Diffraction and Interference of Light

<table>
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<tr>
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<td>Light Sensor</td>
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</tr>
<tr>
<td>1</td>
<td>Rotary Motion Sensor</td>
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</tr>
<tr>
<td>1</td>
<td>Single Slit Set</td>
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</tr>
<tr>
<td>1</td>
<td>Multiple Slit Set</td>
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</tr>
<tr>
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<td>Linear Translator</td>
<td>OS-8534</td>
</tr>
<tr>
<td>1</td>
<td>Laser</td>
<td>OS-8525A</td>
</tr>
<tr>
<td>1</td>
<td>Optics Bench</td>
<td>OS-8518</td>
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Purpose
The purpose of this activity is to examine the diffraction and interference patterns that occur when monochromatic laser light passes through difference combinations of apertures.

Theory/Background
In 1801, Thomas Young obtained convincing evidence of the wave nature of light. Light from a single source falls on a slide containing two closely spaced slits. If light consists of tiny particles (or ‘corpuscles’ as described by Isaac Newton) then on a viewing screen placed behind those two slits we would two bright lines directly in line with the two slits.

However, Young observed a series of bright lines. Young was able to explain this result as a wave interference phenomenon, because of diffraction, the waves leaving the two small slits spread out from the edges of the slits. This is equivalent to the interference pattern of ripples, from two wave sources, to the top for a body of water crossing each other’s paths, and interference with each other when they do.
In general, the distance between the slits is very small compared to the distance from the slits to the viewing screen where the interference pattern is observed. The rays from the edges of the slits are essentially parallel to each other. Constructive interference will occur on the screen when the distance that the rays from each of the slits travels to the screen is different by a whole number multiple of the wavelength of the light itself. Those spots are where the bright spots in the observed interference pattern form. While destructive interference will occur on the screen when the different distances that the rays from each of the slits travels to the viewing screen is related to half a wavelength of the light itself.

When the monochromatic (single wavelength) light is passed through two slits the bright spots (maxima) of the interference pattern that forms is symmetric around a central bright spot. Each of the maxima are evenly spaced, and of the same width. They will get slightly dimer as the get further away from the central maxima.

When the monochromatic light is passed through one slit a slightly different interference pattern (also called a diffraction pattern) will form. In the case of one slit the pattern will still be symmetric around a central bright spots, but the central bright spot will be twice as wide as all the other maxima, and will also be much brighter than all the other maxima. For diffraction of light to occur when monochromatic light passes through a single slit the width of the slit mustn’t be too much larger than the wavelength of the light itself.

**Equations for Double Slits**

If we draw a diagram for the double slit configuration we can use simple trigonometry to determine where the bright spots will form on the viewing screen. Here $d$ is the distance between the two slits. $L$ is the distance from the two slits and the viewing screen. $y$ is the displacement from the center point of the viewing screen to the point $P$ where the bright spot forms. $\theta$ is the angular location of the bright spot. Finally $S$ is the difference in the distance traveled by the two light rays $r_1$ and $r_2$. From the properties of the right triangle it is clear that $S = d \sin \theta$. Since we know that the bright spots will form where $S$ is equal integer multiples of the wavelength ($\lambda$) of the light that means;
\[ d \sin \theta = n\lambda \]

As previously stated L is going to be much larger than d, which is going to result in L also being much larger than y. This means that \( \theta \), the angular position of the bright spots, is always going to be very small. So we can invoke the small angle approximation of \( \sin \theta \). (\( \sin \theta \cong \tan \theta \), when \( \theta \) is small) Which makes our equation;

\[ d \tan \theta = n\lambda \]

Finally, since \( \tan \theta = \frac{\text{opp}}{\text{adj}} \) we have \( \tan \theta = \frac{y}{L} \) in this case. Substituting that in gives us:

\[ d \frac{y_n}{L} = n\lambda \]

Solving for \( y_n; \)

\[ y_n = n \frac{\lambda L}{d} \]

Our equation tells us that for the two slit configuration the various maxima will be located integer multiples of the wavelength of the light multiplied by the distance from the slits to the viewing screen, and all divided by the distance between the slits. So \( y_n \) is the linear location of the \( n^{th} \) bright spot, measured from the location of the central bright spot.

