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Subwavelength resolution of delaminations

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Abstract

In this paper, we demonstrate the application of a holey structured metamaterial lens for sub-wavelength imaging of defects in a laminated metallic sample in the ultrasonic regime. Finite Element (FE) simulations are used to study longitudinal wave interaction with ideal delaminations in isotropic elastic materials. Holey-structured metamaterial lens is then used to transmit the scattered wave field. This paper discusses the subwavelength resolution of λ/7 delamination in a laminated aluminium sample which to the best of our knowledge this is the highest resolution achieved in the ultrasonic regime.

Keywords: Diffraction limit, Delamination, Subwavelength imaging, and Holey-structured metamaterial lens.

1. Introduction

Delamination is a common and critical failure mechanism in aerospace structures, created by fatigue, impact stresses during in-service applications [1]. In these applications, the most commonly used non-destructive test is ultrasonic inspection. Diffraction sets a natural limit on resolution, by any wave modality which limits to half the wavelength of the wave used for inspection [2]. To inspect small delaminations, it is necessary to use high frequency (for small wavelength), but in composites high frequency waves are highly attenuated [3]. Hence it is difficult to characterize the small delaminations in the composites. Detection and characterization of subwavelength delaminations are most important in aerospace structural applications otherwise these leads to the sudden catastrophic failure at the high speed. Here we present a technique to characterize the subwavelength delaminations in metals by using periodic holey structured metamaterials. We report the resolution of a subwavelength (λ/7) delamination in a bonded 2 layer metallic (aluminium) sample.

This paper is organised as follows. We begin with an introduction to delamination in layered media, and its detection and characterization importance during the in-service applications fallowed by its background. Then we present the problem studied for analysis and the detailed explanation of the procedure followed for Finite Element (FE) simulation. Then finally we present the results and discussions with an implication to the future work.

2. Background

Holey structured metamaterials work on the principle of Fabry-Perot resonances inside the holes when the scattered waves are propagating through it. With this concept holey-structured meta-lens transfers both the propagating and evanescent waves from input to output surfaces and hence subwavelength information carried by the evanescent waves helps to create the image with high resolution [4, 5].

2.1 Problem studied

We consider a laminated aluminium sample having a subwavelength delamination of length 1.8 mm as shown in Figure 1. The delamination present in the laminated aluminium sample is considered as the defect for imaging purpose. The length of the crack (1.8 mm) is about λ/7 for a frequency of 500 kHz. This object is imaged with ultrasonic immersion through transmission to resolve the subwavelength delamination in its image with the help of periodic holey-structured metamaterial lens.

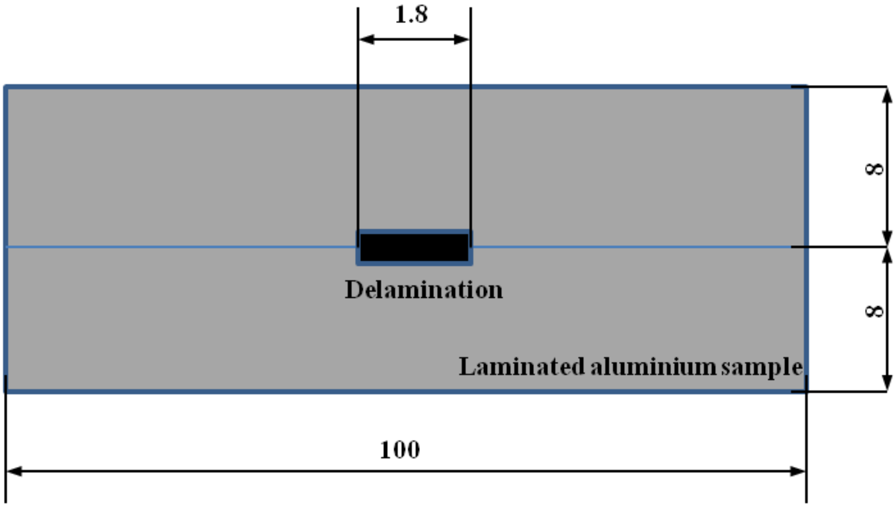

Figure 1. Aluminium sample with the details of subwavelength delamination presented in it (dimensions are in mm).

3. FE simulations

Commercially available Finite Element (FE) package [6] is used to model the wave propagation through the Aluminium sample and metamaterial. This was modelled by two parts, one is aluminium sample with delamination and the other is metamaterial immersed in water as shown in Figure 2. A 2-D FE model was created with dimensions 200x200 mm2 chosen to avoid reflections from the boundaries. Mechanical properties of aluminium were assigned to the model, with density ρ = 2700 kg/m3, Young's modulus of elasticity E = 69 GPa, and Poisson's ratio υ = 0.334. Delamination was created in the aluminium by selecting the nodes of required dimension (1.8mm) and applied rigid boundary conditions (displacement is zero). A 2-D model of size 240x120 mm2 was created and assigned water (acoustic medium) properties, with density ρ = 1000 kg/m3 and Bulk modulus K = 2.2 GPa. 2.2 Gpa.

