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Optimisation of data acquisition and processing for laser induced ultrasonic phased arrays

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A laser induced phased array (LIPA) synthesizes an ultrasonic array, performing beamforming in post processing and using lasers for ultrasonic generation and detection. It is a non-contact technique, with a small footprint and no need for couplant, offering remote ultrasonic imaging. In a previous work, the Full Matrix Capture (FMC) and the Total Focusing Method (TFM) have been adapted to LIPAs, providing superior imaging quality, overcoming the poor signal-to-noise ratio of conventional laser ultrasonics. However, long scanning times compromise industrial applications. Our aim is to optimise FMC for LIPAs, to achieve faster data acquisition, while ensuring that ultrasonic imaging is not undermined. In the work presented, optimisation of the data acquisition and signal processing is achieved by considering the directivity and sensitivity patterns of laser ultrasound. The array characteristics, such as the number of elements, pitch and distribution were optimised according to the location of defects, receiving input through post-processing performed performed in parallel. The potential of this method is demonstrated using previously experimentally acquired data. These simulated results are compared to the scanning times and image quality of conventional FMC. Results confirm that scanning time can be significantly reduced, leading to almost 10 times faster data acquisition for LIPAs.

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Introduction

Laser ultrasonics (LU) is based on generating and detecting ultrasound using lasers[2] and offers a remote, non-contact, small footprint alternative to piezoelectric transducers. These benefits make LU an excellent candidate to tackle the challenges of performing Non-Destructive Evaluation (NDE) in hazardous or extreme environments, on components of complex shape, or in places of restricted access.[3-5]

Inspection using ultrasonic phased arrays, consisting of conventional piezoelectric transducer elements, has become an industry standard for performing NDE.[6] This gives the ability to electronically focus and steer ultrasound, making it possible to carry out inspection on a region of the sample rapidly from one location.

Lasers as ultrasound transmitters and receivers have been used in phased arrays as far back as the early 90's.[7] Phased arrays using lasers up until a few years ago could be put into two main categories: a laser beam that is split and guided using optic fibres[7-9], and arrays consisting of multiple laser sources.[10-11] The former is a cost effective option with only requiring one generation and one detection laser, with the split beam resulting in a weaker signal, while the latter can generate stronger waves, however the cost greatly limiting the possible number of elements in the array.

It wasn't until a few years ago that Laser Induced Phased Arrays (LIPAs) could synthesise arrays with number of array elements compared to that of conventional phased arrays.[1,12] This was due to capturing the Full Matrix, a method for acquiring data from all transmit and receive pairs[13]. Full Matrix Capture (FMC) was performed by scanning a generation and a detection laser over the sample, synthesising the array. The steering and focusing were done in post-processing using the Total Focusing Method (TFM), a technique that focuses on each individual point of the image in post processing.[13] While this was a big advancement for LIPAs, a limiting factor was the long scanning times it required for data acquisition.

In this work, a scanning method is proposed for faster data acquisition for LIPAs. This is achieved by optimising the element count and location according to the acoustic wave's directivity and sensitivity patterns.

Methodology

The procedure consists of two stages. Initially, a large aperture, large pitch array is synthesised, whose geometrical characteristics correspond to low frequency and low imaging resolution. It is used to determine the possible location of defects in the component. Next, this initial array is populated with more elements with smaller pitch, on locations around the possible defect positions, which are selected based on the directivity and sensitivity patterns of LU. As the smaller pitch is suitable for higher frequencies, better resolution is achieved.

Array Building for Defect Location

In order to locate the defect, a so-called array building scan is performed. This involves starting with a large aperture, then iteratively increasing the number of elements until the defect can be decisively detected. The total aperture is kept constant, reducing the element spacing at each iteration.

The broadband ultrasonic signals were filtered at different frequencies at each stage, ensuring that the pitch stays lower than half the wavelength. This ensured that no grating lobes were generated.[14] The array building stage is represented in fig. 1, showing the generation and detection points in orange while the distance between them are shown in grey.

