Holography and Measurement

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I. Abstract

In this laboratory an apparatus was created to in order to make transmission holograms. This setup was most successful with shiny, metallic objects with a 2:1 object to reference beam ratio and a 3.5-minute exposure time. Holography was also used to examine thermal and pressure related expansion of a coin. Pressure related experimentation provided a rough estimate for how much the coin compressed under pressure. The thermal expansion experiment, however, did not work as hypothesized but could likely produce desired results with a few changes.

II. Introduction

Holography is a technique that allows the recording and viewing of a three-dimensional image. This method is in contrast to traditional photography, which is only able to capture an image in two dimensions. A two-dimensional photograph is taken either by exposing a film that reacts with light chemically or by using an electronic image sensor such as a digital camera. Depth of field is lost in this case however. Holography operates under the same principle, but with some alterations. A monochromatic beam (from a laser) is used as the light source. This beam is split, with part of it hitting the film directly and the other reflecting off the object to be imaged before hitting the film. These two beams then form an interference pattern on the film, which can be used to reconstruct the image of the object. The recording on the film itself is not actually the image and may appear largely random in intensity and shape. Shining the same beam back on the film with the object absent creates the holographic image. Looking through the film, the hologram will be in the original position of the object. The hologram will appear to have depth and if you move to the side, the lighting and other visual factors on it will change as if the object were actually present.

In this lab, a holographic imaging system was first set up. It was based upon common designs in literature, with some alterations as desired. Holograms were taken using a number of objects and reconstructed using the apparatus. After satisfactory holograms were obtained, double exposure holography was experimented with as a means to measure effects of temperature and pressure changes. Double exposure holography is accomplished with virtually the same set up as single exposure (normal) holography, but as the name suggests two exposures are taken. In between the two exposures the object is displaced. An interference pattern is formed that allows determination of the size of the displacement. This method was experimented with as a means to quantitatively measure minor displacements of a coin.

III. Theory

A holographic image is formed from an interference pattern of two light beams, the reference and the object beam. The displacement equation for the two beams at a point 'r' is:

$$D_1(r,t) = A_1(r)e^{i[\phi_1(r)-\omega t]}$$
$$D_2(r,t) = A_2(r)e^{i[\phi_2(r)-\omega t]} \qquad (1).$$

In equation 1, A represents the magnitude of displacement, ω is the angular frequency, and ϕ is the phase of the light beam. The intensity at a given point for an individual wave is equal to:

$$I(r) = \int D(r,t)D^*(r,t)dt \qquad (2).$$

Using these equations, one can find the intensity of the two summed beams. The displacement is merely the sum of the two beams:

$$D(r,t) = A_1(r)e^{i[\phi_1(r)-\omega t]} + A_{21}(r)e^{i[\phi_2(r)-\omega t]} \qquad (3).$$

Taking the intensity of the sum of the two beams using Equations (2) and (3) yields:

$$I(r) \;\alpha\; A_1^2(r) + A_2^2(r) + 2A_1(r)A_2(r)\cos\left[\phi_1(r) - \phi_2(r)\right] \qquad (4).$$

Note that the intensity of a light beam is proportional to the square of the average amplitude of the wave. Using this relationship gives a more convenient equation for the intensity of the two beams:

$$I(r) = I_1(r) + I_2(r) + 2\sqrt{I_1(r)I_2(r)}\cos[\phi_1(r) - \phi_2(r)] \qquad (5).$$

From this equation, one can see that the intensity is not just the sum of the individual intensities. The waves form an interference pattern showing the difference in phase between the two beams. Maxima occur when the phase difference is 2πn and minima occur when the phase difference is 2π(m+1/2) where m and n are integers. This interference pattern is what is recorded on the film. The hologram is created using the same apparatus as was used to expose the film, except the object beam is removed. The reference beam hits the interference pattern present on the film and 'reconstructs' the object as a hologram.

