Experiment 6

Geometrical Optics

Although light behaves as a wave, if the dimensions used in an experiment are sufficiently large, we can neglect diffraction and interference effects. Hence, in this experiment we represent the propagation of light as a series of rays which follow straight lines (in optically homogeneous media). Results from ordinary geometry can then be used to aid our investigations.

Equipment Needed

- Incandescent Light Source (OS-9102B)
- Optics Bench (OS-9103)
- Angular Translator (OS-9106A)
- Component Carrier 4×(OS-9128)
- Glass Plate (OS-9128)
- Acrylic Plate (OS-9129)
- Flat Front Surface Mirror (OS-9136)
- Viewing Screen with Metric Scale (OS-9138)
- Aperture Mask (OS-9139)
- Crossed Arrow Target (OS-9121)
- 22 mm F.L. Lens (OS-9131)
- 18 mm F.L. Lens (OS-9132)
- 48 mm F.L. Lens (OS-9133)

- 127 mm F.L. Lens (OS-9135)
- 252 mm F.L. Lens (OS-9135)
- razor blade
- mm graph paper

6.1 Reflection

6.1.1 Angles of Incidence and Reflection

A. Position the incandescent light source on the left end of the optical bench and place the angular translator about 25 cm from the end of the light source housing. Make sure the 0° mark lies on a line parallel to the bench. Adjust the rotating table so that the scored lines run perpendicular and parallel to the bench.

B. Attach the aperture mask to the standard component carrier and place it between the light source and angular translator so the the mask is d centimeters from the center of the translator. The distance d (about 6.5 cm) is the measured distance from the center of the angular translator to the first analyzer holder on the movable arc. (See Fig. 6.1.2.)

C. Center the viewing screen of the special component carrier designed for use with the angular translator, and place the assembly on the rotating table of the translator so that the front surface of the viewing screen coincides with the scored line on the table which runs perpendicular to the optical bench.

D. Now switch on the light and adjust the aperture mask's position (don't move the component carrier) until the entire image is on the viewing screen. With the aid of the millimeter scale marked on the screen, center the image horizontally. Turn the screen 90° and center the image vertically.

E. Replace the viewing screen with the flat surface mirror (be careful not to touch the front surface of the mirror) such that the mirror surface coincides with the perpendicularly scored line. Move the viewing screen to the first analyzer holder on the movable arc.

F. Rotate the table a set number of degrees (for example 30°), and then move the arm until the reflected image is centered horizontally on the viewing screen. Record the angle which the arm makes with the mirror. Repeat for several settings of the rotating table. What is the relation between the angle of incidence and the angle of reflection? Both of these angles are measured from the ray to the normal of the reflecting surface.

G. Rotate the viewing screen and measure the vertical position of the reflected image. Compare this with the vertical position of the incident beam (from your initial alignment of the laser beam). Check that the incident ray, reflected ray and normal to the mirror at the point of reflection all lie in the same plane.

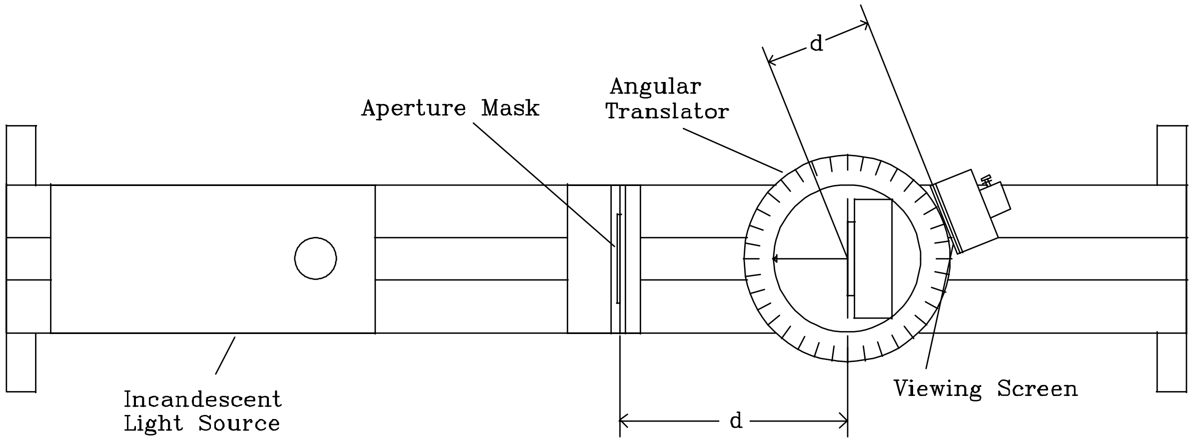

Figure 6.1 – Experimental Setup.