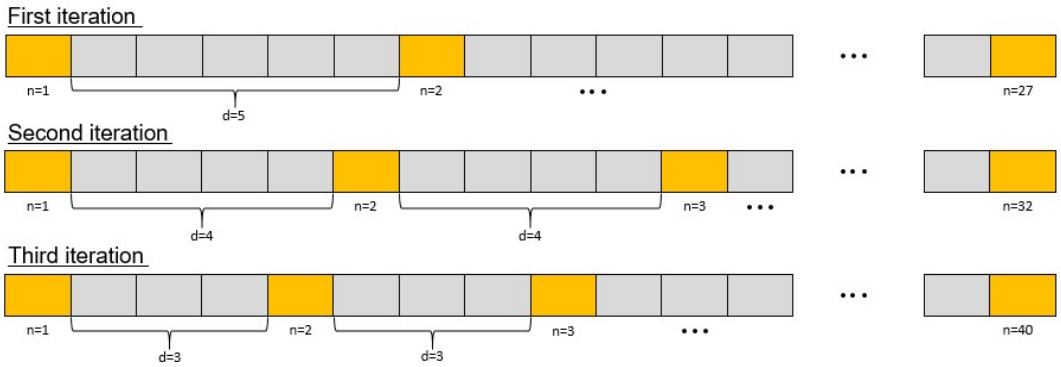

Figure 1. Iterative array building for defect detection

Selective Matrix Capture

After detecting a defect, it can be better resolved by a scan of elements with smaller pitch, the locations of which are selected considering the directivity and sensitivity patterns of laser generated and detected waves. These patterns were considered only for shear waves as they are generated 10 times more efficiently than longitudinal waves in aluminium.[15] The directivity[16] and sensitivity[17] patterns of the ultrasound generation and detection processes are depicted in fig. 2.

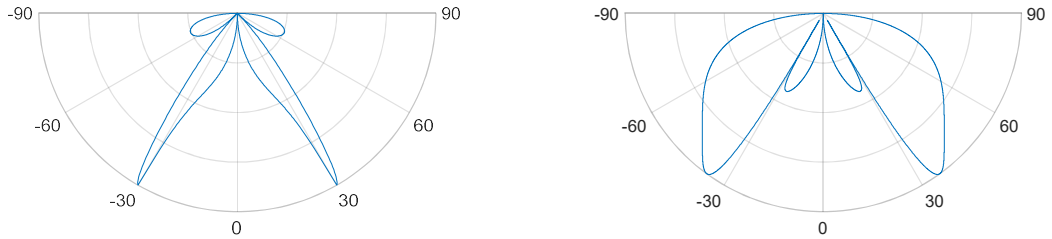

Figure 2. Directivity (a) and sensitivity (b) patterns for shear waves

From these diagrams it can be concluded that LU in aluminium is generated and detected best at around 30°. As a consequence, Selective Matrix Capture (SMC) can be performed, which involves collecting data with all transmit receive combinations near these angles from the surface to the defect while ignoring other locations.

Results and discussion

The data were previously acquired on an aluminium sample with the experimental setup described in [18]. The sample had 9 defects (side through holes of diam. 1 mm) arranged in a radial distribution, of radius 20 mm from the surface, in angles of 0°,±15°,±30°,±45°,±60° from the surface normal. The aim of the present study was to selectively increase the image quality at a specific location in the sample and for this purpose, our interest was focused at detecting the defect located at +45° from the array centre (shown as 14 mm horizontally and vertically in fig. 3). The position of this defect is highlighted in fig. 3 by a red circle, whereas the positions of all other defects are marked with white arrows. The array building and SMC were performed only in post processing, however this should have no effect on the methodology.

Figure 3 shows images obtained during the array building stage. The defect can be decisively distinguished from the noise floor (-6 dB threshold) with as few as 40 elements, with 616 μm pitch, as do most of the other defects on this sample. The data acquisition time would have taken 11 minutes, 11 seconds with our current experimental setup.

