Super Resolution Imaging using Off-the-Shelf Ultrasonic Probes

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Abstract

High resolution ultrasonic imaging systems are of much interest in non-invasive diagnostics and non-destructive evaluation. By harnessing the evanescent wavefield, recent developments in metamaterials offer the promise of sub-wavelength and super-resolution imaging, but such advances require sophisticated reception making practical realization challenging. Set in this context, this paper presents the development of a portable device for achieving super resolution ultrasonic imaging using conventional transducers. A prototype of the device has been built and practical super resolution ultrasonic imaging down to one-fifth of the operating wavelength is demonstrated using commercial probes.

Keywords: *Ultrasonic imaging, Sub-wavelength imaging, Super resolution, Metamaterials, Holey lens, Fabry-Perot resonance, Evanescent waves, Conical baffle, Commercial Transducers.*

1. Introduction

Super resolution imaging systems are of much interest in fields such as non-invasive diagnostics and non-destructive evaluation. Although Ultrasonic Imaging (UI) is attractive for offering safe, cost-effective and portable inspections with good penetration [1], conventionally, this modality suffers from poor resolution. Improving the resolution requires beating the diffraction limit [2], and for this, high frequency evanescent waves which decay quickly within the near-field must be captured. However, near-field imaging [3,4] approaches typically involve complex post-processing that is sensitive to noise, making hampering practical realization. An alternative is to harness the information carried by the evanescent waves by successfully transferring them to the far-field. This approach has attracted much interest in recent years with concepts such as negative indexed media, super-lenses and hyperlenses in the electromagnetic [5-11] and acoustic domains [12-15]. Holey metamaterial lenses (or 'metalenses') are simple in design, easy to fabricate, and can be used to achieve super resolution beyond diffraction limit [16,17]. Metalenses employ Fabry-Perot resonances to amplify evanescent waves scattered by defects in the sample and transfer them to the far-field. The dimensions and arrangement of the holes in such metalens must be subwavelength compared to the incident waves used for the imaging [16]. Recent demonstrations from our research group, the Center for Nondestructive Evaluation (CNDE), IIT Madras, have shown the application of periodic [18-20] and non-periodic [21] metalenses for super resolution imaging in the ultrasonic domain.

Although the potential of metalenses in super resolution imaging is remarkable, they have only been demonstrated in laboratory experiments using heavy, sensitive and expensive equipment such as the Laser Doppler Vibrometer (LDV). This is due to the fact that for successful imaging, waves passing through the holey lenses must be captured discretely at fine spatial intervals. Capturing waves at fine intervals under water immersion is a significant further challenge. This makes the practical field implementation or widespread deployment of metalens based imaging challenging. In view of this, the work reported here focuses on developing a portable and scalable device for super resolution ultrasonic imaging (SUI) that can be used in the field without requiring special instruments for wave reception. This work also incorporates an effective signal reception technique using commercial transducers attached with a conical hollow horn [22, 23].

The paper is organized as follows. The underlying physics of the holey metalens is first described, followed by a discussion of the problem studied. The design of a super resolution imaging device is then presented, followed by the description of the prototype and experiments. Results so obtained are then presented and discussed, after which the paper concludes with consideration of implications and further work.

2. Background

Periodic holey metalenses harness Fabry-Perot resonances when the hole length L satisfies the condition:

$L = m\lambda/2n$……………………………….(1)

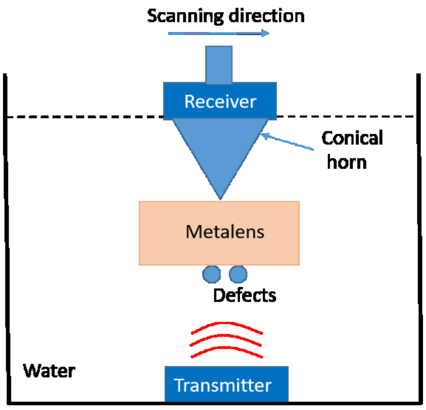
where *m* is an integer, λ is the wavelength of the wave used for imaging, and *n* is the refractive index. Consider the example of a plane ultrasonic wave with normal incidence on a defective sample. Waves scattered by the defects in the sample pass through a metalens immersed in water before being picked up by a receiver. Assuming that the features of the sample act as the perturbation to the plane wavefield, the transmission coefficient T can be expressed as [24],

$$T = 4(d/\Lambda)^2 Ye^{-ikL}/((1 + y(d/\Lambda)^2)^2 - (1 - Y(d/\Lambda)^2)^2 e^{2ikL}) \;\ldots.(2)$$

