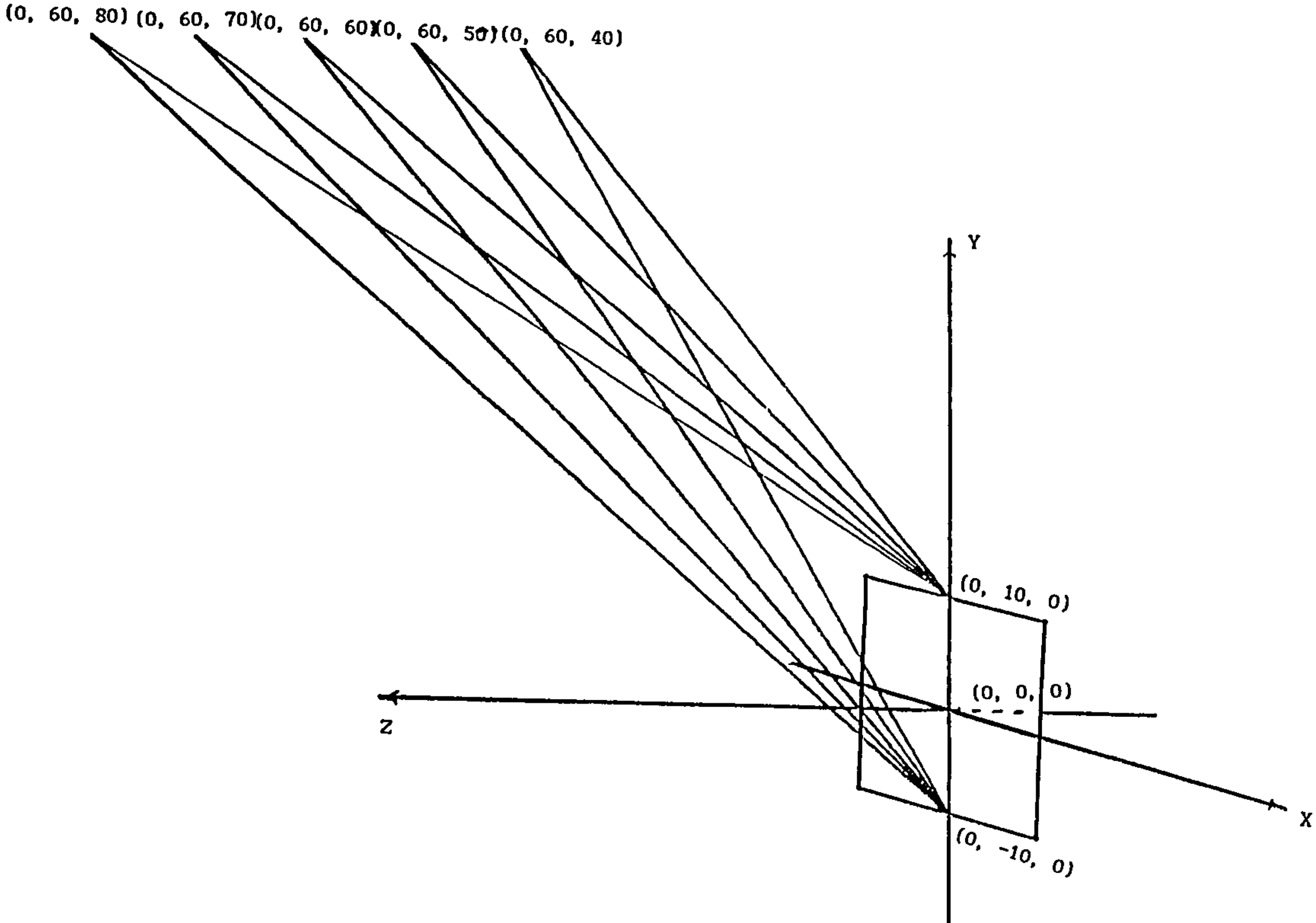


Figure 7. 4

A diverging white light source illuminates H_2 with different incident angle

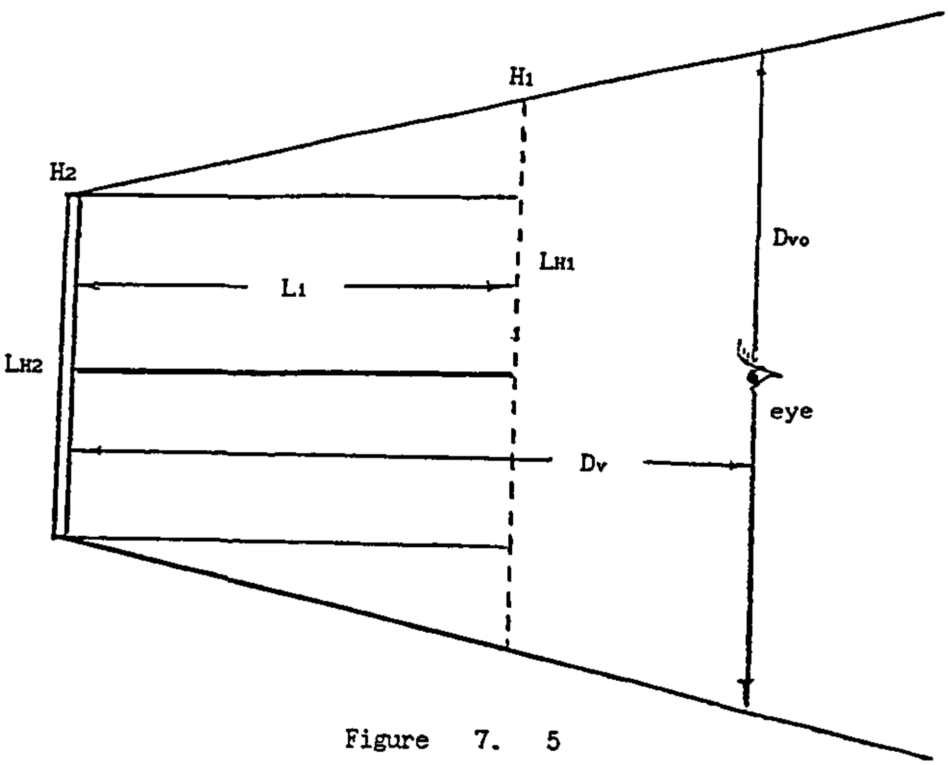


Figure 7. 5

The viewing over distance D_{vo} is related to the viewing distance

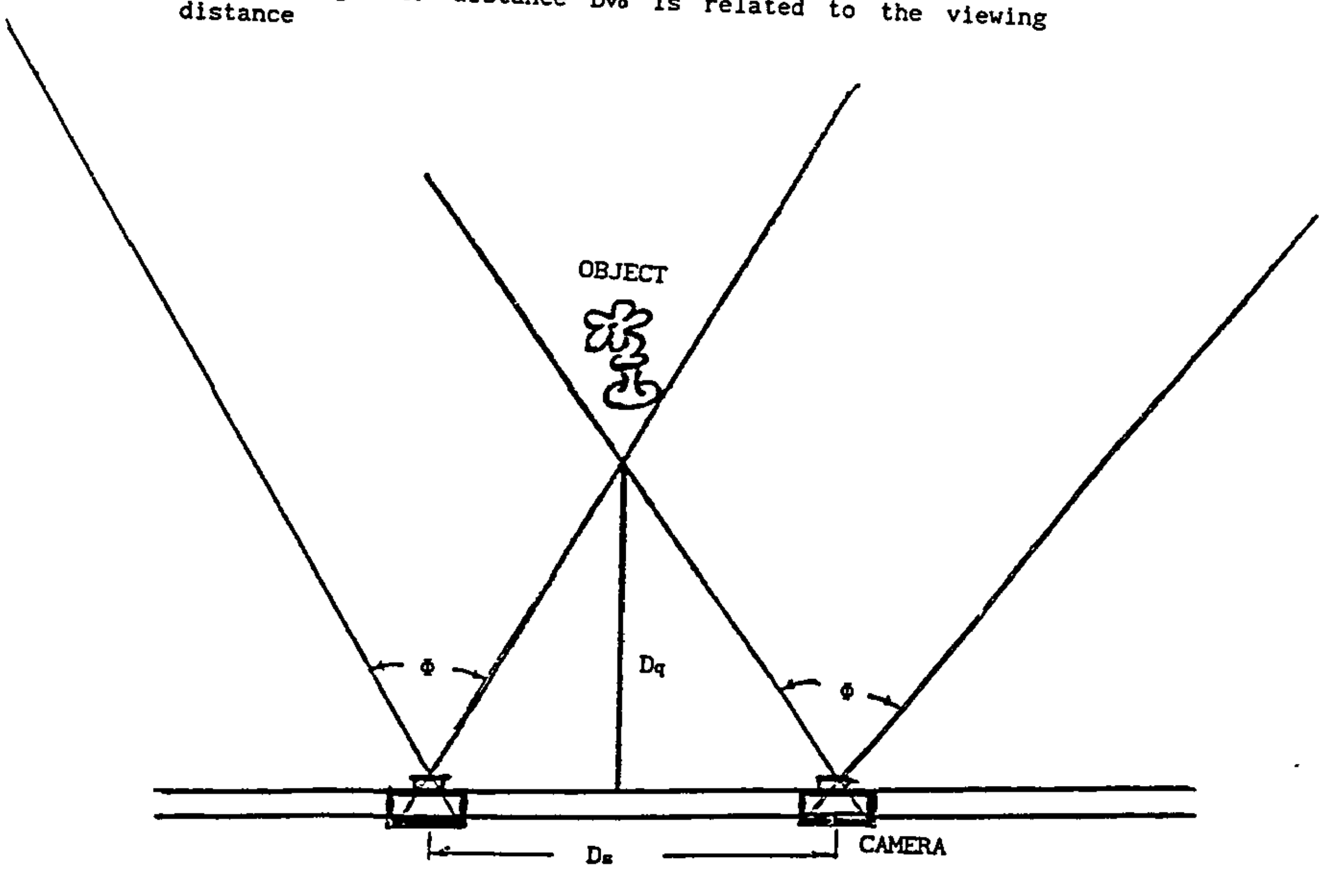


Figure 7. 6

D_q the shortest distance between camera and object

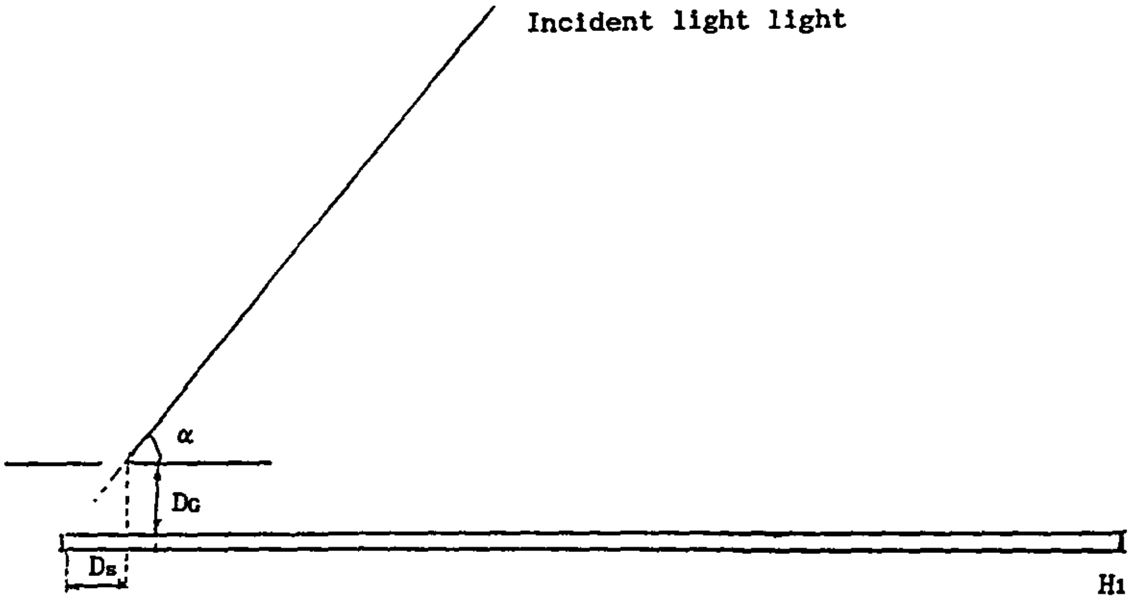


Figure 7. 7

For sharp edge slit, the shadowing effect is caused by the incident light can not reach the shadowing area D_s

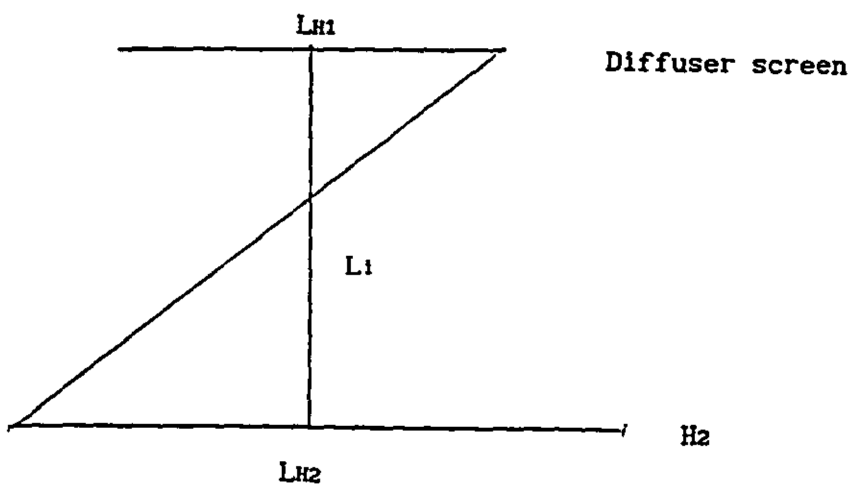


Figure 7. 8

The distance for transferring is often determined by the distance between H_1 and diffuser.

