

Holography

Casey Soileau

Physics 173

Professor David Kleinfeld

UCSD Spring 2011

June 9th, 2011

I. Introduction

Holography is the technique to produce a 3-dimensional image of a recording, hologram. In everyday life, photography has become a very common and popular method to record an image of objects. A film and CCD records the intensity of waves. With photography, however, it is only possible to record the different amplitudes of the light waves scattered from the objects on a plane, and therefore it is only 2-dimensional. When photography records the intensities of the light, it loses the phase information of the wave. For example, two rocks are placed at two different positions. The human eye detects information of how far the rocks are placed horizontally and vertically, the color (or just the brightness of the rocks), and the depth of the rocks from the observer. Photography loses the last information, the depth of the image. The human brain can, however, interpret the 2D information of photography to 3D information because of the human experiences in the past; by just looking at the pictures, the human brain automatically assumes and determines the depth of the objects. In 1947 Gábor Dénes, a Hungarian physicist, invented the technique of holography that enables the recording of the phase difference of the objects, which is the depth information.

In this undergraduate lab, there are two previous articles about holography. The first one was to set up the basic model to record, develop, and reconstruct a hologram. The second was to produce a cylindrical hologram that recorded an entire object so that the complete shape of an object can be viewed. In the past two years, all of the projects were done by film, which is analog technique. Therefore, it is reasonable to let analog technique meet the digital by capturing the holographic image by CCD (charge-coupled device) instead of a film, and reconstructing the image by a computer programming language. In this way, there is wet process in developing the hologram. Producing a digital hologram is a very good way to learn about how optics works theoretically and experimentally.

II. Theory:

Wave is generally described by:

$$E = E_0 e^{-i\phi} \quad \dots (1)$$

where E_0 is the amplitude of the wave, and ϕ is the phase of the wave. The film or CCD can record the intensity of the light wave. For photography, the intensity of the wave is the square of the light wave:

$$I = |E|^2 = E \cdot E^* = E_0 e^{-i\phi} \cdot E_0 e^{i\phi} = E_0^2. \quad \dots (2)$$

This intensity only has amplitude information, but does not have any phase information. Therefore, photograph does not have information about the depth of the object. Hologram, however, introduces the

second beam, called reference beam, in addition to the object beam that comes from an object (Fig. 1).

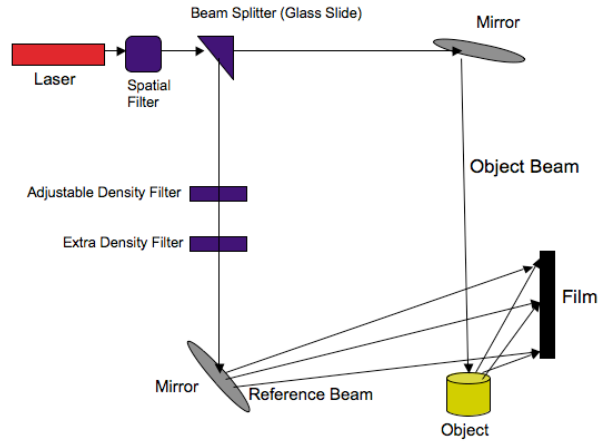


Figure 1. Set-up for Holography

When two beams collide at the position of the film, it creates the interference patterns of intensity that contain the phase information of the waves:

$$\begin{aligned}
 \vec{E}_R &= E_R e^{-i\Phi} \\
 \vec{E}_O &= E_O e^{-i\Psi} \\
 I &= |\vec{E}_R + \vec{E}_O|^2 \quad \dots (3) \\
 I &= E_R^2 + E_O^2 + 2E_R E_O \cos(\Phi - \Psi)
 \end{aligned}$$

where \vec{E}_R is a reference beam and \vec{E}_O is an object beam. Thus, when a film records the intensity of two beams, the resulting intensity contains information of phase difference that creates the depth of the object when the image is reconstructed. It is important to note that the property of coherence of the wave is the fundamental of this experiment. Since the original beam is split into two beams, at the position of the film, the two waves must be in phase for object beam to “refer” the reference beam. If object beam and the reference beam are not in coherence, the object beam does not have any beam to “refer,” and hence the patterns at the film will be random, and will not produce the original image later. After developing the film, the hologram must be reconstructed by the original reference beam in order to view the image, because the film itself only has the interference pattern of the two waves. For the transmission hologram, the reference beam hits the film as it was for the recording, and the viewer observes the image from behind the object (Fig. 2).