Double exposure holography involves two exposures of the film, rather than the typical single exposure. To do this, the film is exposed exactly as in the single exposure case. Then the object being imaged is displaced and the film is exposed again. Due to the interference of these two exposures, dark fringes form on the resultant hologram. Each dark fringe indicates a difference of one wavelength of light (as determined by the laser) of distance traveled by the object beam. This means that if the object beam has to travel two wavelengths farther during the second exposure then two fringes should be observed on the hologram. Using this knowledge, the displacement of the object can be calculated from the number of dark fringes as follows:

$$Displacement = \frac{\lambda}{2}(\#\ of\ dark\ fringes) \qquad (6).$$

Note that the wavelength of light must be divided by two, as any movement of the object away from the film is accompanied by movement away from the incident beam. As such, if the object is moved half a wavelength away from the film, the beam will have to travel a full wavelength further to reach the film.

One important component of the apparatus to discuss in detail is the pinhole. The pinhole aperture allows for the original laser beam to be “cleaned up”. Often times, there is not a smooth intensity profile in commercial laser beams, and unwanted energy peaks can occur at higher orders in the intensity profile. This occurs because of diffraction interference patterns in the original beam. Cleaning up the beam refers to blocking these higher-order peaks in order to obtain a smoother Gaussian distribution of laser beam intensity. It should be noted that these higher order peaks are not completely eliminated by the use of a pinhole, yet the pinhole is successful in reducing the higher order intensity peaks while allowing the central maximum peak to remain unaltered. This cleaned up beam results in higher quality resolution in a holographic image. Since holograms are the result of diffraction patterns from the reference and object beams, unnecessary diffraction within the beam itself will lead to messy holographic images. The pinhole also serves as a good tool for reducing the high beam intensities of the laser, allowing for more freedom in exploring a range of exposure times. Without the pinhole, the film would be easily overexposed in less than 30 seconds.

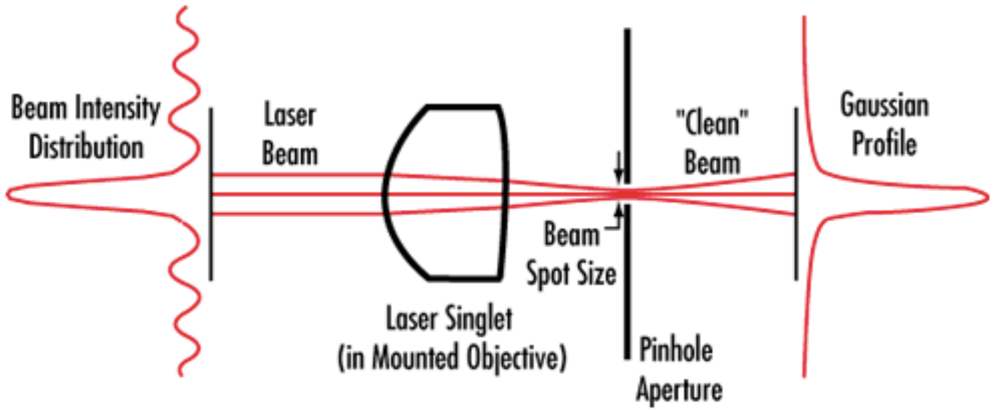

Figure 1: Gaussian distribution intensity profile before and after the pinhole (4).

It should also be noted that for good resolution holograms, coherence length of the laser must also be taken into account. The coherence length of a laser is related to the purity of the phase of the laser light, as well as the wavelength of the laser. A perfect laser will have only one wavelength and the light will be completely in phase with itself. This makes the coherence length of the laser infinite. In reality, however, the laser may have more than one wavelength of light, and these wavelengths may not be exactly in phase with each other. Once the object beam and reference beams are separated using the beam splitter, the path distances that they travel must be roughly equal. For example, the coherence length of the average 5mW HeNe laser is about 6 inches (3). This fact means that the path distance traveled by the reference beam must be within 6 inches of the path distance traveled by the object beam in order to negate laser wavelength phase interference. Holograms will not be formed otherwise.

IV. Methods and Materials

The holography setup for transmission holograms is indicated in Figure 3. The key components for this setup include a Helium Neon laser, a beam splitter, and various mirrors and lenses that are required for beam expansion and for directing the laser beams towards the film.