COLLIMATED WHITE LIGHT ILLUMINATION

Table 7. 1

Coordinates (0. ± 10, 0) $\alpha = \alpha' = 45^{o}$ $\beta = 17.10^{o}$

Wavelength (nm)	sin β'	β'	sin β''	β''	D (cm)
700	0.1446	8.31	- 0.6563	- 41.02	19.69
670	0.1687	9.71	- 0.5979	- 36.72	21.81
640	0.1928	11.12	- 0.5395	- 32.65	23.89
610	0.2169	12.53	- 0.4810	- 28.75	25.94
580	0.2410	13.95	- 0.4226	- 25.00	27.98
550	0.2651	15.37	- 0.3642	- 21.36	30.03
520	0.2892	16.81	- 0.3057	- 17.80	32.09
490	0.3133	18.26	- 0.2473	- 14.32	34.18
460	0.3374	19.72	- 0.1889	- 10.89	36.31
430	0.3615	21.19	- 0.1304	-7.49	38.52
400	0.3856	22.68	- 0.0720	-4.13	40.81

Diverging laser light illumination

Table 7. 2

No	Coordinates	L + ΔY	$\alpha' = tg^{-1}\left(\frac{L + \Delta Y}{60}\right)$	$\beta' = tg^{-1}\left(\frac{Y}{32.5}\right)$
1	0, 10, 0	50	39.80	17.10
2	0, 9, 0	51	40.36	15.48
3	0, 8, 0	52	40.91	13.83
4	0, 7, 0	53	41.98	12.15
5	0, 6, 0	54	41.99	10.46
6	0, 5, 0	55	42.51	8.75
7	0, 4, 0	56	43.03	7.02
8	0, 3, 0	57	43.[illegible]	5.27
9	0, 2, 0	58	44.03	3.52
10	0, 1, 0	59	44.52	1.76
11	0, -1, 0	61	45.47	-1.76
12	0, -2, 0	62	45.94	-3.52
13	0, -3, 0	63	46.39	-5.27
14	0, -4, 0	64	46.84	-7.02
15	0, -5, 0	65	47.29	-8.75
16	0, -6, 0	66	47.72	-10.46
17	0, -7, 0	67	48.15	-12.15
18	0, -8, 0	68	48.58	-13.83
19	0, -9, 0	69	48.99	-15.48
20	0,-10, 0	70	49.40	-17.10

L = 50 cm $\alpha = 45^{\circ}$ $\lambda = 514$ nm

Diverging laser light illumination

Table 7. 2 -- Continued

$\sin\alpha + \sin\beta$	$\sin\beta' = \sin\alpha' - (\sin\alpha \pm \sin\beta)$	β'	D (cm)
0.4130	0.2271	13.13	41.46
0.4401	0.2057	11.98	41.19
0.4680	0.1869	10.77	40.89
0.4965	0.1655	9.53	40.80
0.5255	0.1435	8.25	40.63
0.5549	0.1208	6.94	40.49
0.5848	0.0975	5,60	40.36
0.6152	0.0735	4.22	40.42
0.6456	0.0494	2.83	40.32
0.6763	0.0249	1.43	40.20
0.7377	-0.0248	-1.42	
0.7684	-0.0498	-2.85	
0.7988	-0.0747	-4.28	
0.8292	-0.0991	-5.69	
0.8591	-0.1243	-7.14	
0.8885	-0.1486	-8.55	
0.9175	-0.1726	-9.94	
0.9460	-0.1971	-11.37	
0.9739	-0.2193	-12.67	
1.0010	-0.2417	-13.99	

Table 7. 3

TABLES FOR DIVERGING WHITE ILLUMINATION

(0, ± 10, 0) $\alpha = 45^o$ $\alpha' = 39.80^o$ $\alpha'' = 49.40^o$

Wavelength (nm)	sin β'	β'	sin β''	β''	D (cm)
700	0.0776	4.45	- 0.6041	- 37.17	23.92
590	0.1659	9.55	- 0.3900	- 22.95	33.80
514	0.2269	13.12	- 0.2420	- 14.00	41.56
470	0.2633	15.27	- 0.1563	- 8.99	46.38
400	0.3188	18.58	- 0.0199	- 1.14	36.18

Table 7. 3

TABLES FOR DIVERGING WHITE ILLUMINATION

(0, ± 8,0) $\alpha = 45^o$ $\beta = 13.83^o$ $\alpha' = 40.91^o$ $\alpha'' = 48.58^o$

Wavelength (nm)	$\sin\beta'$	β'	$\sin\beta''$	β''	D (cm)
700	0.0174	1.00	- 0.5386	- 32.59	24.36
590	0.1176	6.75	- 0.3361	- 19.64	33.67
514	0.1868	10.77	- 0.1962	- 11.31	41.00
470	0.2269	13.11	- 0.1152	- 6.62	45.85
400	0.2906	16.89	0.0136	0.78	55.17

Table 7. 3

TABLES FOR DIVERGING WHITE ILLUMINATION

(0, ± 6, 0) $\alpha = 45^o$ $\beta = 10.46^o$ $\alpha' = 41.99^o$ $\alpha'' = 47.73^o$

Wavelength (nm)	$\sin\beta'$	β'	$\sin\beta''$	β''	D (cm)
700	- 0.0468	- 2.68	- 0.4703	- 28.05	24.69
590	0.0657	3.77	- 0.2801	- 16.27	33.54
514	0.1434	8.24	- 0.1487	- 8.55	40.66
470	0.1884	10.86	- 0.0726	- 4.16	45.34
400	0.2600	15.07	0.0484	2.77	54.33

Table 7. 3

TABLES FOR DIVERGING WHITE ILLUMINATION

(0, ± 4, 0) $\alpha = 45°$ $\beta = 7.02°$ $\alpha' = 43.03°$ $\alpha'' = 46.85°$

Wavelength (nm)	sin β'	β'	sin β'	β''	D (cm)
700	- 0.1144	- 6.57	- 0.3998	- 23.57	24.86
590	0.0108	0.62	- 0.2224	- 12.85	33.48
514	0.0973	5.58	- 0.0998	- 5.73	40.39
470	0.1473	8.47	- 0.0288	- 1.65	45.01
400	0.2270	13.12	0.0841	4.83	53.84

Table 7. 3

TABLES FOR DIVERGING WHITE ILLUMINATION

(0, ± 2, 0) α = 45° β = 3.52° α' = 44.03° α'' = 45.94°

Wavelength (nm)	sin β'	β'	sin β''	β''	D (cm)
700	- 0.1844	- 10.63	- 0.3280	- 19.15	25.07
590	- 0.0462	- 2.65	- 0.1635	- 9.41	33.48
514	0.0493	2.83	- 0.0499	- 2.86	40.24
470	0.1046	6.00	0.0159	0.91	44.83
400	0.1925	11.10	0.1205	6.92	53.46

(0, + Y, 0) are the co-ordinators along Y axis ' and -' are the incident angles above and below the origin respectively +' and ' are the project angles above and below the origin.

C. callimated laser reference light and diverging white displaying light

Table 7. 4

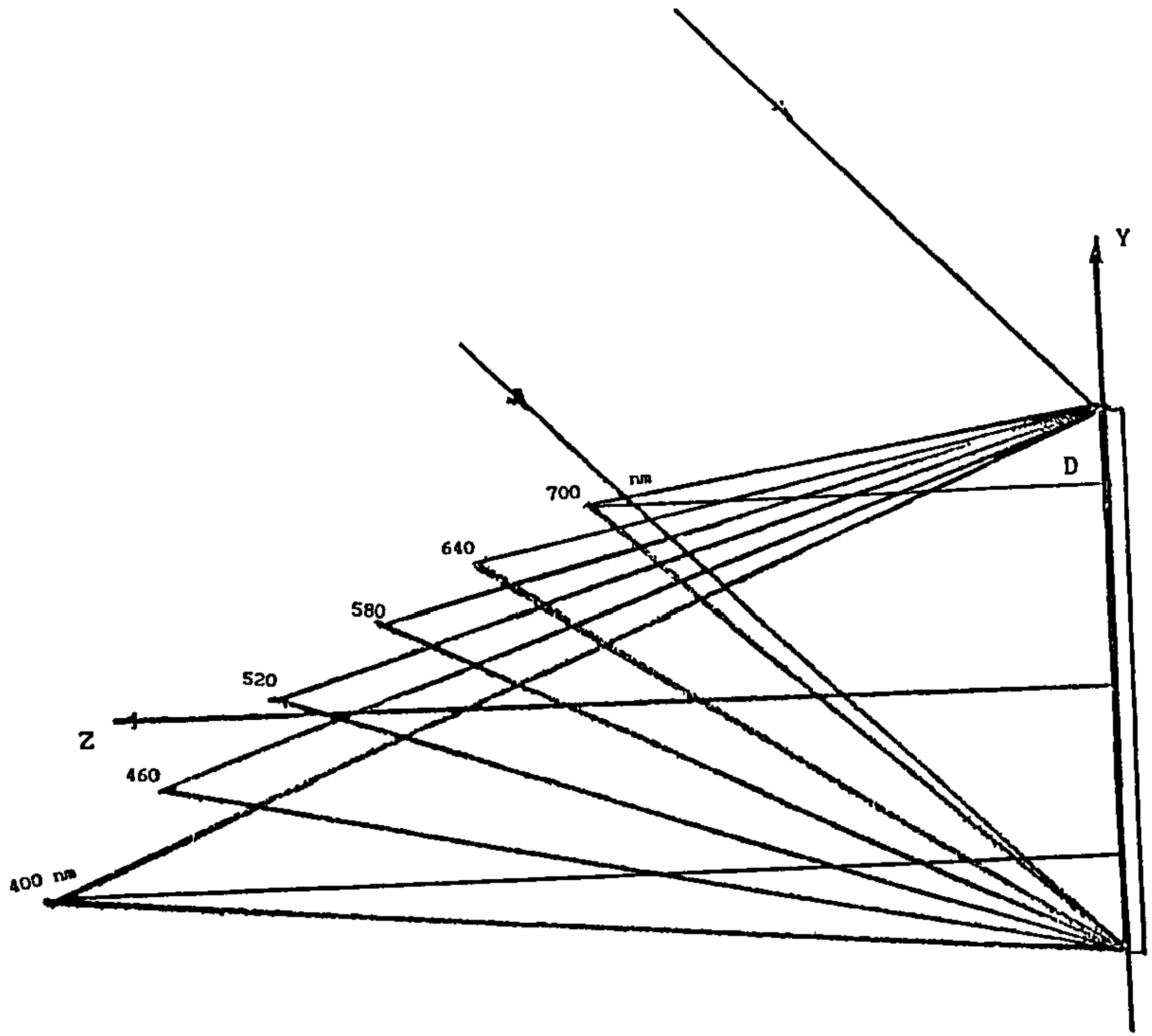
MOVEMENT OF ILLUMINATING DISTANCE

Coordinates	Wavelength (700nm)			Wavelength (400 nm)		
	β'	β''	D(cm)	β'	β''	D (cm)
0.40,40,	2.15	- 35.63	26.52	16.17	0.1	69.39
0.50,50,	3.57	- 36.53	24.09	17.65	- 0.63	60.76
0.60,60,	4.46	- 37.17	33.82	18.58	- 1.14	56.18
0.70,70,	5.06	- 37.65	23.25	19.22	- 1.52	53.31
0.80,80,	5.51	- 38.02	22.77	19.70	- 1.81	51.33

Table 7. 5

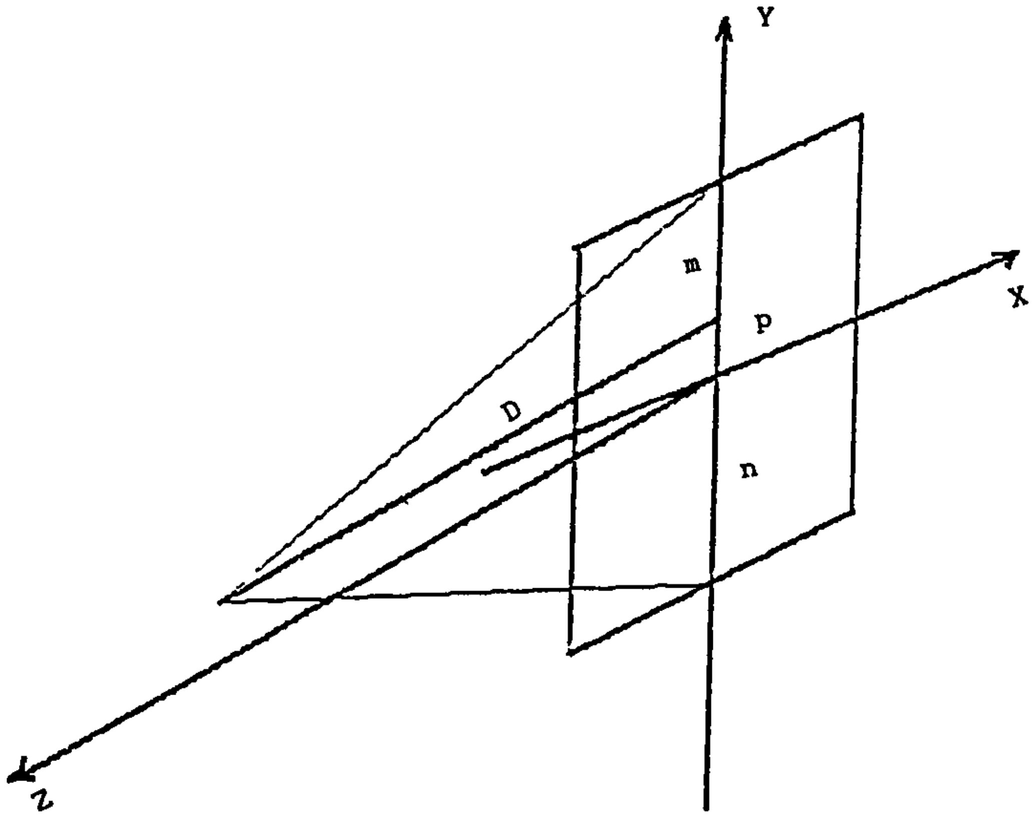
CHANGING ILLUMINATING ANGLE

Coordinates	Wavelength (700 nm)			Wavelength (400nm)		
	β′	β″	D (cm)	β′	β″	D(cm)
0.60,40,	12.61	- 29.67	25.21	27.35	5.12	46.76
0.60,50,	8.31	- 33.35	24.87	22.68	1.98	52.17
0.60,60,	4.46	- 37.17	23.92	18.58	- 1.14	56.18
0.60,70,	1.07	- 41.02	22.51	15.03	- 4.13	58.70
0.60,80,	- 1.87	- 44.81	20.81	12.03	- 6.91	59.83