If we want to find the angular location of the bright spots we just return to our original equation and solve for \( \theta; \)

\[ \theta_n = \sin^{-1} \left( \frac{n\lambda}{d} \right) \]

**Equations for Single slit**

If you draw a diagram of the single slit configuration we can also use simple trigonometry to find the where the dark spots will form on the viewing screen. These are the spots of destructive interference located right in the middle between any two consecutive bright spots. In this diagram a is the width of the single slit. L is the distance from the slit to the viewing screen. y is the
displacement from the center of the viewing screen to the bring spot. \( \theta \) is the angular position of the bright spot. Using a similar argument as we did with the double slit configuration we get the following:

\[
\theta_m = \sin^{-1}\left(\frac{m\lambda}{a}\right)
\]

\[
y_m = m\frac{L\lambda}{a}
\]

In these equations \( m \) is an integer, **excluding zero**. Remember these equations give you the location of the dark spots between the maxima, because of this the difference in the value of \( y \) for two consecutive whole numbers is considered to be the width of a bright spot. (Not including the central bright spot)

\[
\Delta y = \frac{L\lambda}{a}
\]

The central bright sport has a width that is twice as large as all the other bright spots due to \( m \) being an integer excluding zero, as can easily be shown. Let \( m = 1 \), be for the first dark spot to the right of the central maxima, and \( m = -1 \) be for the first dark spot to the left of the central maxima, then the distance between these two dark spots is given by;

\[
\Delta y = \frac{L\lambda}{a} - \left(\frac{-1L\lambda}{a}\right) = \frac{2L\lambda}{a}
\]

**What happens when both conditions are meet?** Meaning when there are two slits, and the width of the slits is about the size of the wavelength of the light passing through them what sort of pattern forms of the viewing screen? Well, then you get a composite of the two patterns, where the double slit interference pattern is encased in the diffraction pattern associated with the width of the slits. If you were to plot out the Intensity vs. Angular Position graph of a double slit interference pattern you would obtain something like the following. The central maxima is located at 0°, and all the peaks are evenly spaced out, and about the same height, means all about the same brightness.
If you were to plot out the Intensity vs. Angular Position graph of a single slit diffraction pattern you would obtain something like the following. Here the central maxima is still located at 0°, but the central maxima is twice the width of all other bright spots, and the central maxima is much taller than the rest meaning it is much brighter than all other bright spots.

Now when BOTH conditions are meet the something similar to the following graph is obtained. As stated before, the double slit interference pattern is encased in the single slit diffraction pattern. The intensity of any given peak from the double slit interference pattern is determined by the local intensity of the single slit diffraction pattern. Even so much that the bright spots of the interference pattern that are at the locations of the dark spots of the diffraction pattern are completely suppressed, and there is a dark spot at that location.

We call the central bright spot of the diffraction pattern the Central Envelope of the composite pattern, and we can determine how many of the bright spots from the double slit interference pattern are encased in the Central Envelope by using the equation for the linear positions of the interference pattern, and the linear equation for first dark spot of the diffraction pattern, \( m = 1 \). Set the interference equation equal to the diffraction equation when \( n = 1 \).

\[
\frac{m \lambda}{d} = \frac{1 \lambda}{a}
\]

\[
m = \frac{d}{a}
\]
This ratio tells us that the m\textsuperscript{th} bright spot of the inference pattern should form at the same location that the first dark spot of the diffraction pattern. But we are not finished yet. First the ration of $\frac{d}{a}$ is most likely not going to be an integer, meaning these two spots don’t line up exactly so the last bright spot is only partially encased in the central envelope. In this case we need to round down to the closest integer. (Always round down, never round up. Example 3.9 is rounded to 3, not 4.) In the case that the ratio $\frac{d}{a}$ is an integer that means the m\textsuperscript{th} bright spot of the interference pattern, and the first dark spot of the diffraction pattern are at the exact same location. This means that the m\textsuperscript{th} bright spot is completely suppressed by the first dark spot, and is NOT in the central envelope, so you need to round down to the next integer. (Example 4 is rounded down to 3.) The end result being is that you \textbf{ALWAYS} round the ratio down to the next integer. Next, since the pattern is symmetric about the central bright spot, we have to double the rounded down value to account for the bright spots on the other side of the central bright spot, and finally we have to add 1 to account for the central bright spot itself. (As an example let $d = 0.30 \text{ cm}$, and $a = 0.30 \text{ mm}$ then we get;

