ACOUSTIC LENS

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ABSTRACT

Fresnel plate consists of radially symmetric zones. Zones alternate between opaque and transparent, and are spaced so that wave transmitted by the transparent zones constructively interferes at the desired focus. Modeling and experimental results of a flat lens for use in air are presented and the optimized design parameters are used to fabricate the lens. The theoretical calculation for the focal length is determined to be 20.0 cm and the incident wave length of 3500 Hz. The results show a sharp focal spot with very high amplitude.

Keywords : *Acoustic Lens, Sound Waves, Focal Point, Diffraction, Interference*

1. Introduction

Acoustic Fresnel lenses have a great application in acoustic microscopy and different category. They have emerged as an alternative to the conventional due to ease of fabrication even with the low efficiency of 40% of input waves[2]. Different from usual lenses, Fresnel lenses use diffraction mechanism to redirect waves at the desire focus.

Fresnel lenses with concentric rings are widely used in optical applications, however a similar principle can be used to focus acoustic waves. Designing and producing an acoustic lens and investigating its properties, such as amplification, and its dependence to relevant parameters is the main goal of this paper Many methods have been studied to focus sound waves such as using Fresnel binary lens consist of alternating transmitting and opaque rings as a scattering elements . Due to diffraction and interference theory zone plates can be able to focus the sound waves because of their wave behavior. Other way that has been used to focus sound waves was using a regular array of cylinders . These cylinders also work by diffraction and interference theory too. In these two methods that we talked about the goal was to make constructive interference of waves and also try to make it in one point rather than many of them, then more sound pressure can be detected. These two methods are good for high frequencies of sound, because in low frequencies a big structure is needed; And the solutions was just for plane sound waves.

Some different mechanisms to achieve sound collimating have also been explored. Like using negative refraction in metamaterials that is because of different refractive indexes then it may be possible to focus acoustic waves.

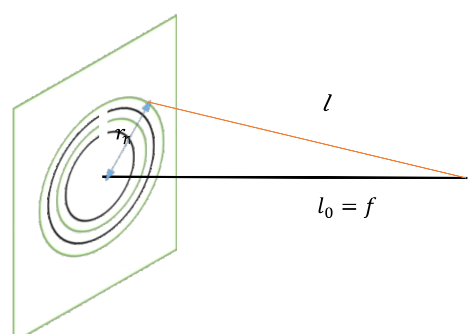
In this paper we investigated the effect of relevant parameters on an acoustic lens amplification and introduce some methods to design it with the best quality. Also make it appropriate for low frequencies of sound and see the effect of spherical source.

2. Methodology

Our method for an appropriate design of the lens was using COMSOL software for simulations and numerical solution to reach a good design that can make constructive interference on lens's axis. Except previous researches our numerical solution has been done for spherical wave front which is more close to reality. Effect of each parameter and boundary condition has been considered in our simulations. Another reason to use simulation is that number of possible designs that can focus sound waves is not limited, but we wanted to find optimum of them. After that making experiment's setup to check our results from simulations and compare with experimental data because finding the effect of each parameters and then finding the appropriate one by experiments was hard and waste our time.

3. Theory

a) Basic calculations :



By writing a simple Pythagorean relation, diameters can be calculated.

$$f^2 + r_n^2 = l^2$$

As we now. $l - l_0 = \frac{n\lambda}{2}$

so

$$\boldsymbol{f^2 + r_n^2 = (f + \tfrac{n\lambda}{2})^2}$$

$$r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4}$$

The term $n^2\lambda^2/4$ represent spherical aberration .

b) Fresnel geometry

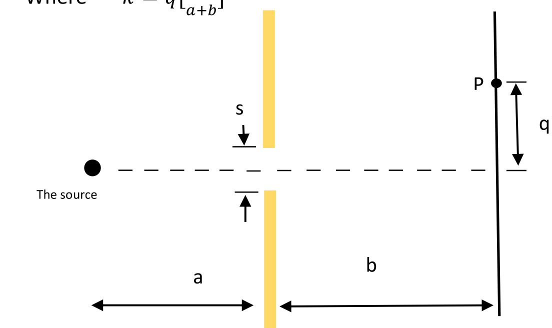
To calculate the intensity at point P, the geometry is setup in terms of the parameter v which is used with the Cornu's spiral.

