Amplification Characteristics of Fresnel Zone Plate Acoustic Lens

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Abstract

This paper aims to determine the effects of a Fresnel Zone Plate on the intensity of sound waves upon their interaction. To observe these effects, a prototype Even Fresnel Zone Plate, composed of four concentric rings, was made from an acrylic sheet with the dimensions 60.0cm x 60.0cm x 3.13mm. The exact dimensions of the prototype were calculated using the selected focal length and working frequency in order to optimize for the constructive interference of sound waves. After a sound wave at the selected frequency is produced, a small region of highly amplified sound is formed and studied. It was discovered that the amplification of sound waves is highly dependent on the frequency of sound, as well as the location at which the sound intensity level is measured.

Key Words

Fresnel Zone Plate, Sound Amplification Properties, Concentric Rings

Introduction

Fresnel zone plates can be used to focus waves by producing a wave of greater amplitude at the focus, similar to the function of a traditional optical lens. Some previous studies have indicated that Fresnel zone plates can amplify sound waves in certain areas. This paper aims to study the phenomenon thoroughly by combining a known theoretical model with laboratory data.

It is important to first note that Fresnel zone plates are fundamentally different from optical lenses[1]. The main difference between the two is that the former works based on the principle of diffraction rather than refraction. The width and radius of each ring is calculated for the sound wave to have path lengths that will constructively interfere at the focus. This would increase the amplitude of the wave and therefore achieve the objective of focusing sound. The difference between even (centre being empty) and odd (centre being filled) Fresnel zone plates will be demonstrated in the preliminary experiment.

Figure 1: Labelled Zones.

The darker zones represent regions opaque to the incident wave.

Figure 2: Fresnel Zone Plate with focal point labelled f-focus.

r -radius, l -distance from the focal point to each zone.

Theory:

A Fresnel zone plate consists of a set of concentric rings, dividing the plate into different zones.

Zones are labeled as shown in figure 1. For the n-th zone:

$$l_n = \sqrt{r_n^2 + f^2}$$

where the distance from the outer rim of the n-th zone to the focus, is the outer radius of the n-th zone, and f is the focal length[2] (Figure 2).

At the path length difference increase with the radius of the lens, the phase of the sound wave changes with time. Two radii that results in a path length difference of exactly will have the same phase which will constructively interfere. Two radii that result in a path length difference of will have negative phase which will destructively interfere. At path length differences where the phase is negative, the lens is opaque (shaded), preventing waves from passing and destructively interfere with waves that have positive phase. The same effect could be achieved by blocking out either the odd zones or even zones. The performance of the two different designs can be investigated in the preliminary experiment.

In order for constructive interference to occur, all even, or all odd, plates can have a constructive effect. The path difference between the light passing through the plate's center and the light passing the n-th zone's outer rim should satisfy

$$\Delta l = l_n - f = \sqrt{r_n^2 + f^2} - f = \frac{n\lambda}{2}$$

Simplify yields,

$$r_n = \sqrt{n\lambda\left(\frac{n\lambda}{4} + f\right)}$$

Therefore, the radius can be calculated based on a specific focal length (as shown in the design section).

A prototype is created to test its amplification properties at the frequency and distance chosen. Other properties of the acoustic lens were also explored in the experiment.

The constructive interference of sound waves is achieved when two path lengths have a difference of an integer number of wavelengths. The acoustic lens are zones that change from transparent to opaque and back to transparent. The beginning and end of the transparent zone corresponded to two path length differences that causes destructive interference. The wave would diffract off the edge of the opaque zone.

Design:

The size of the setup was limited by the quantity of the material available. The prototype was cut from a acrylic sheet of 60cm x 60cm at x 3.13mm. It was clear, based on the equation, that as and f increase r_n^2 also increases. and f must be optimized for the ease of experiment, given the limitation of material. A focal length of 20cm was chosen to give enough space for the microphone to be placed behind the acoustic lens. The wavelength of sound was determined based on the fact that air travels at the speed of 346.46 m/s at the temperature of 25°C. Due to the limitation of material size and sound generator, the frequency of 10 kHz was chosen to maximize the number of zones and fit the range of the sound generator. The optimized diameter of each ring, according to the equations, were shown below.