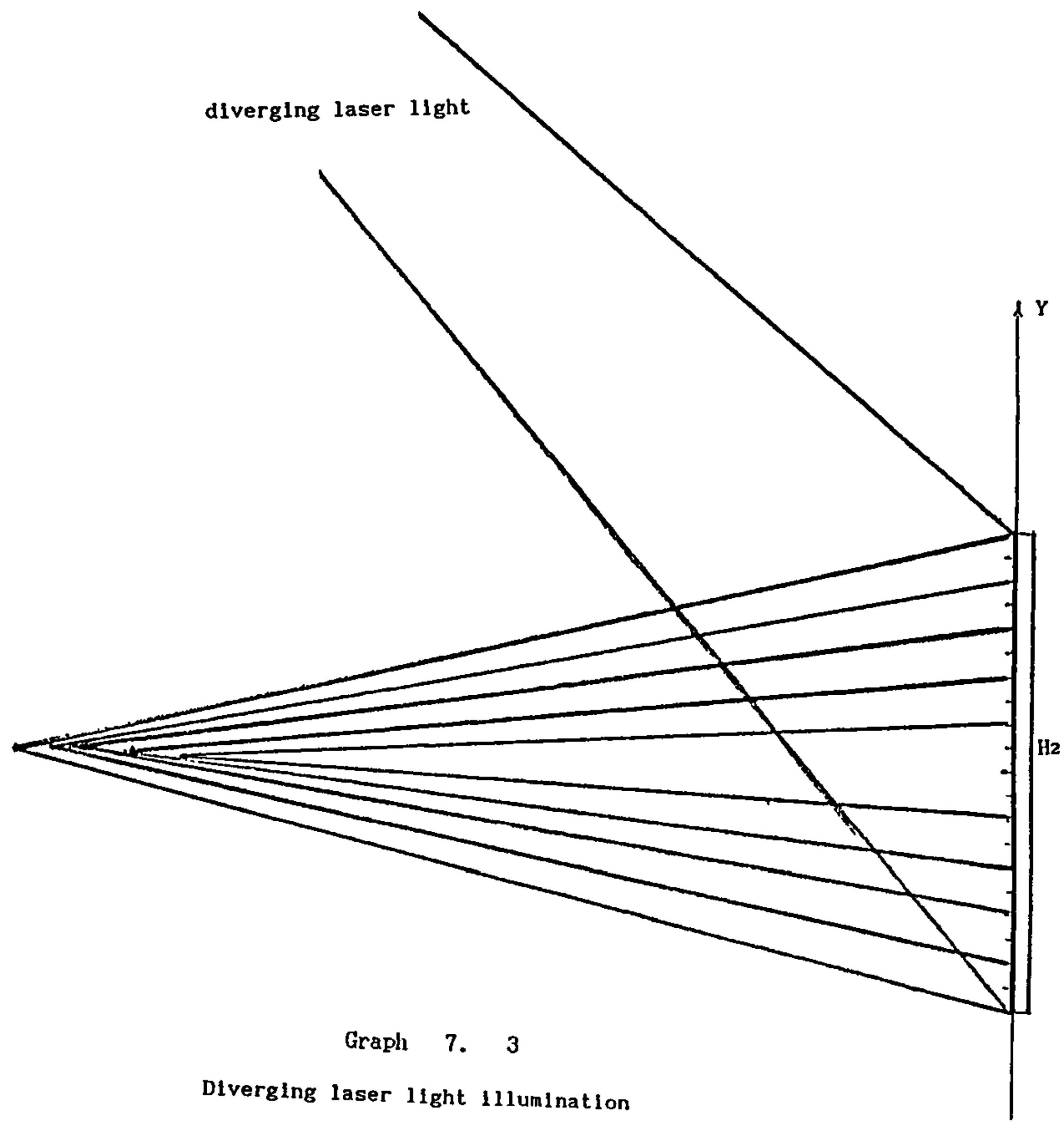
Graph 7. 1

Collimated white light illumination



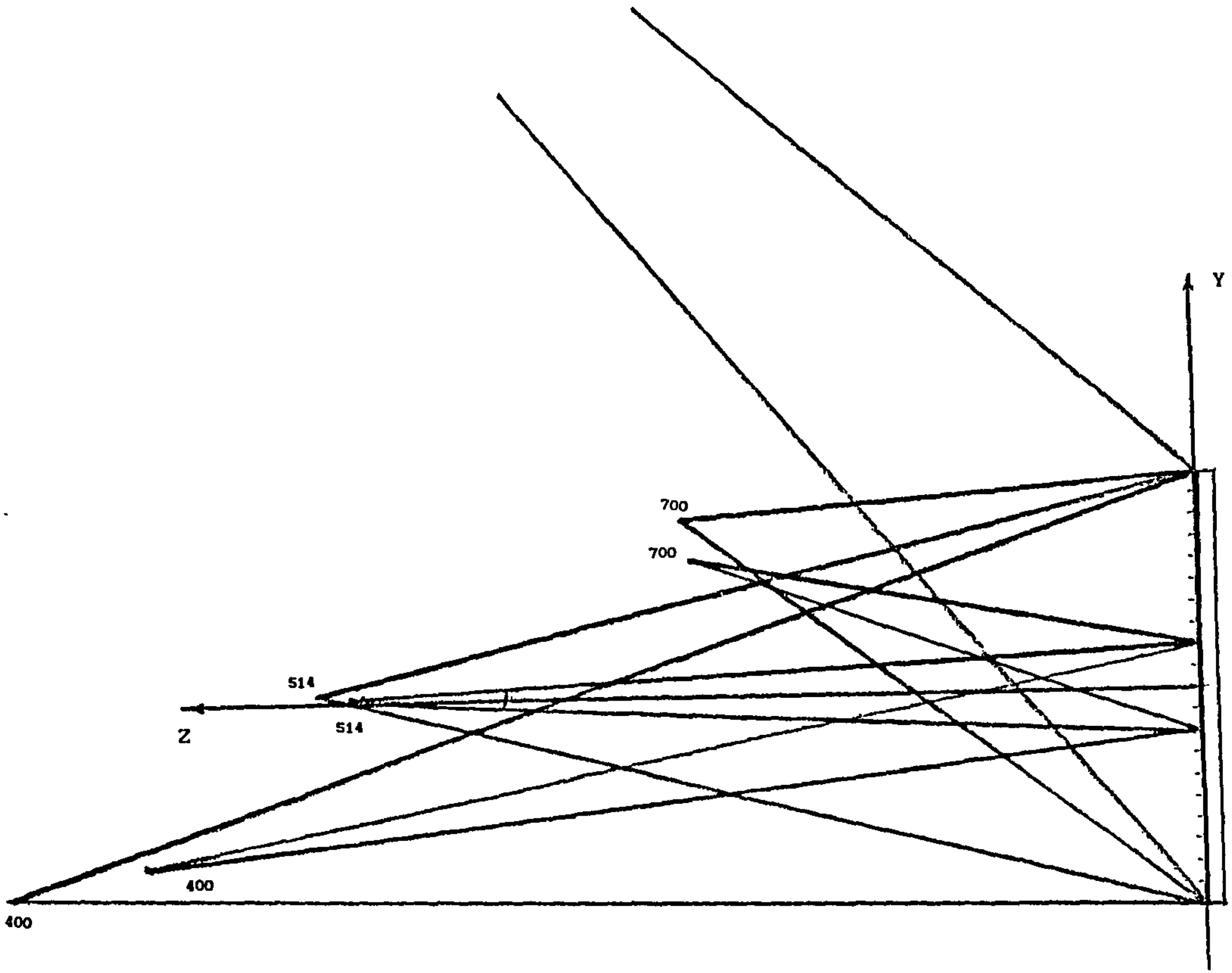
Graph 7. 2

Distance between a slit plane centre and H_2



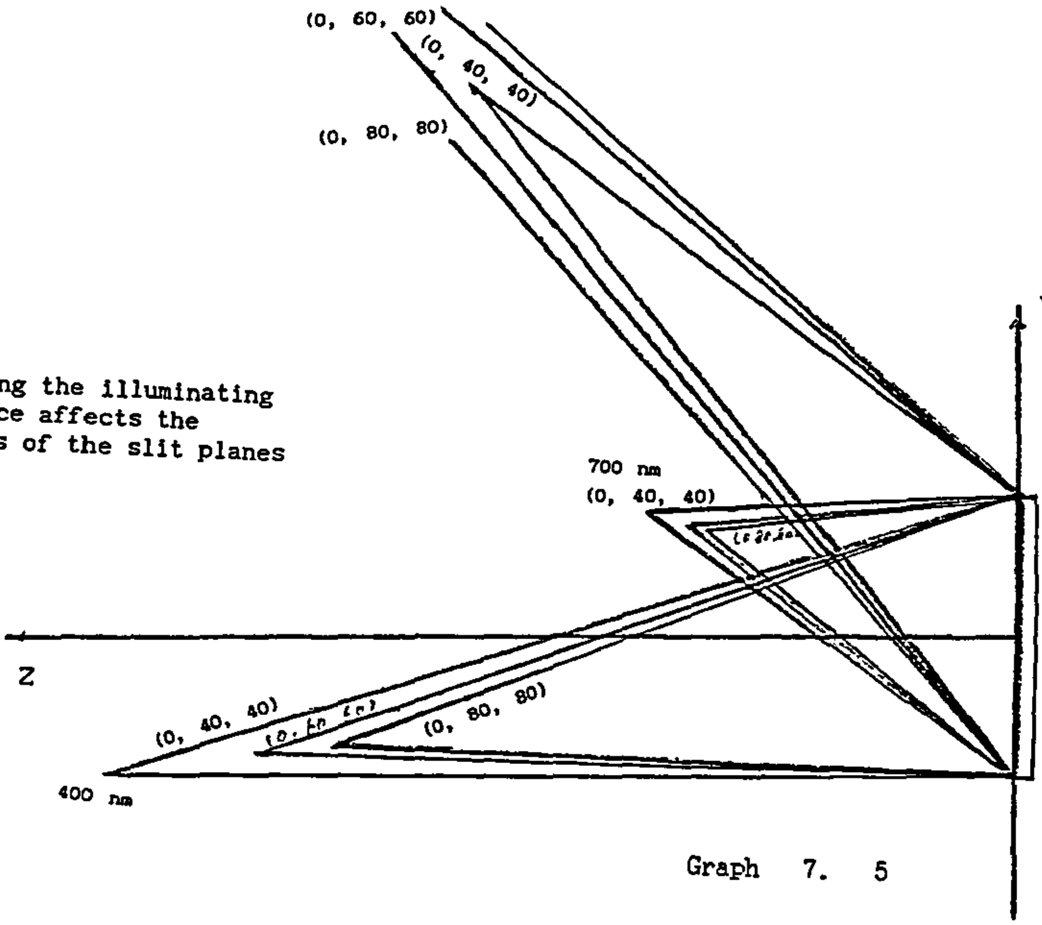
Graph 7. 3

Diverging laser light illumination



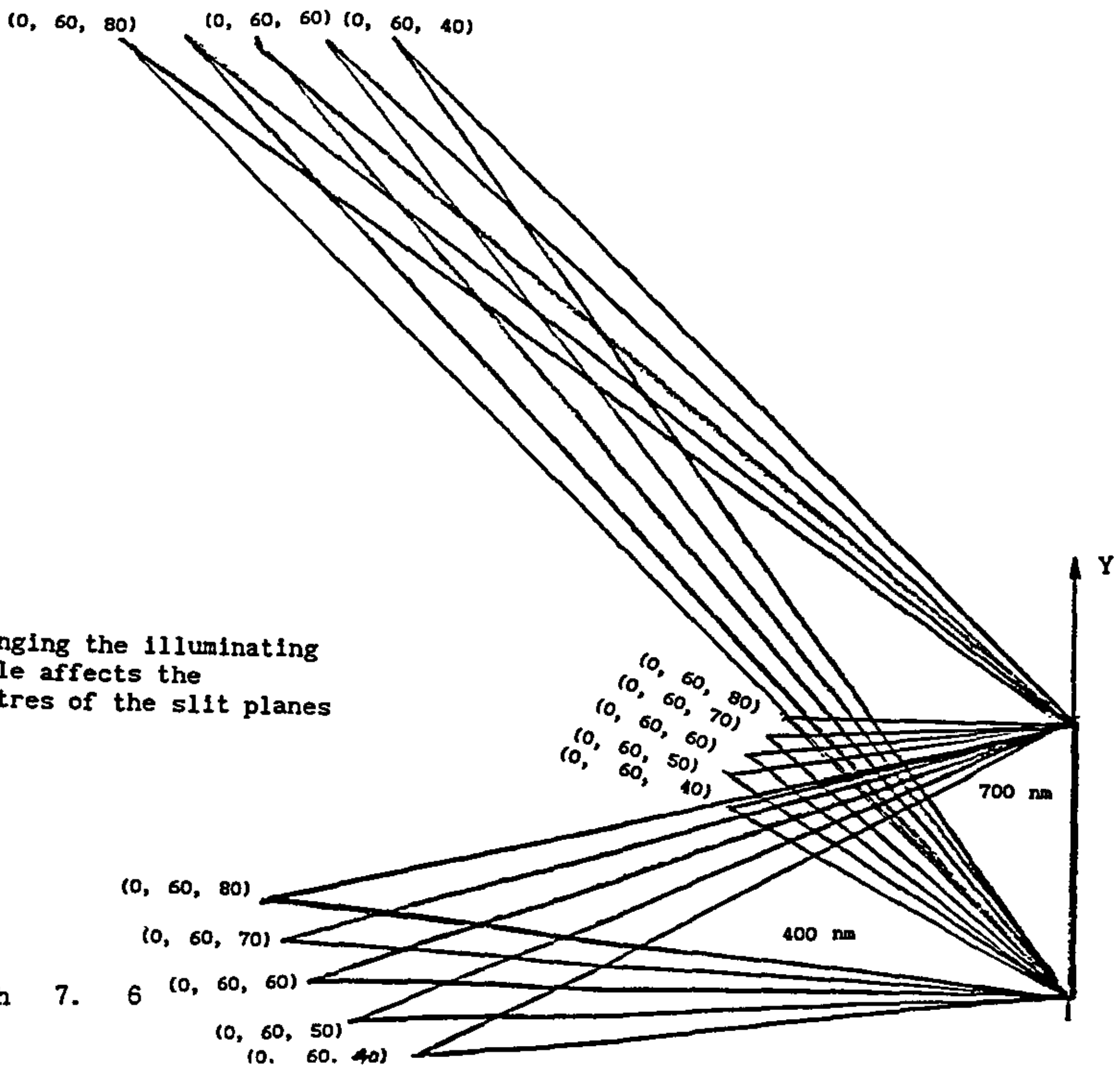
Graph 7. 4

Diverging white light illumination



Changing the illuminating distance affects the centres of the slit planes

Graph 7. 5



Changing the illuminating angle affects the centres of the slit planes

Graph 7. 6

CHAPTER VIII

SHAPE OF THE SLIT PLANE

If a white light source is used to illuminate the displaying multiplex hologram, all the wavelengths simultaneously produce real images of each slit plane in space in front of H_2. The slit plane is the window for the viewer of the hologram. Whether the slit planes are flat and parallel to each other ? It is important that a viewer sees a single perspective view in a wide range of colours or in an achromatic [26]. The following calculations are going to prove that those slit planes are neither flat nor parallel to each other.

For the rainbow hologram (for details see chapter 2), the image on H_2 is transferred from a slit masked master hologram. While it is reconstructed, the slits are formed in front of the H_2 similar to the process described for the multiplex hologram. The slits are not formed in a plane as shown in fig (8. 1) and fig (8. 2). Viewing from different heights or looking through different slits, the viewer can get different colours of the image. At certain heights there is only one appropriate slit and the shape of the slit can not affect the quality of the image although the slit may not be formed as a straight line at that height. The shape of the slit can not affect the rainbow hologram much because it is not expected to form an achromatic rainbow hologram. However, this provokes one way of thinking: what is the shape of the slit plane of multiplex hologram?

The achromatic multiplex hologram is an attractive way to get an uncoloured image. It is in accordance with the above idea of overlapping several colour slit planes to get an achromatic view while displaying. From the introduction of the achromatic images, the idea of the slit plane(s) has been set up. The diagrams show the prime and general figure of the slit plane(s) as shown in fig (8. 3). But is it true that the slit plane is a flat plane? The analyses and calculations are carried out below.

Supposing all parameters are the same as those introduced in subsection 7.1.1. If H_2 were illuminated with collimated laser light, every point on H_2 will contribute its own slit plane on the exact place where the H_1 was forming a whole and flat plane. The collimated white displaying light, however, reconstructs different slit planes because different wavelengths result in the spatial displacements of the slit planes. One colour of light forms its own slit plane, which also follows the formulae (7. 1), (7. 3) and (7. 4). Since the incident angles of the reconstructing light are constant in the X direction, as introduced in chapter 7, there is no displacement of the slit plane centres along the x axis. If the illuminating light has a wavelength identical to that of the laser, the slit plane should be flat and identical to the one reconstructed by a collimated laser light. But what happens for the other wavelengths? What are the shapes and locations of the slit planes?

As shown in fig (8. 4), the origin of coordinates is at the centre of H_2. Five points are chosen (0, 4, 32.5), (0, 2, 32.5), (0, 0, 32.5), (0, -2, 32.5) and (0, -4, 32.5). These five points are on the slit plane which is reconstructed by the same laser light as the reference light for transferring. Also five wavelengths are considered namely 700 nm, 590 nm, 514 nm, 450nm and 400 nm.

As it has been done before the top and bottom points on H_2 are used for calculation and their coordinates are (0, 10, 0) and (0, -10, 0), and for an incident angle $\alpha = \alpha' = 45^\circ$ and a wavelength of 700 nm, one obtains: project angle β_0 (for 514 nm). Different points can be worked out by the trigonometric formula: for the point (0, 4, 32.5) and the diffraction project angle from (0, 10, 0)

$$\beta_4' = \text{arc tan} (6 / 32.5) = \text{arc tan} (0.1846) = 10.46^\circ$$

the same point but the diffraction project angle from (0, -10, 0):

$$\beta_4'' = \text{arc tan} (14 / 32.5) = -23.30^\circ$$

using the same methods the project angles of the other points can be obtained. For the point (0, 2, 32.5):

from (0, 10, 0): $\beta_2' = 13.83^\circ$; from (0, -10, 0): $\beta_2'' = -20.27^\circ$

For the point (0, 0, 32.5):
from (0, ±10, 0): $\beta_o = \pm 17.10^\circ$

For the point (0, -2, 32.5)
from (0, 10, 0): $\beta_{-2}' = 20.27^\circ$; from (0, -10, 0): $\beta_{-2}'' = -13.83^\circ$

For the point (0, -4, 32.5):
from (0, 10, 0): $\beta_{-4}' = 23.30^\circ$; from (0, -10, 0): $\beta_{-4}'' = -10.46^\circ$

Bringing these data into the Eqs (7.3) and (7.4). One obtains the project angles of the appropriate point on the red slit plane: (the coordinate on Y axis is 4)

$$\begin{aligned}\beta' &= \arcsin [\ \sin \alpha' - 0.7 / 0.514\ (\sin \alpha - \sin \beta)\ ] \\ &= \arcsin [\ \sin 45^\circ - 1.3619\ (\sin 45^\circ - \sin 10.46^\circ\ ) \\ &= \arcsin (\ -0.0086\ ) \\ &= -\ 0.49^\circ\end{aligned}$$

and $\beta'' = \arcsin [\ \sin 45^\circ - 1.3619\ (\sin 45^\circ + \sin 23.30^\circ\ )\ ]$
$= -\ 52.63^\circ$

further $$\begin{aligned}D &= L\ /\ (\tan|\beta'| - \tan|\beta''|\ ) \\ &= 20\ /\ (\tan 52.63^\circ - \tan 0.49^\circ\ ) \\ &= 15.38\ \text{cm}\end{aligned}$$

Using the same methods other results can be obtained, please see the table (8. 1) and graph (8. 1). The data of other colours can be inferred; for the wavelengths of 590 nm, 514 nm, 450 nm and 400 nm. The tables (8. 2), (8. 3), (8. 4), (8. 5) and graph (8. 2) show the calculations and results respectively.

