Holography

Introduction

Holography is the technique of using monochromatic light sources to produce 3D images on photographic film or specially designed plates. In this experiment you will learn about one of the simplest types of holograms — the *white-light reflection hologram* — and, in the end, will produce a hologram of your own.

Holography arose as an alternative to photography, which produces inherently two-dimensional images and thus is often seen as unnatural. Even though light from a given 3D object passing through a regular photographer's camera's lens forms a 3D image, the technique used to record it (be it on negatives or digitally) only captures a slice of it that is in focus, thus resulting in a flat image. The human eye is often compared to the optical arrangement of a camera: and yet perception of depth is an area that clearly distinguishes the two. In order to understand how humans perceive three-dimensional images, we need to consider the *parallax effect*. Parallax is the apparent difference of appearance of an object with a change in viewpoint from which it is observed. Notwithstanding the fact that a human has two "cameras" which inherently have different viewpoints with respect to any object, even a single eye performs rapid motions during observation to see an object from different sides, thus gaining more information about it. By seeing an object from slightly different positions, the eye captures different parts of the wavefront of light that is reflected by the object, which allows the brain to reconstruct the image with depth. This is not something a regular camera can do (although one can create a somewhat 3D image by taking photos of an object from an array of different angles and then splice them together, resulting in a *parallax stereogram* — an approach providing a mere illusion of depth). Hence the only way to create a truly 3D image is to obtain all of the information carried by the wavefronts, which is precisely what a hologram does.

If you split a beam of light and send the two parts along different optical paths, and then recombine then on a screen, you will observe an interference pattern — like, for example, in the Michelson interferometer. If you then insert an object into one of the optical paths, the pattern will be disturbed by it, in a manner dependent on the spatial configuration and dimensions of the object. What's more, this disturbance is a full account of the information about the object's wavefront. The disturbance of the pattern can be captured by a photographic plate or film located in place of the screen (after sufficient exposure): the resulting image will contain all of the information about the object and hence will be a complete three-dimensional representation of it — a *hologram*. Moreover, not only does the hologram contain all of this information, but so do its individual parts: any piece of the original hologram can be used to reconstruct *the entire* *thing.* When light is shun on such a hologram, instead of propagating through the plate freely, it is forced to follow the diffraction and interference patterns captured by the plate, thus resulting in reconstruction of the wavefront of the original object. This wavefront, when perceived by the brain, is indistinguishable from that of the actual object — thus one sees a three-dimensional image of the object.

As mentioned earlier, in this experiment we shall restrict ourselves to single-beam reflection holograms. There are two main types of holograms: ones that require laser light or at least partially coherent (same-phase) light to be replayed, and ones that can be viewed with just regular white light. Single-beam reflection holograms are different from other types of holograms: most holograms split the original beam into two parts before the object. Consequently, one is unimpeded by the object (the reference beam) and one strikes the object; they then interfere at the photographic plate, the angle between them as they are incident on the plate being under 45°. By contrast, single-beam hologram does not split the beam before the object: instead the photographic plate is placed in front of the object, and the reference beam passes through it first. It then hits the object and bounces back, interfering with the reference beam at the plate in a standing wave pattern.

We now describe in detail the process of producing such a hologram.

Experiment

We have equipment for a single beam reflection hologram. The set-up will look like fig. 1. The laser beam originates in the 5 mW laser device, which is firmly mounted onto the vibrationless table (a slab of granite outfitted with metal plates bolted to it): it then passes through the electro-mechanically operated shutter (just press the shutter slide button and it opens — remains open for about 3-4 seconds) and bounces off of the adjustable tilt mirror. It then passes through a spatial filter, which consists of a 10× microscope objective lens and a pinhole with a mirror (its purpose and way of operation is described below) before hitting the emulsion plate, passing through it and forming a standing wave with its reflection from the object positioned immediately behind the plate. The fringes formed in this way are captured by the plate, resulting in a holographic image.

