Michelson Interferometer Noise Floor

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Abstract:

The scope of this project was to construct a Michelson interferometer, find the noise floor, and then to use the available adjustable parameters to improve the noise floor of said interferometer. The original hypothesis was that as the arm length of the interferometer increased, the sensitivity would also increase. After construction of the interferometer, we managed to determine a frequency range of high sensitivity and the minimum noise floor. This was done through the data collection of several different frequencies, fast Fourier transform of the data, and observational data gathered using diffraction patterns and the oscilloscope.

Introduction:

Albert Michelson was an American scientist at the turn of the 20th century. He designed the Michelson interferometer in order to try and detect the luminiferous ether. The ether was thought to be the medium in which light moves through. The basic design for his interferometer took a beams of light and split it. It then bounced off two mirrors and when it was recombined it created an interference pattern. He could then use this interference pattern to detect the Earth's movement through the ether. When this didn't work at first Michelson teamed up with Edward Morley to try and improve the instrument. They succeed in making the interferometer more sensitive by adding more mirrors to make the path length longer and by floating the device in a pool of mercury to reduce the amount of vibrations. When they didn't detect anything, they reported their findings that there was no ether in which light moved through. From here the use of interferometers took off in the world of science [6].

Our inspiration to build an interferometer came from LIGO (Laser Interferometer Gravitational-Wave Observatory). LIGO is fundamentally a Michelson interferometer, but it is designed to be a lot more sensitive. The arm length of LIGO is 4 km long, but using a system of mirrors LIGO is able to make their arm length about 1120 km long [3]. LIGO also uses a powerful laser, a vacuum, and seismic isolation to make it the most sensitive instrument ever built on an order of magnitude of 10^{-19} meters [4]. Because of this sensitivity LIGO was able to detect gravity waves and win the Nobel Prize in 2017. Our group knew that we did not have the budget to build an interferometer as big as LIGO, but we wanted to see how close we could get.

We wanted to reach the capability of detecting the interference due to a large range of frequencies. Another method that we would want to use is to reduce seismic interactions from the ground. An optical table is commonly used in the creation of Michelson Interferometers and reduces the seismic noise successfully. We would be using both the optical table in the Advanced Lab as well as the optical table in the G-15 Lab. The table in G-15 is not as stable as the table in the Advanced Lab so we expect different results to come from using that table. Our goal was to determine the noise floor of the interferometer as well as finding out how sensitive it was. In this experiment we predict that by changing the arm length and by having changing the laser we can lower the noise floor if the interferometer.

Methods:

Materials:

Laser- provided by Dr. Fischer, must be cooled
ThorLabs TA0505D024W Piezoelectric (PZT) Actuator
ThorLabs 7.0 mm Protected Silver Mirror
Second mirror
Diverging lens- provided by Dr. Fischer
Filter to cut laser intensity- Dr. Fischer's
Beamsplitter, non-polarized- again, provided by Dr. Fischer
2 kinematic optical mirror mounts
Beamsplitter platform mount
Mount for filter
Mount for lens
Circular mount for photodiode
Electronic breadboard and associated wiring components
Various optical posts, post holders, and table screws
Edmund Optics Photodoide and Photodiode Amplifier
Aglient 33220A Function Generator
German-to-English dictionary or translator (for Function Generator)
Aglient MSO6012A Mixed Signal Oscilloscope
Raspberry Pi
Raspberry Pi Camera V2

We will now briefly discuss the purpose of each of the components. The purpose of the laser is to provide a beam for interference, and the mirrors, beamsplitter, diverging lens, filter, and all associated hardware are for providing the physical setup to achieve interference. The PZT actuator and breadboard are for introducing a known wave into the system, and this wave is necessary because it allows the size of other disturbances to be calculated. The photodiode and photodiode amplifier is to measure the intensity of the output of the interferometer, so that one may detect disturbances in the interference pattern. The function generator is to drive the PZT at any given frequency and voltage, and the oscilloscope is for viewing the waves generated by the PZT, as well as the disturbances detected by the interferometer. The Pi camera cannot be used in conjunction with the photodiode, but it can be used to obtain a visual reference for the interference pattern.