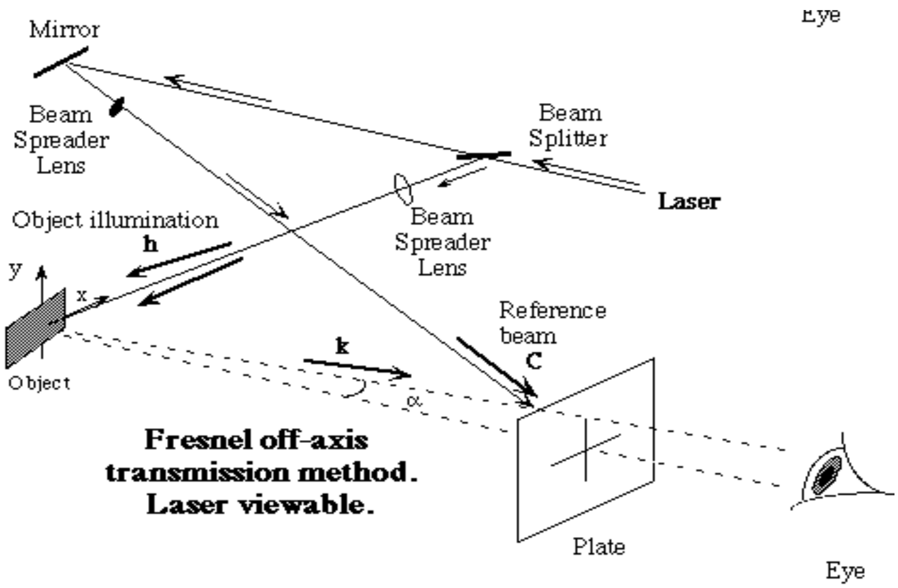

Figure 2: Image for a theoretical setup for transmission holography (2). Note that there is no pinhole apparatus included in this image, which was included in our setup before the beam splitter. No beam spreader lens was used in the object beam as well, in order to increase the intensity of the object beam.

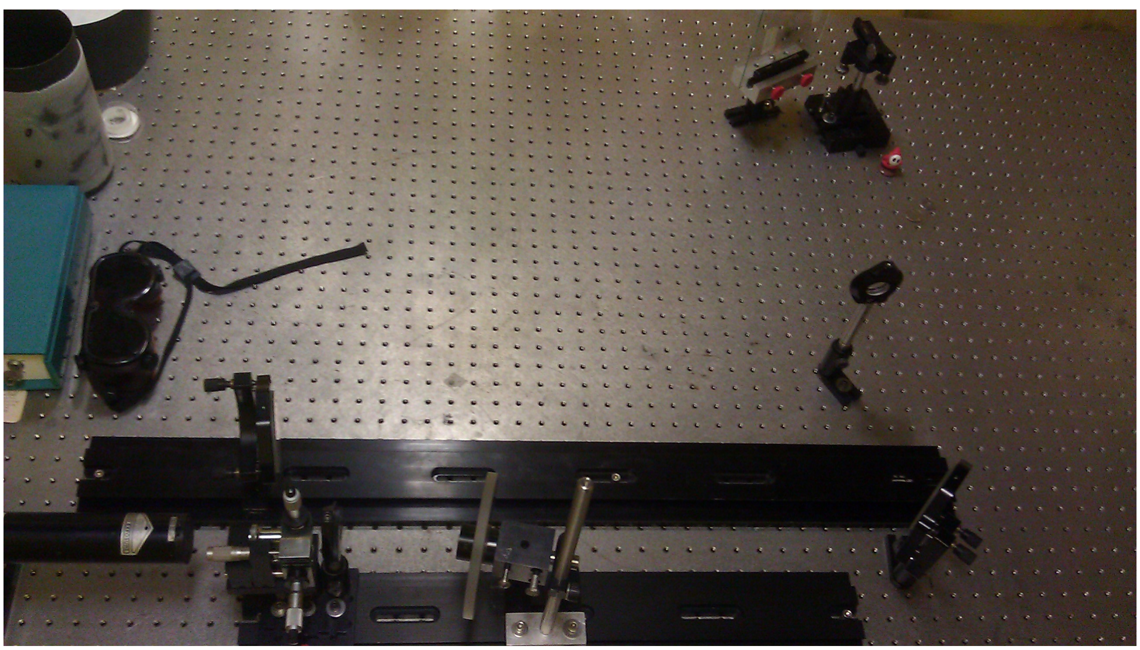

Figure 3: Transmission holography experimental setup.