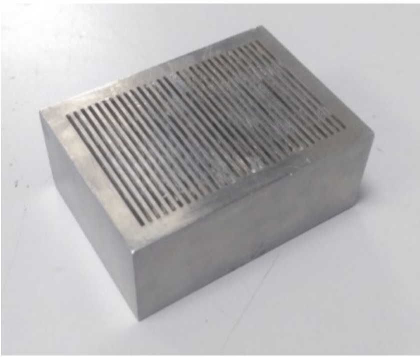
where d is the diameter of the hole, Λ is the periodicity of the hole array of metalens, k is the wavenumber, Y is the admittance of the waveguide mode within the holes, and L is the length of the holes. At resonance, the metalens transfers all the waves from the input side to the receiver-side without any loss. For better resolution, the geometry of the metalens should satisfy the following guidelines [19]: The diameter of the holes should be λ/n, where n is an integer of value >= 10. The length of the hole should be an integer multiple of half the wavelength mλ/2 and the periodicity should be 2pλ/n, where m and p are integers.

3. Problem Considered

To experimentally demonstrate super resolution ultrasonic imaging using the proposed device and signal reception technique, two thin metallic rods/wires separated by sub-wavelength distance were considered as objects for imaging. Two aluminium rods of 2.5 mm diameter were used with a center-to-center distance of 5 mm, corresponding to $\lambda/5$ for a frequency of 100 kHz. The rods were placed in front of the metalens in a water bath as illustrated in Fig.1a. A ‘through-transmission’ configuration was considered for imaging whereby the transmitter and receiver probes were placed at either side of the assembly of metalens and rods. A 1D metalens made of stainless steel (see Figure 1b) with periodic channels/grooves of 1 mm which is much sub-wavelength to the operating frequency, was used for imaging. The length and periodicity of the channels were 45 mm and 2 mm, respectively.



(a)



(b)

Figure 1. (a) Schematic illustration of the problem considered and (b) Photograph of the 1D metalens used for imaging.

4. Super Resolution Ultrasonic Imaging (SUI) Device

The device proposed here aims to simplify the practical super resolution ultrasonic imaging for the end user by avoiding the complex experimental setup used in laboratory demonstrations. The proposed device is a stand-alone component that allows for the easy placement of a probe, a sample specimen, a metamaterial, and a receiver. It comprises several parts, namely (a) Immersion container, (b) Positioning system, (c) Specimen holding platform, and (d) Metalens and receiver holding platform, which are described below

4.1 Immersion Container

The container is used to hold water for immersion ultrasonic scans. Also, it serves as a base for the other parts of the device. At the bottom of the container, there is a provision for placing the ultrasonic probe. It also has a pipe and drainage system for filling and emptying water. The sidewalls of the container are provided with a see-through glass window to position the specimen and metalens properly. One of the side walls has a door to enable the user to place the specimen and metalens in their respective platforms. The areas corresponding to the door and the probe are sealed with rubber gaskets to arrest water leakage. The top of the container is kept open to allow manual or automatic scanning. There is no restriction on the material of the container except that it should hold water and support the other parts of the device, so it should be rigid and rust-free.

4.2 Positioning System

The positioning system is one of the crucial aspects of the SUI device. The vertical movements of the sub-assemblies (c) and (d) are designed to be controlled by a positioning system. There are four columns designed inside the container to support the sub-assemblies (b), (c) and (d). Actions are guided along the diagonal columns for the vertical motion of the platforms used in (c) and (d). A hand-controlled knob is used to manoeuvre the positioning. For the work reported here, a positioning system based on bevel gears as shown in fig. 2 was considered. For demonstration purposes, only the vertical movement of the metalens holding platform was considered. Nevertheless, the positioning system can also be designed to allow independent motion to all the platforms holding the specimen, metalens and receiver.