6.1.2 Reflections from Glass and Acrylic

A. Replace the flat mirror with the glass plate, taking care that the front surface coincides with the scored line.

B. Rotate the table until the glass plate rests at a convenient angle with the optical bench.

C. Move the arm until the reflected image is visible on the viewing screen. How many images of the beam are there? Why?

D. The brightest image is the reflection from the front surface of the glass. Center this image on the screen and record the angle which the translator arm makes with the glass plate. Repeat the procedure with the rotating table set at several different angles. What is the relation between the angle of incidence and the angle of reflection?

E. Measure the height of the middle of the reflected image; determine whether the incident ray, reflected ray and normal to the glass at the point of reflection are coplanar.

F. Replace the glass plate with the acrylic plate and repeat the above procedure. Does the material used as the reflecting surface affect the relationship between the angles of incidence and reflection?

6.2 Refraction

The velocity of light in free space is very close to 3×10^{10} cm/s; moreover, the velocity is the same for all wavelengths. The situation is different in most material substances. With few exceptions, the velocity of light in material substances is less than the velocity in free space. Not only is the velocity less, it varies with the wavelength of the light passing through the medium.

If light travels through two media with different velocities, the wave nature of the light causes its direction to be altered as it passes from one medium into the other. This phenomenon is referred to as *refraction*. We can define the index of refraction (n) of a material to be the ratio of the velocity of light in free space (c) to its velocity in the given material (v). Since the velocity (v) varies with wavelength, we must specify the corresponding wavelength when referring to an index of refraction.

The purpose of this portion of the experiment is to determine the relation between the direction of the incident ray, the direction of the refracted ray, and the index of refraction. The index of glass (for example) varies by less than 2% throughout the visible spectrum. Therefore, using the incandescent light source (rather than a single frequency laser source) doesn't introduce much error.

6.2.1 Index of Refraction

A. Take a square piece of millimeter graph paper about 5 cm on a side. Place the paper between the glass plate and the special component carrier on the angular translator. The magnetic surface will hold the glass plate and paper in place.

B. Adjust the position of the special component carrier until the back surface of the glass plate coincides with the perpendicularly scored line on the table.

C. With the glass plate sitting perpendicular to the bench, adjust the position of the aperture mask so that one vertical edge of the image on the paper lines up with the scored line on the table which is parallel to the bench. If the glass does not alter the lights's path, the vertical edge which was centered should remain centered although the translator's table is rotated.

D. Rotate the table and record what happens to the previously centered edge. Is the incident ray refracted toward or away from the normal to the glass? **Before arriving for the experiment**, work out how to calculate the index of refraction given the angle of rotation and the edge displacement of the image using the quantities shown in Fig. D.

Note: Using this method, a small error is introduced since we are not certain that the light very near to the image's edge was exactly perpendicular to the glass plate in the beginning. (Why?) Hence the measured value of θ (as shown in Fig. D is not accurate. The method in the following section gives more accurate results.

E. Remove the paper from between the glass plate and component carrier. With the glass place perpendicular to the bench, put the viewing screen directly behind the plate and adjust the aperture mask to center the image on the screen. Rotate the table to a convenient angle. Light is refracted toward the normal when passing from air to glass. Is the same true when light propagates from glass to air? By observing the position of the image on the viewing screen, you can see that the refraction must be away from the normal at a glass–air interface (see Figure E).

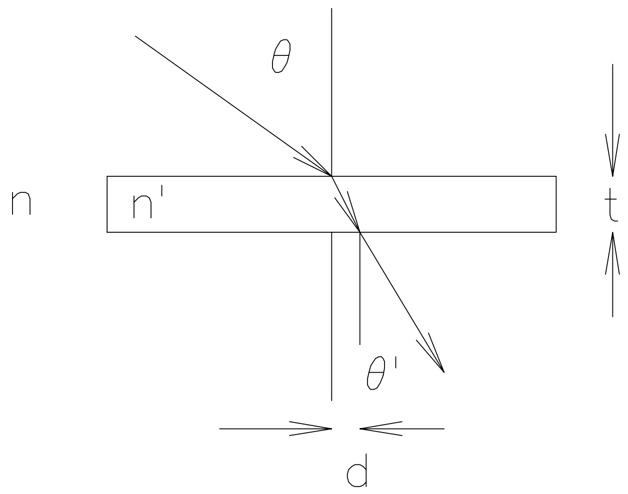

Figure 6.2 – Calculating the index of refraction.