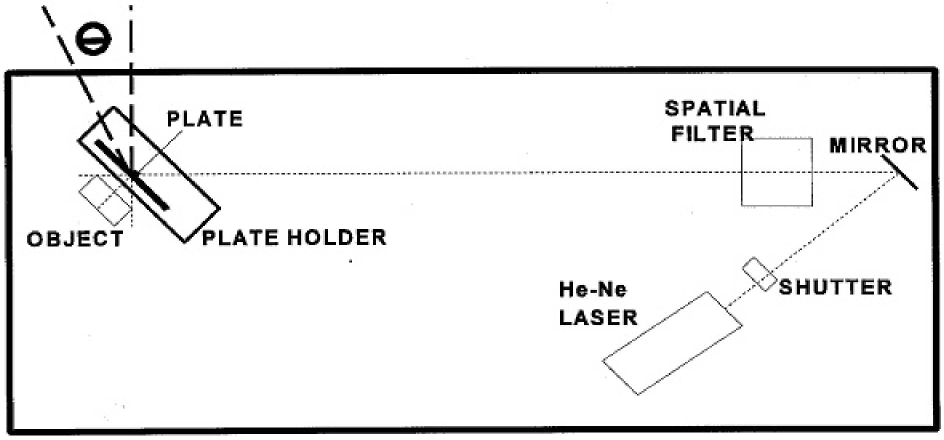

Figure 1- Basic single-beam reflection hologram arrangement

When you will first turn on the laser and observe the beam on a distant screen as it passes through the microscope lens, you will notice multiple dark swirls and tiny interference and diffraction patterns, making the field of illumination of the laser non-uniform. Fortunately, there is a device that helps remedy this problem — it is termed a *spatial filter*. Our spatial filter consists of a $10\times$ microscope objective lens and a $25\mu m$ pinhole arranged as in fig. 2. The microscope lens diverges the laser beam so that it covers the whole photographic plate, while the pinhole serves to remove spatial noise from the beam. As you have probably guessed, just like our object creates a unique interference pattern that allows us to make a hologram of it, so do the other "objects" in the optical path, such as dust particles in the air or optical imperfections of either the laser itself or the microscope lens. It so happens (see [1], p. 99) that the parts of the beam that were diffracted due to these imperfections separate from the undiffracted beam precisely at the focus of the objective, leaving the undiffracted beam in the dead centre of the illuminated field. Hence we simply install a tiny pinhole that only lets through that middle, central part of the beam, and we can get rid of most (in most cases, all) imperfections and spatial noise in the beam.

Of course the size of the pinhole depends on the setup we are using. In fact, there is a lower bound D on the diameter of the opening, below which the brightness of the beam is seriously affected. It is given by

$$D = \frac{0.6\lambda}{Md}$$

where λ is the wavelength of the laser light in nanometres, D is the required pinhole diameter in micrometers, M is the magnification of the objective and d is the diameter of the beam in millimetres. However, this is only a lower bound: there is a range of sizes to choose from, as a smaller opening not only helps clean the beam, it also reduces its brightness.

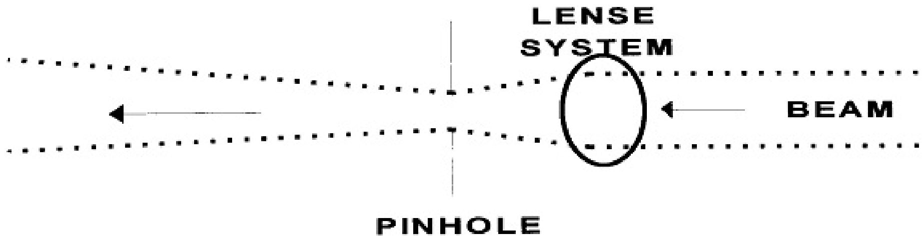

Figure 2

Finally, a few notes on treating the optical setup with care:

- Do not touch any silvered mirror surface.
- Do not touch, leave out for extended periods of time, or try to clean the pinhole with your hands, tissues, etc. Do not put it down of a bench top, regardless of how clean you think it is, and do not ever allow any fluid to come into contact with it. Whenever not is use, it should be kept in its plastic box. If the diameter of the pinhole is correct for the laser beam arrangement, but it does not allow a clean beam through in optical alignment, it is probably dirty. The only acceptable way of cleaning the pinhole is by ultrasonic cleaning: if you think your pinhole is dirty, ask the Technologist about the cleaning process.