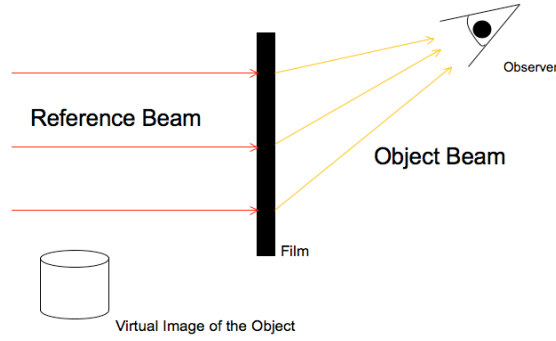


Figure 2. Reconstruction of Holography

For the digital holography, the reconstruction step becomes the tricky part. Intensity at the CCD (CCD is used to record the interference pattern for digital, instead of a film) is still described in Eq. 3. In analog holography reference beam was multiplied to the hologram function $h(x, y)$ to reconstruction:

$$E_R(x, y) \cdot h(x, y) = AE_R + BE_O + CE_R^2 E_O^* \quad \dots (4)$$

where A, B, and C are some constants. The first term on the right side of this equation is the reference wave times a constant A. The second term is the object wave times a different constant B. Because of this, it is possible to view the virtual image of the object if there is a reference beam. The third term generates the distorted real image of the object because of the spatially varying complex factor E_R^2 ,

which modulates the image forming conjugate object wave E_O^* .¹ For a digital holography, undistorted real image is wanted. In order to generate an undistorted real image, instead of reconstructing with a regular reference beam, it is necessary to generate the image with the conjugate of the reference beam:¹

$$E_R^*(x, y) \cdot h(x, y) = AE_R^* + BE_O^* + CE_R^{*2} E_O \quad \dots (5)$$

For this reason, it is necessary to change the reference beam in the Fresnel-Kirchhoff integral, which describes the diffraction of a light wave at a hologram with the incoming beam, to the conjugate of reference beam and generate a different complex function:

$$\Gamma(\xi', \eta') = \frac{i}{\lambda} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} h(x, y) E_R^*(x, y) \frac{\exp\left(-i \frac{2\pi}{\lambda} \rho\right)}{\rho} dx dy \quad \dots (6) \quad ^1$$

where x-y is the hologram plane, ξ' - η' is the image plane, ρ is the distance between a point in the hologram plane and a point in the reconstruction plane. By performing a numerical approximation, Schnars and jueptner¹ calculated the discrete Fresnel transform:

$$\Gamma(m,n) = \frac{i}{\lambda d} \exp\left(-i\frac{2\pi}{\lambda}d\right) \exp\left[-i\pi\lambda d\left(\frac{m^2}{N^2\Delta x^2} + \frac{n^2}{N^2\Delta y^2}\right)\right] \dots (7)^1$$

$$\times \sum_{k=0} \sum_{l=0} E_R^*(k,l)h(k,l) \exp\left[-i\frac{\pi}{\lambda d}(k^2\Delta x^2 + l^2\Delta y^2)\right] \exp\left[i2\pi\left(\frac{km}{N} + \frac{nl}{N}\right)\right]$$

where Δx and Δy are the distance of each pixel in CCD, and N is the total pixel size. Although this is a powerful equation, for a common computer simulating program, it takes a fairly long time to simulate the Γ matrix because common pixel size is in these days is 1024×1024 or bigger, which could take several hours to calculate. Therefore, the convolution approach of this integral was introduced:

$$\Gamma(\xi',\eta') = P(\xi',\eta')\mathfrak{S}^{-1}\{\mathfrak{S}(h \cdot E_R \cdot L) \cdot G\} \dots (8)^1$$

where P is just a correction factor for a phase aberrations caused by the lens L:

$$P(\xi',\eta') = \exp\left[i\frac{\pi}{\lambda}\left(\frac{1}{d} + \frac{1}{d \cdot M}\right)(\xi'^2 + \eta'^2)\right] \dots (9)$$

$$L(x,y) = \exp\left[i\frac{\pi}{\lambda}\left(\frac{1}{d} + \frac{1}{d \cdot M}\right)(x^2 + y^2)\right]$$

where M is the image magnification. $G(n,m)$ is the Fourier transformation of the impulse response $g(\xi,\eta,x,y)$;

$$G(n,m) = \exp\left\{-i\frac{2\pi d}{\lambda} \sqrt{1 - \frac{\lambda^2\left(n + \frac{N^2\Delta x^2}{2d\lambda}\right)^2}{N^2\Delta x^2} - \frac{\lambda^2\left(m + \frac{N^2\Delta y^2}{2d\lambda}\right)^2}{N^2\Delta y^2}}\right\} \dots (10)^1$$

This convolution approach allows a simulator to calculate $\Gamma(\xi',\eta')$ significantly faster than the original discrete Fresnel transformation (Eq. 7).

