HIGH-FREQUENCY SIMULATION OF ACOUSTIC LENSES

BASED ON FRESNEL ZONE PLATE

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Abstract

In this work, we develop a Fortran program to simulate the propagation of high-frequency plane acoustic wave through Fresnel zone plate (FZP) in two dimensions. The simulation was carried out at the frequency of 200 kHz with the wave speed of 1,500 m/s. The thickness of FZP was also varied to determine its effect on the focusing of FZP. Numerical results show that FZP could successfully focus the acoustic wave. The results also matched well with the simulation result of a previously published work of underwater acoustics. An efficiency comparison between FZP and a scattering-type acoustic lens focusing a wave at the frequency of 2140 Hz and wave speed of 330 m/s was also reported.

Keywords: Fresnel zone plate; acoustic lens; finite difference method; numerical simulation

INTRODUCTION

A Fresnel zone plate (FZP) is a thin lens that focuses wave fields based on the concept of Fresnel zones and diffraction. It has been applied to both electromagnetic waves [2-4] and acoustic waves [5]. This study demonstrated that sound waves could be focused to a desired position. Using an FZP acoustic lens. The optimize design parameters for fabricating a lens [6] used a hybrid genetic-greedy algorithm constrained to a linear structure. The experimental results were compared to the simulation results for ultrasonic waves in air [7], verifying the simulation method. The simulation for ultrasonic underwater, used FZP to focusing [8]. The results showed that a designed FZP effected low energy loss. Moreover, the authors did not disclose the computer codes that they used in their studies. Therefore, we had to develop a computer program in Fortran programs to evaluate our design Materials and Method.

FRESNEL ZONE PLATE

A Fresnel zone plate is a thin lens consisting of a set of radically symmetric rings, which alternate between opaque and transparent as shown in Figure 1a.