$$m = \frac{d}{a} = \frac{0.30}{0.030} = 10$$

$$10 - 1 = 9 \quad 2 \cdot 9 = 18 \quad 18 + 1 = 19$$

So in such a configuration there would be 19 bright spots from the double slit interference pattern encased in the Central Envelope of the diffraction pattern.)

\textbf{Setup}

1. Connect the aperture bracket screen to the light sensor by placing the light sensor is aimed through the circular opening for the brackets, and the bolt opening on the bottom of the light sensor is aligned with one of the circular openings on the bottom of the bracket.
   - Then screw in the cylinder mount to the bottom of the light sensor
2. Attach the light sensor to the rotary motion sensor by inserting the cylinder mount through the holes at the front of the rotary motion sensor, and then tightening the front screw.
   - Make sure that the light sensor is mounted on the rotary motion sensor such that the light sensor and the axle of the rotary motion sensor are both oriented upwards.
3. Attach the rotary motion sensor to the linear translator first unscrew one of the ends of the metal bar with gear teeth, and completely remove the screw.
• Then slide that end of the bar all the way through the rotary motion sensor, and then reattach the loose end of the bar.

4. Attach the linear translator to the optics bench sliding the loosely connected screw and bolt, at the bottom of the linear translator through the groove along the middle of the optics bench till the very front of the aperture bracket screen is at the 100 cm mark and pointing towards the other end of the optics bench, then tighten the screw to hold the setup in place.
  • Rotate the aperture disk of the aperture bracket screen till the #2 slit is aligned with the light sensor.

5. Attach the multiple slit set slit accessory and attach it to the optics mount, then insert the optics mount into the optics bench the very front of the slit accessory is at the 10 cm mark, and it is facing the setup at the other end of the optics bench.
  • Rotate the slit set till the combination of $a=0.04\text{mm}$, and $d=0.25\text{mm}$ are at the center of the optics mount’s opening. Remember that $a$ is the width of the slits, and $d$ is the separation between the slits.
  • Then insert the laser into the optics bench so that it is behind the optics mount and facing the optics mount.

6. Double click the Capstone icon to open up the Capstone Software.

7. Make sure the PASCO 850 Interface is turned on, and plugged in.

8. In the Tool Bar, on the left side of the screen, click on the Hardware Setup icon to open the Hardware Setup window.
  • In the Hardware Setup window there should be an image of the PASCO 850 Interface. If there is skip to step 9. If there isn’t click on Choose Interface to open the Choose interface window. Now select PASPORT, the Automatically Detect, then click OK.

9. On the image of the PASCO 850 Interface click on the Digital Inputs Ch(1) to open the sensor list, then scroll down, and select the Rotary Motion Sensor.
  • The rotary motion sensor icon should now be showing connected to Ch(1), and Ch(2).
  • Plug the rotary motion sensor into the Digital Inputs, yellow to Ch(1), and black to Ch(2).

10. On the image of the PASCO 850 Interface click on the Analog Inputs Ch(A) to open the sensor list, then scroll down, and select the Light Sensor.
  • Plug the cord into the back of the light sensor, and the other end into Analog Inputs Ch(A).
• At the bottom middle of the of the screen change for sample rate, change it to Common Rate, and set it to 100 Hz.

11. In the Tool Bar click on Data Summary to open the Data Summary window.
    • In the equipment list click on the rotary motion sensor’s properties icon to open its properties window.
    • In the properties window where it reads Linear Accessory select Rack & Pinion.


13. Plug the laser’s power cord into a power outlet, and the other end into the back of the laser. BECAREFUL NOT TO LOOK INTO THE LASER BEAM! LOOKING INTO THE LASER BEAM COULD CAUSE PERMENATE LOSE OF SIGHT.
    • Use the two knobs on the back of the laser to aim the laser beam such that it passes through the double slit configuration at the center of the optics mount opening, and that it hits the #2 slit on the aperture bracket screen. One knob moves the laser up and down, the other moves the laser right and left.
    • The interference pattern that forms on the aperture bracket screen needs to be horizontal. If it is not, slowly rotate the multiple slit set on the optics mount till the interference pattern is horizontal.