The first and leftmost component in Figure 3 is the HeNe laser, followed by the pinhole apparatus, which uses one lens to focus the light on the pinhole. After the pinhole, a 25.4mm lens was used to collimate the light. The beam splitter splits the collimated light onto 2 mirrors, which then reflect the light to the film (reference beam), and onto the object (object beam). Light from the object beam reflects off the object and will also hit the film.

Everything in the setup had to be tightened to the optical bench to avoid slight movements in the equipment that cause the beams to become misaligned. A 15μm pinhole was used for this setup. Using a string to measure the path from the beam expander to the film for each beam equalized the path lengths for the object and reference beams. This equalization does not have to be exact, but the path length should be roughly the same distance in order to produce satisfactory hologram interference patterns. Exposure times were experimented with a great deal, but the optimal exposure time was between 3 minutes and 3.5 minutes. The best reference to object ratio is debated among sources, but with this setup a 2:1 object beam to reference beam ratio was determined to be the best. One source suggests that the reference beam should be 2x to 5x brighter than the object beam; however, these ratios only resulted in overexposed film when implemented (3). With the proper beam splitter intensity ratios and exposure times determined, taking the holographic pictures became a simple task.

The object imaged was mounted to a stage so that there was no accidental movement of the object during the exposure. The exposure and development processes also had to be done in dark room settings, so that film was not accidentally exposed to other sources of light. Holographic film was attached to a clear glass plate using tape during exposure. A shutter on the laser was also implemented to control exposure time. Once exposure of the film was completed, the film was developed using the following development process.

Developing Process:

1. Place film in the Kodak Developer Solution for 7 minutes. Agitate occasionally.
2. Place the film in the 2% Acetic Acid Solution for 30 seconds. Agitate frequently.
3. Place the film in the Kodak Fixer Solution for 3-4 minutes.
4. Leave the film in water and hang to dry.

Once the exposed film has dried, it is ready to check for a holographic image. In order to reconstruct the image and see the holographic image on the film, the beam splitter must be set to maximum reference beam intensity. Any light remaining in the object beam must be blocked off so that it does not hit the film. The film should be placed in the approximate position that it was in during exposure for the hologram to become present. For transmission holograms, the image is visible when looking through the film towards the position of the original object, as indicated in Figure 2. The hologram will be clearest at eye level.

Two experiments were done using double exposure holography. The first experiment was used to measure the compression of a nickel. The same setup as for single exposure holography was used, except that the object mount was replaced with a clamp. The nickel was placed in this clamp under light pressure, but still sufficient to hold the coin in place. An exposure was taken. Then the clamp was tightened to the extent possible by hand. After this a second exposure was taken. The film was developed as usual and the image was reconstructed using the same method as single exposure holography.

The second double exposure experiment was designed to measure thermal expansion. A nickel was heated in a boiling water bath to raise its temperature to 100 °C. To limit potential cooling time, this heating was done in the dark room. The nickel was placed on the object mount in limited light while the already loaded film was covered. The light was then extinguished, the film uncovered, and an exposure taken. Following this, the nickel was left to sit for 20 minutes as it cooled down to room temperature (~25 °C). After the nickel cooled, a second exposure was taken. The film was then developed and viewed as usual.

V. Results

The best holograms obtained from this setup were the holographic images of shiny objects. The washer and the coin provided the best results, with a clear holographic image formed in image reconstruction. A two to one ratio of object beam to the reference beam was the optimal beam splitter ratio as well. Holographic images that were made with non-shiny objects were unable to be reconstructed using the reference beam, making these objects unsuccessful.

