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SURFACE ACOUSTIC WAVE SUPPRESSION FOR NEAR-SURFACE DEFECT IMAGING USING LASER INDUCED PHASED ARRAYS

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ABSTRACT

Laser induced phased arrays (LIPAs) offer fast and efficient remote ultrasonic imaging for processes operating in extreme environments and restricted access such as additive manufacturing and welding. In this work, LIPAs are synthesized in the non-destructive thermoelastic regime using an 8 ns pulsed 1064 nm generation laser and a 532 nm continuous wave detection laser. The acquired Full Matrix data is post-processed using the Total Focusing Method (TFM) to image near-surface side-drilled holes inside an Aluminium sample. The images generated, however, contain contribution from the surface acoustic wave (SAW). In laser ultrasonics, SAW is the strongest wave mode generated, and consequently, a region of the image generated is saturated by the SAW arrival (SAW cross-talk). The SAW cross-talk region extends into the sample starting at the scan surface and hence masks any features/defects within this region. This study explores and compares various signal processing techniques such as frequency-wavenumber filtering, phase coherence imaging and amplitude thresholding of ultrasonic signals in order to suppress/remove the SAW cross-talk from the ultrasonic data captured using LIPA for successful imaging of near-surface defects. The mode suppression is achieved by targeting the characteristics of the SAW: its velocity, amplitude and phase. The different methods of wave suppression are compared, and relative merits of each technique are discussed.

INTRODUCTION

Advanced manufacturing processes require advanced inspection techniques to meet the challenges offered by the manufacturing processes. The current and future challenges of materials and processes include extreme processing environments, places of restricted access and complex geometries [1]. These challenges require the inspection techniques to be non-contact, couplant-free, to be able to have a very small footprint, and have the capability for endoscopic delivery. Laser Ultrasonics (LU) is a non-contact technique that is well suited for such conditions [2].

In laser ultrasonics, the ultrasound is generated using a pulsed laser and is detected by another laser, and hence the technique is completely remote and couplant free [3]. Conventional laser ultrasound suffers from poor signal-to-noise ratio (SNR) especially at the non destructive, thermoelastic regime. However, this drawback is offset by implementing phased arrays based on laser ultrasonics because phased arrays can focus and steer the ultrasound, improving the SNR [4].

In Laser Induced Phased Arrays (LIPAs), the ultrasonic generation and ultrasonic detection lasers are scanned over the component surface to acquire ultrasonic data from all possible generation/detection combinations, with respect to position. Each of the ultrasonic waveform is an element of the Full Matrix and this type of data acquisition is called the Full Matrix Capture (FMC) [5]. The FMC data recorded using LIPAs can be processed us-

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ing a variety of imaging algorithms. One of the most common imaging algorithms is the Total Focusing Method (TFM) [4, 6].

Previously, LIPAs have successfully imaged side drilled holes representing defects in components [7, 8]. However, the TFM images generated using LIPA data contained a region saturated by the surface acoustic wave (SAW). This region, termed as the SAW cross-talk region extends a few millimeters into the sample starting at the scan surface and hence masks any features/defects within this region. Hence any defect present within the SAW cross-talk region is possibly missed. It is critical to detect defects closer to the scan surface for applications such as additive manufacturing and welding, where the manufacturing process is monitored to identify and then rectify the defects formed on the surface or near the surface.

This work demonstrates near-surface defect detection within the SAW cross-talk region by suppressing the SAW mode. This can be achieved by 1) amplitude thresholding, 2) Phase Coherence Imaging and 3) Frequency-Wavenumber Filtering. The following section gives a brief background on laser ultrasonics, laser induced phased arrays, the data acquisition strategy, the imaging algorithm implemented and SAW cross-talk followed by experimental methods, results and conclusion.

BACKGROUND

Laser Ultrasonics

Laser ultrasonics use lasers for generation and detection of ultrasound. The ultrasonic generation is achieved by illuminating the surface of a test material using a short-pulsed laser. This causes localised heating and thermal expansion, which in turn creates ultrasonic waves that propagate the material [9]. Unlike transducers, LU generate broadband signals consisting of bulk (transverse and longitudinal) and surface waves. A defect within the material will act as a reflector of the laser-generated ultrasound, and the reflected ultrasonic energy can be detected as a surface displacement on the test material using a detection laser. The reflected beam is modulated by the surface displacement of the ultrasound. The modulated beam is demodulated inside an interferometric receiver to measure the ultrasonic displacement.

Laser Induced Phased Arrays and the Full Matrix Capture

Laser Induced Phased Arrays (LIPAs) are ultrasonic arrays synthesised in post-processing and based on laser ultrasonic principles [4, 6]. A LIPA consists of a set of generation and detection lasers which are illuminated onto the test material surface, and which are scanned in turn. The scanning continues until all combinations of generation and detection signals have been acquired. This is the Full Matrix Capture data acquisition method, which requires capture of signals from every combination of generation and detection elements in the ultrasonic array.