From these tables and graphs one may reach the following conclusions:

1. The longer the wavelength, the shorter the distance from the slit plane to the displaying hologram

2. A substantial part of the red slit plane is above the Z axis and a substantial part of violet's is below the axis. With the wavelengths tending towards 514 nm, the centres of the slit planes are getting closer to the Z axis

3. The slit planes formed by the collimated white illuminating source are not flat except for the wavelength which is identical to that of the transferring laser light.

4. The curve shape in x direction can be investigated using the same method as in y direction but one obvious difference is that the centres of slit planes do not deviate from the z axis because the incident angles are at constant 0°.

5. If the wavelengths are longer than that of the transferring laser light, the slit planes are concave-upward. The wavelengths are shorter and the slit planes are concave-downward.

6. No matter whether upward or downward, when the wavelengths are tending to the wavelength of the transferring laser light, the slit planes are getting flatter and flatter, please see the graph (8. 2)

7. Since usually the size of H_1 is bigger than that of H_2 and the deviations of the silt planes do not deviate too much from the Z axis, there is certain area near Z axis where several slit planes are overlapped. This implies that achromatic image can be seen in that area.

8. Different points on certain slit plane have different magnifications.

9. The shape of the slit is directly related to the wavelength. It can be seen clearly from the graph (8. 2) that the shape of the red slit plane varies from that of the green and violet ones.

10. The shape of the slit plane is also related to the wavelength of the transferring and recording laser light. If using red or violet coloured laser light, the shapes of slit planes will be very different

The study of the shape of the slit planes is helpful for making an achromatic multiplex hologram. Before starting, the recording and transferring multiplex hologram geometry can be planned. The overlapping areas of slit planes for achromatic images can be worked out. So the shape of the slit plane is another important parameter for making and displaying the multiplex hologram.

In the next chapter, the apparatus for making a master hologram, optical geometry the and computer control systems are introduced. Some detailed description of the slit holder is also given.

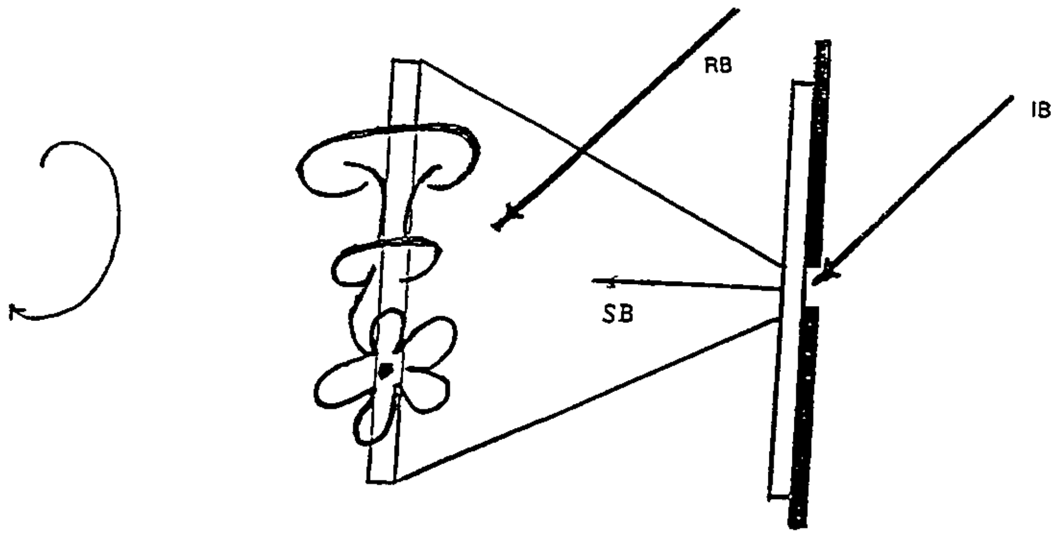


Figure 8. 1

Recording a rainbow hologram

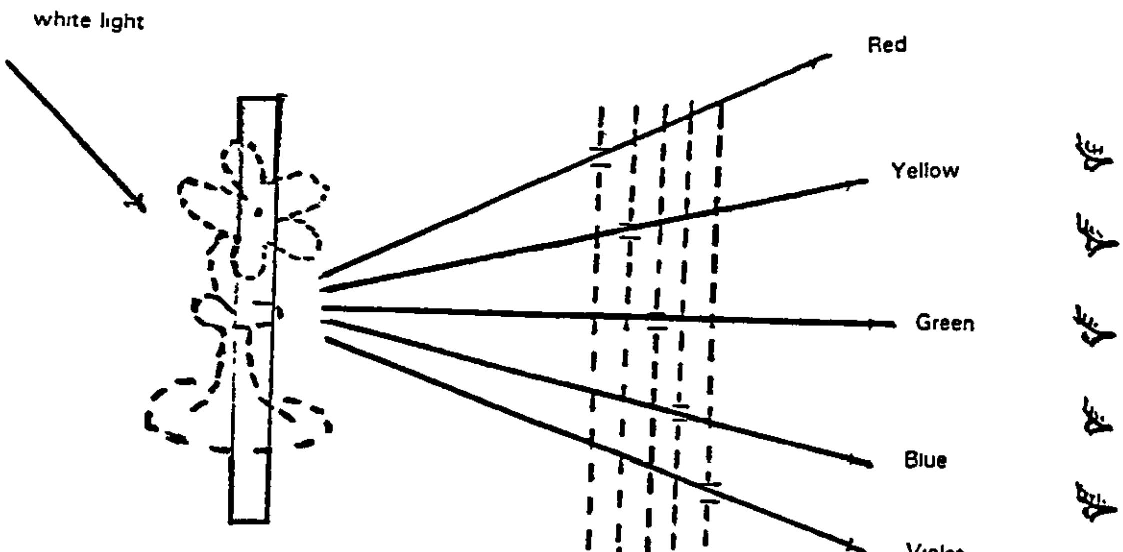


Figure 8. 2

Viewing a rainbow hologram

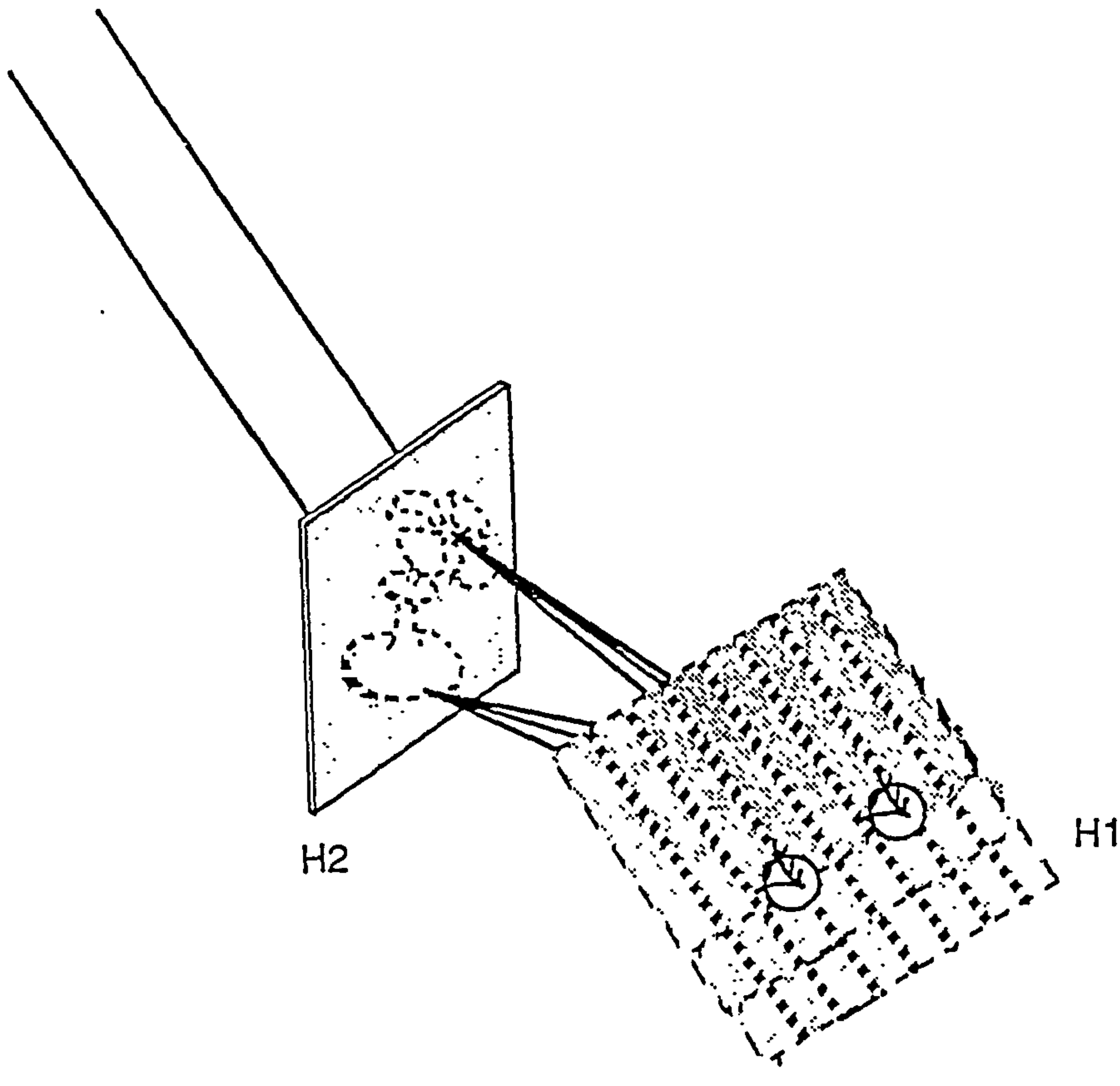


Figure 8. 3

For the conventional consideration, an achromatic image can be obtained by looking through overlapped flat slit planes

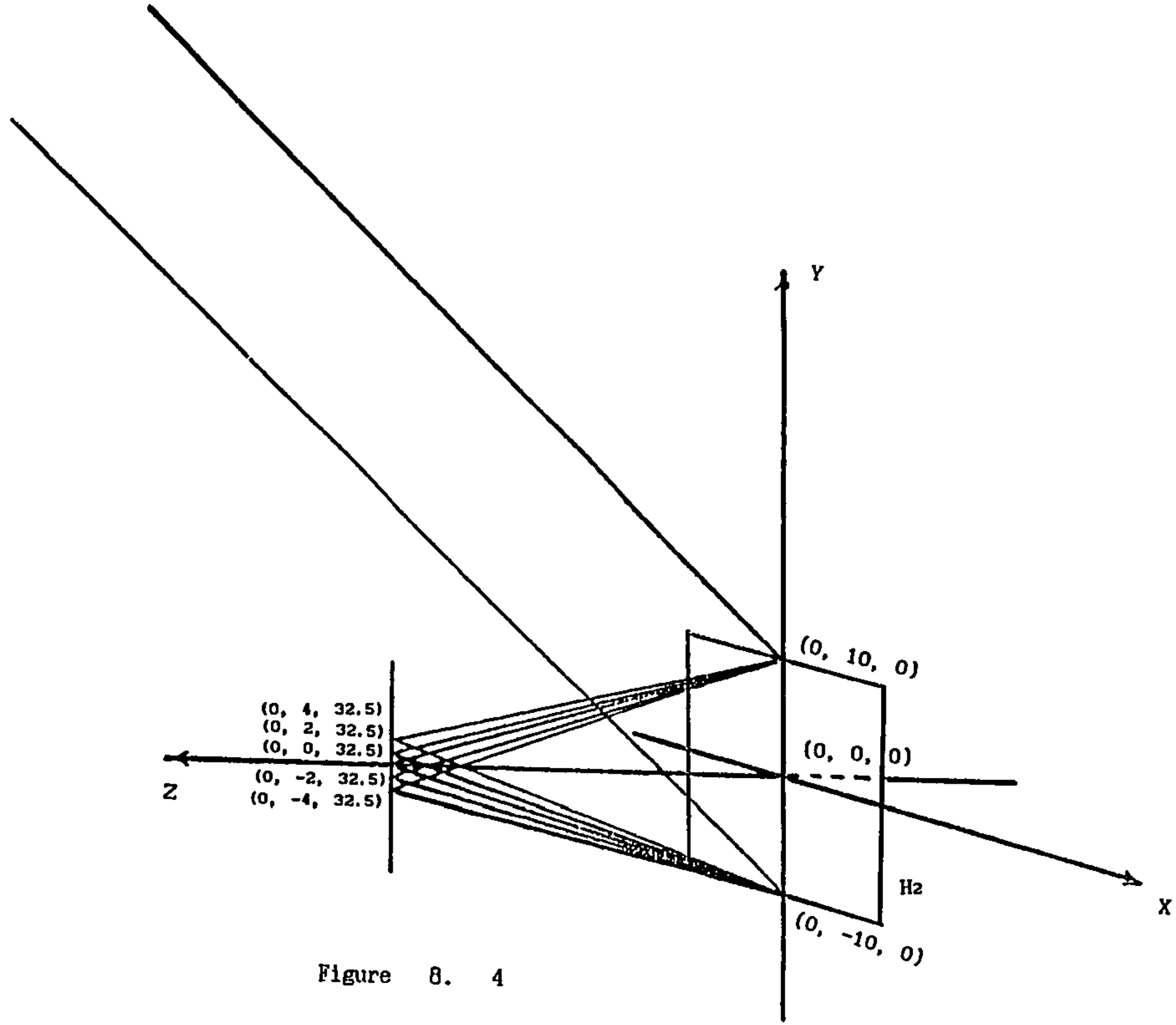


Figure 8. 4

A collimated laser light source reconstructs H2 and forms a slit plane at the place where H1 was. When collimated white illuminating H2, the shape of the slit planes will be curved

Shape of Slit Plane

Table 8. 1

Wavelentgh 700 nm Incident angle 45°

Coordinates	β'(°)	β"(°)	D (cm)
0, 4, 32.5	- 0.5	-52.62	15.38
0, 2, 32.5	4. 49	-46.67	17.56
0, 0, 32.5	8.30	-41.02	19.69
0, -2, 32.5	12.46	-35.55	21.38
0, -4. 32.5	16.43	-30.21	22.80

Shape of Slit Plane

Table 8 2

Wavelentgh 590 nm Incident angle 45°

Coordinates	β'(°)	β"(°)	D (cm)
0, 4, 32.5	5.96	-33.96	25.71
0, 2, 32.5	9.78	-30.14	26.56
0, 0, 32.5	13.47	-26 24	27.31
0, -2, 32.5	17.04	-22.27	27.93
0, -4, 32.5	20.46	-18.24	28.46

Shape of Slit Plane

Table 8. 3

Wavelentgh 514 nm

Incident angle 45°

Coordinates	β'(°)	β"(°)	D (cm)
0, 4, 32.5	10.46	-23.30	32.50
0, 2, 32.5	13.80	-20.27	32.50
0, 0, 32.5	17.10	-17.10	32.50
0, -2, 32.5	20.27	-13.80	32.50
0, -4, 32.5	23.30	-10 46	32.50

