Effect of acoustic vibrations on Michelson interferometry

PH5060

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Abstract

Study of interference of light is the study of how light waves interact with each other depending on the phase difference.
This phase difference between two interfering light waves is caused by the difference in the effective optical path lengths. The effective path length could vary with the physical length or the refractive index. We will be doing this experiment in air and as we know the refractive index of air is a function of its pressure.
Michelson interferometer splits a laser beam in two and sends them into orthogonal directions. These two beams are reflected by two mirrors and then recombine as one beam. Depending on any phase difference caused when the beams travelled across two separate paths, they give rise to an interference pattern on a screen.
Our goal is to use sound waves to create pressure differences in the paths of the laser beams to observe their effect on the interference pattern.
In this paper you will be walked through the experiment performed by me and the discoveries made.

1 Motivation

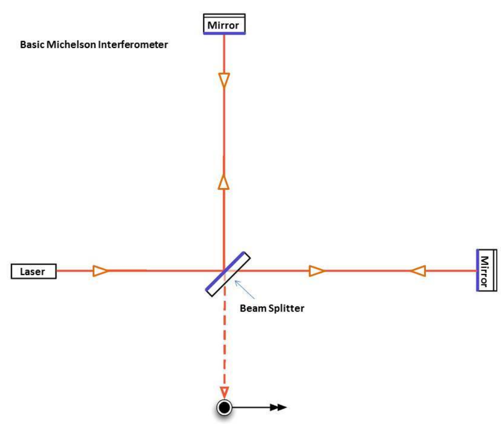
Essentially what we are doing in this experiment is analogous to what LIGO (Laser Interferometer Gravitational-Wave Observatory) does.
As a gravitational wave passes through the arms of a Michelson interferometer, the light travel time of two arms varies, creating a phase difference and causing the interference pattern to change with respect to time.

Figure 1: Virgo: A gravitational wave observatory

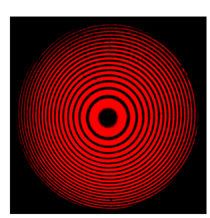
We attempt to recreate the same, except using a Michelson interferometer and sound waves.

2 Michelson interferometer

This powerful device was invented by Albert Michelson and was used to disprove existence of the hypothesised material called Ether in the historic Michelson-Morley experiment.
The light emitted by the laser is split into two beams by the beam splitter which is made of a special crystal. These two beams travel in perpendicular directions and get reflected by a mirror, recombine at the splitter and fall on a screen.
Thus a beam is split into two, and made to combine again. We will study any phase difference picked up by them.
They cause a fringe pattern on the screen which is concentric circles, gradually varying from bright to dark. A continuously monotonously changing phase difference will cause the fringes to either collapse inside or grow outside.



(a) Michelson Interferometer



(b) Ideal fringe pattern

The following figure represents the ideal fringes. In reality you will get noisy fringes, possibly non circular ellipses or even hyperbolas.

3 Modification to the interferometer

We wish to introduce phase difference coming from sound waves which are mechanical vibrations of air molecules.
I made multiple attempts into bringing any visible change in the fringe pattern.I used a frequency generator application on my smartphone to generate sound.