The quality of the holographic images for the washer and the coin were excellent. Very fine details on the coin were able to be distinguished in the reconstruction image, such as the date on the coin and the image in the middle of the coin. The washer, on the other hand, did not have a detailed surface to begin with. However, the shape of the washer was easily distinguishable in image reconstruction. The reconstructed images were viewed using a full reference beam, and any additional light from the object beam was blocked. The biggest problem when viewing the reconstructed images was that the image was initially hard to find. This problem was most prevalent for the first successful holograms, because the proper beam splitter ratio was not yet found and the holographic images were very faint. Once all variables had been optimized, however, the holographic images were much brighter and locating the hologram became less of an issue. The best viewing of the hologram is at eye-level with the location of the original object, and at the angle where most of the light from the original object hit the film.

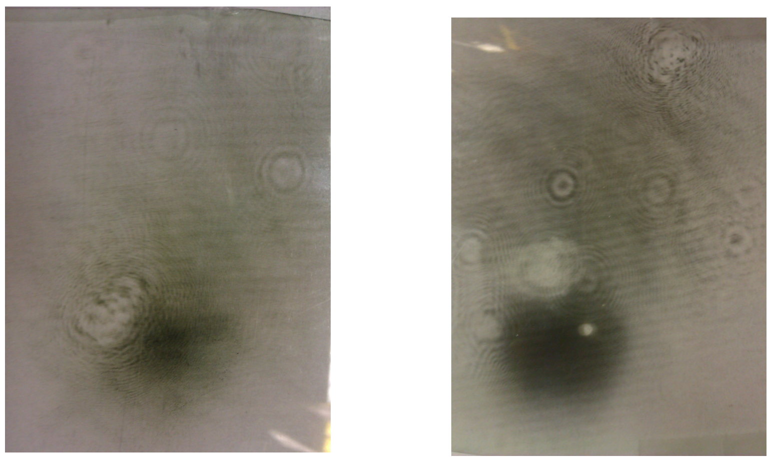

Figure 4: Interference patterns on holographic film. Left: Successful holographic image of a peso. Right: Successful holographic image of a washer. In each image, the dark round spot is where the hologram of the coin/washer will appear during reconstruction.

Figure 4 indicates how the film should look after development. It is simply an interference pattern between the object beam and the reference beam. Once these film pieces are placed in the reference beam, however, the holographic images can be viewed. Capturing a picture of the holographic image was impossible with a simple phone digital camera, but it should be mentioned that the holograms look exactly like a red version of the original object (due to the color of the HeNe laser) and they appear at the same angle of the original object during exposure.

Experiments with double exposure holography were met with limited success. As stated before, the first test measured the compression of a nickel due to an increase in clamping pressure. This was found to be a difficult task to accomplish. In the process of tightening the clamp, the coin appeared to sometimes slide under the pressure. The clamp, although mounted to the table, was prone to movement as well during tightening. Thus, several trials were run before a meaningful result was obtained. In the successful case, 4 dark fringes were visible on the hologram. Using Equation (6) and knowing that the wavelength of the laser was 632.8 nm, the compression of the nickel was found to be 1.3±0.3 μm. This is a reasonable level of compression given the composition of a nickel (25% nickel, 75% copper).

The test of the thermal expansion of a nickel did not produce any meaningful results. Given the thermal expansion coefficients of nickel and copper, one would expect to a compression of ~1 μm after cooling ~75 K. This level of compression corresponds to 3 dark fringes on a hologram. Several exposures were taken, but no dark fringes were observed on the resultant holograms.