General Setup:

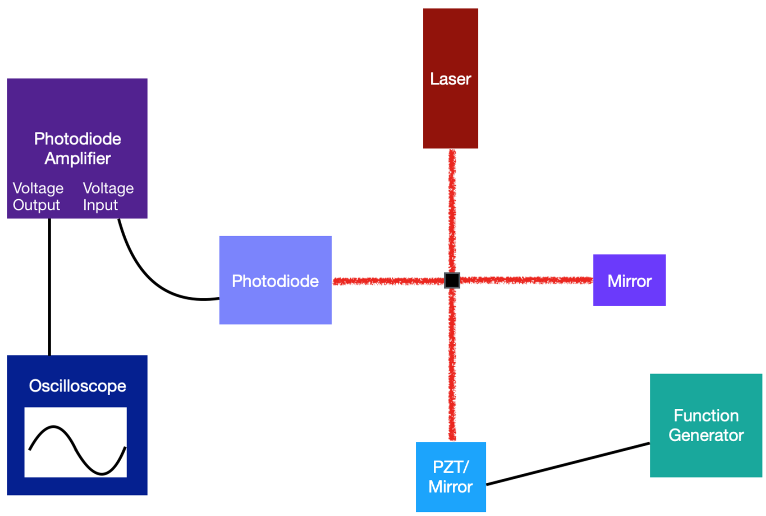

Figure 1. Interferometer with Oscilloscope setup

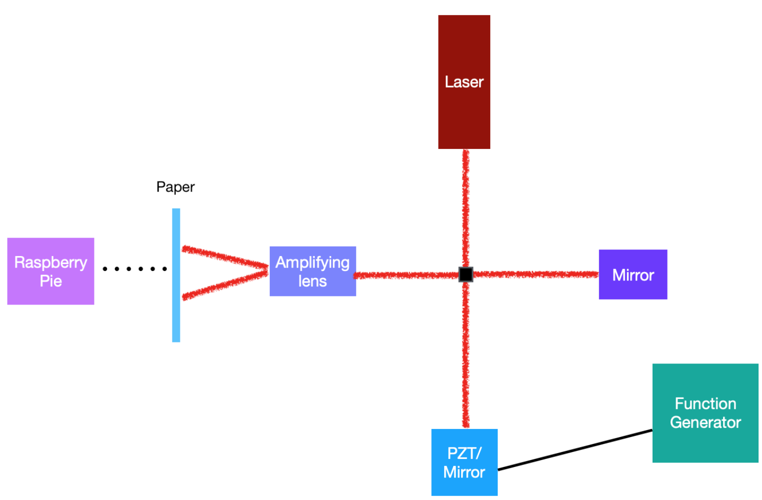

Figure 2. Interferometer with camera setup

Calibration-

The calibration of the interferometer involved both the focusing of the beams and the setup of the oscilloscope/photodiode pair. First, once the interferometer had been set up in such a way that the beams existed (i.e. mirrors, laser, and beamsplitter bolted to the table in approximately the correct positions), the laser had to be turned on in order for the mirrors to be able to be adjusted to be in a position to allow for interference. This required small adjustments to the position of the mirrors, such as rotating the mounts slightly, and adjusting the mounts with the screws on the back, to move the mirror within the mount. It was first necessary to simply make the mirror reflect the beam back through the center of the beam splitter's face, and, if desired, to 'parallel align' the beam, or have the secondary reflection go back into the laser cavity. Once both beams were aligned thusly, it is necessary to adjust both under observation until the desired interference pattern is observed. Once this is achieved, one may turn their attention to the oscilloscope. Set a known frequency and voltage and simply try to find the wave made by the interferometer. Once found, small disturbances may introduced, such as tapping the table, speaking aloud, or walking around the room. For a more precise calibration, drive a known frequency through a speaker and hold the speaker either on the table or just above it. Set the oscilloscope to display the FFT. The known frequency (provided that it is within the detectable range of the interferometer) should appear as a singular spike on the FFT function. If this is not the case, adjust the PZT settings(raise the frequency to ~500 Hz, lower the voltage to 500 mV) to try to find this spike, or try to see if the frequency is out of the detectable range by sweeping a range of frequencies.