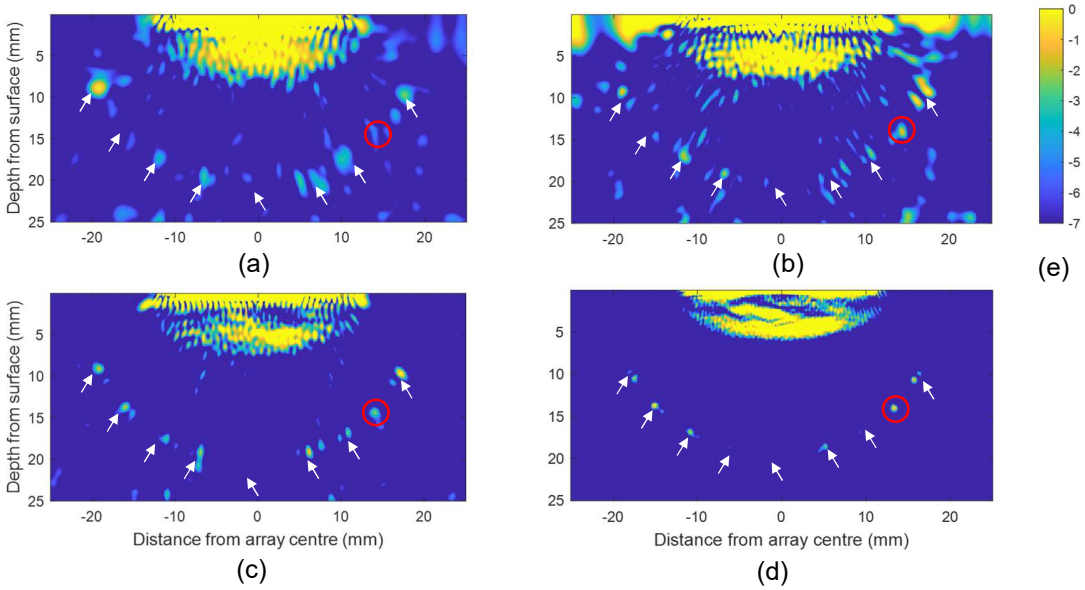

Figure 3. TFM images using shear waves, generated by (a) 27, (b) 32, (c) 40, (d) 161 elements, at (a) 1.67 MHz, (b) 2 MHz, (c) 2.5 MHz, (d) 4 MHz with the (e) dynamic range. White arrows: expected positions of sample defects. Red circle: expected position of defect of interest.

Images captured using SMC, with 3 different angle sets are shown in fig. 4. Scanning with 22 elements covering the locations between 25-35° from the location of the defect with a pitch of 1.54 μm, gives a total array aperture of 3.23 mm, while coverage between 20-40° requires twice as many elements doubling the size of the array. This increase in element count increases SNR and the larger aperture gives better steering and focusing ability resulting in better resolution. Data captured during the array building stage that happen to be from the selected locations of the SMC, further reduce the scanning time. At the previous stage 11 positions out of the 44 have already been scanned leaving only 33 locations to scan over.

The final image, shown in fig. 4.c was achieved having only synthesised a 40 and a 33 element array during the two stages respectively, with a total scan time of 19 minutes and 7 seconds. Conventional FMC would have required 161 elements to achieve the same image quality of this particular defect and would have taken around 180 minutes of scanning. A more detailed comparison of conventional FMC and the above proposed technique is presented in table 1.

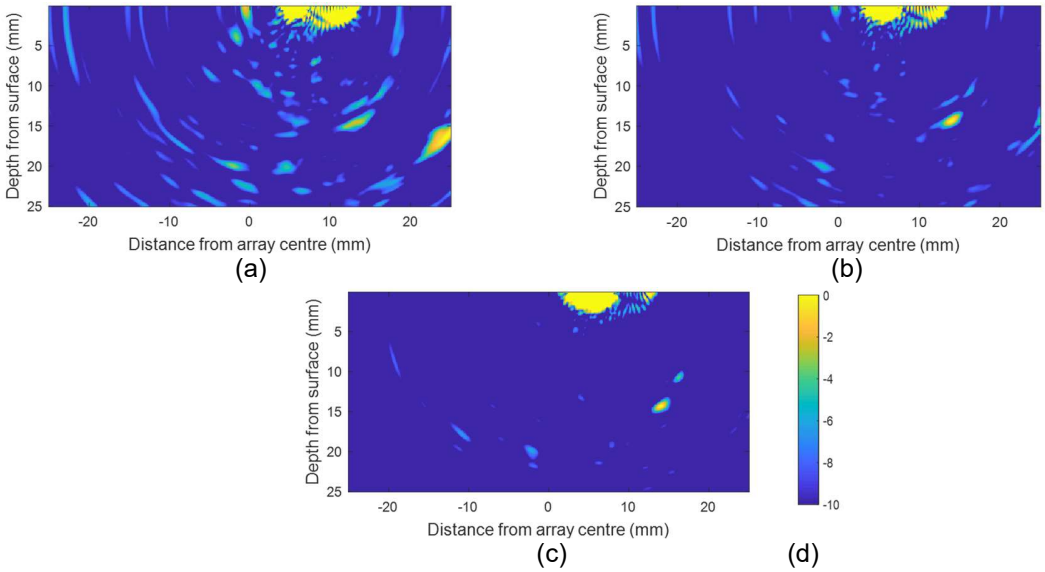

Figure 4. Images created using SMC data, with 1.54μm pitch and elements at (a) 25-35°, (b) 22.5-37.5° and (c) 20-40° to the defect at 4MHz with (d) dynamic range

Table 1. Comparison of conventional FMC and the optimised algorithm

	Element count	Scan locations	Total scan time	SNR
Conventional FMC	161	25921	~180 min	19.98
Array building	40	1600	11.11 min	-
SMC	33	1089	7.56 min	19.75

Conclusion

The proposed technique, implemented in post-processing, achieved almost 10 times faster scanning for LIPAs than conventional FMC. This could reduce a 3-hour scan to 19 minutes for a 25 by 50 mm image. The image quality for regions of no interest (not containing defects) was reduced, while, at the defect, the SNR and resolution achieved were comparable to that of conventional FMC. The faster scanning advances LIPAs toward in-process inspection for manufacturing processes and real time monitoring in hazardous environments.

Acknowledgements

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