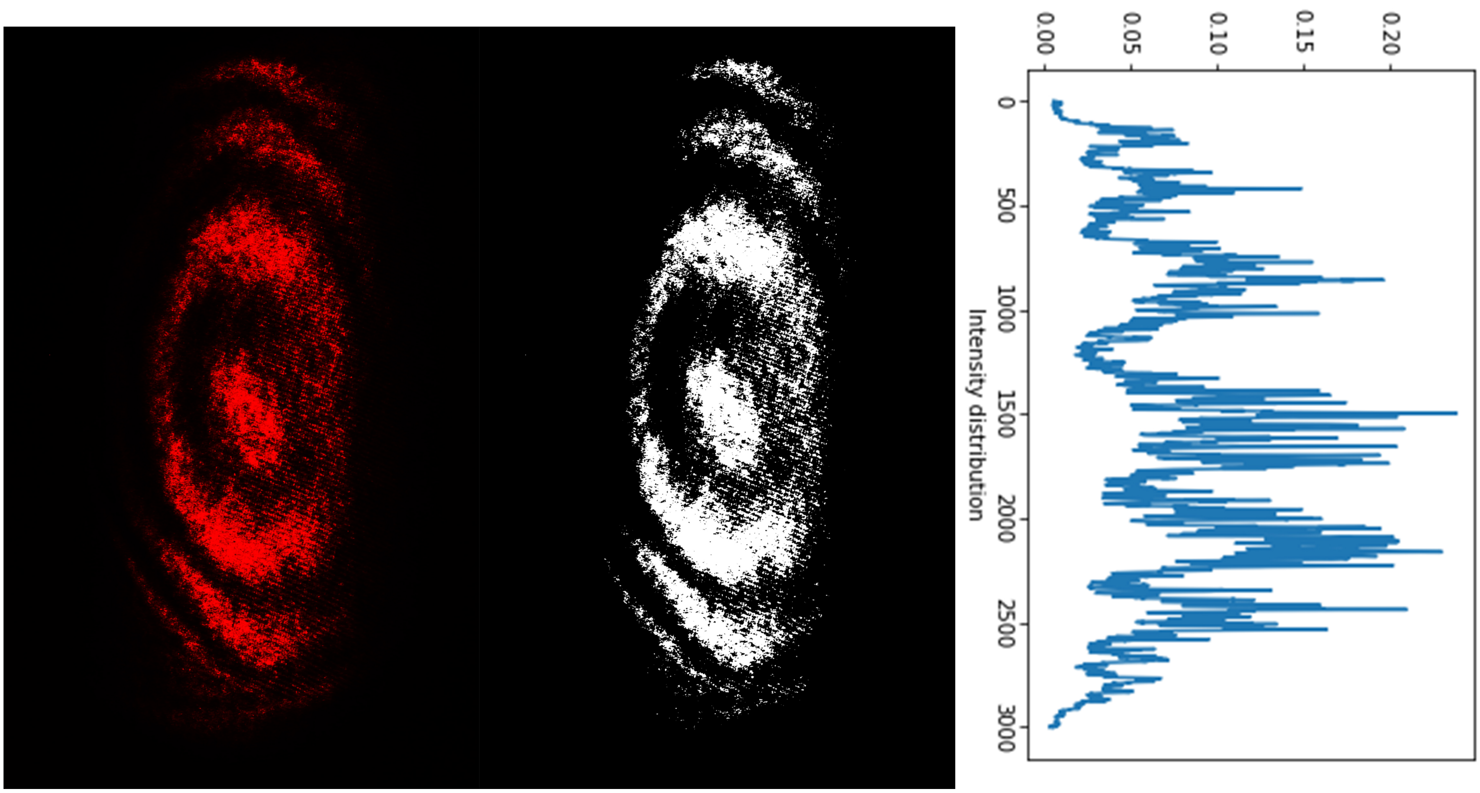


Figure 2: This is how the fringes look like in our set-up

3.1 First attempt

I directly used my phone's speakers at maximum values and various frequencies.