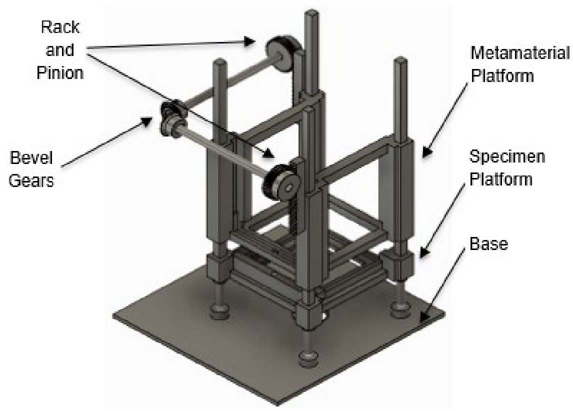


Figure 2. Snapshot of 3D model of the bevel gear based design of the SUI device

4.3 Specimen Holding Platform

The primary purpose of the platform is to hold the specimen in the water at a specific elevation from the probe to achieve plane wave incidence. Typically, the specimen should be kept farther (>>λ) from the transmitter to ensure a plane wave incidence, where λ is the wavelength. The rectangular holes in the platform are for guiding along the supporting columns during the vertical movements. The platform is designed to have a plug-in mechanism, where the tray as shown in fig. 3 can be pulled out through the door provided in the immersion container and plugged back after placing the specimen. A lock provided with the platform ensures that the tray does not move once placed inside. It is essential to ensure the flatness of the specimen holding platform, for which level measuring scales were given at the columns. These scales were placed next to the glass window to be seen outside. Similar scales are also provided on the platform to help center the specimen. Diagonal columns can be used to change the vertical location of the specimen after it has been placed on the platform.

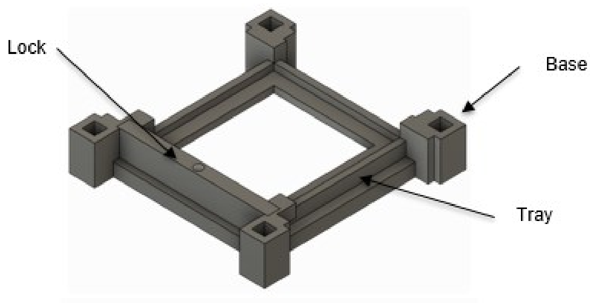


Figure 3. Snapshot of 3D model of the specimen holding platform.

4.4 Metalens and Receiver Holding Platform

The SUI device also has the platform to place the metalens and receiver. Similar to the specimen holding platform, this platform is also designed with a plug-in/out mechanism such that the metalens can be placed by pulling the tray out through the door provided on the container. Level measuring scales are also given on the platform to position the metalens. Racks are attached on the diagonal sides of the platform to couple with the positioning system. The receiver can be positioned on top of the platform using additional supports. The receiver must be able to freely slide in both X and Y directions to facilitate the scanning. The 3D model of the metalens platform is shown in fig. 4.

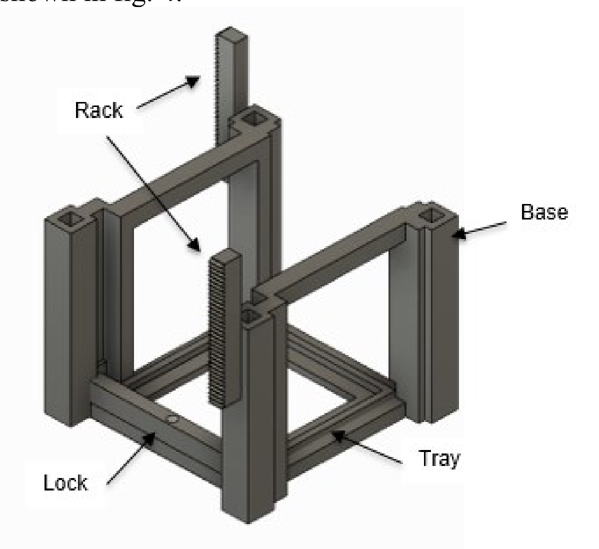


Figure 4. Snapshot of 3D model of the metalens and receiver holding platform.