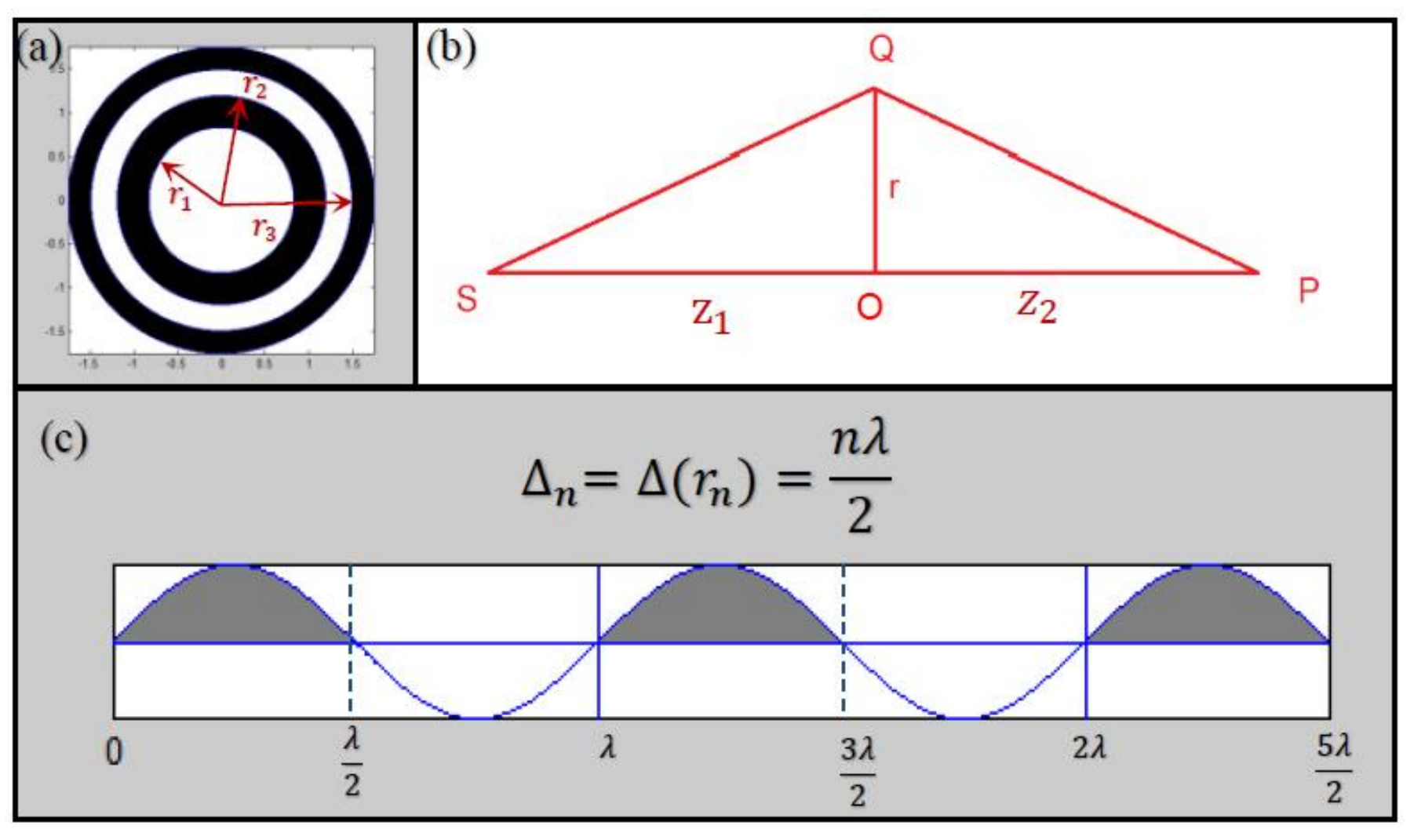

Figure 1. (a) Fresnel zone plate with opaque (black) and transparent (white) zones where r_n is the radius of the n^{th} zone. (b) Sketch of path difference between the point source S and focus point P. (c) Show wave diffraction make path difference depend on $n\lambda/2$.

Fresnel Zone Plate for plane Waves

In this section we derive the formula of the radius of the n th zone for focusing spherical waves. According to Figure 1b, the path difference between paths SOP and SQP is

$$\left(\sqrt{z_1^2+r_n^2}+\sqrt{z_2^2+r_n^2}\right)-\left(z_1+z_2\right)=\frac{n\lambda}{2},\quad n=1,2,\ldots \tag{1}$$

A plane wave can be thought of as a wave front of a spherical wave emitted from a point source located very far from the zone place, i.e., $z_1 \to \infty$. The first term in Equation 1

$$r_n^2 = n\lambda z_2 + \left(\frac{n\lambda}{2}\right)^2 \tag{2}$$

NUMERICAL SIMULATION OF FZP ACOUSTIC LENSES

In this section, we present numerical methods for the simulation of FZP acoustic lenses by solving the two-dimensional acoustic wave equation

$$\frac{\partial^2 u(x,y,t)}{\partial x^2}+\frac{\partial^2 u(x,y,t)}{\partial y^2}-\frac{1}{c^2}\frac{\partial^2 u(x,y,t)}{\partial t^2}=S(x,y,t) \tag{3}$$

where u and s are the pressure and source fields, respectively, and c is the phase velocity of acoustic wave.

A. Finite Difference Method

The second-order derivatives in Equation 5 are approximated by the second-order finite difference approximation, e.g. for second derivative in x direction,

$$\frac{\partial^2 u}{\partial x^2}=\frac{u(x+\Delta x)-2u(x)+u(x-\Delta x)}{\Delta x^2}+O\left(\Delta x^2\right). \tag{4}$$

Approximating all second derivatives in the wave equation yields the discrete wave equation

$$\left(\frac{u_{i+1,j}^n-2u_{i,j}^n+u_{i-1,j}^n}{\Delta x^2}+\frac{u_{i,j+1}^n-2u_{i,j}^n+u_{i,j-1}^n}{\Delta y^2}\right)-\frac{1}{c_{i,j}^2}\frac{u_{i,j}^{n+1}-2u_{i,j}^n+u_{i,j}^{n-1}}{\Delta t^2}=s_{i,j}^n \tag{5}$$

B. Boundary Conditions and absorbing boundary

In this work, we use two types of boundary conditions: perfectly matched layer and Neumann boundary condition.