III. Method (Film Holography):

The basic set-up for film holography is diagrammed in Fig. 1. *JDS Unipahse 1125* was used for the laser. This laser generates 632.8nm-wavelength Helium-Neon beam. This beam has approximately 11cm of coherent length, which means the distance of the object beam and the reference beam need to be within 11cm in difference, yet closer is better. Even though the beam already is an excellent beam producer, it is ideal to have better and cleaner intensity distribution in space to produce a better hologram. Spatial filter was introduced to “clean up” the small fluctuations of the intensity distribution (Fig. 3). The positive lens in the spatial filter maps out the intensity frequency distribution where higher the frequency, the outer they are mapped after the positive lens. Pinhole then can block the outer circles of the mapping, eliminating the higher frequency intensity distributions; thus, it generates an ideal Gaussian distribution after the pinhole. For this particular project, since the object was fairly small (diameter of 2 ~ 3cm), a lens was placed collimate the scattered light after the pinhole.

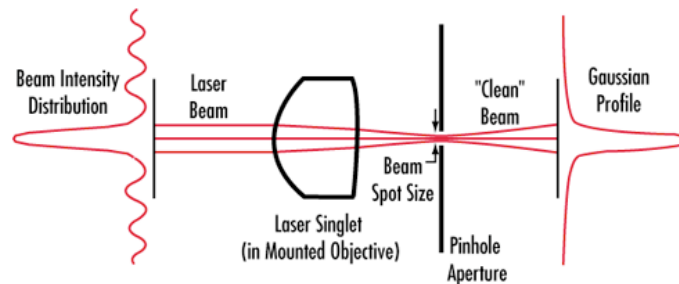


Figure 3. Spatial Filter

First, 50/50 beam splitter was used to split the beam into reference beam and object beam. However, because the first object used was a white golf ball, the intensity of the reference beam was approximately 100 times higher than the object beam at the point of the film, even when a density filter was placed for the reference beam to reduce 90% of the intensity. The ratio of reference beam and the object beam ideally should be 1:1 to 1:5. Even with the density filter placed on the path of reference beam, it was very difficult to reduce the intensity of reference beam to the degree of object beam. Instead of using a beam splitter, a glass slide was introduced to split the beam. Glass slide only reflects 8% and transmits 92% of the beam. Even with this reduction of reference beam and the increase in object beam's intensity, at the point of film, the intensity of the reference beam was still higher. Two density filters were placed to reduce the intensity of the reference beam (Fig. 1). Recording takes approximately 130 ~ 150 seconds for this particular situation.

After the recording, the film needs to be developed (Fig. 4):

1. Place a film in the Kodak D-76 developer solution.
2. Agitate for 15 seconds.
3. Let it sit for 30 seconds.
4. Repeat 2 and 3 for at least 5 times.

5. Place the film to the Stop Bath (2% Acetic Acid).
 6. Agitate it for 15 seconds.
 7. Place it to the Kodak Fixer.
 8. Agitate for 15 seconds.
 9. Let it sit for 30 seconds.
 10. Repeat 8 and 9 for at least 4 times.
 11. Wash the film with DI-water.
 12. Dry the film.
- *Recording and steps 1-10 need to be done in a dark room.*



Figure 4. Developing Process

After the developing, mount back the film to the original position where the recording occur. Block the object beam completely. Remove the object beam, and with solely a reference beam, viewing through the film from behind, if the object image can be observed in the original position, the holography is complete.

IV. Results (Film Holography):

First, as it is mentioned, the object was a white golf ball with a very complicated surface. It was indeed possible to create a hologram, yet because the object beam was only from one direction, it was only possible to capture a very small portion of the golf ball. Intensity at one position was significantly higher than the other portion, too much exposure blacks out the film due to the high intensity portion, but less exposure time could make a good hologram of a very small portion of the golf ball.

Determining that the golf ball is not the best object when only one object beam strikes the object, a metal washer, which has a simpler shape and shinier surface, replaced the golf ball as an object. A better hologram than the golf ball was able to be produced with the washer (Fig. 5).

The biggest concern of the glass slide that front side reflects 4%, and the backside reflects 4% and

due to the different path length, the reference beam was interfering by itself. First, this was considered as a problem, but since it was able to capture the phase difference of the object beam and the reference beam, it doesn't appear to be the biggest problem to create a film hologram.