Raspberry Pi Set up:

To study the diffraction patterns, we used a raspberry pi, raspberry pi camera, and diffraction lense. The OS system used for our Raspberry Pi was Raspbian Stretch. Using python 3 and camera specs, we could record the diffraction patterns of the interferometer when in the configuration of Figure 2. The camera took videos in *.h264 file formats using this code:

```
from picamera import PiCamera
import datetime
import time

#timestamp for filename
T = time.asctime(time.localtime(time.time()))
T = T.replace(" ","_")
T = T.replace(":",".")

#coment for filename and length of time
comment = input("Enter comment for run: ")
comment = comment.replace(" ","_")
time = int(input("Enter number of seconds for run: "))
camera = PiCamera()
camera.resolution = (640, 480)
camera.exposure_mode = 'off'
camera.framerate = int(input("Enter framerate (30-90): "))
```

```
filename = 'recordings/' + T + "--" + str(time) + 'sec_' +
str(camera.framerate) + 'fps_' + comment + '.h264'
camera.shutter_speed = int( 1/(int(camera.framerate)) )
print(filename)
print('Begin recording...')
camera.start_recording(filename)
camera.wait_recording(time)
camera.stop_recording()
print('End recording')
```

In the code you can specify the length of time, the frame rate, and a comment for the video file name. The code would also attach a date for the filename and could be run using the command:

```
python3 camera.py
```

A sample frame of a video is shown in Figure 3. It is best reduce all other light sources to a minimum when recording a video.

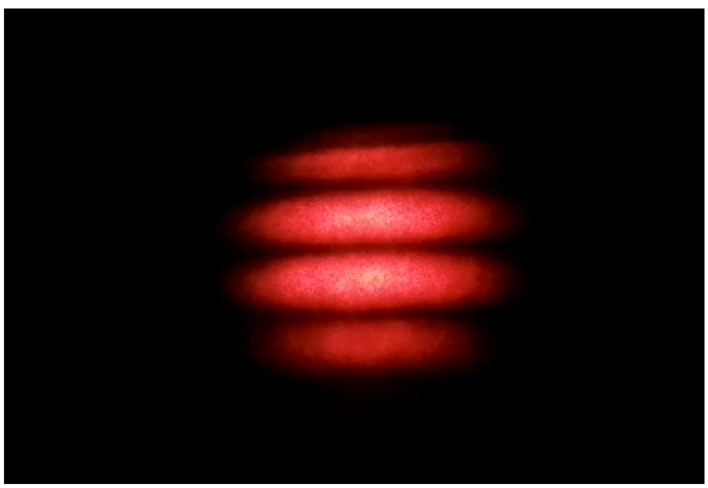

Figure 3. Sample frame from video of Raspberry Pi camera

Calculations:

In order to detect specific frequencies we used a Fast Fourier Transform (FFT) which is an approximation of the Discrete Fourier Transform (DFT) given by equation (1):

$$X[k] \triangleq X(k/N) = \sum_{n=-\infty}^{\infty} x[n]e^{-j2\pi kn/N} \qquad \text{for } 0 \leq k \leq N-1$$

(1) [1]

The FFT returned the amplitude values in dBV, which occasionally needed to be converted to Voltage using equation (2):

(2) $$V = V_0 \cdot 10^{\frac{L \text{ in dB}}{20}}$$ [5]

To calculate the the strain in standard units, we used the PZT information to find the ratio of ΔL to Voltage and then measured the arm length of out interferometer which was 0.445 m. This combination gave us an equation for the strain.