Shape of Slit Plane

Table 8. 4

Wavelentgh 450 nm

Incident angle 45°

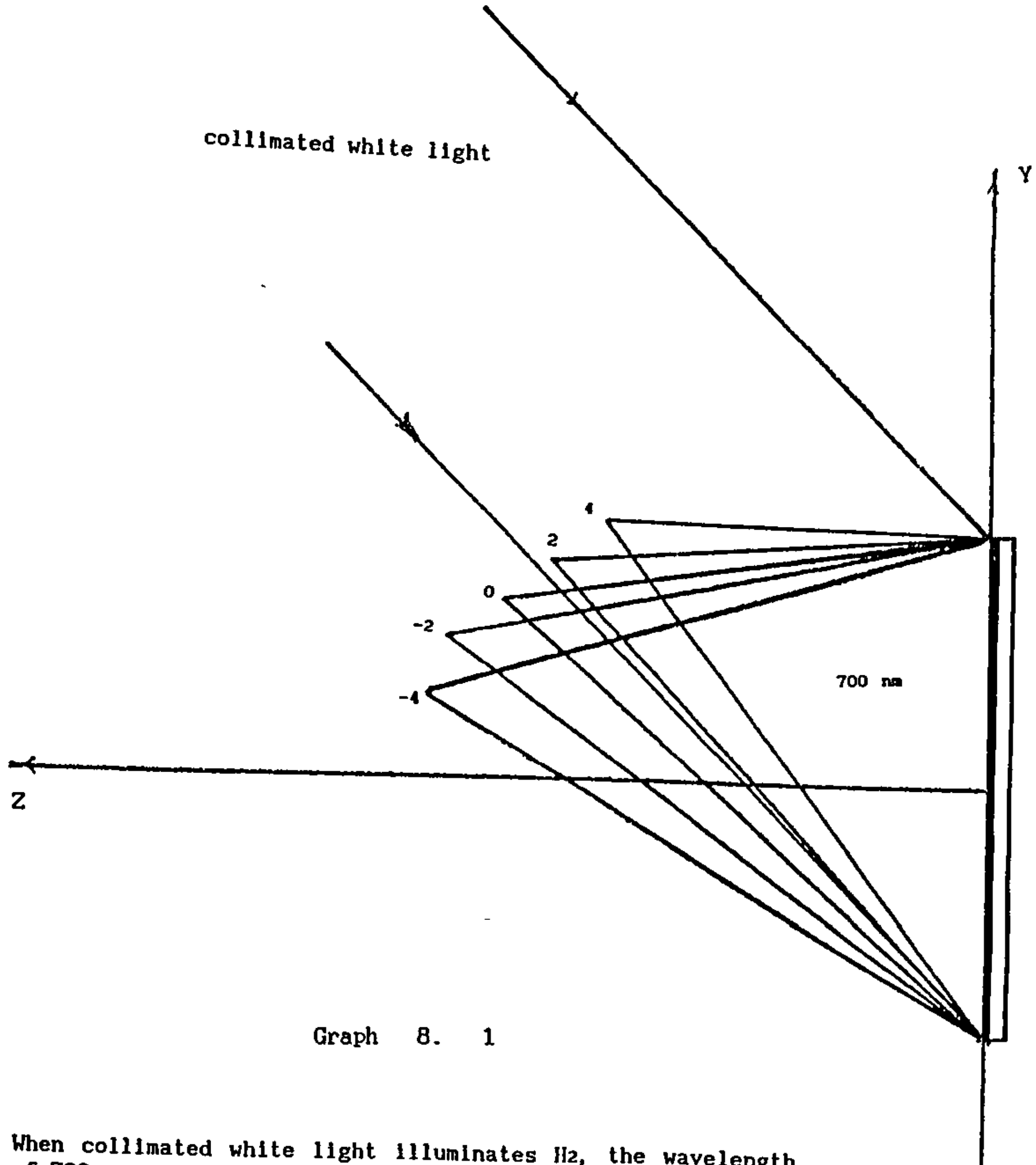
Coordinates	β'(°)	β"(°)	D (cm)
0, 4, 32.5	14.30	-14.97	38.29
0, 2, 32.5	17.30	-12.43	37.60
0, 0, 32.5	20.21	-9.76	37.03
0, -2, 32.5	23.04	-6.96	36 54
0, -4, 32.5	25.75	-4.06	36.15

Shape of Slit Plane

Table 8. 5

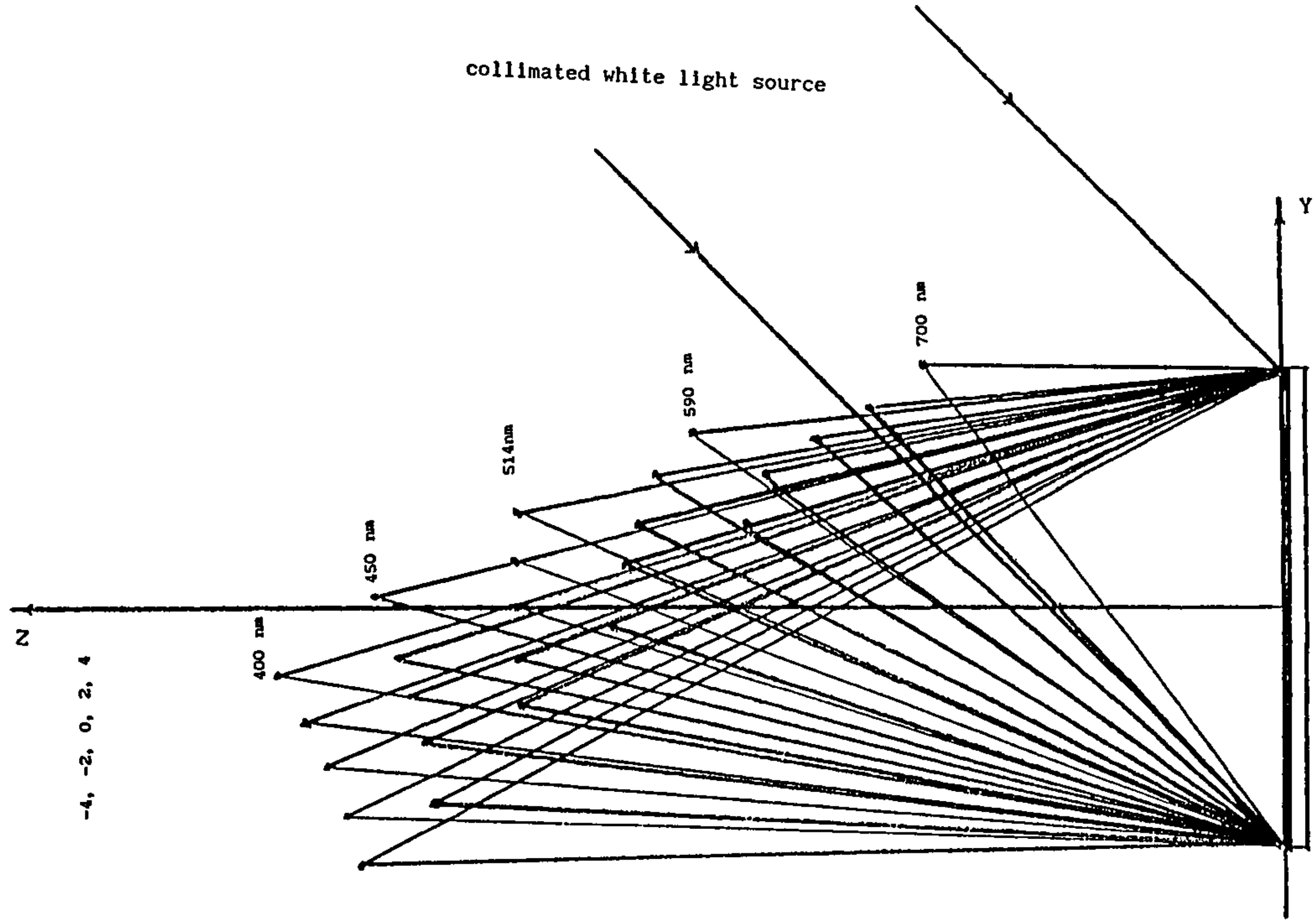
Wavelentgh 400 nm　　　　Incident angle 45°

Coordinates	β' (°)	β'' (°)	D (cm)
0, 4, 32.5	17.43	-8.69	42.84
0, 2, 32.5	20.35	-6.47	41.30
0, 0, 32.5	22.69	-4.13	40.79
0, -2, 32.5	25.23	-1.67	39.97
0, -4, 32.5	27.83	0.9	39.28



Graph 8. 1

When collimated white light illuminates H2, the wavelength of 700 nm forms a curved slit plane



Graph 8. 2

Curved slit planes are formed for different wavelengths

CHAPTER IX

EXPERIMENTAL APPARATUS

In this chapter the apparatus, used for making multiplex holograms, including the optical system, the mechanical hardware and the electronic control system, are introduced as well as the purposes and techniques

9. 1 GENERAL INFORMATION ABOUT THE MULTIPLEX HOLOGRAPHIC SYSTEM

All the experiments were carried out on a 3 m wide and 6 m long concrete bench which sat on an air-filled-tyre tube base to prevent vibration. Plastic curtains were hung around the bench to prevent the drift interference fringes caused by wind. Outside the plastic curtain, several rubber sound proofing curtains were hung for reducing disturbances due to sound.

The optical system was composed of a Spectra Physics 170 Argon ion laser, an object beam and a reference beam system including a collimated mirror and a film transport system with a diffuser screen, a plate and a slit holder system and a computer control system. After being exposed, the multiplex holographic plate would be processed in a dark room. All these systems will be introduced in the next few subsections.

9. 2 OPTICAL SYSTEM

The optical geometry for shooting the multiplex master hologram H_1 has been briefly described in chapter 4. Its layout is as simple as that of the split beam transmission hologram. There are only three obvious differences between them. First the reference beam is collimated because the master hologram has to be flipped in order to form a real image transfer hologram H_2 and to avoid distortion. It is necessary to use a reconstruction beam that is the conjugate of the original reference beam. It is very difficult to get a conjugate light if the reference beam originates from a diverging light source. However a conjugate collimated light beam is also a collimated beam. So one uses the reference beam and flip the master hologram during transferring. Secondly there is the object. A series of images are projected from cinema photographs onto a diffuser screen instead of the real and solid object used in a conventional transmission hologram. Finally there is the master holographic plate which is masked off by a moving slit for recording the series images in one individual strip hologram after another.

9. 2. 1 OBJECT BEAM

As shown in fig (9. 1) the output of a Spectra Physics 170 Argon ion laser was reflected by optical mirrors M_1 and M_2 and then divided by using the beam splitter B_s. One beam went straight ahead to form the object beam and the other went towards mirror M_6 to form the reference beam. The object beam was reflected by mirrors M_3, M_4, M_5 and went through a ten times microscope objective and a pinhole (O_{B1} and S_{F1}), which had a precision x, y positioners and a focus adjuster. The pinhole spatially filters the beam which was allowed to expand up to a diameter of 5 cm before being collimated by a 5 cm in diameter and 15.5 cm of focal length bi-convex lens L_1. Actually the lens had another function. It acts as a spatial filter, too, to obtain a uniform distribution of intensity. The light source of 5 cm in diameter was large enough to cover all of the 35 mm frame. It was then directed through the film transport F_T. Subsequently it was focused into an enlarger lens and projected with the image recorded on the frame onto a ground glass diffuser screen Ds. This image now constitutes the object for the recording of the hologram.

9. 2. 2 REFERENCE BEAM

The reference beam has been mentioned in the above subsection. That part of the laser beam which was divided by the beamsplitter Bs and went towards mirror M_6 forms the reference beam. After being reflected by M_6, it went through a set of microscope objectives and pinholes as described above and then was reflected by a collimated mirror C_M which has 60 cm in diameter. Because the size of the holographic plate was 30 * 40 cm (30 in horizontal direction while recording and transferring but not displaying), the diameter of the reference beam now should be larger than 50 cm to cover the whole holographic plate.

As shown in fig (9. 1), the reference beam was falling onto a holographic plate at the Brewster angle which will be introduced in the next chapter. In front of the holographic plate both the object and reference beams were prepared. When the shutter S_H was lifted, a strip hologram would record one image from the diffuser screen holographically.

In fig (9. 1), F_1 (with a rather small aperture) and F_2 were the spatial filters used to obtain a uniform intensity distribution of light, to filter out any unnecessary light and to prevent reflecting laser beams into the laser. This would cause an instability of the laser. (It is equivalent to changing the length of the resonant cavity of the laser.) P_{z1} and P_{z2} are polarizers which were used for adjusting the polarizing orientations of both the incident light beam and the reference light beam. The Effect of the polarization will be discussed in (10. 1. 3). S_M was a stepper motor which controlled the slitholder system and moved the slit to the requested position.

The intensity ratio between object and reference lights was 1:8 in the experiments. This ratio could be easily obtained by adjusting the beam spitter B_s. A power meter should be used for testing the intensities of incident light and reference light. It was noted that in our experiments the sensor of the power meter was always facing either the incident light or the reference light. [46]

9. 3 SLIT

Before introducing the plate and slit holder system, the key part for making a good multiplex hologram glass slit should be clearly described. The techniques for making glass slit and soft edge slit are also introduced.

9. 3. 1 MAKING A GLASS SLIT

The key step for making a good master hologram is to manufacture the slit. When making a glass slit, one first requires a mask. This mask could be made from either solid materials, coloured plastic, tapes or computer designed patterns. It is easy to choose the material, colour, shape and pattern according to the necessity. Colour for example, if the holographic plate was red light sensitive, then the dark green colour materials could be chosen. Putting the ready made mask on a holographic plate, exposing, processing, and then, a contact copied glass slit could be obtained. With this method we could easily get a sharp edge slit.

9. 3. 2 SOFT EDGE SLIT

We can make soft edge slits which darken gradually from the middle to the edge of the slit. There are two methods for making a soft edge slit; diffraction and computer design. In this thesis, only the diffraction way of making a soft edge slit is introduced. If the mask and the holographic plate are separated (not in contact) by a certain distance and exposed, a slit results for which most of the area in the middle is transparent. Near the edges two grey spaces are located which get darker and darker until they become opaque. This phenomenon followed the Fresnel's diffraction law and the Cornu-spiral [47]. Then one obtains the following equations:

$$v = 197.25 * (D_s / D_c^{1/2}) \qquad (9.1)$$

where v is the variable in the Fresnel integrals and the value can be obtained form Cornu-spiral, D_s is the distance which the diffraction light reaches and D_c is the distance between the mask and the holographic plate. After finding out the magnitudes of v and the unobstructed incident light V, one can insert these data into the equation below:

$$P = (v / V)^2. \qquad (9. 2)$$

Where p is a ratio which is determined by the intensity of the diffraction light compared to the intensity of the incident light. This equation is derived under the following conditions: (a) The wave length of the incident light is 514 nm. (b) The incident light is well collimated so that the distance between the mask and the holographic plate r_o can be ignored when it is compared with the radius of light source R. If the width of the grey space and the ratio between the intensities of the incident light and the diffraction light are determined, the distance between the mask and holographic plate could be easily worked out.

9. 4 PLATE AND SLIT HOLDER SYSTEM

For making better and brighter multiplex holograms, the plate and slit holder system should have the following functions: 1) The whole system guarantees that the signal light and reference light can come through and interfere with each other on the emulsion plane; 2) The system is stable enough while shooting; 3) The system ensures that the slit moves up and down smoothly and precisely; 4) The parallel orientation and distance between the slit and the holographic plate should be kept; 5) All the parts (in the slit holder system) could be changed easily.

As introduced in subsection 9.2.2, the diameter of the collimated mirror was 60 cm from which a diameter of more than 50 cm reference beam could be obtained. This reference beam could cover the whole holographic plate. Because the reference beam was a collimated light source, it would not form a shadowing effect at all. However the signal light exactly faced the slit (see photo 9.1), so we had to consider the incident light coming either from the top or from the bottom of the image. It should reach every point of the strip hologram. As discussed in section 7. 9, for the extreme cases the maximum angle could be worked out as 45° (the slit was at the top position and the incident light came from the bottom and it was the same if the slit position was at the bottom). That means everything in the slit holder system could not block the signal light coming through from the angle of 45°. In this system, the slit holder was designed to accept the coming light from 45° and larger, which made sure that the slit could accept a large image from diffuser screen with a fixed distance between the slit and diffuser screen. This is shown in photo (9. 2) and (9. 3).