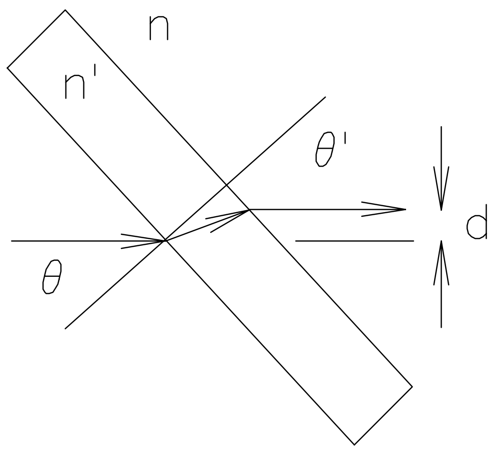

Figure 6.3 – Index of refraction: improved method.

6.2.2 Critical Angles

A. Remove the special component carrier from the angular translator table and replace it with the $90° - 45° - 45°$ prism.

B. With the scored lines running perpendicular and parallel to the bench, position the prism so that one of the small faces is centered on the table and coincides with the perpendicularly scored line.

C. Check the position of the aperture mask so that the center of the light beam travels directly over the center of the table and parallel to the bench.

D. Move the arm until the refracted beam is imaged on the viewing screen. Now rotate the table and watch the movement of the image (move the arm if necessary). Although the prism is continually rotated in the same direction, note that the image moves in one direction and then begins moving in the other direction. The point where the image reverses direction coincides with the angle of minimum deviation. That is, at that particular angle of incidence the light beam is deviated least from its original path.

E. From the angle of minimum deviation, calculate the index of refraction of the prism material. **Before coming to the lab**, work out how to find the index of refraction from the measured minimum deviation angle.

Note: The edges of the image are colored. Why? This phenomenon is called *dispersion*.

F. Rotate the table until the refracted beam is parallel to the large surface (slanted surface) of the prism. In this position, no light propagates through the slanted surface; all of the light is internally reflected.

G. Knowing the angle of incidence θ we can calculate the angle of incidence θ' of the light in the prism as it reaches the slanted surface. The angle θ' is called the *critical angle*.

H. The $90° - 45° - 45°$ prism is designed so that any light normal to the slanted surface is totally internally reflected. Position the prism to observe this phenomenon.

6.3 Lenses

A lens is merely an optical system which includes two or more refracting surfaces. From the geometry of light rays, it turns out that spherical refracting surfaces are most interesting and practical. We define the first focal point of a lens to be the point F_1 such that if a point source of light is placed at F_1, all rays will be parallel after passing through the lens. Similarly, the second focal point F_2 is the common point where formerly parallel light rays meet after passing through the lens. In the case of a lens which is relatively thin compared to the distance from one surface to F_1 or F_2, the first and second focal lengths are the respective distances from F_1 and F_2 to the center of the lens. If the refractive index of the materials on either side of the lens is the same (*e.g.* if the lens is in air), the first and second focal lengths are equal to a common value f.

If, in a thin double convex lens, we take the radius of curvature (R_2, R_2) to be positive for both surfaces, we can derive the equation

$$\frac{1}{f} = (n-1)\frac{R_1 + R_2}{R_1 R_2} \tag{1}$$

where n is the refractive index of the lens material.

In a lens system the image of an object often appears to be larger than the object itself; this is referred to as *magnification*. If s is the distance from the object to the lens and s' the distance from the lens to the image, then the magnification m is given as

$$m = \frac{s}{s'} \tag{2}$$

Moreover, if $d = s - f$ (*i.e.* distance from the object to the closest focal point) and $d' = s' - f$, then

$$m = \frac{f}{d} = \frac{d'}{f} \tag{3}$$

In this part of the experiment you will verify these theoretical results and investigate the distortion (called *aberration*) that spherical lenses introduce into images.

6.3.1 First Focal Length

A. Position the incandescent light source at the left end of the optical bench.

B. Attach a double convex lens to one component carrier and the viewing screen to another.

C. Position the lens and screen at the extreme right end of the bench so that the lens is between the light source and the screen. The further the lens is from the light the more parallel are the rays entering the lens.

D. Adjust the position of the screen until the image is as thin as possible. Then the distance between the middle of the lens and the screen is an approximation of the first focal length. Enumerate all the possible errors. Find the focal length of the other double convex lens. (The focal lengths of the plano-convex lenses are so large compared to the length of the optical bench that the incident light rays are not parallel enough to measure the focal length with any accuracy. We will use another method outlined below.)

E. Attach the plano-concave lens to one side of a component carrier and attach the aperture mask to the other side. Position the assembly about 40 cm from the light source.