(3) $$\frac{\Delta L}{L} = \frac{1}{0.445\ m} \frac{0.5\ \mu m}{10\ V} V\, min$$ [PZT specs]

Results:

For measuring the output of our interferometer, we used two different methods: we took camera recordings of the diffraction patterns of the laser output, and we used a photodiode and oscilloscope setup to collect data. We initially used the diffraction patterns to optimize the laser and test basic sensitivity such as hitting the table or talking, but because it is difficult to present this data on a report, we will only be discussing the data taken with the oscilloscope. In this section three numbers are important: they are the driving frequency, the driving voltage, and the audio frequency. The driving frequency and voltage are what we apply to the to the function generator and in turn to the PZT (refer to General Setup). The audio frequency is what we apply using a separate source and hope to detect in the Fast Fourier Transform of our data.

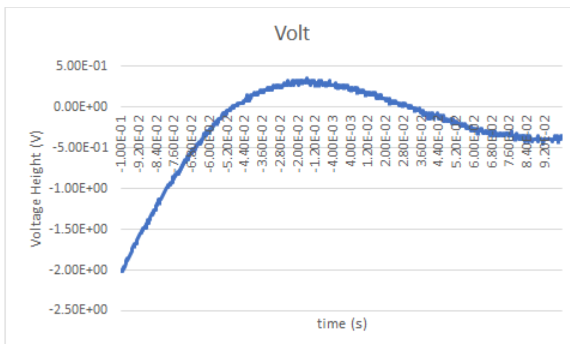

Figure 4. Interferometer intensity data is shown here in a 0.2 second interval with PZT driving 5 V and 1 Hz.

Figure 4 is an example of the intensity over time. Here, the intensity of photons measured by the photodiode is represented by voltage. The voltage has a linear relationship with the intensity of photons hitting the silicon detector. Because of the oscilloscope settings, we could only ever record 0.2 seconds of data. The oscilloscope also computed its own fast fourier transform (FFT). To determine the accuracy of this we compared the FFT of the oscilloscope to the FFT of Origin data analysis software.

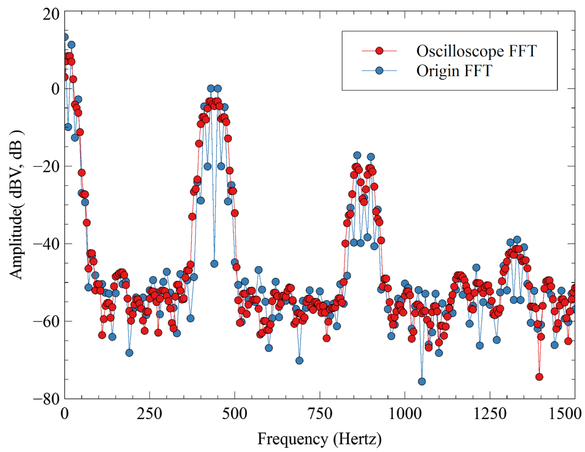

Figure 5. FFT of PZT parameters of 5V, 10 Hz and audio frequency of 440 Hz data completed by the oscilloscope and by Origin software.

Both of the FFT's in Figure 5 have peaks at the locations of 440 Hz, 880 Hz, and 1320 Hz which corresponds to the audio frequencies applied to the interferometer. Though the Origin FFT has higher peak heights, the Oscilloscope FFT has higher precision in the frequencies range. All further FFT graphs are performed by the oscilloscope.

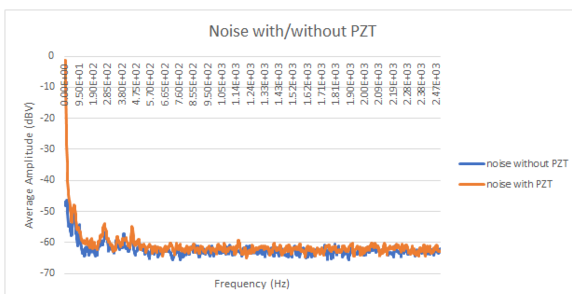

Figure 6. FFT of noise floor with and without the Piezoelectric Tube (PZT) driving a frequency of 1 Hz and voltage of 5 V.