For best results:

- To eliminate reflection in the glass plate, the laser beam should be horizontally polarized and θ should be Brewster's angle: this way the reflection of the beam from the plate is minimized, as per definition of Brewster's angle. The photographic emulsion should be placed on the side of the glass near the object to be photographed (fig. 3). You can determine which side is the emulsion side by looking for a small dark mark in one of the corners of the plate in safelight: the side on which the mark is on is the emulsion side;
- The apparatus must be set up on the vibration-free table. All components must be firmly anchored. Avoid excessive elevation with magnets — both setups available should not require any (for propping purposes, that is — might still use them to hold down the mirror stand, etc.);
- All extraneous light sources must be masked;
- Keep the image face as close to the emulsion as possible without touching it: this will allow for maximum exposure.
- Use a white or bright object, avoid dark and metallic ones as you will likely not be able to see them very well even though you might have a great hologram.

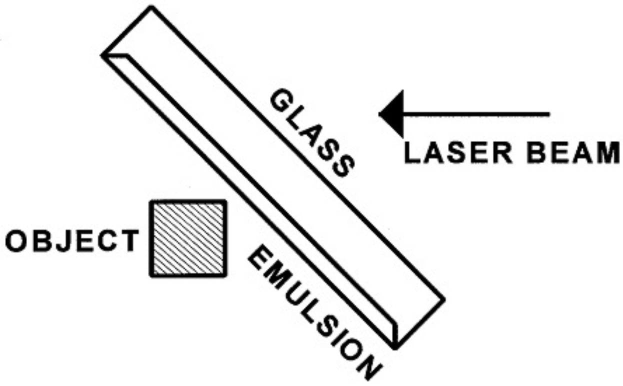

Figure 3

To obtain the hologram, you will likely be using the 5 mW laser: it is rather powerful, and so only exposures of approximately 3-5 seconds will likely be required. As the electromechanical shutter is already set to open at a press of a button for exactly that length of time, you do not need to time your exposures — just press the button when you are ready.

The photographic plate must be handled in the total darkness with only the safe light on (the greenish-blue lamp on the wall). Practice loading the plate holder in the dark with a dummy plate before using the real thing (Each plate costs $20.00). Avoid, if possible, touching the plate's front and back surfaces with your fingers or against other objects.

Procedure

Obtaining a hologram

In this section we briefly outline the procedure for producing a single-beam reflection hologram.

1. Begin by ensuring that all of the elements of the setup — the shutter, the mirror, the stand that supports the spatial filter and the plate holder — are as close to the table surface as possible, that none of them are resting on extra unnecessary magnets/other props. It should be possible to obtain a clean beam path with only the adjustments on the stands themselves.

2. Turn on the laser and position the mirror in its path. Keep the shutter out of it till the very end. Make sure that the laser beam is horizontal by measuring the vertical distance between the laser opening and the table directly below and then comparing that to the distance between the table at the base of the mirror and the incident laser beam.

3. By turning and moving the mirror first with your hands, and then more precisely by using the tilt control knobs, aim the reflected laser beam directly through the

middle of the opening into which you will later screw in the microscope lens (you may wish to use a small slip of paper to help you see the beam).

4. Position the plate holder about 1 m away from the spatial filter stand, and aim it as in the diagram (fig. 1). Direct it at an angle of $50 - 60°$ to the direction perpendicular to the incident beam[1] (this is close to Brewster's angle for a standard glass plate) to help minimize reflection by making the reflected beam p-polarized. Note: this will work best if the laser beam if horizontally polarized: check this with a polarization filter. If you do not have one, ask the Technologist.

5. Screw in the microscope lens, on the side of the stand away from the beam, and play with the mirror tilt adjustment along with the positioning of the plate holder until you have a direct beam illuminating most of the white dummy plate in the holder (mind Brewster's angle). Try to keep the beam focused on the middle of the plate and away from the sides — this can result in refraction, which would destroy the hologram.