$$v = v_1 - v_2$$

$$v_2 = [\frac{s}{2} + k]\sqrt{\frac{2(a+b)}{ab\lambda}}$$

$$v_2 = [\frac{-s}{2} + k]\sqrt{\frac{2(a+b)}{ab\lambda}}$$

Where $k = q[\frac{a}{a+b}]$



These equations would be useful in the days before computer programs like "cool edit" -that has been used in the experiment- but today one can compute the intensity of different points.

When a set of incident waves strike the lens, the obstacle is not a simple geometric shadow, it is a diffraction pattern. When the source wave is not distant and the incident waves are not plane, the Fresnel diffraction pattern can be observed and its theory is, unsurprisingly, a little more difficult than the theory for Fraunhofer diffraction.

4. Experiment

Here we explain 2 different symmetry designs.

4.1. First model

To clarify one of the techniques consider an array of nonoptimized circles in x-y plane with the axial symmetry x (Fig. 1a). These circles by transition from 2D to 3D by extruding them along z axis can make a 3D acoustic lens consist of cylinders as a scattering elements capable of focusing sound in a line parallel to the extrusion direction. The acoustic waves impinges the structure from the left. We considered PML (perfectly matched layer) for boundary conditions to transmit the sound perfectly. The results of simulation show us sound pressure in all point toward the structure. Some pair of the cylinders have been discarded to optimize the design because they make a destructive interference in our focal point (Fig.1b). So we discarded some of them. By Changing the position and radius of cylinders and see the results we tried to find the appropriate design.

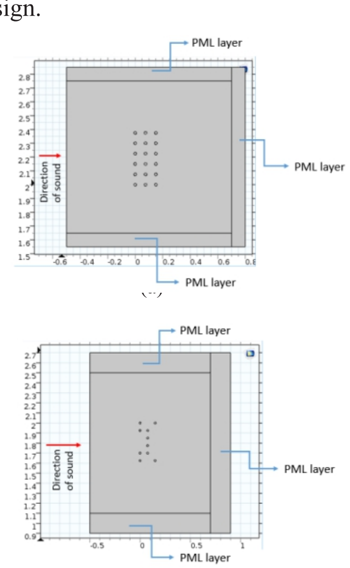


Fig 1: a) Structure of simulation with nine pair of cylinders. b) some pairs of cylinders have been discarded

Absorption, transition and reflection of cylinders can also effect on sound pressure in focal points. These three properties are related to the material used for make cylinders. To consider effect of these three we must choose something which is more close to reality. The material with sound velocity of 1040 m/s and density of 4.1 kg/m^3 are chosen as the material of cylinders. About the effect of sound frequency, if one setup be good for one frequency it also can focus sound for other frequencies but with a small change in lens dimensions. Thus simulations done with same frequency and after finding one appropriate design, the design examined by various frequencies then the best frequency for maximum sound amplitude found.

4.2. Second model (Fresnel zone plate)

Simulation

Fresnel binary lens consist of concentric rings is the second method to focus sound wave, that we explain this method here. Using Fresnel lens formula ($r_{n=}\sqrt{nf\lambda}$) that gives the radius of nth rings for determined focal length. λ is the wavelength of sound. Then the 2D simulation done using axisymmetrical method. The boundary conditions were PML too . Sound emits the structure from bottom. Then the results of our simulations gave us the appropriate setup to focus sound waves. The material used for rings was same as the material of cylinders. And also the same frequency. Here like before if one design can be good for one frequency it also can be useful for other frequencies but with some changes in dimensions. Here the relation to change dimensions is $r_{n=}\sqrt{nf\lambda}$ (Fig. 2).