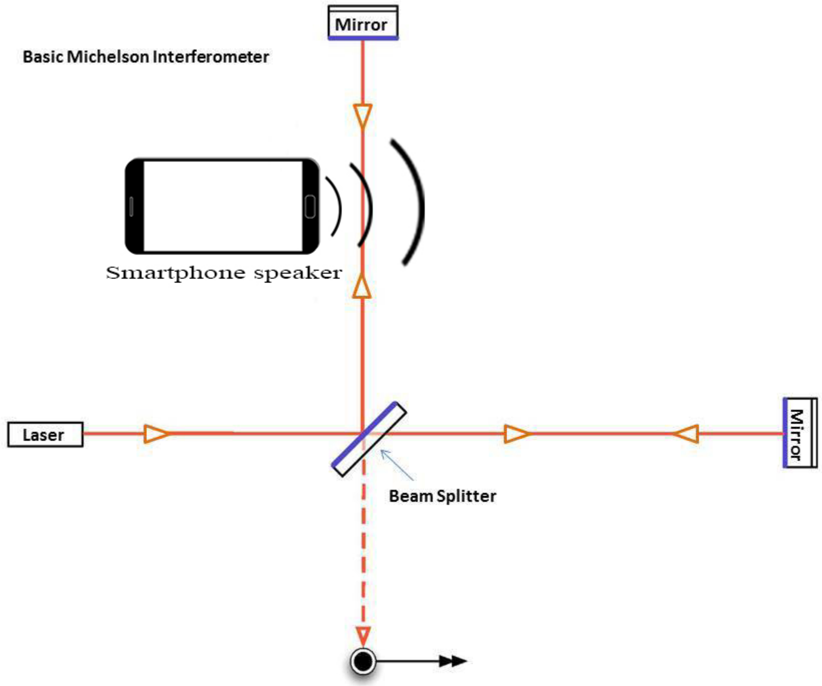


Figure 3: Attempt with smartphone speaker

But no effect was seen on the fringes. I also tried changing the speaker's position and direction but couldn't find any results.

3.2 Second attempt

Next, out of curiosity I tried the same with tuning forks. I tried three different frequencies and in many orientations and positions in the set-up

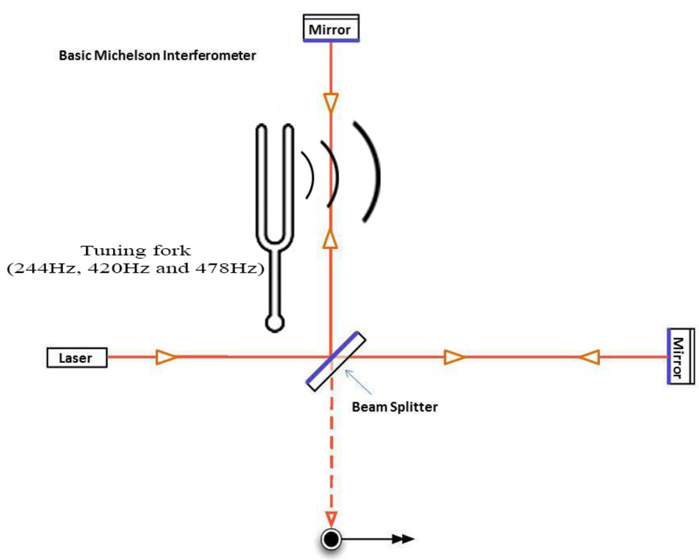


Figure 4: Attempt with tuning forks

But the amplitude of the sound was low and it had no effect on the fringes.

3.3 Third attempt

Finally I placed two speakers in one of the paths.
In the hopes that the actual mechanical vibrations of air will give rise to some sort of fringe variation.