The collimated reference light fell on the holographic plate with the incident angle of 57° (Brewster angle) as shown in fig (9. 1). As discussed before the laser light was linearly polarized. While falling on the glass slit, 100% of the reference light would be transmitted to the holographic plate. This has two advantages; firstly, all the energy of the reference light was absorbed by the emulsion; and secondly, there is no reflected light. The reflected light may result in background noises. Since all the frames and post on the left side of the slit holder had about 60 degree tilt, it would never be a barrier for the reference light. The designation of the slit holder could guarantee both the signal light and reference light falling on the strip holograms and interfere with each other.

There were two tufnol posts fixed on a very heavy metal base. Along each of the posts, there was a small ridge (about 5 mm) to prevent the plate from falling out and behind the plate there was an angle bar for clamping it. These devices ensured the stability of the holographic plate. Also along the other side of each post, there were a pair of steel rails and slides which were able to locate the slit holder within a horizontal plane. These parts of the device allowed the slit holder to move up and down smoothly and kept both the plate and the slit system stable during exposures. How did the slit holder keep the distance and parallel orientation between the slit and the holographic plate? The glass slit was glued on two aluminium bars which were also glued on four very sleek steel rods. These rods were covered by four springs which were seated between the bars and the inert frame and let the rods get through the four allocated holes on the four corners of the inert frame. There were two turning frames (designed like a campus), an inert one and a middle one. The inert one was able to let the glass slit turn freely around a vertical axis and the middle one turns around a horizontal axis. All of these axes were fixed precisely by a pair of bearings and their screw supports as shown in photo (9. 4).

The outer frame had two major functions; one was to fix itself and other frames on the steel rails so that the distance between the holographic plate and the frames were fixed; the other was to fix the moving distance of the slit as determined by the moving distance of the outer frame. The outer frame was connected to an accurate positioning device, and the strip holograms could be shot one after another.

The campus-like middle and inner frames helped to keep the distance between the holographic plate and the slit when the plate was not parallel to the glass slit. The inner frame was able to turn $\pm 3^{\circ}$ in the vertical direction and the middle one turned $\pm 3^{\circ}$ in the horizontal direction. The four springs between the bars were connected by four small rods. The inner frame forced the glass slit to touch the holographic plate evenly. Two strip PTFE tapes fixed on two shorter ends of the glass slit were designed for keeping and adjusting (because the thickness of the tapes could be varied) the distance between the plate and the slit. This prevented the scratching of the emulsion. If there was a small distance change or tilt between the slit and the plate during the series of exposures, the springs and turning frames would adjust the slit automatically and keep the even and smooth tapes at both ends of the slit contacting the plate closely and evenly to ensure parallel orientation.

The glass slit was glued onto the aluminium bars and these bars were also glued onto the four short sleek steal engaging rods. At the other ends of the rods, small stopping pins were fixed to stop the rods from falling back. The engaging rods got through four holes with sleek brass bushes in the inner frame. The coaxial (with engaging rods) springs were located between the bar and inner frame. If the slit needed to be replaced, one had to undo the stopping pins and take the glass slit, the bars and the four rods out. Then all of them could be renewed and refixed easily.

There are several other important pieces of equipment which have to be introduced here. The whole positioning control system of the slit holder was composed of a pulley system, a stepper motor, a computer and an interface. The pulley system held the slit holder moving along the rails vertically. There was a pair of wire ropes connecting the slit holder with the stepper motor. The commands of the computer program were sent to the interface and executed by the stepper motor. The slit holder moved a precise predetermined distance .

9. 5 COMPUTER CONTROL SYSTEM

The experiments were carried out under the control of a BBC Master computer. An analogue digital converter which was suitable for the BBC computer was used to connect the computer with the electronic devices. The computer controlled not only the stepper motor but also an exposing shutter and the film projector respectively. Before the first exposure, one had to wait for a relatively long time to allow the bench vibrations to die out. Then the computer gave a 10ms pulse to trigger the exposure. After that it would turn on the film transport, advance one picture and then turn it off. The last step was to send a command to the stepper motor to move the slit to the place for exposing the next strip hologram. After waiting for a shorter period of time (compared to the waiting time for the first exposure), the computer was ready to perform another exposure.

9. 6 MULTIPLEX HOLOGRAM PROCESSING SYSTEM

The holographic plates used in the experiments were Agfa-Gevaert(Holotest), 8E56HD plates. Their dimension was 30 by 40 cm^2 and its spectral sensitivities were in the blue and green range. This kind of holographic plate matched our Argon ion laser (the laser was able to emit blue light and green light). Because the intensity of green light was much stronger than that of blue light (considering the stability of laser and the holographic bench), the green laser 514 nm was chosen in the experiments.

Ready made CODAK HRP developer and KODAK Replenishing fixer (liquids) for holographic plates were used. One CODAK developer mixed with two portions of distilled water and one fixer mixed with four portions distilled water. The developing temperature was restricted at 20° C. So a temperature controller was needed. The safe light for 8E56HD should be red and several bath troughs and running water troughs were equipped. For drying the plates, methanol and plate racks were necessary.

When processing multiplex holograms, the plate was developed for 90 seconds, washed with running water for 3 minutes, fixed for two minutes and washed again with running water for ten minutes. For drying the plate; they were placed into 50% Methanol plus 50% distilled water for 3 minutes and then into 100% Methanol for three minutes. Top edges were wiped with lint free tissue, then pure Methanol was squirted to dislodge dust before leaving it to dry. The plate was then placed in a suitable rack and transferred to the drying cabinet immediately.

While making sharp edged or soft edged glass slits, the processing steps were nearly the same. However, one difference was that the light source was white light projected from a photographic enlarger. Before the exposure the uniformity of the intensity on all sides should be measured. The following steps were developing, fixing and reducing. A special high contrast developer was used

Metol	2g	Sodium sulphite anhyd	90 g
Hydroquinone	8g	sodium carbonate anhyd	45 g
Potassium bromide	5g	Distill water	1000 ml

The fixer was

sodium thiosulphate	100 g	ammonium chloride	10 g
distilled water	1000 ml		

The reducer was

stock A	sodium thiosulphate anhydrous	100 g
	distilled water	2000 ml
stock B	potassium ferricyanide	6 g
	distilled water	60 ml

Stock A and stock B could be mixed up only a few minutes before reducing the plate. If it was kept for a long time, the result would be not as good as expected. The reducing time was 20 seconds. [48]

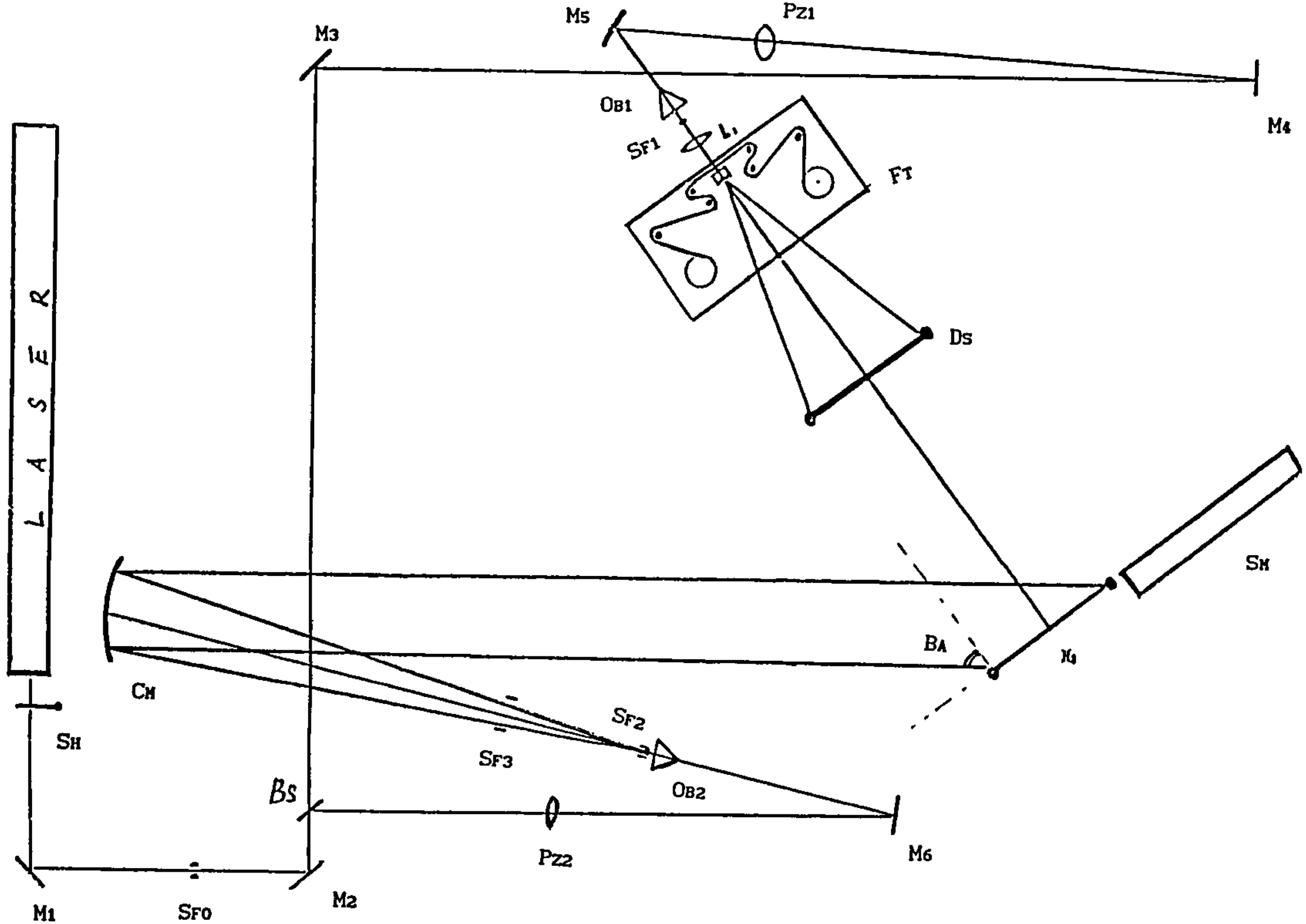


Figure 9. 1

The optical geometry of a multiplex hologram. Sh -- shutter, M1-M6 -- reflection mirrors, Sf0-Sf3 -- spatial filters Ob1-Ob2 -- objectives, Pz1-Pz2 -- polarizers, Ds -- diffuser Cm -- collimated mirror, Ft -- film transporter Sm -- stepper motor, Ba -- Brewster angle