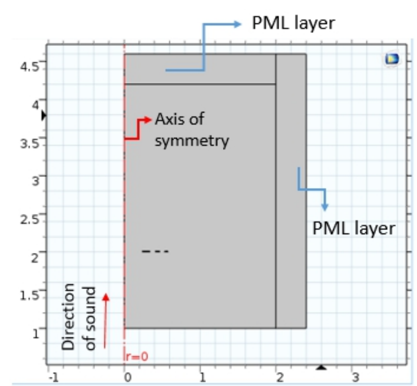


Fig 2: Second model

5. Numerical Solution

Calculations have been done for Fresnel zone plate to find out sound amplitude in each arbitrary point (x1,y1). The sound source is assumed spherical so the path length difference has been calculated before emitting the structure and after it to the point(x1,y1)(Fig. 3).This figure shows a 2 dimensional Fresnel zone. Blue lines on x axis shows rings. The width of the rings decreases by increasing distance from the central point $O(x_0,y_0)$. The space between $-r_1$ and r_1 didn't assumed opaque to transmit the sound. To find out the amplitude of the wave traveling along m1-l1 path (or others) and reaches to the point p, we need to know the remainder of division of l1+m1/ λ (here we called that mod(ln+mn,landa). The amplitude is given by the equation:

$$A= \sin(\mathrm{mod}(ln+mn, \lambda)/2\pi$$

This amplitude A, is the amplitude without considering the effect of distance from the source point to the point p that can make the intensity less. To solve this problem we considered I as the initial intensity of sound. So the real intensity at the point p can be found by:

$$A= [\sin(\mathrm{mod}(ln+mn, \lambda)/2\pi]/4\pi r^2$$

we divided the intensity to $4\pi r^2$ that is the surface of a sphere sound traveled to consider the effect of traveled distance on total amplitude.

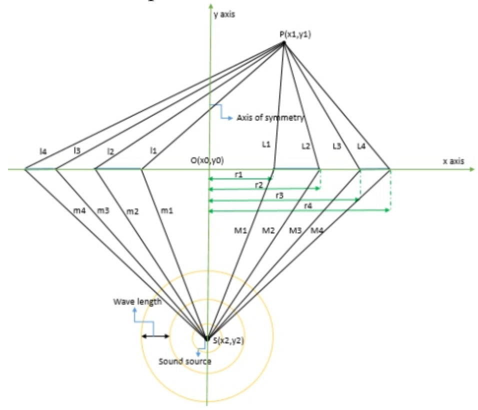


Fig. 3 : 2D scheme of Fresnel zone plate by a spherical sound source P is any arbitrary point and the black lines from source to the point p show the path difference. The rn introduce the radius of nth ring

6. Results of These Two Models

1.First model results

The final design that we reached was the design shown in (Fig. 4). An array of cylinders with outside radius 1.59 cm and inside radius of 1.41 cm and the material in which the sound speed is 1040 m/s and the density is 4.1 kg/m^3.

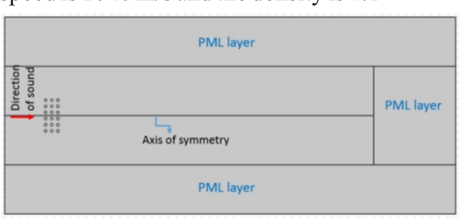
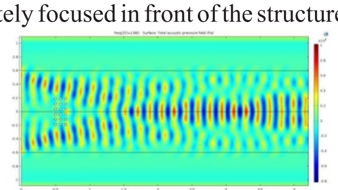
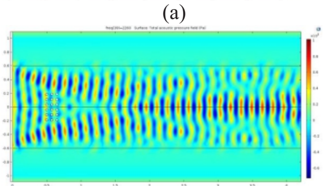


Fig. 4: The final design that was appropriate for our goal

This structure examined for various frequencies from 1500 Hz to 3000 Hz by the step of 20 Hz. The results was appropriate for the frequencies 1980 Hz, 2000 Hz, 2260 Hz and 2900 Hz (Fig.5). This figure shows the acoustic pressure in all points. The sound wave has been approximately focused in front of the structure.