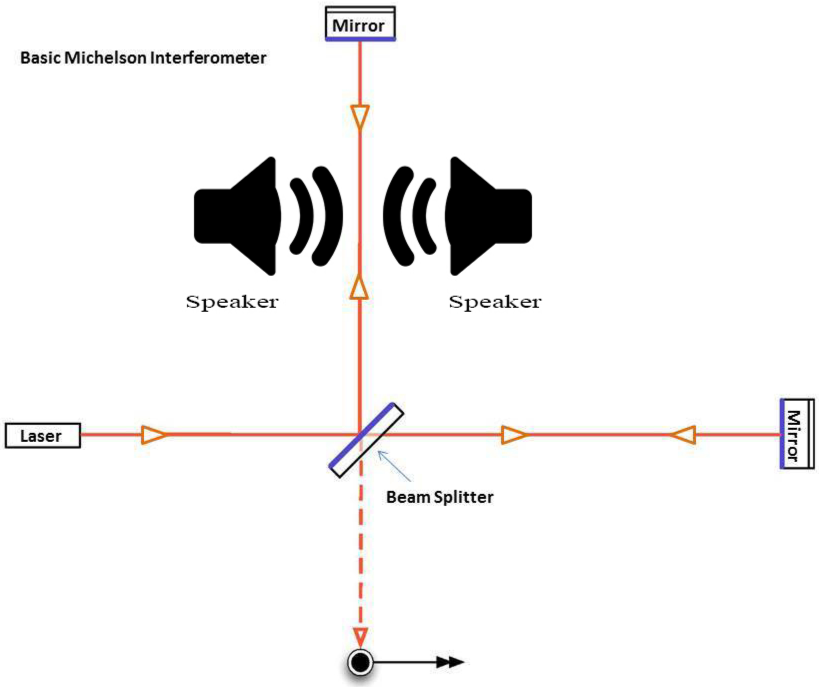


Figure 5: Attempt with speakers

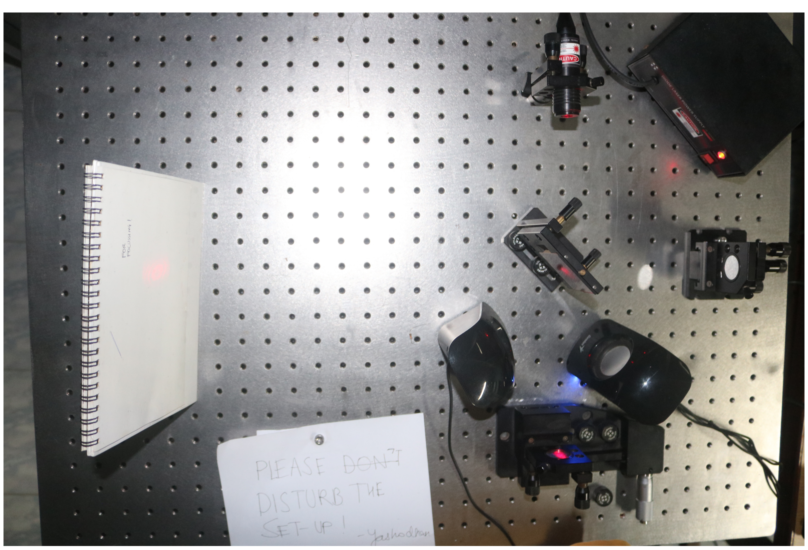


Figure 6: Photo of the actual set-up

4 Findings

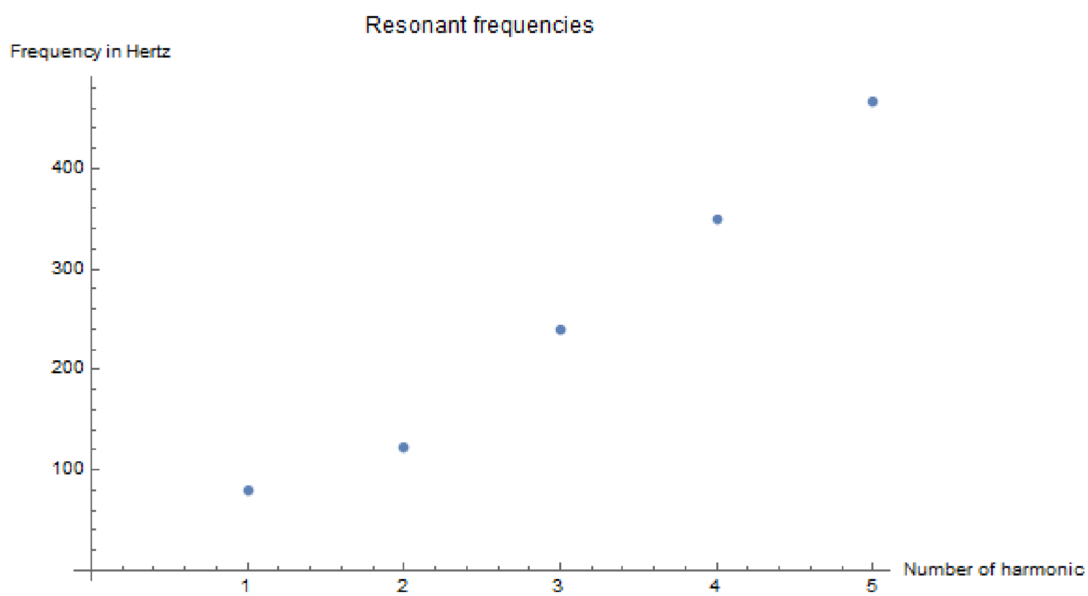
I kept a steady volume (amplitude) and smoothly varied frequency from 10Hz to 2000Hz.