Table 1: Optimized Diameter Of Each Ring.

Ring Number	Diameter (m)
1	0.1699
2	0.2452
3	0.3062
4	0.3603
5	0.4102
6	0.4573
7	0.5024
8	0.5459

Hypothesis

Based on the theory provided, the point with the highest amplification should be 20.0 cm behind the lens colinear with the speaker and the center of the lens. Amplification could be achieved with sound waves around the optimal frequency but to a lesser degree. The lens could cause the reduction of sound intensity at certain frequencies.

Materials and Methodology

The experimental setup is very similar to existing studies regarding the same topics[3]. In the experiments, a frame of 2m x 2m x 1m was constructed with wood. Fabrics and blankets are attached on to the walls and under the floor and roof of the frame to form a test chamber (Figure 4d.). The fabric helps to minimize the reverberation of sound inside the chamber, because the reflection of sound waves could cause sound to reach the microphone at unwanted angles producing noise that can't be eliminated. Hooks are attached to the wood columns. This allow the test equipment to be suspended in air rather than contacting the ground. This reduces noise transmitted via the vibration of the ground. The combination of suspended testing equipment and fabric lined floor ensures that the test chamber and its equipment are isolated from outside vibration.

The signal of sound is produced by a tone generator software (Online Tone Generator) in a PC, the signal is transmitted through

a 3.5mm audio jack into a tweeter suspended inside the chamber (Figure 4b). Sound waves are produced, which pass through the acoustic lens (Figure 4a) and reaches a microphone supported by a stand which is on top of a centimeter grid (Figure 4c). The grid allows for the change of position on a plane parallel to the ground. The microphone consists of an analogue to digital converter and outputs a signal which is transmitted to the same PC through a USB cable.

Results and Discussions

Preliminary Experiment

Before a full-size prototype was fabricated and tested, some preliminary experiments were done to test the theory and to calibrate equipment. In the experiment, a version of the lens with designed frequency and focal length of 10 kHz and 10 cm respectively, is made with cardboard. Both the even and odd zones were tested. The results show that the even zone has focusing power much greater

Sound Absorbing Material

Figure 3: Schematic of the experimental setup.

The devices enclosed by the brown rectangle are contained in the test chamber with sound absorbing material.

Figure 3: Photograph of the experimental setup.

- a) Acoustic lens suspended in front of the microphone.
- b) A tweeter acting as the sound source to produce high frequency sound.
- c) Grid drawn on MDF board to adjust the position of the microphone to measure the sound intensity level behind the acoustic lens.
- d) Test chamber constructed with wood frame and sound absorbing fabric.

than that of the odd zone.

As shown in the graph the even plate, in the described setup, has significantly higher amplification power over the odd plate.

The calibration of speaker microphone system is performed to eliminate the irregularity in sensitivity of the system at different frequencies. The speaker microphone system is placed at a fixed distance. Sound of different frequencies are played and the sound intensity level is recorded. It is then compared to the measurement

taken at 10 kHz and the difference is recorded. A curve of sound intensity level plotted against frequency is constructed in software. This equalization curve is applied to every measurement that needs to be corrected ensuring that the sound intensity level measurement is free from any bias inherent to the testing hardware.

The following experiment is conducted with the even Fresnel Zone Plate.

Figure 5: A) Odd Plate Design B) Even Plate Design.

Amplification of Sound at Various Frequencies

The frequency is set as the independent variable, and amplification is the dependent variable. In this experiment, the position of the speaker, lens and microphone remains constant. External noise and reverberation is minimized. Sound wave is produced from the source. Measurements of the sound intensity level are taken in a range from 2 kHz to 16 kHz in intervals of 0.2 kHz. At each frequency, a recording of 10 seconds is recorded. A root mean square value of the sound intensity level is taken and recorded. This process was repeated for each frequency two times, once with the acoustic lens and once without. The sound intensity level with and without the lens, measured in dB, is compared. Sound intensity levels are converted to intensity (W/m^2).

