Sub-wavelength resolution of cracks in metallic materials

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Sub-wavelength Resolution of Cracks in Metallic Materials

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Abstract. In recent years, various types of acoustic metamaterials have been proposed with capabilities for overcoming the diffraction limit. However, typically such developments only consider the acoustic regime or imaging in liquid media. In this paper we show the application of a holey structured metamaterial lens for sub-wavelength imaging of defects in a metallic sample, in the ultrasonic regime. Finite Element (FE) simulations are used to study longitudinal wave interaction with ideal cracks in isotropic elastic materials. Holey-structured meta-lenses are then used to transmit the scattered waves. We present a super resolution of λ/7 with a subwavelength crack in an aluminium sample, which to the best of our knowledge this is the highest resolution achieved in the ultrasonic regime.

INTRODUCTION

Ultrasonic imaging is one of the popular tools used to detect and characterize the defects that are presented in the metallic materials by Non-Destructive testing (NDT). Wave scattering effects such as diffraction establishes a tradeoff between the depth of image and the range. Due to this the resolution of an imaging system is restricted to half the wavelength of the wave used for the imaging [1]. To overcome the diffraction limit requires the information from the evanescent waves, which carries the information of fine features of the object but decays exponentially in all natural materials away from the source [1, 2]. Research in recent years, finds solution to overcome the diffraction limit by artificial metamaterials, Viz. Photonic [3], Phononic crystals [4] and Negative indexed materials [5]. Much attention has been paid to perforated metallic materials with periodic hole arrays [6-8] for extraordinary optical transmission [9]. Recent research in this area reveals possibilities for extraordinary transmission [10-12] as well as to explore applications to sensing and super resolution [1, 13]. In this paper we present numerical results showing super resolution of subwavelength cracks in metallic materials using periodic holey-structured metamaterial lens.

This paper is organized as follows. We begin with a brief description of ultrasonic imaging and its limitation for resolution, then the solutions to overcoming the resolution limit by holey structured metamaterial lens, after which we define our problem of interest. This is followed by a detailed procedure followed for numerical (FE) studies to model the metamaterial lens. Finally results are presented to demonstrate the subwavelength resolution in to the ultrasonic regime, after which we conclude with an outline on implications and further work.

BACKGROUND

In the holey structured metamaterial lens each 'hole' acts as a pixel for imaging and improves resolution by amplifying the decaying evanescent waves through Fabry-Perot resonant modes [2]. At the resonance all the waves constructively interfere with each other and transmission coefficient becomes 1 and hence the metamaterial lens transfers all the waves from object plane to image plane without any loss. Evanescent waves also transfer with them without much loss, and hence the subwavelength information carried by them will construct the image with high resolution.

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Problem Studied

We consider an aluminium sample having a notch or crack of length 1.8 mm as shown in the Figure 1(a). The crack present in the aluminium sample is considered as the defect for imaging purpose. The length of the crack (1.8 mm) is about $\lambda/7$ for a frequency of 500 kHz. This object is imaged with ultrasonic immersion C-scan technique with through transmission mode to resolve the subwavelength crack dimensions in its image with the help of periodic holey-structured metamaterial lens.

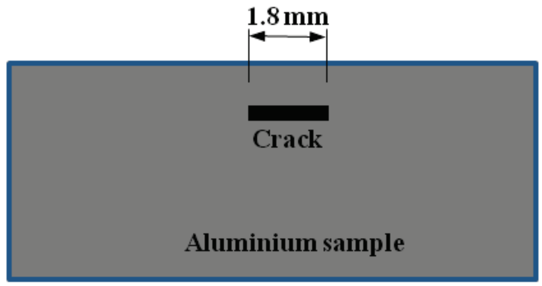

FIGURE 1. Aluminum sample with the details of crack presented in it.

METHODS

FE Simulations

Commercially available FE package [14] is used for modeling. A 2D- FE model was created with dimensions 200x100 mm^2, chosen to avoid reflections from the boundaries. The overall model consists of one part each for the defective sample (aluminium block with crack in it) and the metamaterial immersed in the water respectively, as shown in Figure 2. For both parts 4-noded quadrilateral mesh with a seed size of 0.1 mm was used. For the model of defective sample, mechanical properties of aluminium were assigned, with density ρ = 2700 kg/m^3, Young's modulus of elasticity E= 69 GPa and the poison's ratio υ = 0.334. To create crack in the aluminium sample, a node set of length = 1.8 mm is chosen and setting rigid (displacement is zero) boundary conditions on the selected nodal line.

For modeling of metamaterial lens immersed in water, 2-D model of 240x120 mm^2 was created and assigned acoustic media (water) properties, with density ρ = 1000 kg/m^3 and bulk modulus K = 2.2 GPa. A 2-D holey structured metamaterial of length 13 mm with a hole thickness of 1.5mm and a periodicity of 2mm is created as shown in figure 2. The aluminum block with crack and metamaterial lens immersed in water are assembled and a tie constraint is given at the interface to allow the wave propagation from one media to other. Waves are generated in the aluminum sample by exciting the source (left node set in the aluminum block) in horizontal direction by 3 cycle Hanning windowed tone burst signal of central frequency at 500 kHz. Wave propagation in the model was simulated using the explicit FE algorithm provided in the commercial package [14]. This was run for a total time period of 90 μs which is sufficient for longitudinal waves to reach other end of the model. The transmitted waves from the metamaterial lens were collected at the monitor set on the time trace.