1. Perfectly matched layer

We simulate an acoustic wave propagation in an unbounded domain using the perfectly matched layer (PML) method proposed by Berenger [7] to absorb wave energy at the boundary of the computational domain.

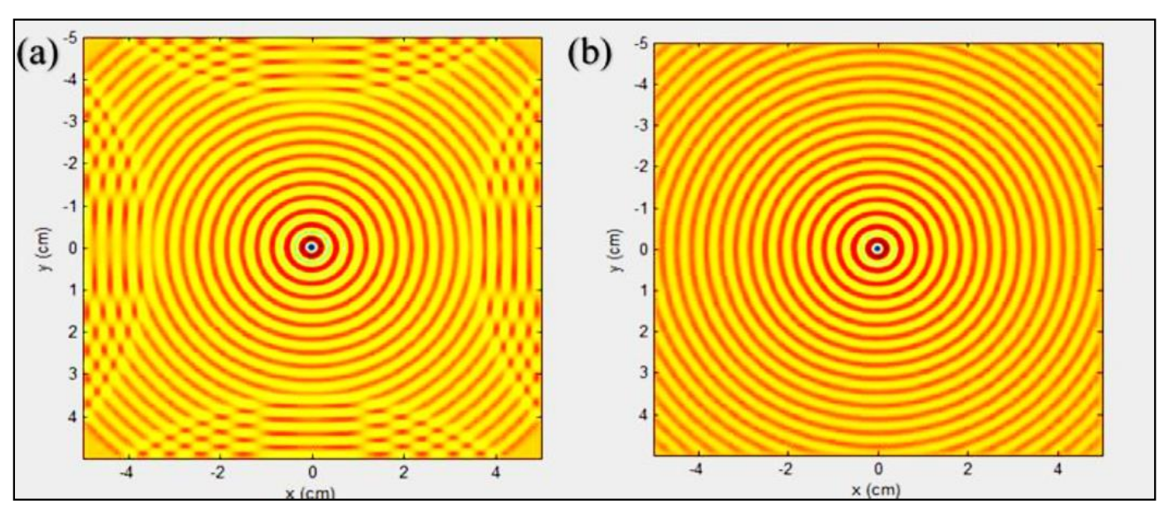

Figure 2. Simulation of a spherical wave propagation in 2D (a) without PML and (b) with PML