Expectation: Fringes collapsing/expanding at a rate equal to the frequency of the sound wave.

Findings: I didn't find what I expected, however I found something astonishing.
The fringes completely disappeared at certain specific frequencies.
Following are the frequencies:

Frequencies	80Hz	122Hz	240Hz	350Hz	466Hz

Here is a scatter plot of the same:



More interestingly, I found these results:
1) Direction of speakers was not very relevant.
2) Speakers could be suspended mid-air and the effect would still take place.
3) Even pointing the speakers at the optical bench caused the effect.
4) However on certain areas of the table, the speakers stopped having any effect at all.
5) Adding weights to the table had no effect on the resonance frequencies.
6) All of this points towards a hypothesis that these frequencies are probably resonant frequencies of the beam splitter.

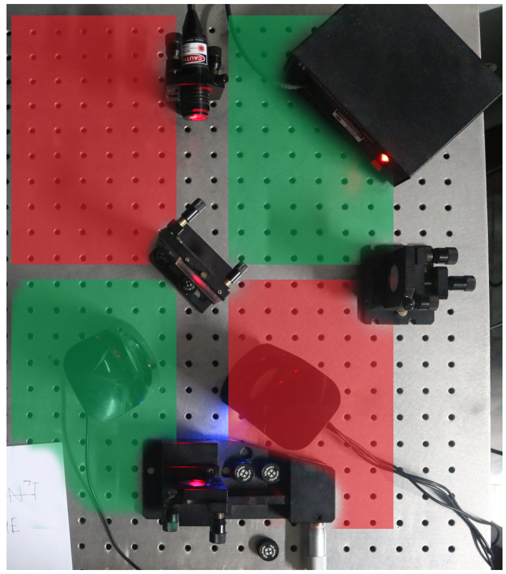


Figure 7: Areas where the effect was observed

Great realisation: The fringes were not actually vanishing but they were getting inverted!

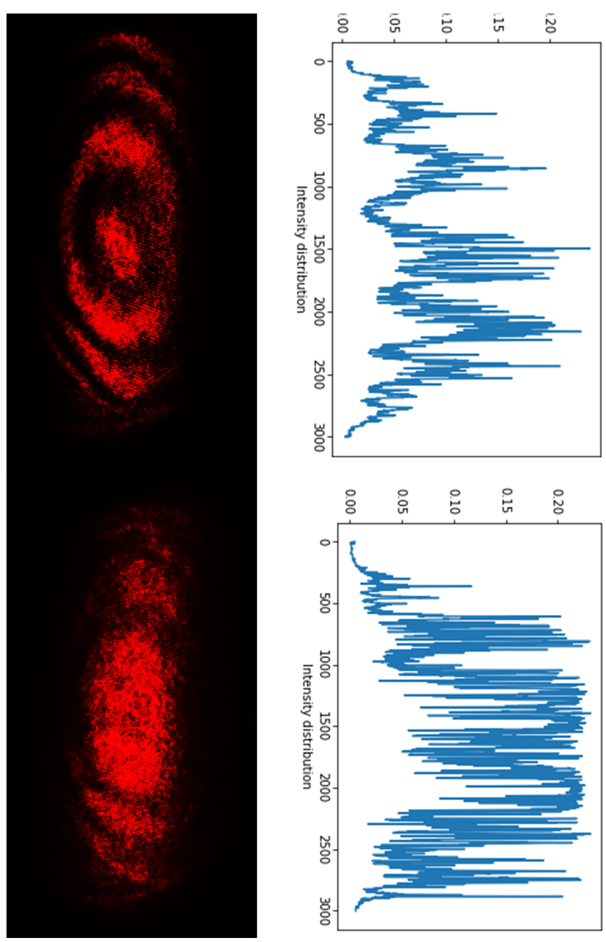


Figure 8: Exact inversion of fringes!

5 Passing beats through speakers

Next I gave a composite signal. I gave 2 exact frequencies, 236.0 Hz and 236.5 Hz. Such a signal forms a pattern known as beats.