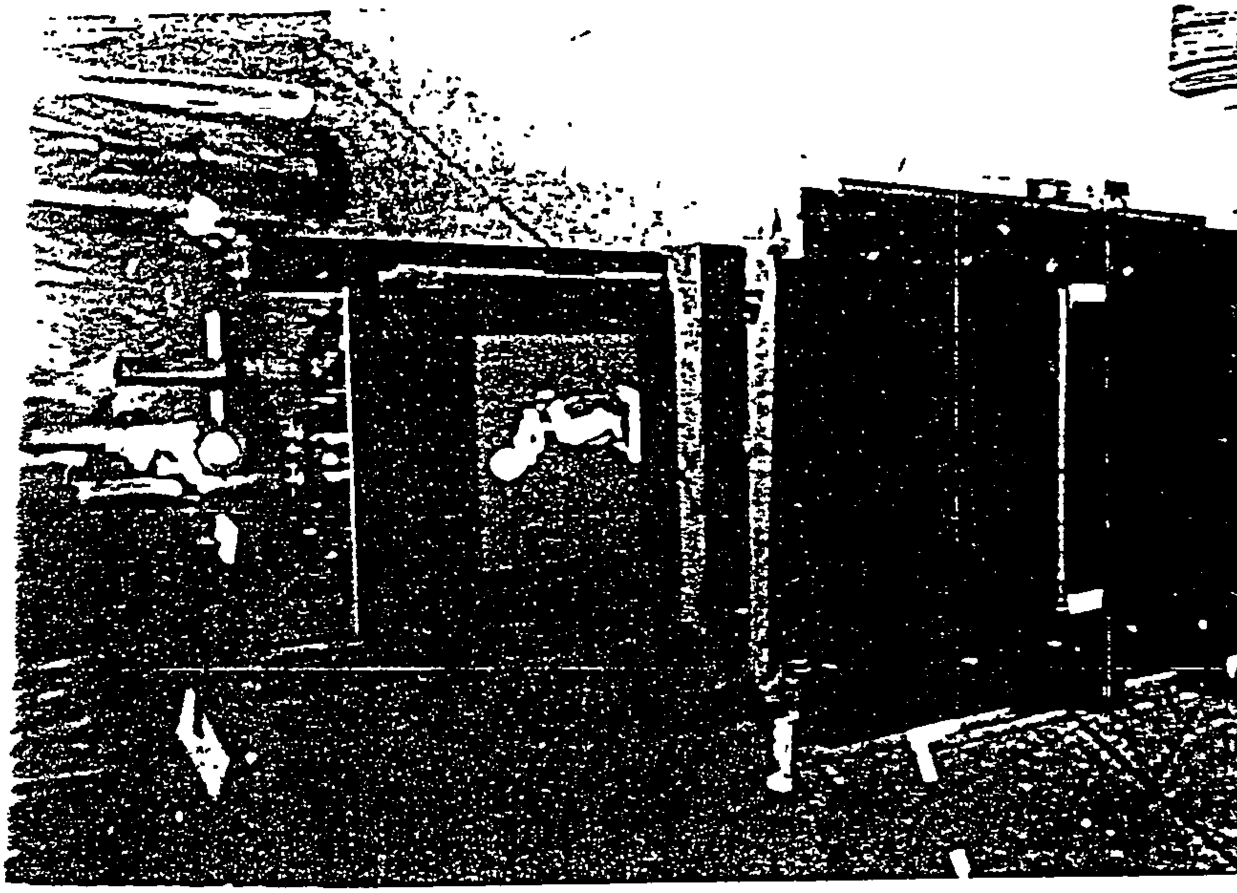


Photo 9. 1
Signal beam path and devices

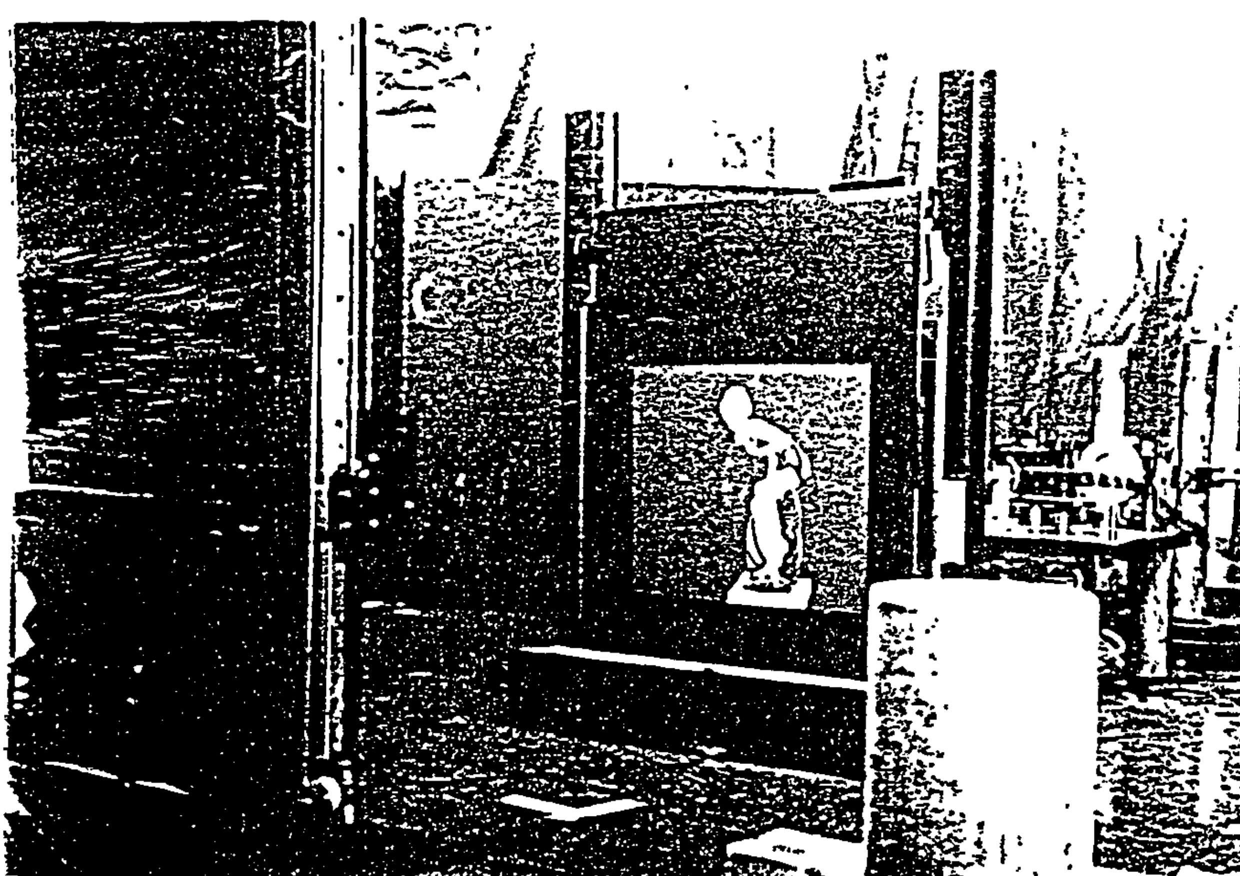


Photo 9. 2
Image on diffuser screen and the slitholder system

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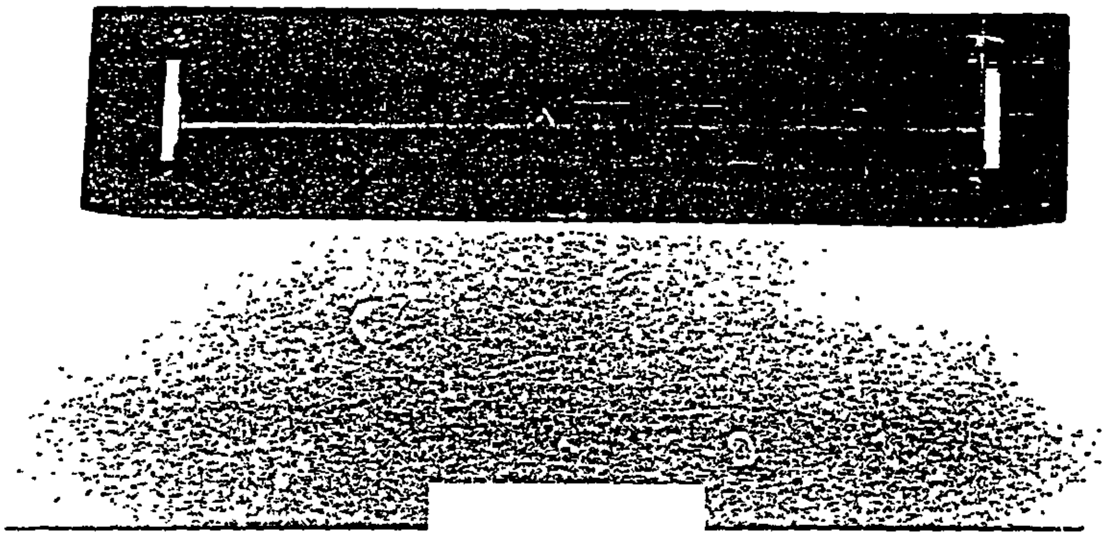

Photo 9. 3

The inner frame of the glass slitholder

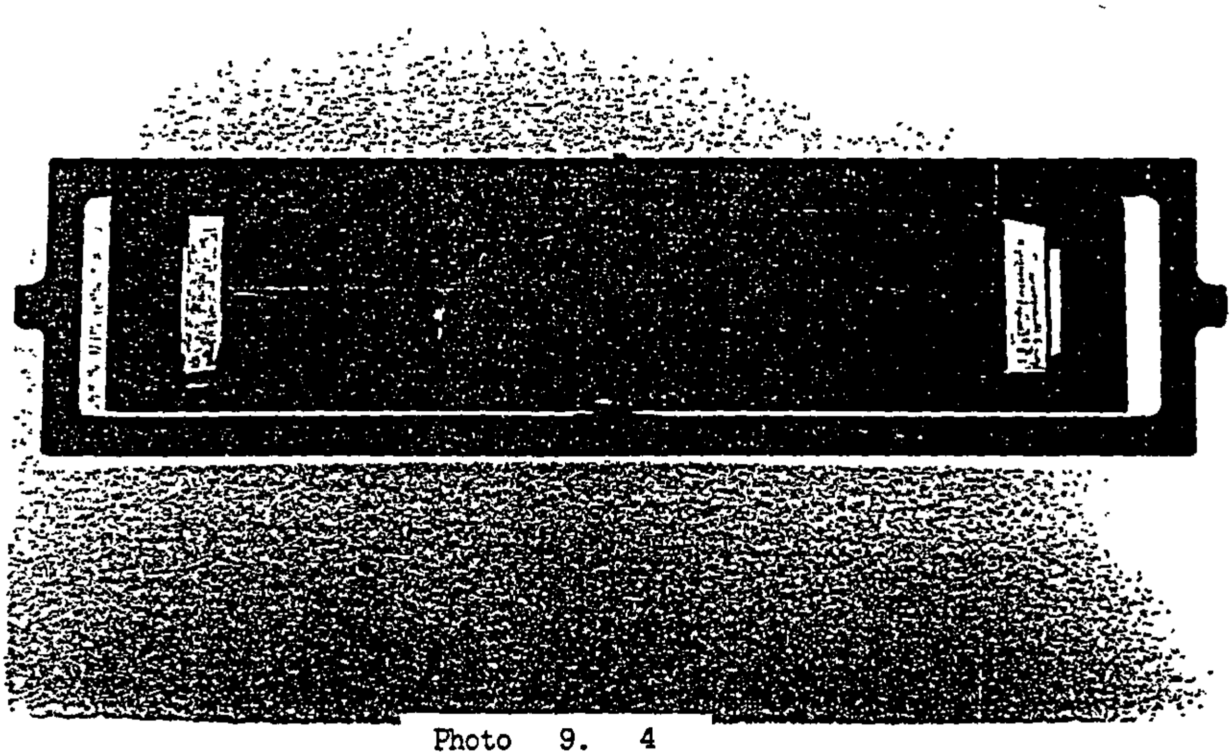

Photo 9. 4

The inner, middle and outer frames of the slitholder

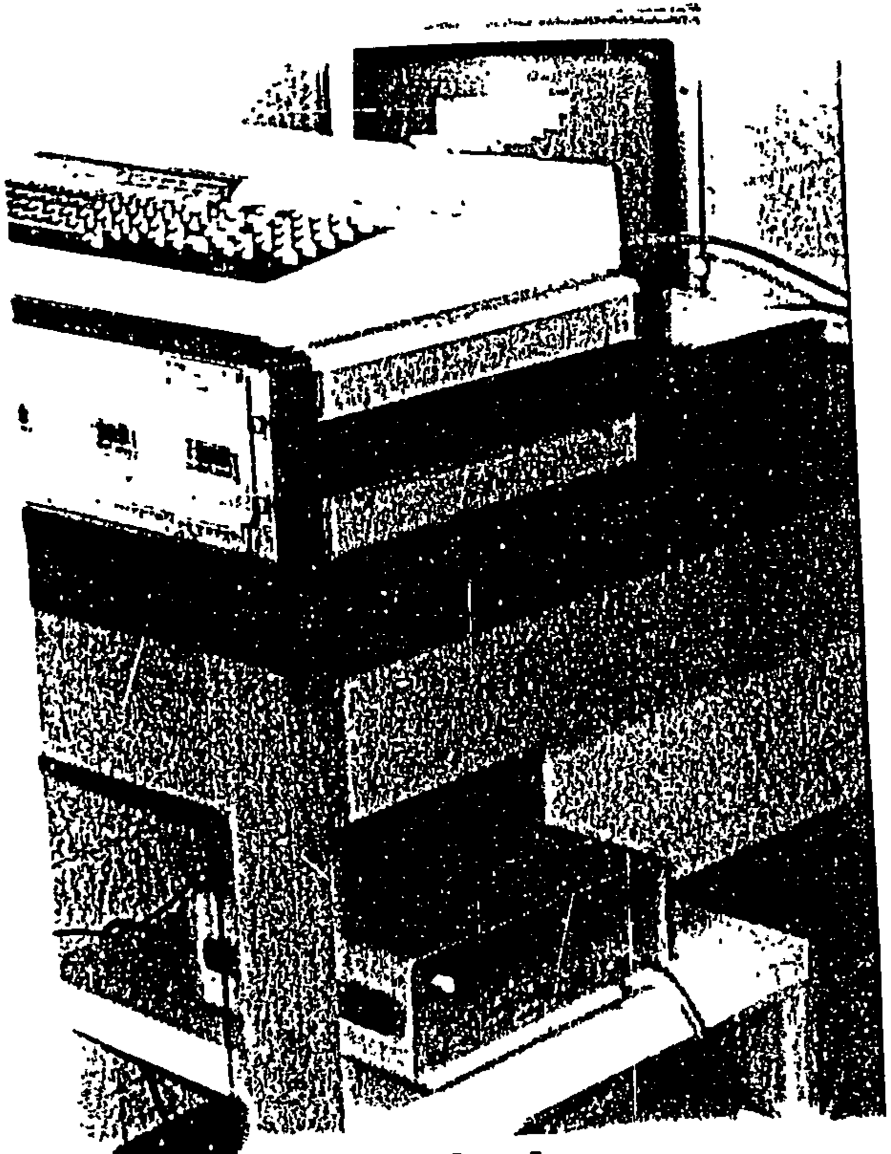

Photo 9. 5

computer control system

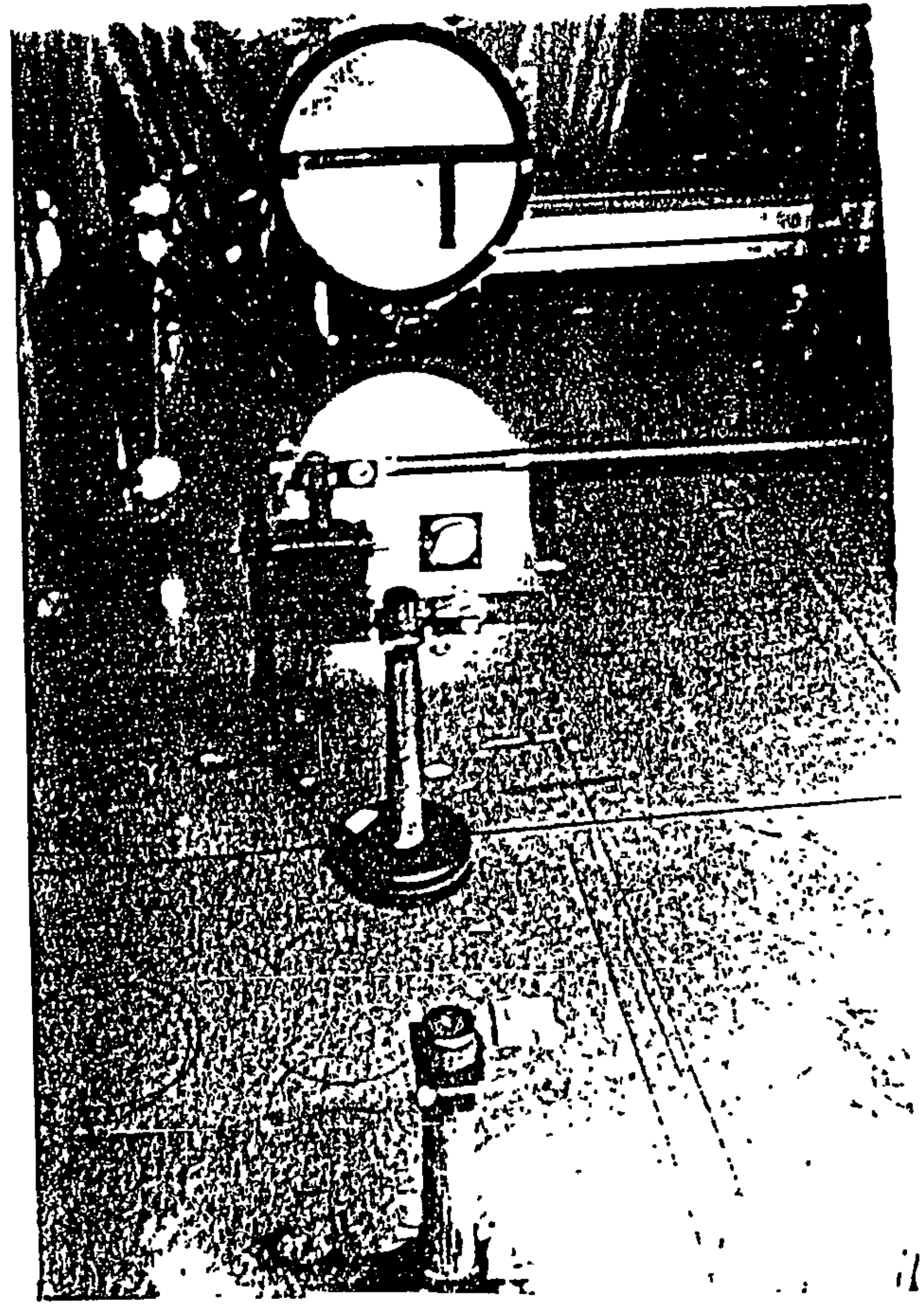

Photo 9. 6

Reference beam path and devices

CHAPTER X

RESULTS AND DISCUSSIONS

10. 1 <u>OPTICAL GEOMETRY</u>

The optical devices provided by the Advanced Holographic Laboratories at the Physics department of Loughborough University could meet the requirements of making multiplex hologram. The optical layout was well designed, calculated, measured and arranged. The whole system was tested to ensure it could make high quality holograms. During setting the optical geometry, several factors for making a successful multiplex hologram were considered.

10. 1. 1 HEIGHT CONSIDERATION

For a simple geometry to make an ordinary hologram, it is very easy to adjust every device at the same height. For the multiplex hologram, some of the big and heavy devices can not be easily adjusted in a large range or they may even not be adjustable at all. The height of the collimated mirror was fixed. The laser should not be too high above the bench. The film transport, the diffuser screen and the plateholder were also very difficult to adjust.

Since the height of the collimated mirror was fixed, its height was taken as a reference point. Every optical component had to be centred according to this height with the exception of laser. After the laser beam had been divided by the beamsplitter B_s, both the object beam and the reference beam were raised by two pairs of mirrors which ensured that these beams had the same height as the collimated mirror. M_4 and M_6 were two pairs of reflection mirrors. Each pair were fixed on the same post with the correct heights and angles to reflect the laser light at the same height compared to the the height of collimated mirror Hc.

10. 1. 2 COHERENT LENGTH CONSIDERATION

Both the object light and the reference light finally reached the holographic plate and interfered with each other on the emulsion surface. All the information would be recorded by the interference fringes. One of the important factors affecting the result of the recording was the coherence length. If the difference between the signal and the reference light paths was longer than the coherence length, it was impossible to obtain a good hologram or interference fringes. Although the light source from Spectra Physics 170 Argon ion laser had a very long coherence length, if the difference between the two light paths was relatively long, the quality of the hologram was not as good as desired. Usually the path difference was confined to a few centimetres or less.

After being divided into two branches by the beamsplitter B_s (see figure 9. 1), the reference light path would be much longer than that of the signal light path if the signal light from M_3 were directly reflected by M_5. So M_4 was needed to expand the signal light path a little more than 5 m. M_4 had a very large range for the adjustment of the light path.

10. 1. 3 POLARIZATION AND BREWSTER ANGLE CONSIDERATIONS

Laser light is linearly polarized or p-polarized, a property which is important for making a successful hologram. The planes of polarization of both signal and reference beams should be in the same plane. Otherwise they would not be able to form strong interference fringes. If the planes of polarization were at right angles to each other, no fringes would be formed. In order to align the polarization angles, two polarization rotators were introduced into the geometry. Pz_1 and Pz_2 were used to make the two planes of polarization coincide with each other.