F. Place the screen behind the lens and notice that as you move the screen further from the lens, the image expands.

G. Measure the image width and corresponding distance from the lens to the screen for two different screen positions. Using simple geometry, calculate where the rays diverted by the lens would theoretically converge at a point in front of the lens. This is an approximation of the focal length.

6.3.2 Second Focal Length

A. Attach a double convex or plano convex lens to a component carrier.

B. The light source is a line filament, so if we consider only lateral dimensions the source is essentially a point source. The equipment instructions for the source give the distance from the filament to the front surface of the light source to be approximately 21 mm.

C. Adjust the lens position so that the image on the screen is the same width no matter where the screen is placed (*i.e.* the emergent rays are parallel). The distance from the lens to the filament is the second focal length. Compare your result to the first focal length.

D. You cannot use the above method to measure the focal lengths of the 18 mm F.L. convex lens or the −22 mm F.L. plano-concave lens. These lenses cannot be positioned sufficiently close to the filament. Thus, as an alternative, place the 48 mm F.L. double convex lens between the light and the lens to be measured. The focal point of the first lens now becomes the point source for the second.

6.3.3 Improved Method

A. From the formulae above, if the magnification $m = 1.0$, then $s = s'$, $d = d'$ and $f = d$. Hence, at such a lens position, $s + s' = 4f$.

B. Place a double convex lens or a plano-convex lens between the crossed-arrow target and the screen. (All the components should be on separate carriers.)

C. Adjust the position of the lens and screen until the image is in focus and is the same size as the original object. The target has a millimeter scale on it. At the final position, the distance from target to screen is four times the focal length.

D. With the focal length, compute the radius of curvature for the lenses. Assume $R_1 = R_2$ for the double convex lenses; the radius of curvature of a plane is infinite. Also verify Gauss' formula:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \tag{4}$$

6.3.4 Magnification

A. Position a double convex lens or plano-convex lens between the crossed arrow target and screen.

B. Adjust the position of the lens until the image is focused.

C. Measure the distance from the target to the lens and from the screen to the lens. Calculate the theoretical magnification.

D. Measure the actual magnification by measuring the distance between the scale markings on the image and compare with the theoretical value.

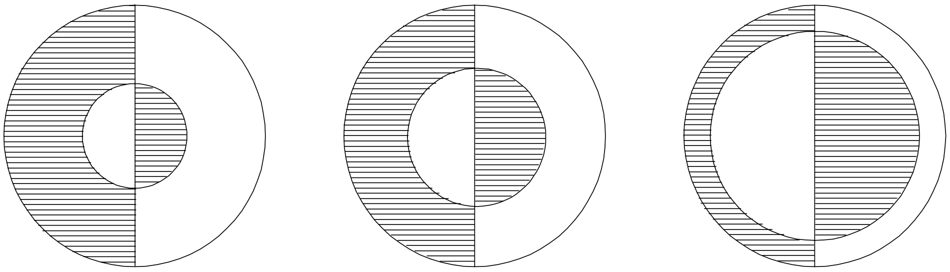

Figure 6.4 – Spherical aberrations.

6.3.5 Spherical Aberration

A spherical surface lens does not form a point image of a point object originally positioned on the lens axis. Instead, the image is a line segment collinear with the lens axis. Thus, there is no exact screen position where the image is "in focus". Conversely, the point object can be moved slightly along the axis and still appear "in focus". The amount of movement which maintains a given image sharpness is called the *depth of field*.

A. Position the 188 mm F.L. double convex lens in front of the incandescent light source (about 30 cm away). Attach a sharp razor blade to a component carrier and position the assembly to the right of the 18 mm lens. Adjust the assembly position until the razor blade is in the focal plane of the lens. The lens image on the razor blade should be a small dot.

B. Carefully adjust the razor blade on the carrier until the sharp edge cuts across the center of the focussed dot. Place the viewing screen to the right of the razor blade and examine the image. It should resemble one of the patterns shown in Fig. B. Move the razor blade assembly slightly forward or backward and observe the pattern changes. The patterns will only approximate those in Fig. B since razor edges are not usually optically perfect. This technique is the *Foucault knife test* for lenses. Convince yourself that the patterns are due to spherical aberrations. Try using the 48 mm F.L. lens.

C. Place the variable diaphragm just in front of the test lens. By varying the opening, notice that the patterns degenerate. A small aperture gives a more unique focal point. If you placed the crossed arrow target between the light source and the variable diaphragm, you can observe that the point where the image is in focus becomes more distinct as the aperture closes. Thus, depth of field varies inversely with aperture size. This phenomenon is familiar to photographers.