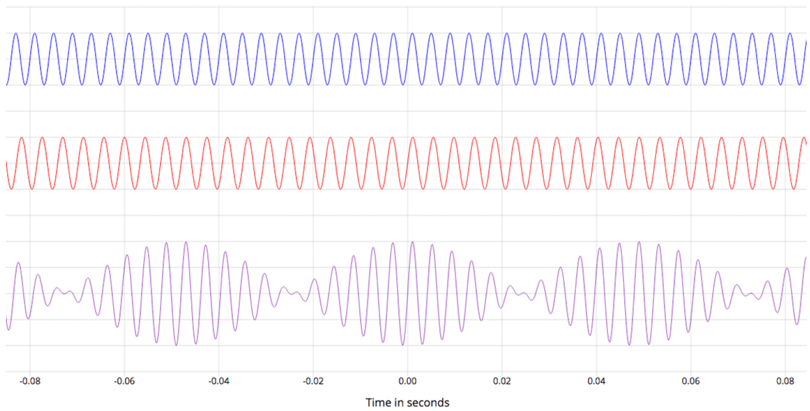


Figure 9: How beats work

As expected we got a similar time varying inversion of the fringes. I captured this in a video and analysed the video to calculate the beats frequency.

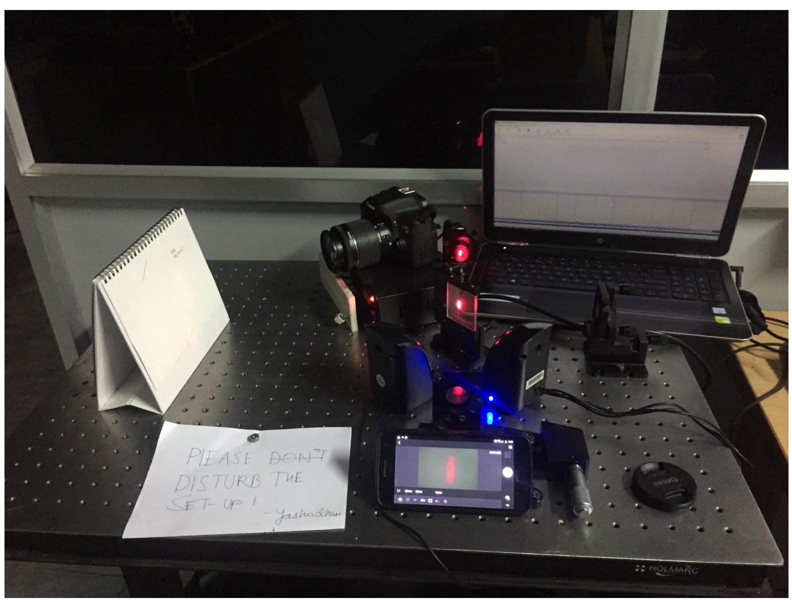


Figure 10: Final set-up

I then performed frame by frame analysis of the video to calculate the beat frequency. Find the image below. Note that at larger amplitudes, the contrast of inverted fringes decreases to a point where you cannot distinguish them. And hence if you watch the video, you won't necessarily see the inversion properly. This video has 50 frames per second.