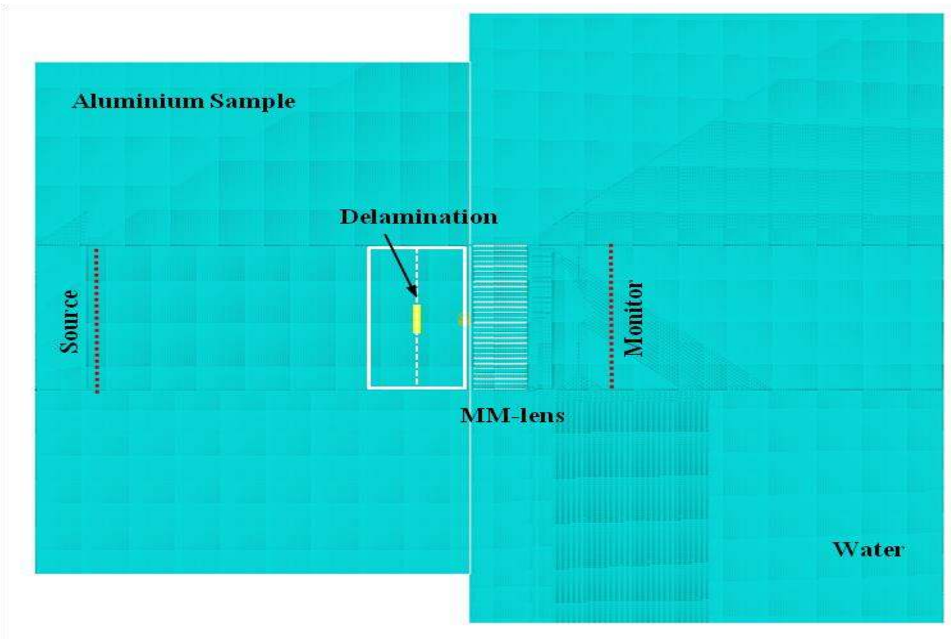

Figure 2. Snapshot of FE model with mesh.

A 2-D holey structured metamaterial of length 13 mm with a hole size of 1.5 mm and a periodicity of 2 mm is created by setting rigid (pressure is zero) boundary conditions on selected nodal lines. CPE4R- A four-node bilinear plane strain quadrilateral, reduced integration, hourglass control mesh was used for aluminium sample and acoustic element AC2D4R was chosen for meshing of metamaterial region with a seed size of 0.15mm. This is about λ/20 for 500 kHz in water for mesh convergence [7]. Tie constraint was given between the two models to allow the wave propagation from one part to other. The model was excited by applying a periodic force of 3 cycle Hanning windowed tone burst signal of central frequency 500 kHz. An iteration step time of 1μs was used. This analysis is run for a total time of 90 μs which was enough for the waves to reach the end of the model once.

4. Results and Discussion

After completion of the line scan the maximum amplitude variation across the measurement positions (for both experiment and simulation) are plotted as shown in Figure 3. In this plot we can clearly see that at the position of the delamination the amplitude drops down which is indicated with dotted rectangular box. The two edge diffractions from the delamination in the results are clearly matching with the exact dimension in the sample.

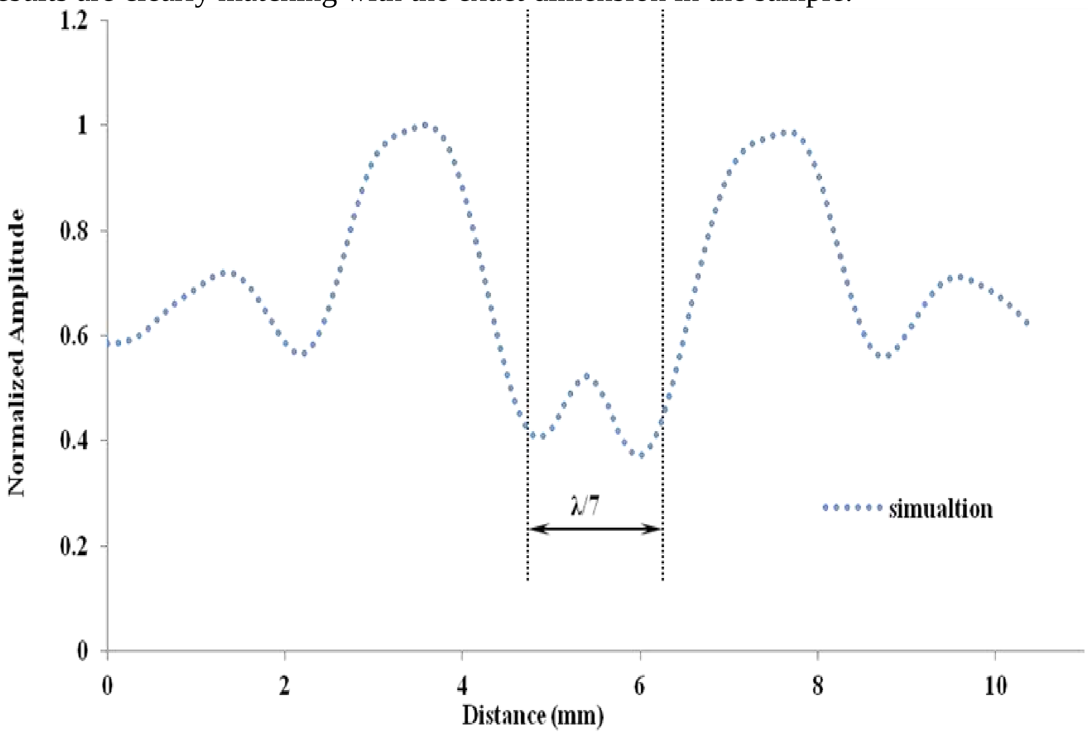

Figure 3. Experimental and simulated results for normalized amplitude variation with the measurement position across the sample. The dashed lines represent the position of the subwavelength (λ/7) delamination in the laminated aluminium sample.

This clearly shows that the holey-structured metamaterial is resolved the subwavelength (λ/7) sized delamination in the laminated sample. Hence the proposed technique can useful to detect and characterize the subwavelength sized in-service defects like delaminations, disbanding, in the composite laminates. By changing the parameters of the holey structured metamaterial the resolution can be greatly improve and the authors are presently working on it.

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