Figure 5. Holography with a Metal Washer

V. Method (Digital Holography)

Recording of a digital holography is very simple. With the exact same set-up for the film holography, replace the film with CCD (Andor iXon3 EMCCD Camera 885 was used). First, record the interference pattern of the reference beam and the object beam. Save it as .tif file so that it is possible to use it for the coding in MatLab (for this project, MathWorks MatLab programming language was used to simulate the digital holography). In the same way, block the object beam and record the reference beam alone. It generally takes 0.001 seconds to 0.05 seconds to record for this particular situation. Since it is recorded on the CCD, there is no developing process needed, no wet chemicals. For the reconstruction process, first numerical approximation with discrete Fresnel transform (Eq. 7) was programmed in MatLab. In order to achieve a reasonable hologram, the size of the image needs to be at least 512×512 pixels, and ideally 1024×1024 pixels were the minimum goal for this project. With Eq. 7, even generating 512×512 matrix takes at least an hour, and if 1024×1024 matrix was attempted to be generated, it takes several hours, which is not an efficient way. The convolution approach (Eq. 8) was used for the reconstruction, instead. Even generating 1024×1024, it takes less than 10 seconds to generate the resulting Γ matrix. Therefore, the image taken by iXon3 was interpreted in MatLab as .tif file, and the convolution approach was performed for the reconstruction, instead of a discrete Fresnel transform.

VI. Results (Digital Holography)

CCD was indeed able to capture an interference pattern of the object beam and reference beam (Fig. 6) very clearly. With the convolution approach method, short recording time, and without any

developing process, it was possible to generate a hologram in less than 1 minute. Therefore, multiple attempts were made. Nevertheless, no good results were generated. Fig. 7a shows the results without any suppression of DC term (0th order). Fig. 7b shows the hologram that the brightness of the DC term was suppressed by subtracting the intensity of the reference beam in the hologram function. Even with suppression of DC term, the original image did not show up.

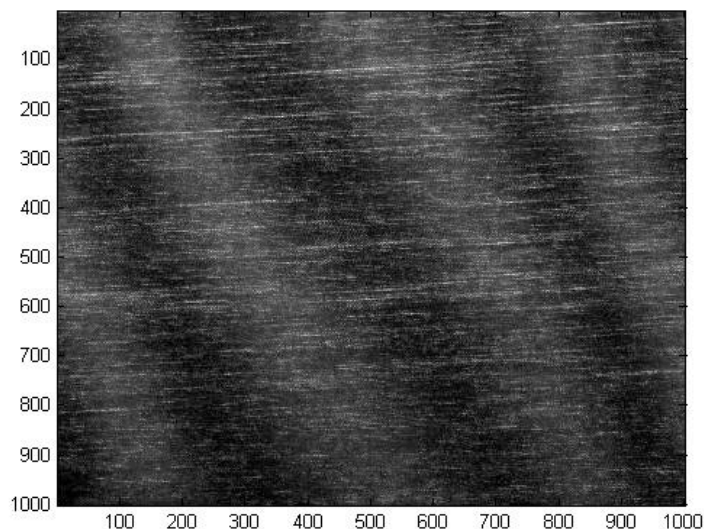
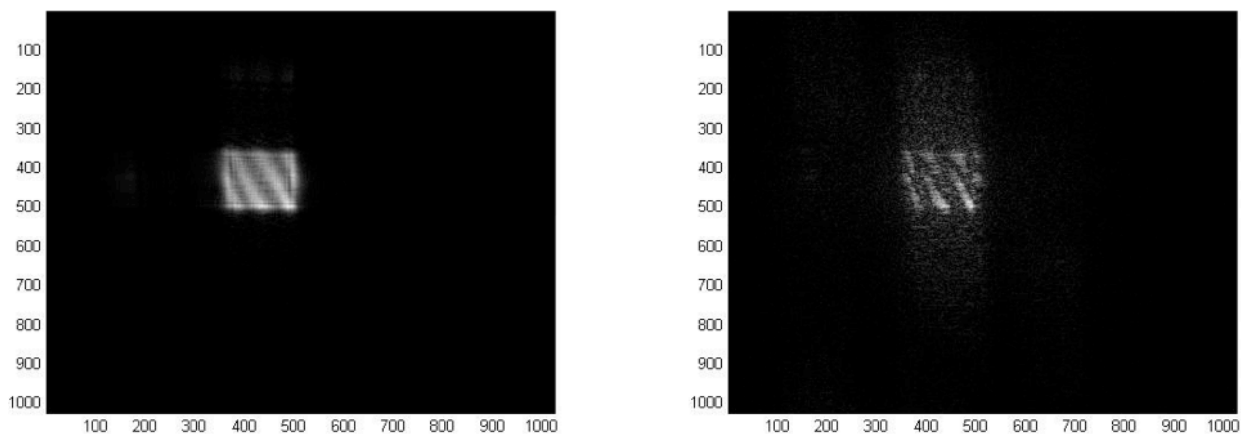