2. Neumann boundary condition

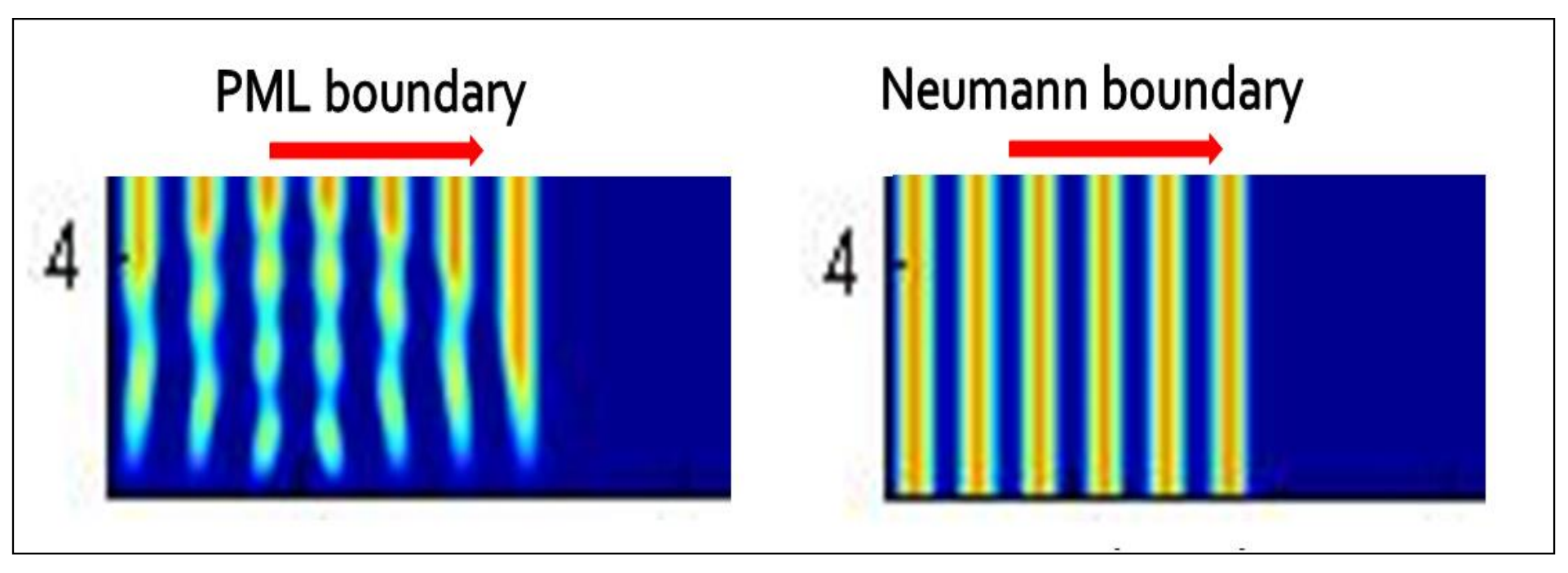

Figure 3. Simulation of a plan wave propagation in 2D
(a) with PML and
(b) with Neumann boundary condition

Numerical Results

In this section, we present the numerical results of simulating acoustic wave propagation in 2D domain through two types of Fresnel zone plate. In all simulations, the source frequency is 200 kHz, and the wave speed is 1,500 m/s. a desired focal position at z = 10 cm and x = 0 cm. Then we use Fortran programs to simulate this.

Due to the significant effect of the thickness of FZP for plane wave, we set it to 3 different values: 4, 8, and 16 mm. Figure4-6 show the simulation results with these 3 thickness, respectively. The results for the 4-mm lens were the following: the focal point was at z = 9.8 cm. and x = 0 cm. and a peak to null = 16 mm. Those for the 8-mm lens were the following: the focal point was at z=9.6 cm. and x=0 cm. and a peak to null = 17mm, while those for the 16-mm lens were as follows: the focal point was at z = 9.0 cm. and x = 0 cm. and a peak to null = 17 cm.

The conclusion is that the thicker the lenses the farther the resultant focal point is displaced from the desired focal point. In other words, the thinner the lenses the better the quality of the focusing mechanism. In addition, our results agree closely to those reported in [6], demonstrating that our developed simulation programs is reliable.