4.4.1 Holding Mechanisms

In practice, the samples or the imaging objects and metalenses can be of different sizes. To accommodate the various sizes of objects, the platforms need to be designed with an adjustable holding mechanism. One design can be a screw mechanism, as shown in fig. 5, which allows the two ends of the tray to move with respect to each other, allowing them to hold objects of different sizes.

5. Prototype of the SUI device

A prototype of the bevel gear based design of the SUI device was fabricated. The immersion container was made using stainless steel. To be cost-effective and rust-free, the steel grade 304 was used along with a coating. The prototype was made for a 100 kHz frequency imaging application where the wavelength in water is about 15 mm, and a standard probe for the given frequency has an average diameter of 40 mm. These are the main factors deciding the device dimensions, and the current rectangular container with an open top is about 250 mm x 255 mm x 350 mm. The base of the container has four circular cylinders with inner threading to fix the supporting columns in the container. A circular opening was provided at the bottom of the container to fix the probe (transmitter) from the bottom. The probe can be plugged in/out with the help of a gasket placed on the circular opening. Also, to ensure that the container's weight does not fall on the probe, four legs are provided at the bottom of the container. A door made of Plexiglass is provided on one side of the container using hinges to provide visibility during the experiment and ease of access for placing the metalens, specimen, and the receiver. To prevent water leakage, gaskets were attached to the door and provided multiple locks using the screw and nut mechanism. Figures 6a and b show the photograph of the fabricated porotype of the SUI device. Metallic racks were attached to the metalens platform with the help of screws.

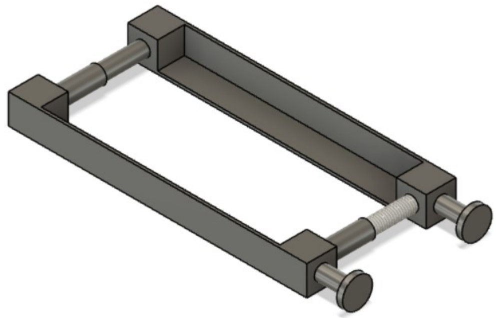
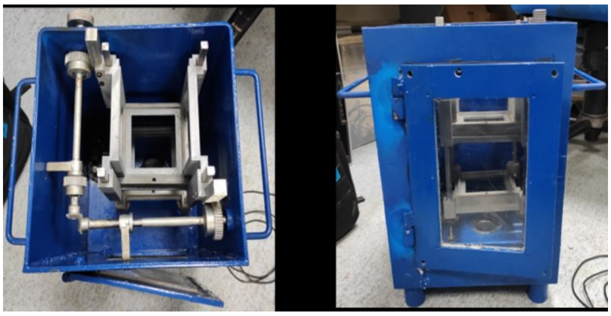


Figure 5. Snapshot of 3D model of specimen/metalens holding platform to hold objects of various sizes.

In contrast, the specimen platform is stationary at a sufficient distance from the transmitter probe with the help of stoppers on the supporting columns. The positioning system, including the gears and the shafts, was also made using steel grade 304 and provided with a rust-free coating. Bearings were provided on the walls of the container to facilitate the rotation of shafts connected with gears.



(a) (b)

Figure 6. Photographs showing the fabricated prototype of the SUI device. (a) top view, and (b) front view.

6. Signal Reception Technique

To capture the waves from each hole of the metalens discretely, a conical hollow horn attachment to a commercial probe [23] was considered. The conical add-on acts as a mechanical filter and enables a spatially narrowband or 'point' reception. The cone has a fine opening at its apex whose size is comparable to that of the hole/channel width in metalens. Thus the conical baffle serves as a bridge between each channel of the metalens with the commercial transducer and helps to capture the waves discretely. The cone was made using a 1 mm thick copper sheet with a narrow hole of less than 1 mm on its apex. The height of the cone was 15 mm, corresponding to the operating wavelength. Figure 7 shows the photograph of the receiver probe attached with the conical horn. Copper was chosen because of its higher impedance mismatch with water compared to other similar materials and ease of availability.

Figure 7. Photograph showing the conical horn attached to the transducer.