(a)



(b)

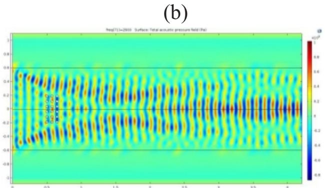


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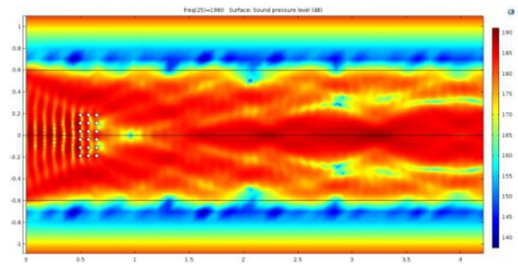
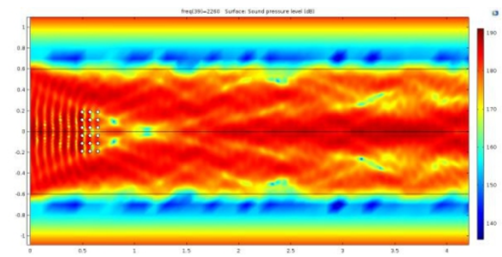
Fig. 5: Results of acoustic pressure for frequency a) 1980 Hz b) f=2260 Hz c) f=2900 Hz. The red parts have the most acoustic pressure

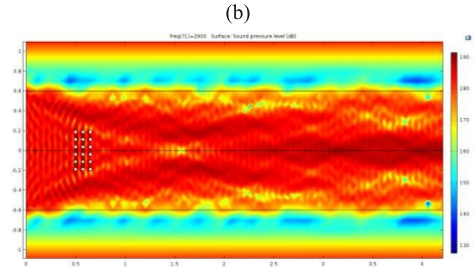
The results for these 3 frequencies for the sound pressure which human can hear is shown in (Fig.6).



(a)



(b)



(c)

Fig. 6: The results of sound pressure in all points towards the structure for the frequencies a)1980 Hz b)2260 Hz c)2900 Hz

The maximum and minimum sound pressure place changes by sweeping on frequencies (Fig. 7).

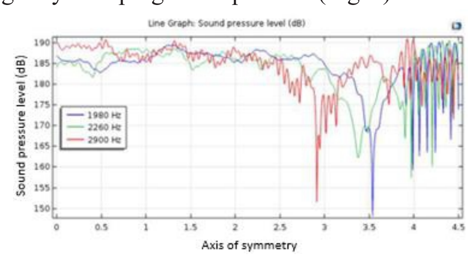


Fig.7: Comparing sound pressure for 3 frequencies. Red one is frequency of 2900 Hz, green one frequency 2260 Hz and the blue one for the frequency of 1980 Hz.

2. Second model results

The 2D design of Fresnel zone plate is shown below (Fig.8). The diameter of rings considered 0.002 m. And the material used for rings was the same as the material used for cylinders before. (Sound speed=1040 m/s and density of $4.1 kg/m^3$).

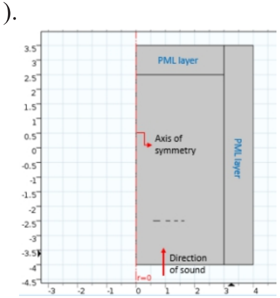


Fig. 8: 2D appropriate design of Fresnel zone

This design examined for various frequencies. From 2500 Hz to 3000 Hz by the step of 50 Hz and the maximum sound pressure measured in each simulation. The peak sound pressure for 2650 Hz had the best result (Fig. 9).

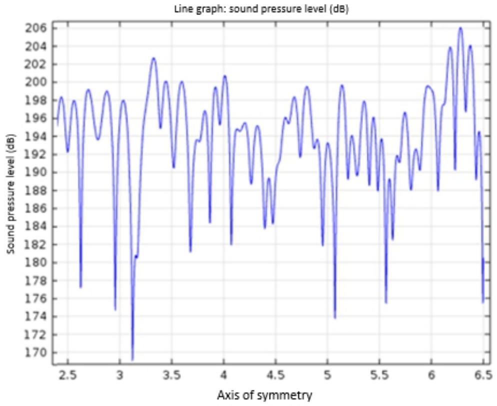


Fig. 9: Sound pressure on each point on the axis of symmetry of the design. The maximum sound pressure is 206.115 dB at the distance 3.75 m in front of the structure

7. A Handmade Lens

The lens consists of Styrofoam with radially symmetric zones. A signal generator with specific frequency and amplifier connected to speaker. In order to find the experimental focal point, placing the microphone in the different location is needed. By analyzing and comparing the intensity of the different focal points, the sharpest focal point with very high amplitude can be observed (Fig. 10).