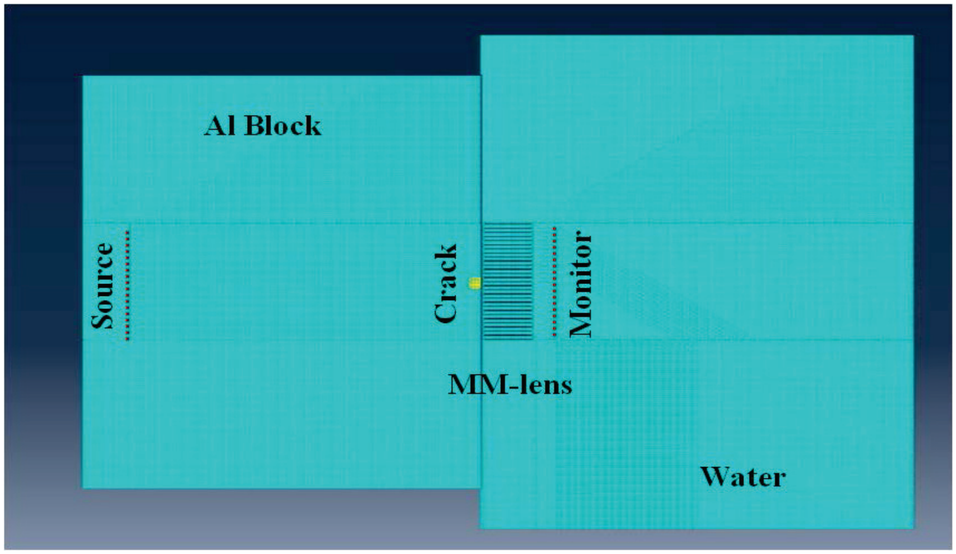

FIGURE 2. Snapshot of FE model with mesh.

RESULTS AND DISCUSSIONS

The maximum amplitude variation from the each A-scan (amplitude variation on time trace) as obtained from the simulations is then plotted against monitored positions as shown in the Figure 3. At the crack position the amplitude drop is observed and it is indicated with dashed lines in the plot. Diffractions from the both edges of the crack are clearly resolved in its image. This shows that the periodic holey-structured metamaterial lens helps to effectively resolve the subwavelength (λ/7) crack in the aluminum sample to the ultrasonic regime.

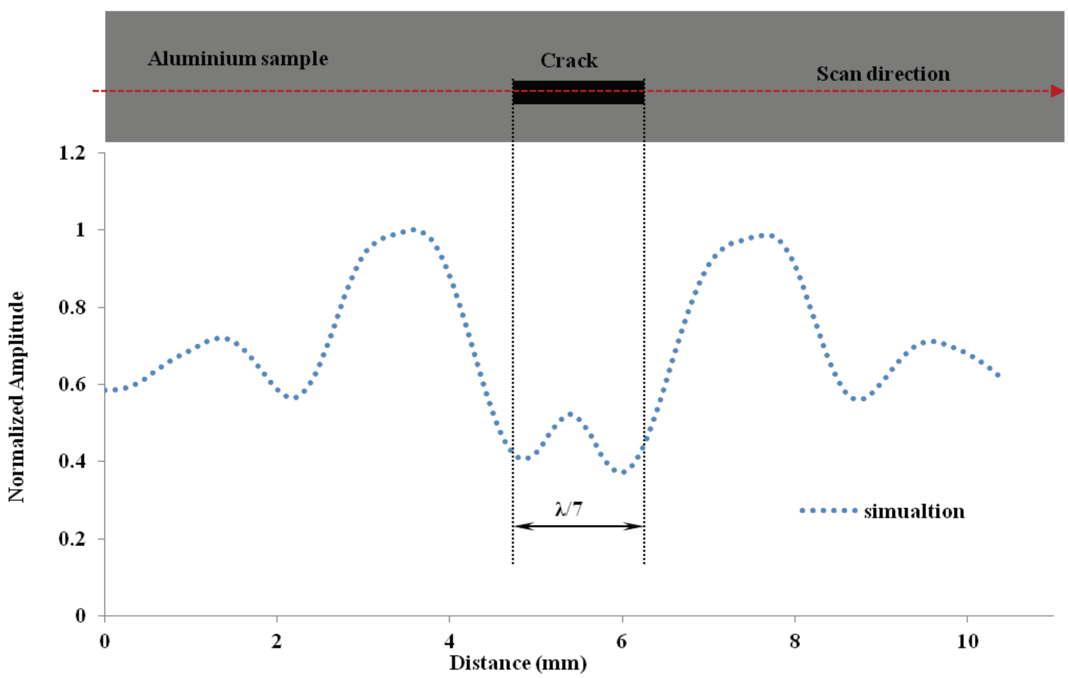

FIGURE 3. Simulated results for normalized amplitude variation with the measurement position across the sample with the meta-lens. The dashed lines represent the position of the subwavelength (λ/7) crack in an aluminum sample.

CONCLUSIONS

Our results show that a periodic holey-structured metamaterial can act as a perfect lens for subwavelength imaging in the ultrasonic regime. This device operates at set of frequencies of Fabry-Perot resonant modes. Reduction of the geometrical parameters like, hole diameter, periodicity and the length of the meta-lens will further improves its resolution capacity.

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