Amplification is defined as the intensity values measured with the lens is divided by the intensity values measured without the lens. The calculation is performed for each frequency interval, and the result is graphed.(Figure 7.).

The result (Figure 6) of this experiment shows that the amplification at frequencies near 10 kHz the amplification of sound is significantly greater than that of other frequencies. This shows agreement with the hypothesis that was made. There is also small variation to the amplification in frequencies other than what was designed. The

degree of amplification is not comparable with what's near 10 kHz but it is significant compared to the intensity level measured without the acoustic lens.

Amplification Characteristics Around the Focus

The displacement from the focal point is set as the independent variable. The amplification is the dependent variable. The frequency of the sound source, the position of the sound source and the acoustic lens are kept constant. The microphone is mounted onto a stand with height adjusted to be colinear with the center of the lens and the sound source. The stand is then placed onto a placed to MDF board secured to the frame of the test chamber after being aligned with the axis formed by the center of the lens and the sound source. A centimeter grid is draw on the board. The stand and microphone is placed on grid line intersections corresponding to the position in which the sound intensity level is measured. The sound intensity measurement method is identical to what is used in the first experiment. The stand is moved a distance 10 cm from the focus in both axes to start. The stand is then moved 2 cm in one of the axis and the sound intensity value is measured and recorded. The stand and the microphone is placed at each intersection of the centimeter grid .This process repeats until an area of 20cm x 20cm

Amplification of Even and Odd Plates

Figure 6: Intensity amplification of even and odd plate with largest amplification labelled.

Amplification vs Frequency

Figure 7: Amplification at different frequencies.

Figure 8: Surface plot of amplification and displacement

This graph contains the same data as Figure 8. The z-axis allows for a 3-D representation of the strength of amplification at distances from the focus.

centered at the predicted focus is covered.

The result of this experiment demonstrated significant levels of amplification along the principal axis of the system, but the location at which the peak amplification is reached was behind the focus.

The measurements showed that the lens could achieve an amplification of more than 25 times for sound waves at 10kHz. (Figure 8). This confirmed the hypothesis despite the shift in the peak. The possible explanation for the peak shift could be the result of the

uncertainty in the diameter of each ring and the frequency produced by the tone generator. This could be solved with better tools used in fabrication and better equipment used to generate, process and transmit sound wave signals.

Conclusions

In summary, an acoustic lens based on Fresnel Zone Plate was designed, constructed and tested. It was shown that such a design was effective at focusing and amplifying sound waves at multiple frequencies with various results. The sound intensity level within the chosen region of space (behind the lens) was measured and compared. This made the information of the amplification properties of the lens obtainable. Limitations of the equipment and mate-

rial caused practical deviations from the theory, however the understanding of the effectiveness of the acoustic lens is still achieved. Although the lens is tested on the mid to high end of the audible spectrum the same device could be made to function at frequencies across the audible spectrum and beyond.

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REVIEW

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This paper discusses an application of the Fresnel lens to acoustics and performs a set of experiments studying the dependences of the amplitude amplification as a function of frequency and the lens' design. The paper presents some theoretical predictions and describes in great detail the experimental setup. It is fairly well written (despite some occasional inusual choice of phrases). The motivation behind this research and the innovation part of the experiment seem to be missing from this paper. I dare suppose, that the motivation behind was to develop an educational demo for studying fresnel lenses, or perhaps develop a laboratory exercise for such an experiment. As for the innovation, the paper seems to be following fairly closely its reference [3] for the experimental setup and calculations.

While we do not criticize the form and the content of the paper, in our opinion it is the innovation and the motivation that sets apart a real research paper from a lab report.