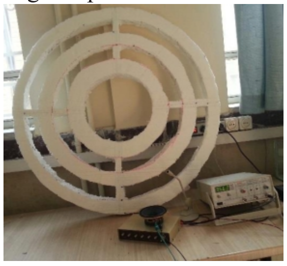


Fig. 10: Handmade lens

The microphone had been recorded the sound and with "cool edit pro" the intensity can be calculated (table 1).

Table 1: Intensity by the lens

X(cm)	Y(cm)	Intensity(dB)
3.5	21.5	-25.49
3.5	35.0	-25.66
-6.5	32.5	-27.95
*0.5	39.0	-20.96
-3.5	35.0	-26.44
6.0	30.0	-30.12

x=the horizontally distance of microphone from the center of the lens; y=the vertically distance of microphone from the center of the lens. *the sharpest intensity among the measurements.

Table 2: Figure (2.5) Different amplitudes for the sharpest focal point (0.5, 39.0) lead to different intensities

Intensity(dB)	Amplitude
-25.30	3
-23.94	4
-20.96	5
-18.63	6

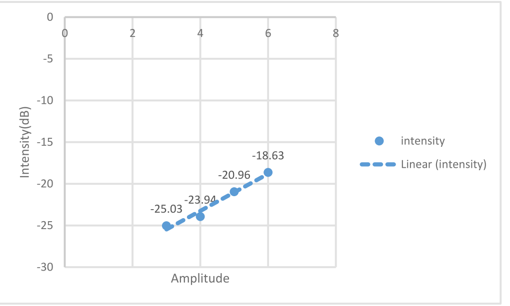


Fig. 11: By increasing the amplitude the intensity of the main focal points increased

Table 2: Intensity A is when the lens is set to the setup and Intensity B is the Intensity without lens and the intensity Gain is portion of intensity A to intensity B.as it can be observed the lens is amplifying the amplitude

amplitude	Intensity A(dB)	Intensity B (dB)	Intensity Gain
1	-34.88	-31.21	1.117591
2	-31.78	-28.44	1.11744
3	-25.03	-22.33	1.120914
4	-23.94	-21.3	1.123944
5	-20.96	-18.55	1.129919
6	-18.63	-16.38	1.137363

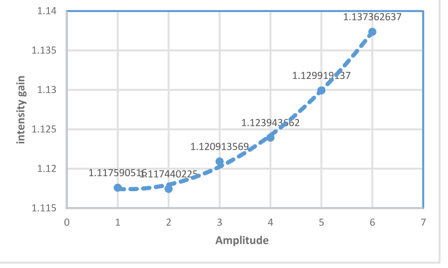


Fig. 12: By increasing the amplitude the intensity gain is increasing slightly

7. Conclusion

In this paper we talked about the methods already used to focus sound wave and their weaknesses and we tried to introduce the design that can focus sound. COMSOL software used to discover a lens capable focusing sound. The effect of relevant parameters that can effect on amplification of the lens investigated and also boundary conditions considered. So some designs introduced. An array of cylinders is able to focus waves in appropriate conditions.

Discarding some pairs of cylinders avoided destructive interference at the focal point , so we reached to that condition. The final system examined by many frequencies and the frequencies that could focus sound rather that other founded. Fresnel zone plate can also be helpful to focus sound. For a determined focal length we calculated the radius of rings then simulate them. Sweeping on frequencies gave us the frequency that has a maximum peak. These two designs can made and use to focus sound waves.

Also We have done the experiment with a handmade Styrofoam lens which has a low efficiency because of errors of fabricating, thus the theoretical calculation for the main focal point was different from the experimental focal point. The experiment shows that by increasing the amplitude the intensity of the focal points would be increased also the intensity gain is calculate and the result shown the amplification of the lens. The Fresnel lenses use the diffractive properties to focus wave which can be explained with Fraunhofer diffraction theory.

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