6. Use the light sensor to measure light intensity in the middle of the beam.

7. Slide in the pinhole — it is magnetically attached to the three x, y, z controls on the spatial filter stand — with the mirror facing toward the incoming beam. Move it as far back from the lens as possible and place a white screen (a sheet of paper will do) almost immediately in front of it. Attempt to align the spatial filter by changing its x and y positions via the micrometer screws: first simply position it so that the beam goes through the middle of the mirror as you perceive it, and then start slowly adjusting the controls to fine tune it. You will know it is aligned when you see an interference pattern on your screen — it should consist of concentric rings of uniform illumination. Once you locate the pattern, adjust the knobs again until you maximize its brightness and make it as circular as possible.

8. The interference pattern is there because the pinhole is not at the focal point of the lens. To get a uniform field of illumination with no rings, you start moving the pinhole slowly toward the lens. You will observe that the rings are growing, and soon the central one will fill the whole field of view. Proceed slowly, as you will need to re-adjust the x, y alignment of the pinhole along the way.

9. Once you have a uniform beam illuminating the middle of your dummy plate, use the light sensor to make sure that the light intensity of the beam after it passes through the pinhole is $70 - 90\%$ of what it was without the pinhole.

10. Now position the shutter in place. Finally, fix the desired object behind the dummy plate, as close as possible. You are now ready to make a hologram: simply mask all

[1] we are referring to θ in fig. 1.

the room lights, obtain the emulsion plate from the Technologist, place the emulsion plate into the holder, and open the shutter. You will then have to develop the film: transport it in a box with no light exposure to the dark room.

Developing the plate

See the Technologist in the Resource Centre about developing the plate after exposure. The procedure involves:

1. After closing the door to the dark room tightly, turn on the safe light and slide the plate into a metal holder;

2. Put it for 4 minutes into the developer (Kodak D-19 (1:1) developer) (with blue safety light) while slowly moving it back and forth.

3. Give it a short rinse in water.

4. Put it for 10 minutes into the fixer while still moving it back and forth in the solution.

5. Wash thoroughly under running water for 5 minutes — you can put it into a bin and open the tap, letting the water overflow. You can now turn on the light and look at it.

6. Dry for at least 10 minutes in the dryer.

Viewing Reflection holograms

Reflection holograms do not require a laser for image reconstruction. Just about any source of light will work, including sunlight or the light from an incandescent bulb. Avoid greatly diffused light such as that from a fluorescent lamp, or the hologram will look fuzzy. The ideal light source is a point-source, such as an unfrosted filament bulb — there is one in the holography room. You will see the image as you tilt the hologram at angles to the light.

Note the many colours in the picture, particularly green. Although made with a red He-Ne light, the film shrinks after processing, so it tends to reflect shorter wavelength light. The amount of shrinkage varies depending on the film, but it often correlates to 50 to 100 nm, reducing the red 632.8 nm wavelength of the He-Ne laser to about 500 to 550 nm.

The best viewing setup for a reflection hologram is shown in fig. 4. Tilt the hologram toward you until the image becomes clear (about 45 to 50 degrees).

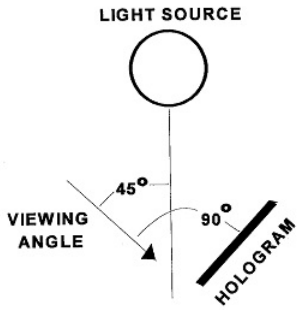

Figure 4 - How to view the processed (and dried) reflection hologram in white light.

WARNING: Finger prints, dirt, dust, or chalk dust on the pinhole, the microscope objective lens or the mirror can introduce spatial noise in the form of diffraction patterns from the patterns of dirt. The pinhole is particularly subject to this problem, as it cannot be used to filter out its own imperfections. When the pinhole is not in use, store it in its box.

Questions

In addition to making the hologram, answer the following questions in your lab notebook:

1. A latent image is an image formed on photographic negatives after exposure but before it has been developed (see [1], p. 68-69). Is it different from a holographic image? If so, how?

2. Suppose you dropped your hologram and it shattered into small pieces. What do you expect to see on each piece?

3. How is the image on a piece of a hologram different from one on the hologram before it shattered?

4. Holographic images have a special property that the information contained on one piece has the ability to reconstruct the entire image. Why does this happen?

v - jan 95, ts - sep 96

The lab manual was revised in 2014 by P. Albanelli and S. Fomichev.

References

[1] Graham Saxby, Practical Holography (available in room 229).