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# Metamaterial enhanced subwavelength imaging of inaccessible defects in guided ultrasonic wave inspection

John Kiprotich Birir [a], Michael James Gatari [a], Mohamed Subair Syed Akbar Ali [b 1], Prabhu Rajagopal [b]

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## Abstract

Detection of defects located close to design features such as welds and supports remains a challenge in guided ultrasonic wave inspection, primarily due to the diffraction limit. Although metamaterial based approaches hold promise, the best previous work in this regard required placing a sensor right above the defect location to achieve resolution. Here, a novel angled channel metamaterial concept is proposed to overcome this limitation, thus permitting placing of a sensor at an offset from the defect location. The concept is demonstrated and discussed using simulations validated by experiments. It is shown that sub-wavelength resolution of crack-like defects is possible using the angled channel metamaterial offset by a distance of up to half the operating wavelength. The physics of this problem is further discussed using simulations and analysis, bringing out the strengths and limitations of the proposed technique, highlighting the benefits for guided wave screening of hidden regions.

## Introduction

Non-destructive testing (NDT) is of interest in many sectors including nuclear, petrochemical, automotive, railway, aerospace and biomedical industries for determining integrity and residual life of critical components. Different NDT methods exist based on electromagnetic (for example radiography, infrared thermography, magnetic particle testing, eddy current testing) and elastic waves (for example acoustics, ultrasonics). Ultrasonic testing offers advantages including an ability to penetrate thicker samples, detect hidden internal defects, and the absence of radiation hazards as well as being cost-effective. The traditional bulk ultrasonic testing method (UT) uses high frequency sound waves to interrogate a material for defect detection and thickness measurements. Many other techniques based on ultrasonic waves have been developed for improved sensitivity and efficiency including phased arrays (PA) and time of flight diffraction (TOFD). The above bulk ultrasonic methods however, still require point by point inspection and thus there has been much interest in the development of guided wave techniques that can allow scanning from a single transducer position.

Guided ultrasonic waves (GUW) are of great interest for nondestructive testing, structural health monitoring and medical imaging due to their long-range inspection and measurement capabilities. GUW are generated when the wavelength of the propagating ultrasonic wave is larger than the thickness of 'waveguide' or structure of interest. In uncoated structures, they can travel tens of meters in both directions from a single transducer location. Thus, GUW find applications in inspection of extended structures such as pipes [1], railroads [2], cables [3], plates [4], bars [5], composites [6], aircraft wings [7], and in biomedical diagnostics [8].

Conventionally, defects cannot be resolved beyond half the operating wavelength and this particularly impacts GUW testing due to the lower frequencies typically employed [9]. A shorter wavelength (higher frequency) could be used as an alternative, but wave attenuation effects mean that the long-range advantages of GUW testing may be lost. Therefore, GUW are generally used for screening purposes to rapidly identify areas of concern in the long range [10]. Once such an area is identified, a secondary higher resolution technique (such as conventional high-frequency bulk ultrasonic waves or focusing techniques) is employed to quantify the feature identified. GUW reflections from natural design features such as welds, elbows, supports and bends, are usually identified as non-relevant indications ignored in practical inspections [11]. On the other hand, structures may often be embedded within concrete or otherwise concealed (for example buried) because of which any defects occurring near or inside these design features (within half the wavelength of the probing wave) poses the risk they may go undetected. This distance is in the order of several centimeters for the GUW frequencies generally used for rapid long range structural inspections.

Bringing the resolution of GUW to levels comparable to those of bulk ultrasonic waves can help to achieve a single-step process of inspection without the need for a secondary method. This has potential for remote inspection of structures located in areas that are difficult to access including buried regions and high temperature and radiation zones. This can also lead to a reduction in the cost and time of inspection in many application areas of interest including non-destructive testing and biomedical diagnostics. There are different techniques that have been explored in literature to overcome the diffraction limit, including super-resolution imaging algorithms [12], array imaging approach based on deep learning [13], nonlinear ultrasonics exploring higher harmonics [14], waveform inversion for accurate defect characterization [15], time-reversal-based super resolution imaging [16], frequency domain analysis [17], and adaptive beamforming [18]. These techniques have specific weaknesses associated with them, including computational complexity, requirement of large datasets for training deep learning models, increased signal complexity, sensitivity to noise, sensitivity to the wave propagation medium, challenges in extracting relevant information from the frequency domain, and the need for careful calibration, respectively. Hence the motivation for the work reported here was to explore a technique that does not require significant changes to existing inspection systems, with no complicated algorithms and is also simple to implement practically.