Figure 6. Interference Pattern of Object Beam and Reference Beam



a)

b)

Figure 7. Hologram with Convolution Approach. a) without a suppression of DC term. b) after the suppression of DC term.

VII. Discussions:

For a simple holography set-up, the object matters. A white object is generally better than a very

shiny metal object because some portions of a shiny object might reflect the light to the film very strongly, but some portion might not reflect the object beam to the film at all. A white object is ideal, but since it does not reflect the beam as well as the shiny object, it is necessary to reduce the reference beam or significantly increase the object beam. A white golf ball, however, has a sphere shape with a very complicated concave surface. With only one object beam, the film was not capturing a good portion of the golf ball. The shiniest part at the golf ball, which is only a small portion, was more than 10 times more intense than the other portion, and therefore that small portion was the only place the film was able to capture, but very clearly.

The film (analog) hologram, with a simple glass slide, was able to meet the requirement to capture the correct phase information of the object. Having an interference pattern by itself does not completely hinder the production of a hologram (Fig. 8). However, this glass slide might have affected the results in digital holography. In reconstructing the digital holography, it was not possible to record the reference beam with phase information. The recording by CCD of the reference beam only captured the amplitude of the reference beam, and not the phase. In reconstruction, the reference beam was assumed as a plane wave so that the phase information for the reference beam recording did not matter. However, because of where the collimating lens was placed or because of the glass slide, the reference beam might have not a plane wave that the reconstruction coding assumed. That is one of the possibilities for these results.

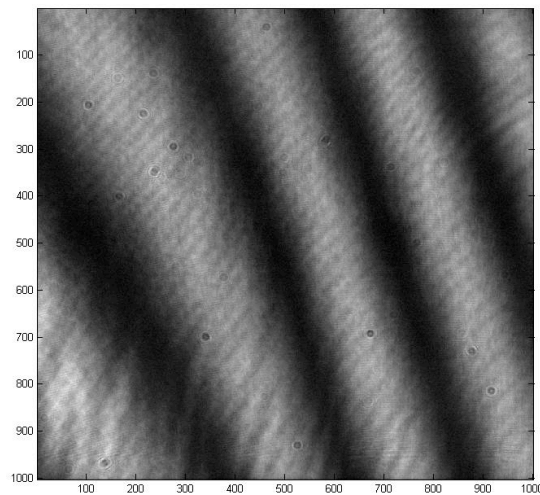


Figure 8. Reference Beam reflected by the glass slide.

VIII. Future Plan:

1. Obtain a glass slide or clean beam-splitter that reflects and transmits perfect original beam distribution, and use it to split the beam with better ratio, such as 10/90, object beam and reference beam, respectively.

2. More accurately create the plane wave for reference beam.
3. Or figure a way to record the phase information of only the reference beam.
4. Check the MatLab coding with arbitrary hologram function and reference beam. For example, create a hologram function with an object as a point source.
5. Just to improve the quality of hologram, split the object wave into two or more and shine the object from several directions, but not only from one direction as this experiment was done.

IX. Conclusion:

Holography is one of the best ways to learn how the optics works, and to learn how to experimentally set up the optical experiment with a laser. Film holography can be done by simple idea with simple steps: recording, developing, and reconstruction. A digital hologram can be made in a similar way, with the same set-up without any developing process, yet it requires better understanding of holography in physics, minimum programming skills, and possibly more accurate physical set-ups. Holography is believed to have the potential to be used for many applications in many other fields.

Reference

1. U. Schnars, W. Jueptner. (2005). *Digital Holography: Digital Hologram Recording, Numerical Reconstruction, and Related Techniques*. Springer.
2. Understanding Spatial Filters. Edmund Optics. <http://www.edmundoptics.com/technical-support/lasers/understanding-spatial-filters/>.

Acknowledgement

David Kleinfeld, Ph.D., Professor
Ted Stinson, Teaching Assistant
Dr. Philbert Tsai, Research Scientist
Professor David Kleinfeld Laboratory