7. Experiments

Experiments were conducted in a through transmission configuration. The probe was plugged-in into the bottom of the SUI device. The two aluminium rods with sub-wavelength separation and the metalens were placed on the respective platforms of the device. The distance between the rods and the transmitter probe was adjusted by moving the platforms using the positioning system and maintained a sufficient distance to ensure plane wave incidence on the rods. A RITEC 4000 pulser-receiver (Ritec Inc., USA) was used to give a 3 cycle Hanning windowed toneburst excitation to the transmitter probe (100 kHz, Panametrics). On the receiver side a higher frequency transducer (500 kHz, Panametrics) was used with a conical horn attachment as described in the previous section. The receiver was mounted on a moving arm of a raster scanning machine to facilitate automatic scanning. The signal received by the receiver probe was fed into a computer through a data acquisition card. The photograph of the experimental setup is shown in fig. 8. The length and step size of the line scan was chosen as 20 and 0.2 mm respectively.

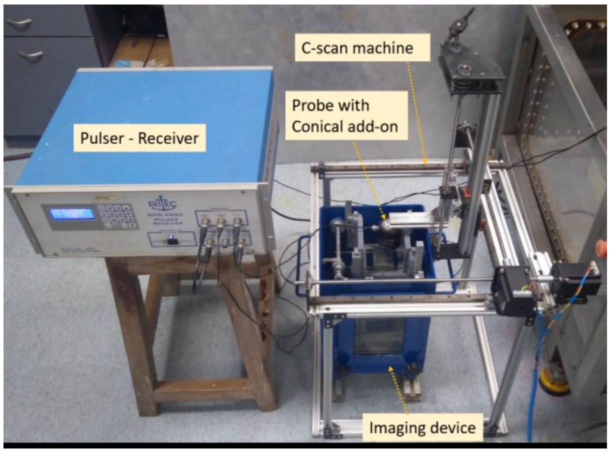


Figure 8. Photograph showing the experimental setup for demonstrating the SUI device.

8. Results and Discussion

Experiments were performed with and without defects for comparison purposes. A line scan was conducted by acquiring the signals along the scanning direction using the conical add-on attached with the commercial transducer. The maximum amplitudes of the time-gated signals obtained from the line scan were plotted against the measurement position. The envelope of the maximum signals was plotted for the cases with and without defect, as shown in fig. 9. It can be observed that the peaks corresponding to the defects appeared when the prospective defects were placed in front of metalens, and the distance between the peaks also closely matches the sub-wavelength (λ/5) spacing between them. The deviation of the peak positions can be attributed to the wave scattering that arises from the defects and corresponds to the gap between the metalens and the tip of the conical add-on. Also, the formation of peak amplitudes corresponding to the defects is due to the scattering phenomena within the near-field, where the wave fields passing around the circular periphery of the defect meet again in the shadow region of the defect and interfere constructively.

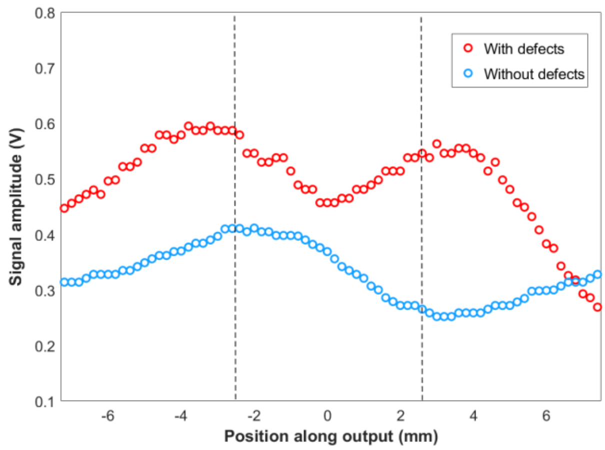


Figure 9. Experimental results showing the envelope of maximum signal amplitude along the scan axis. Dotted lines represent the actual position of defects/scatterers.

9. Conclusion

Research reported here discusses the development of a device for practical sub-wavelength ultrasonic imaging. Imaging of defects separated by one-fifth of the operating wavelength was demonstrated successfully using a prototype of the device. The proposed device, along with the conical add-on based signal reception technique, offers a cost-effective alternative for super resolution imaging at low frequencies and can be easily implemented in industrial and biomedical fields. Further improvement and optimization of the device and the signal reception technique are expected to yield more robust and scalable practical solutions.

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