Recently, a new class of engineered materials referred to as metamaterials has shown promise for overcoming the diffraction limit among other applications. Metamaterials are specially structured materials with exotic properties that can be manipulated through careful design [19,20]. Some areas where metamaterials have been applied for specifically targeted outcomes include optics [[21], [22], [23], [24]], medical imaging [25,26], filtering [[27], [28], [29], [30]], acoustics [[31], [32], [33]], ultrasonics [[34], [35], [36]], seismic applications, and super resolution imaging [37]. Our research group has recently developed metamaterials for various ultrasonic applications including subwavelength imaging of defects. The previous research has mainly focused on bulk ultrasonic wave testing with demonstration of subwavelength resolution of λ/25 for cracks [38] and hole [39] defects using holey-structured metamaterials. The setups used to achieve these resolutions involved the transmitter, defects and the receiver as well as the metamaterial 'lens' being axially aligned.

However, not much investigation has been done in the guided ultrasonic wave regime, where the metamaterial lens and the waveguide typically need to be aligned orthogonally. In an attempt to explore the possibility of improved resolution in the GUW regime, the authors recently developed ‘structured channel’ metamaterials to detect and resolve hole defects separated by distances smaller than a wavelength. A resolution of λ/72 was demonstrated experimentally, which remains the highest reported to date in the ultrasonic regime [40]. The setup used involved the metamaterial and receiver being perpendicular to the direction of wave propagation.

However, in Ref. [40], in order to achieve this resolution, the metamaterial needed to be placed directly above the defects. This is a limitation because in practice, the location of defects is generally not known in advance. The work reported here builds on prior work by our group and aims at the imaging of defects when the structured channel metamaterial is positioned at some offset distance away from the defect location. Crack-like defects are used to demonstrate this capability. This work is relevant to guided wave inspection of buried or otherwise inaccessible regions, see for example Ref. [[41], [42], [43], [44]].

It is useful to bring up the physics of the wave scattering, at this point (see Section 5 for further discussion). Upon guided wave interaction with the defects, an evanescent diffracted wavefield is set-up locally, while in the forward direction they recombine to set up propagating guided waves. The structured channel metamaterial positioned directly above the defect was able to pick up and amplify the diffracted wavefield. However away from the defect, this field would have diminished in strength. Thus, the authors envisaged a metamaterial that could pick up and amplify the multiply-scattered components in the forward direction, and towards this end, an 'angled structured channel' concept as illustrated in Fig. 1 was explored. A transmitter was attached to one end of a bar waveguide. The waves are scattered as they interact with the vertical crack type defects. A metamaterial was positioned at an offset distance from the location of the defects. The receiver was positioned on top of the metamaterial to pick up signals transmitted through.

This paper is organized as follows. Firstly, the working of the proposed 'angled structured channel' metamaterial is discussed. The numerical model used to study the system and the experimental set-up are described next. Finally, the results are presented and discussed in light of the physics of the problem, demonstrating the proposed approach**,** after which the paper concludes with directions for further work.

## Section snippets

## Theory

Various metamaterial techniques have been considered for super resolution including near field imaging, negative index materials, and resonating structures. The method pursued in this work is based on resonating structures, whereby carrying a wave with a very large wavelength $\lambda$ compared to the channel size $a$ ($\lambda \gg 10a$) alters the properties of the waveguide. The metamaterial behaviour is influenced by the propagating wavelength, the channel width as well as the channel length. A state of …

## Materials and methods

An aluminium plate of 1 m length, 50 mm width and 10 mm thickness was considered as a sample for inspection and demonstration of our offset-angled metamaterial approach. Vertical notch or crack-like defects were introduced in the plate as shown in Fig. 1(a). The plate was excited with ultrasonic guided waves from one end while the receiver was located at an offset distance from the defects. A metamaterial was positioned between the sample and the receiver to enhance and tunnel the scattered …

## Results

The results show promising trends for the two most important features of the problem considered, namely the subwavelength resolution and the defect location, as presented and discussed in the following sections. …

## Paramatric studies

To evaluate the resolution limits for the selected defect configuration, cracks of different depths, separation distances and metamaterial offset distances were investigated through numerical simulations, varying each of the parameters keeping all other variables constant. For clarity, only selected results are presented here, as before. The obtained results show that resolution is a function of the proximity of each crack with respect to the metamaterial. This can be explained as follows.

As …

## Conclusions

This paper demonstrated that subwavelength resolution imaging of crack defects using structured channel metamaterials can be achieved without the need to have a sensor located directly above the defect in through transmission guided ultrasonic wave inspection. An angled channel metamaterial lens is proposed to locate and resolve subwavelength spaced defects at an offset distance from the defect location. Imaging of crack defects was demonstrated using simulations with experimental validation. …

## CRediT authorship contribution statement

**John Kiprotich Birir:** Formal analysis, Methodology, Software, Writing – original draft. **Michael James Gatari:** Funding acquisition, Supervision. **Mohamed Subair Syed Akbar Ali:** Investigation, Validation, Writing – review & editing. **Prabhu Rajagopal:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. …

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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1 Present address: Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011, USA.

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