VI. Discussion

The items that worked best with this holographic setup were shiny metal objects, such as coins. Objects that were too dull would not expose the film correctly in order to get a good diffraction pattern, and resulted in no holographic image. Changing the settings of the optical setup, such as the beam ratio or the exposure time, may result in holographic images of these objects. The main issue that was encountered during the construction of the holography setup was the misalignment of mirrors and lenses. Once the pieces were aligned, they had to be properly tightened to avoid misalignment over the course of many weeks. We often had to realign the lenses, mirrors, and the pinhole throughout the 10 weeks due to slipping and slight movements that occurred between lab periods. Another big issue that was initially encountered was with the pinholes. The pinholes used were not as clean as they needed to be for proper holography, causing the intensity of the laser beam after the pinhole to fall dramatically and resulting in very long exposure times (~10 minutes). The pinholes were cleaned using an ultrasonic bath, causing the intensity of the laser beam in the reference and optical beams to be much better for holography. It is highly recommended that the pinholes be cleaned before being placed in the pinhole aperture, since it is very easy for a hole on the order of micrometers to become clogged and dirty just from dust in the air. Yet another difficulty faced was with the developing chemicals. It was initially unknown that these chemicals must be replaced fairly frequently (ideally they should be replaced daily) and for about 5 weeks the same developing chemicals were used. This resulted in poor film development, and it was not until after we had received new chemicals and prepared new developing solutions that results were seen. If these problems are taken into account before any future experimentation begins, a great deal of time can be saved.

For the case of double exposure holography, only one good result was obtained, that being compression of the nickel due to pressure. The number of dark fringes on the hologram was counted and the displacement of the nickel was determined to be 1.3±0.3 μm. This result is useful for multiple reasons. First, the observation of dark fringes is in concordance with theory and indicates that the apparatus used was indeed capable of measuring sub-micrometer displacement. The number of fringes observed was also reasonable given the compressive properties of a nickel coin. Without measuring the pressure applied however, the compression value obtained cannot be verified. It would certainly be useful to have added a pressure sensor to the clamp all things permitting.

The test for thermal compression/expansion was unable to obtain any meaningful results. The seeming advantage of this test over the pressure test was the easy verification of results independent of additional equipment. The thermal compression of the nickel could easily be calculated from known thermal expansion coefficients and the temperature change involved. This value would have allowed for verification of any results, but no fringes were observed in any of the holograms to compare. There are many possible reasons for the failure of this test. Perhaps equipment merely moved during exposure or in between the two exposures. The pressure test required several attempts before a good result was obtained indicating this is a definite possibility. However, the most likely cause of the poor results it seems is due to cooling of the nickel during exposure. In order for the double exposure technique to work, that is for it to form an interference pattern with observable fringes, there must be two definite states. Instead of a definite high temperature state though, the nickel surely cooled during exposure. If a test were designed that could keep the temperature constant during exposure, or the exposure time were reduced to such an extent that almost no cooling occurred over it, then fringes might well be observed.

VII. Future

Given time, we would like to investigate double exposure holography further. One possible application would be to measure compression due to pressure again, but with the addition of a pressure sensor so that the experimental results can be properly verified. Another possible step would be to measure thermal expansion successfully. This could theoretically be accomplished by maintaining a constant temperature during exposure. One way to do this would be to apply a current to the nickel (or other object used). Once the object reaches a constant temperature with the applied current, then an exposure could be taken. Another way to obtain better results would be to reduce exposure time and thus minimize and temperature change during exposure. This could be accomplished by increasing the intensity of the incident beam. Given the equipment in the lab however, this might be a difficult task as one is limited by the laser and the pinholes available. A further use of double exposure holography could be measurement of mushroom or plant growth. For this case, two exposures of a mushroom could be taken at some time apart, say half an hour. From the dark fringes observed on the resultant hologram, one could determine the growth rate of the mushroom.

One other aspect we would like to examine includes the ability to take holographic photos of objects that are not shiny or metallic. Holograms taken of non-shiny objects did not work despite seeing exposed film after developing. It may be that the object beam was not intense enough, resulting in the object not reflecting enough light to expose the film. The metallic objects easily reflect the light onto the film, and this may be the key to a good holographic picture. For this to be tested, the object beam needs to be as intense as possible, and a longer exposure time will be necessary. It may also be necessary to apply a filter to lower the intensity of the reference beam, such that it does not overpower the object's reflected light in the long exposure. These are just a few of numerous possibilities for further study.

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