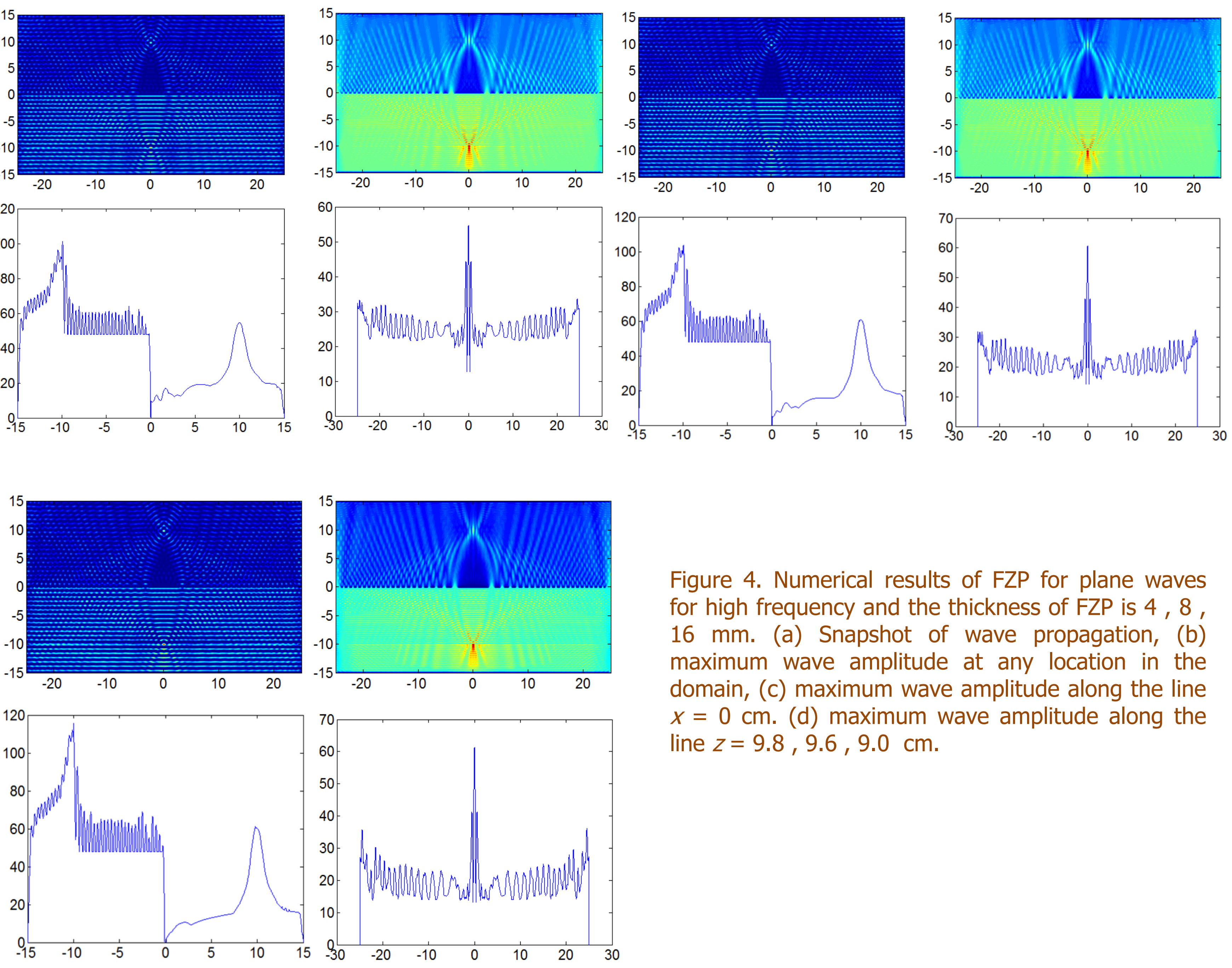

Figure 4. Numerical results of FZP for plane waves for high frequency and the thickness of FZP is 4 , 8 , 16 mm. (a) Snapshot of wave propagation, (b) maximum wave amplitude at any location in the domain, (c) maximum wave amplitude along the line x = 0 cm. (d) maximum wave amplitude along the line z = 9.8 , 9.6 , 9.0 cm.

Comparison between FZP and Scattering method

Following the scattering method reported in [9], a 2D simulation with a speed of 330 m/s and a frequency of 2140 kHz gave the results shown in Figure.5, i.e., the focal point was at z = 0 cm and x= 5 cm and the peak to null = 1.5 cm. The peak to null was rather wide compared to that achieved by the FZP shown in Figure 6. The results from using the FZP were a focal point at z=0 cm and x= 5 cm and the peak to null = 1.6 mm. These results prove that a FZP is more effective than the scattering method since the narrower the peak to null, the more effective the focusing mechanism.