Figure 11: Link to the video data

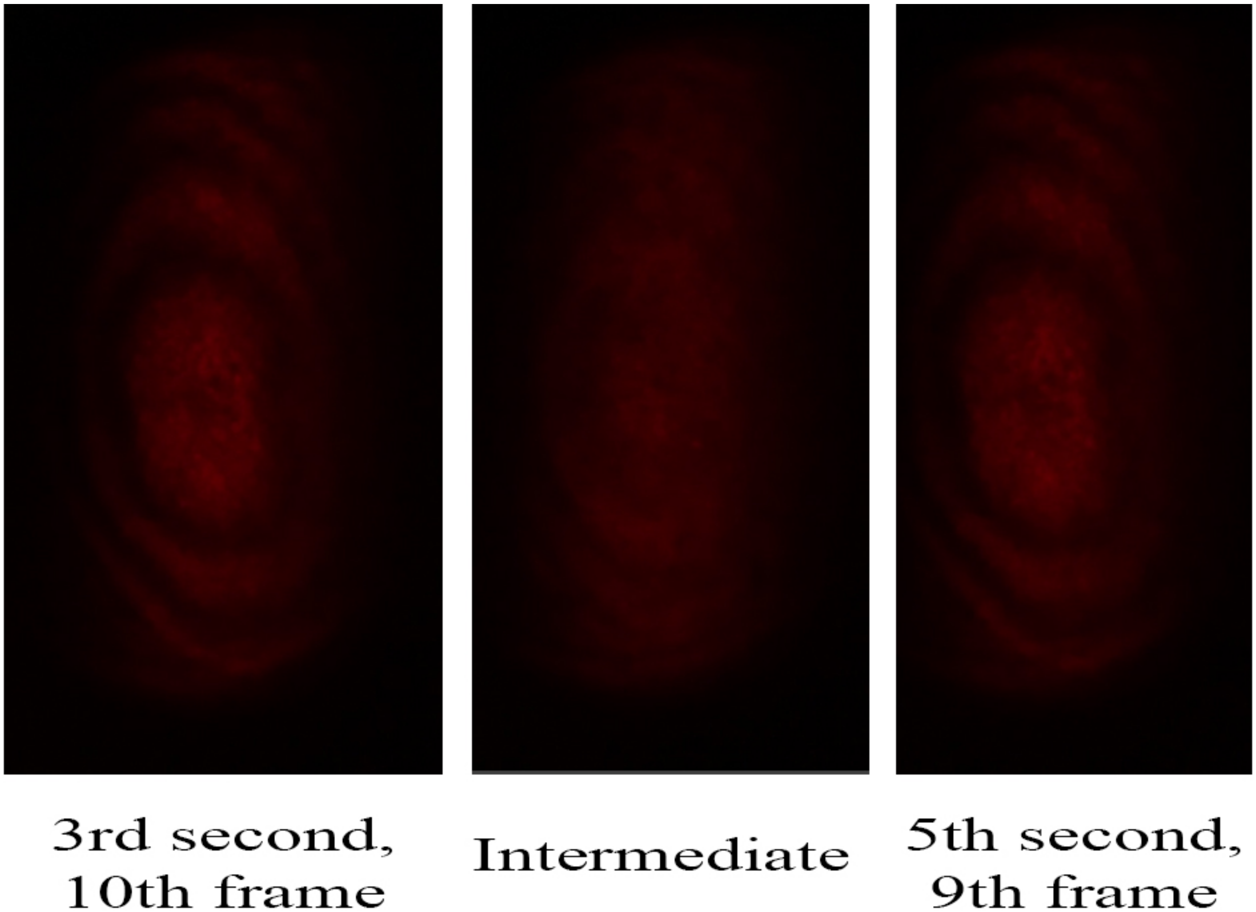


Figure 12: Frame by frame analysis of beats

Note:In the intermediate phase, the fringes remain somewhat constant, revealing non sinusoidal nature of the fringe-variation.

Hence observed beats frequency:

$\frac{1}{(5\cdot18-3\cdot20)s} = 0.505Hz$

And theoretical beats frequency:

$236.5Hz - 236Hz = 0.500Hz$

6 Results and conclusions

1) We studied the effect of mechanical vibrations in the set-up caused by sound waves. We varied different parameters and observed the effect.
2) We found out the resonant frequencies of the beam splitter at which this effect was taking place.
3) We found out that the fringes are actually inverting and not vanishing at these frequencies. We did a line profile analysis of the image.

4) We passed beats signal through the speakers and calculated the beats frequency by frame by frame video analysis.

7 Error analysis

There was really low scope for error in this experiment as we haven't done extensive data collection.
However the frame rate of the camera generates an error in the beats frequency calculation.
Frame rate of the camera = 50fps.
Hence precision of the video analysis = 0.02s
Hence maximum possible error:
$\frac{1}{5 \cdot 16 - 3 \cdot 22} - \frac{1}{5 \cdot 18 - 3 \cdot 20} = 0.015 Hz$

8 References

[1]- Wikipedia- Michelson Interferometer, LIGO
[2]- Optics- *Eugene Hecht, Pearson 2017.*

9 Softwares used

[1]- Adobe Photoshop [2]- Adobe Premiere-pro [3]- Python- skikit-image [4]- Wolfram Mathematica 11