Positioned the polarization rotators in both beams respectively, then carded off the signal beam. The polarizing filter was located at the plane of the holographic plate. The filter was rotated such that its orientation was parallel to the horizontal plane (for Brewster angle consideration). The polarizer Hw_2 was rotated until the light which was passing through the filter was at its brightest. Now carded off the reference beam instead, then using the same procedures, the signal beam was examined and adjusted with its plane of polarization parallel to the horizontal plane. In this way, the optimum conditions for producing interference fringes had been obtained.

Another purpose was served with the adjustment of the plane of polarization of the reference beam. From fig (9. 1), it could be seen that the holographic plate was placed at a certain angle of about 57° with respect to the reference beam. This angle is called the Brewster angle. If polarized light with its plane of polarization parallel to the plane of incidence falls on a piece of glass and the incident angle measured with respect to this piece of glass sets at the Brewster angle, nearly all the light is transmitted. So the reference beam would go through the holographic plate without reflection which could save a lot of energy. This is especially advantageous for a glass slit in front of the holographic plate. Further non-reflection was able to largely reduce the background noise.

However, during shooting the series of strip holograms, it was found out that some of the holograms were good and the diffraction efficiency was high but some others were not. The probable reasons were:

1. The laser was not stable enough and the power of its output was not a constant.

2. The waiting time between two adjacent exposures was not long enough or the bench was not stable while shooting the next hologram.

3. Certain optical devices were not stable such as mirrors, objective lens, film transporter and so on.

4. Outside influence, such as sound, wind, vibration and so on.

10. 1. 4. BEAM RATIO CONSIDERATION

The beam intensity ratio of the reference beam to the signal beam is a variable which may be adjusted for making different holograms. If the ratio (r : s) is low, 2 : 1 or 3 : 1 for example, the total intensity of both beams is too weak to make a multiplex hologram. One needs a very long exposure time. This should be avoided. In contrast, if the ratio is too high, the signal beam is too weak. This affects the forming of the interference fringes and affects the quality of the image. The beam ratio used in the experiments was 8 : 1. This ratio is still relatively high. The future work, a typical ratio of 5 : 1 should be used. In the experiments, the beam ratio was obtained by adjusting the beamsplitter Bs which was composed of a quarter wave plate, a Wallaston prism and a reflecting mirror. This is shown in photo (10. 1)

After coming through the quarter wave plate, the linearly polarizing laser light became elliptically polarized light. Please note that the components were different if the elliptic polarizing light projects on to the horizontal plane and the vertical plane. The Wallaston prism was used to split the original laser light into two beams with orthogonal polarization planes. These two beams were slightly separated by about 7 degrees. One beam was used as the signal beam with its polarization plane vertical to the horizontal plane and the other was reflected by a mirror and used as the reference beam with the polarization plane parallel to the horizontal plane. While turning the quarter wave plate, the components of the elliptically polarized light were varied and intensity ratio of the signal and reference beams were changed.

10. 2 SHARP EDGE AND SOFT EDGE GLASS SLIT

For making multiplex holograms, the glass slit has many advantages compared to the conventional sharp steel knife edge slit. In this new multiplex system, the reduction of the distance between slit and holographic plate brought one important advantage--the reduction of the shadowing effect. The diffraction effect caused by the edges of the slit was also weakened. If a soft edge slit had been introduced, the quality of the multiplexing image would have been improved.

10. 2. 1 STABILITY OF GLASS SLIT

While making a good quality multiplex hologram, the stability of the whole optical system is very important. The glass slit, as introduced in chapter six, was held by a slit holder of the system. The slit holder was designed not only to allow the slit to move forwards and backwards by several millimetres, but it could also tilt by about 6 degrees in both the vertical plane and horizontal plane. In additional, PTFE tapes inserted between the glass slit and the holographic plate allowed to control the distance between the glass slit and the holographic plate. Glass slit was very stable with respect to the holographic plate. This ensured very good interference fringes.

10. 2. 2 SHADOWING AND DIFFRACTION EFFECTS

The gap between the glass slit and the holographic plate was about 0.1 mm. This distance can reduce the shadowing effect which was discussed many times in previous chapters. Furthermore this distance could reduce the effects of diffraction enormously. According to Fresnel's principle of diffraction and the Cornu--spiral, the diffraction affects the shadow area near the slit edges (glass sharp edge) may receive only one percent or less of the incident light compared to the middle of the slit. So the diffraction effect is much smaller than the shadowing effect.

If a soft edge glass slit or a fractal edge slit were introduced for making multiplex hologram, it would not only be possible to overcome the shadowing effect and diffraction effect but also the border between two adjacent strip holograms could be transferred softly. Even if the border can not be connected well, an overlap or a blank space occurred. The soft edge or the fractal edge slit would, within a certain range, make up for these shortcomings.

10. 2. 3 THE GLASS SLIT AND THE SLIT HOLDER

The glass slit and its holder have already been introduced in Chapter 9. The glass slit was an ideal mask for shooting a strip hologram. Its properties of stability, decreasing the shadowing and the diffraction effects, its ability to record a large image from the diffuser screen had been proven by experiments. The glass slit also had some other advantages such as:

1. Making a glass slit was as easy as making an ordinary hologram or a copy of a hologram.

2. It was easy to be fixed. It was simply glued onto a pair of aluminium bars which were also glued onto short (about 1 cm) steel rods with four coaxial springs.

3. If the slit was no longer needed, it was thrown away with bars and rods and a new one was refixed.

4. A glass slit was much cheaper compared to a steel knife edge slit

5. The making and fixing of a glass slit did not need any skills

Spending a long period to design, manufacture and assemble the plate and the glass slitholder, I had not got enough time to make and test the soft edge slit and the fractal slit. It is anticipated that the soft edge slit will be much better compared to the sharp edge glass slit .

The glass slitholder was specially designed for the use of a glass slit. Though it was more complicated than the steel knife edge slit holder, it was only necessary to make the glass slitholder once. Its superiority could not be compared to a knife edge slit holder (campus designation for example). A glass slitholder kept the glass slit stable during exposure. It kept the distance between the slit and the holographic plate which might be tilted or bent. It was possible to have the signal and the reference light falling on the strip hologram without any barrier and it moved smoothly after exposure to the next position. The angles for acceptance of signal light were larger than 90° in the vertical direction and larger than 60° on the horizontal direction.

After shooting some master multiplex holograms by using a sharp edge glass slit, some overlaps and gaps between adjacent strip holograms were found. This may be caused by:

1. The stepper motor not being accurate enough.

2. The steel wire connecting the stepper motor and the slitholder stretching during the experiment.

3. Since the quality of the tufnol for making the posts for the slit and the plate holder was not good, the posts were bent. So the positioning steel rails could not be properly fixed on the posts and accurately positioned. This resulted in uncontrolled motion of the slitholder.

4. Change of friction between the PTFE tapes and the holographic plate.

10. 3 DISPLAYING TECHNIQUE

Many parameters for displaying a multiplex hologram have been discussed in Chapter 5 and 7 and many calculations and theoretical analyses were carried out. The shape of the slit planes, when the display multiplex hologram was illuminated by collimated white light, was not flat. This is in contradiction to conventional opinion. Further relationships between displaying image, magnification, status of slit plane(s) and type of illuminating sources and illuminating position have also been discussed.

According to the analysis 4 given in chapter 8, the centres of the slit planes are altered along the Y and Z axes, but not, along the X axis. How far the centres were moved away from the Y and Z axes depended on the wavelengths. The longer the wavelength compared to the recording wavelength of the laser, the further the centre was located away from Z axis and the closer it was to the Y axis. As to the curvature of the curved surface; the longer the wavelength, the smaller the radius of the surface. A longer wavelength, compared to the wavelength of the laser, formed more concave slit planes.

When the wavelength of the laser for shooting the multiplex hologram was chosen, the magnification was mainly determined by two factors: the type of the light source and the position of the light source. When the illuminating position was fixed, a diverging white light had a bigger range of magnification compared to those of all other light sources including collimated white light, diverging and collimated laser light. A diverging white light source, however, is the easiest light sources obtainable. It is often chosen as a light source for exhibiting multiplex holograms. Although the magnification will be larger. Of course a collimated laser light source used for illuminating a multiplex hologram is the best as it has no magnification. Moving the light source made possible the reduction of the magnifications by changing the illuminating distance or the illuminating angle. This could make up for the shortcoming brought about by the diverging white light source and thereby reduce any distortion of the image.

All the above discussions were based on the calculations of the author who expected his data could help holographers make a multiplex hologram more easily with his discussions of model or shape of slit planes and he also expects the discussions of illuminating light source could help exhibit multiplex hologram correctly with less distortion.

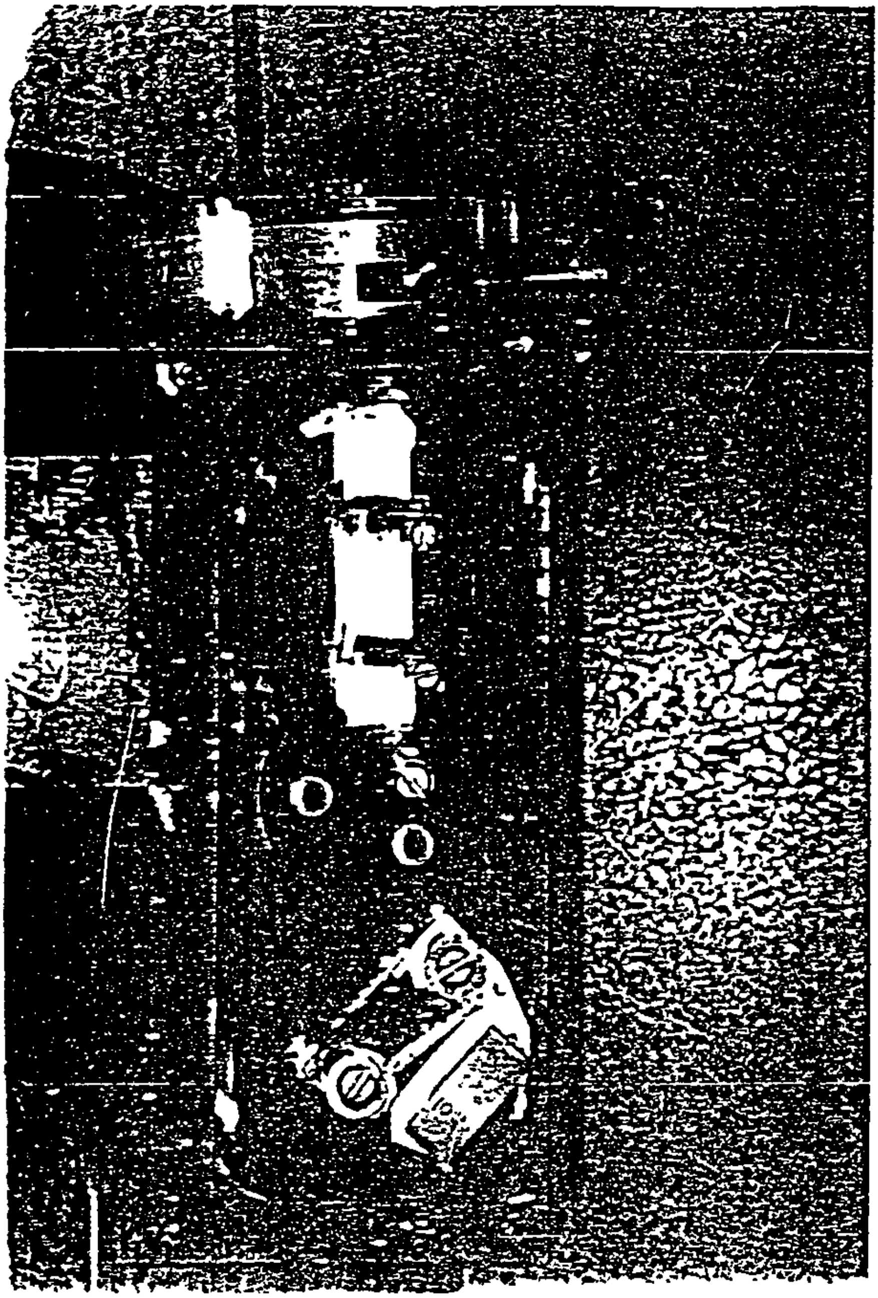

Photo 10. 1

Wallaston prism in beamspliter system

CHAPTER XI

CONCLUSIONS AND FUTURE WORK

11. 1 CONCLUSIONS

The new system of glass slit and its holder was suitable for shooting multiplex holograms. The distance between the glass slit and the holographic plate could be as close as 0.1 mm. The glass slit was forced to contact the holographic plate by means of inserting two strips of PTFE tapes which controlled the distance introduced above. In this way, the glass slit could effectively reduce shadowing and diffraction effects. The glass slit could accept both the incident and the reference light within a relatively large angular range. It was possible to record a hologram with a larger image, shorter distance between the diffuser screen and the holographic plate. This reduced the exposure time. The designation and manufacturing method of soft edge and fractal edge slits have been introduced. A formula for making a soft edge slit by using 514 nm laser light has been discussed.

An appropriate slitholder was designed, manufactured, assembled, tested and operated. This slitholder could be adjusted in four dimensions including moving up and down, adjusting automatically back and forth. This was controlled by four springs behind the slit. The slit could turn about by 6 $^{\circ}$in both vertical and lateral directions (campus design). This could keep a constant gap and ensure parallel orientation between the glass slit and the holographic plate. Two parallel steel rails located along the outer side of the posts held the whole slitholder system (three frames and glass slit) and in the meantime let the system move smoothly along them.

The position of the movement of the slit was controlled by a stepper motor. A BBC Master computer sent commands to an interface from which converted electronic signals were sent to the stepper motor. The commands were carried out. The computer also controlled a shutter for exposure and a film transporter for advancing the film. All parameters including the waiting time were well arranged in a sequence. Though the programme was ready made, it was out of date and could not match the new multiplex system. I therefore had to rewrite some parts of the programme and revise its subroutines. During this year I also wrote some programmes for controlling other more complicated electronic systems.

The Advanced Holographic Laboratories of Markem System provided me with excellent holographic and optical equipment which made things easy and accurate for polarizing both the reference and the signal beams in the same plane, adjusting all the components at the same height and getting a proper beam ratio and coherence length.

The curved surface of the slit plane(s) was obtained from a series of calculations and analyses. From the data which had been obtained, an achromatic multiplex hologram could be achieved although the slit plane(s) were not flat. Different magnifications caused by different light sources (diverging or collimated and so on) and different positions of the sources were calculated and the viewing over distance, quantity of strip holograms and transfer distance were also worked out.

11. 2 FURTHER WORK

Although the sharp edge glass slit has improved the holographic image, a soft edge glass slit and fractal slit could reduce shadowing and diffraction effects even further. By means of using a soft or a fractal edge slit, gaps or overlapping phenomena may be overcome and a comfortably soft transition from one image to another could be obtained. The border of adjacent strip holograms will no longer be a barrier while a viewer is watching the multiplex hologram.

An improvement of the glass slitholder system is an urgent task. The base of the steel rails, tufnol posts of plate and slit holder, was not flat. That resulted in the slitholder not moving smoothly. The slitholder could even be locked somewhere at the beginning. After being adjusted, it was improved but at certain points the slitholder still had problems. That was the main reason that gaps or overlaps occurred. Good quality tufnol should be used for making the posts again. The base of the positioning rails should be flat and parallel to each other.

A better stability of the laser and the bench could improve the quality of the multiplex hologram. The performance of the laser usually lasts for a couple of hours. A constant power output is needed to give better uniformity. Although soundproof, windproof curtains and a heavy bench decreased the sensitivity to sound, air and vibrations, it would not get rid of vibration factors brought about by the optical system itself. The stepper motor might result in a big vibration while moving the slit system. If it could be isolated from the bench, the interference fringes may be improved. The film transport may also cause unnecessary vibration but it cannot be removed from the bench. For good stability, a more stable laser, a proper beam ratio and a longer waiting time are required.

The glass slit system has already achieved good results for making multiplex holograms. It is a big progress to reduce the gap between the slit and holographic plate from 1 mm to 0.1 mm. After the improvements of the slit, the slitholder and the stability of the bench and the laser, a softly transitive, larger imaged, highly contrasted and bright multiplex hologram will be obtained.

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