The major differences between the noise floor with and without the PZT is that the F_0=0 Hz has a much higher value with the PZT. This is a direct result of the FFT where the initial frequency calculation is a sum of the driven voltage. Without the PZT there was no voltage, and with, there is. Both datasets are noisier at lower frequencies less than 400 Hz.

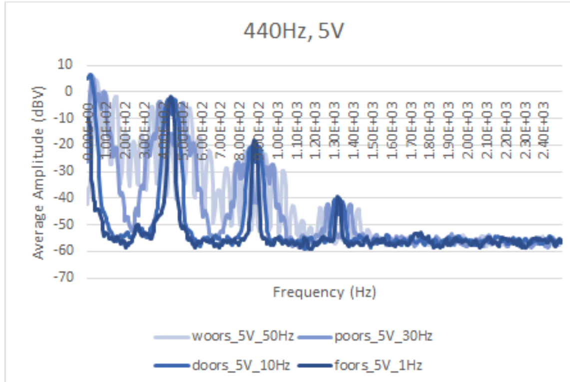

Figure 7. FFT of different values of frequencies driven into the PZT with a set voltage of 5V in the PZT and an audio frequencies of 440 Hz.

The precision of detection of frequencies is ideal, so by testing various driven frequencies (Figure 7), we observe that the higher frequency of 50 Hz has a much noisier FFT than that of 1 Hz, which has cleaner peaks at the desired resonances.

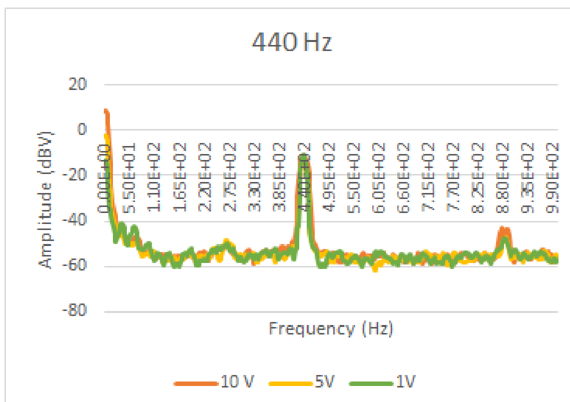

Figure 8. FFT of varying driven voltages into the PZT with the PZT set at 1 Hz and an audio detection of 440 Hz

With the changing driven voltage to the interferometer as shown in Figure 8, there is not much change in the precision or height of the detection of the 440 Hz audio, but the F_0=0 Hz frequency does vary between the multiple voltages.

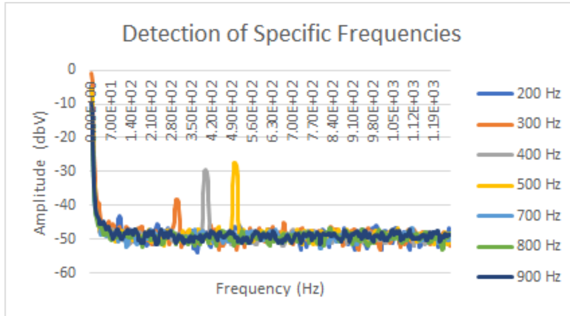

Figure 9. FFT of varying frequency detections at the same volume level while keeping the driven frequency and voltage at 1 Hz and 5V respectively.