14. In the Display Bar, on the right side of the screen double click the Graph icon to open up a graph.
    • For the y-axis click on Select Measurement, and then select Light Intensity (%).
    • For the x-axis the computer will have automatically selected time (s), we need to change it. Click on the word time (s), the available data list will appear, and select Position (m).

**Procedure: Single and Double Slits**

1. Record the values for a, d, L, and λ in the table.
2. Move the rotary motion sensor completely to one side of the linear translator.
3. Near the bottom left of the screen click Record to start recording data.
4. Slowly move the rotary motion sensor to the other side of the side of the linear translator. Then click Stop to stop recording data. (Be careful that the cords don’t get caught up or snagged on something.)
5. Click on the Show Coordinates Tool icon, along the top of the graph, to create a coordinates tool appear in the graph.
    • Use the coordinate tool to measure the position values of all the peaks of the interference pattern, and then record those values in the table for the two slits.
    • Then use the coordinate tool to measure the position of the dark spot right to the left of the furthest left peak, and record the location in the table for two slits.
    • Then use the coordinate tool to measure the position of the dark spot right to the right of the furthest right peak, and record the location in the table for two slits.
6. Move the rotary motion sensor completely back to the original side.
7. Remove the multiple slit set from the optic mount, and replace it with the single slit set.
    • Set the slit a=0.4mm in the center of the optics mount.
    • Make sure the laser passes through the single slit, and strikes the aperture bracket screen.
- Rotate the multiple slit set in the optic mount till the interference pattern formed on the aperture bracket screen is horizontal.
8. Near the bottom left of the screen click Record to start recording data.
9. Slowly move the rotary motion sensor to the other side of the side of the linear translator. Then click Stop to stop recording data. (Be careful that the cords don’t get caught up or snagged on something.)
   - Use the coordinate tool to measure the locations of its edges on either side of the large central bright spot. Record these values in the table for the Single Slit.
Analysis

Tables for Two Slits (5 points)

<table>
<thead>
<tr>
<th>a</th>
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<tbody>
<tr>
<td>d</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>(\lambda)</td>
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</table>

<table>
<thead>
<tr>
<th>Left Dark Spot</th>
<th>Right Dark Spot</th>
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</thead>
<tbody>
<tr>
<td>(\Delta y)</td>
<td></td>
</tr>
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</table>

1. According to the theory the distances (\(\Delta y\)) between consecutive peaks for two slit interference pattern should all be the same. Calculate the distances between consecutive peaks, record them in the chart, and then calculate the standard deviation for the distances between peaks.

   (20 points)
2. Identify the central peak, and then calculate the distance to the third peak to its right, $y_3$. Using this distance, $n = 3$, and the recorded value for $d$ calculate the experimental value for the wavelength of the laser beam. (10 points)

3. Calculate the % error between the accepted value of the laser beam, and your experimental value. (5 points)

4. Calculate the number of peaks that should be encased in the Central Envelope. Is that the number of peaks you counted? (5 Points)
Table for Single Slit (5Points)

<table>
<thead>
<tr>
<th></th>
<th>Position of left edge Central Maxima</th>
<th>Position of right edge Central Maxima</th>
<th>Width of Central Maxima</th>
</tr>
</thead>
</table>

1. Using the equation for the locations of the dark spots of the diffraction pattern calculate the width of the central maxima. Then find the % error of the width of the central maxima using the calculated value as the theoretical. (10 points)

2. Calculate the % difference between the measured width of the central bright spot for the single slit pattern, and the width of the Central Envelope of the double slit pattern. (5 points)

3. For both setups we are using the same laser, the same distance between the slit(s) and the viewing screen (L), and the slits had the same width, then why is the intensity for the double slit so much greater than the intensity for the single slit? (10 points)
4. If we repeated this experiment with a laser of 550 nm what affect would that have on the interference, and diffraction patterns? (5 points)