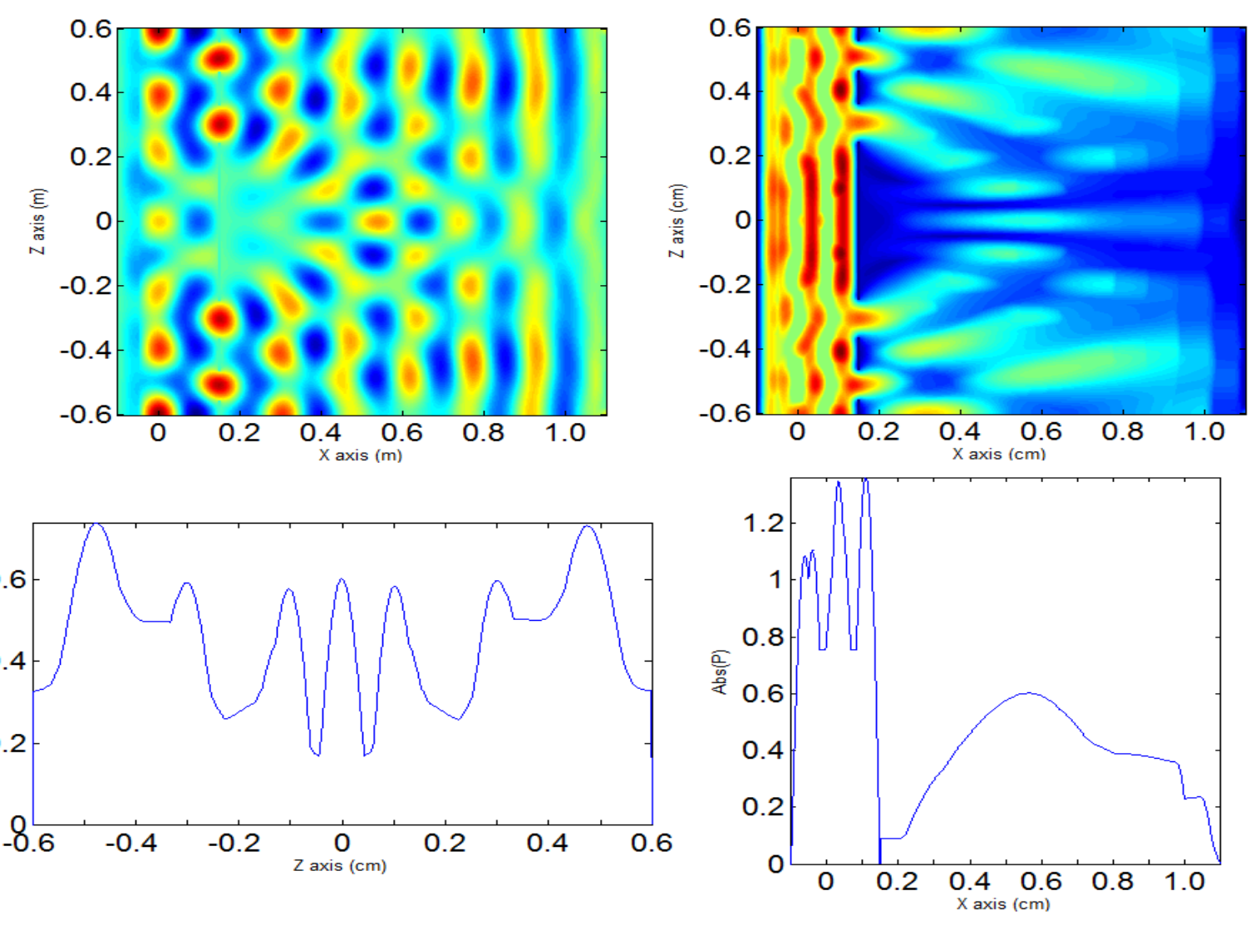

Figure.5 Numerical results of FZP for plane waves for frequency 2140 HZ (a) snapshot of wave propagation, (b) maximum wave amplitude at any location in the domain, (c) maximum wave amplitude along the line x = 5.2 cm., (d) maximum wave amplitude along the line z = 0 cm

CONCLUSION

The presented formulas for Fresnel zone plates for plane waves were validated by numerical simulation based on the finite-difference solution of a PML formulation of a two-dimensional acoustic wave equation. The simulations performed by using our own developed Fortran programs showed that the acoustic waves were accurately focused at the designed locations in both cases.

The thickness of the FZP was shortened, and it was found that the narrower the thickness the more effective the focusing mechanism. The simulation results were found to agree closely to those in a published paper, indicating that our developed simulation programs were a reliable. Compared to the scattering method, the FZP was found to be more effective at focusing acoustic waves.

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