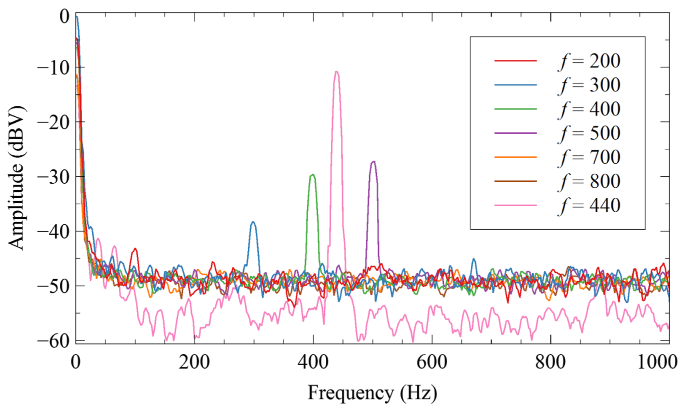

Figure 10. FFT of varying frequency detections at the same volume level while keeping the driven frequency and voltage at 1 Hz and 5V respectively alongside the 440 Hz frequency detection.

In Figure 9, we can clearly see that when detecting varying frequencies there is a clear peak around 440 that falls off around 200 Hz and 700 Hz. This gives us an idea of our frequency range of highest sensitivity. We also see that in Figure 10 that this peak of frequency detection is centered by 440 Hz which abnormally higher than the other peaks.

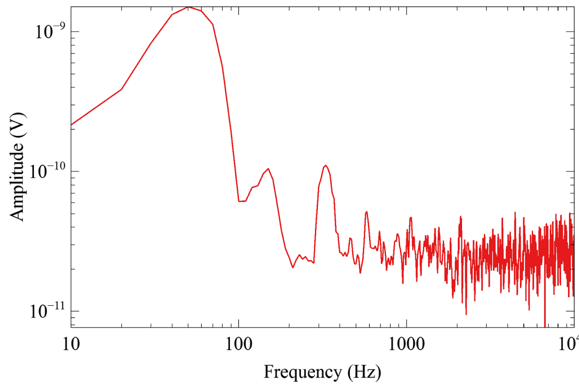

Figure 11. FFT of 100 Hz and 10 mV driven into the PZT and the noise background. Because the sensitivity will have a linear relationship to this data, this will give an idea of where the noise of the surroundings is corrupting our data.

Table 1

Minimum Voltage (mV)	Sensitivity (ΔL/L)
10 mV	1.12×10^{-9}

In Table 1, we use calculations of equation (3) in order to calculate a base sensitivity for our interferometer. We achieved this number by lowering the driving voltage just until we couldn't see a peak on the FFT of the oscilloscope at the driving frequency. This number is not frequency dependant as we are limited by the minimum allowed voltage of our function generator.

Discussion:

During the course of this experiment, not all parts of the hypothesis were able to be tested as fully and rigorously as others. Much data was taken on the noise floor of the interferometer as well as testing the frequency range and interferometer sensitivity, but the ΔL/L had comparatively little data and testing. As for the original hypothesis of constructing the interferometer to i) test and detect the noise floor at the original given parameters and ii) improve the noise floor, there were many results that support this goal, such as finding the ΔL/L figure, testing the interferometer over several different frequencies and voltages in the Advanced Lab and then in the G-15 lab. We can conclude that the maximum detectable strain for the original interferometer that was constructed is about $1.2 * 10^{-9}$m, and that this strain can be adjusted via the voltage settings on the PZT. We did not get to test the interferometer strain by varying the arm length, which was one of the goals. This is not to say that the project was not a success, but it required more calibration of the device and device users than previously planned for, and time constraints did not allow for the second goal to be completely realized. That said, data was taken on multiple tables under different conditions, so there was some progress made towards the comparisons of data to occur. We did get to take data under multiple different PZT voltages, which contributed to the calculation of the strain, as well as calculating the noise floor based on the Figure 3 graphs, which contributed to our second goal. We were also able to observe the effects of a non-temperature-controlled, non single mode laser, which made the experiment quite difficult, and to understand why a temperature-controlled, single mode laser was so important to this setup.

Sources:

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