Total Focusing Method

The Total Focusing Method (TFM) is a delay and sum algorithm. When TFM is implemented, the cross-section of the sample to be imaged is discretised into a grid and the acquired signals from every element in the ultrasonic array are summed using the appropriate time delay. The summation is carried out for each generation-detection pair ultrasonic signal and hence, it uses the full amount of information for every point within the image grid. Due to its ability to focus at each point in the image grid and its ability to delay and sum the ultrasonic signals from each generation and detection pair, TFM allows for a significantly higher signal-to-noise ratio (SNR) than other ultrasonic imaging methods such as the plane B-scan and the focused B-scan [5].

Surface Acoustic Wave Cross-talk

In TFM imaging, cross-talk occurs when more than one wave mode arrives at the same time in an ultrasonic signal. In laser ultrasonics, surface acoustic waves (SAW), longitudinal waves and transverse waves are generated together. As SAWs are generated at a significantly higher amplitude than the other wave modes [10], the SAW wave mode overwhelms the other wave modes that arrive at the same time, hence termed as cross-talk. While SAWs travel a shorter path between the source and the receiver, in most metals, they propagate at a slower velocity than longitudinal and transverse waves. Hence, in a few ultrasonic signals, the SAW arrives at the same time as that of a bulk wave reflected from an internal feature, in spite of the shorter path traveled. When imaging with bulk waves, SAW cross-talk causes a region near the surface, on the image to be over-saturated by the high amplitude surface waves, making it challenging to detect near-surface defects using LIPAs.

METHODS

Experimental Setup

The experimental setup in figure 1 illustrates the beam path of the 1064 nm generation laser (red line) and the beam path of the 532 nm detection laser (green line). In this case the generation laser used had a pulse repetition rate of 1 KHz, a pulse width of 8 ns and an average power of 550 mW. A cylindrical lens is used to convert the collimated generation laser beam in to a line source approximately 1.5 mm tall and 0.25 mm wide. A pair of scanning mirrors are used to translate this generation line source across the surface of the sample.

The detection system used is a rough surface interferometer (Quartet from Sound & Bright). This system consists of a 780 mW continuous wave laser [11]. As shown in figure 1, this system consisted of a compact detection head that was installed on a pair of linear stages so that the detection beam could be translated across the surface of the sample. This detection beam was focused to a 0.15 mm diameter spot and aligned with the middle

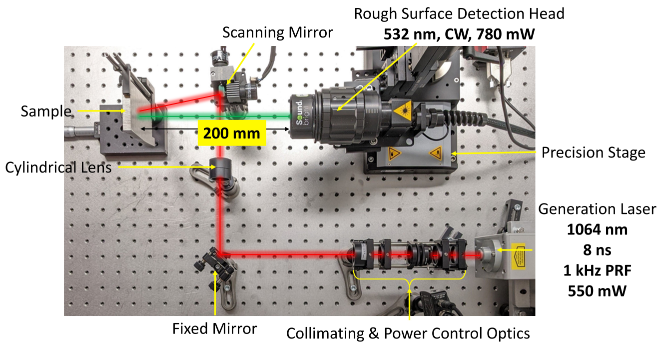


FIGURE 1. PHOTOGRAPH OF THE EXPERIMENTAL SETUP USED IN THE STUDY SHOWING THE LASER BEAM PATHS AND COMPONENTS USED.

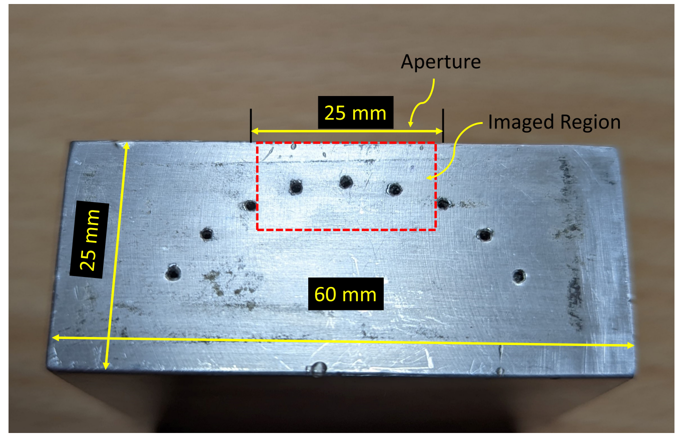


FIGURE 2. PHOTOGRAPH OF THE ALUMINIUM SAMPLE WITH RADIAL SIDE DRILLED HOLES OF 1MM DIAMETER USED FOR THE EXPERIMENTS.

of the ultrasonic generation line source, normal to the surface. The light reflected off the surface of the sample was collected using the detection head. The combination of the scanning mirrors for the generation and linear stage for the detection was used to collect the data for the FMC.

Sample and Test Parameters

The sample used for the experiments was an Aluminium block of dimensions 60 x 25 x 60 mm (Fig. 2). The sample has 9 side-drilled holes of diameter 1 mm arranged in a symmetrical radial distribution at angles of 0, 15, 45 and 60 degrees. The imaged region (see Fig. 2) was chosen to contain the three holes closer to the scan surface. The hole closest to the scan surface was at a depth of 4 mm from the scan surface. The surface of the sample where the scanning was performed had a machined finish.

A 161 element LIPA, with element spacing of 0.155 mm was synthesised, with the array center coinciding with the hole at the center. The acquired signals were averaged 16 times and a digital bandpass filtering with a center frequency of 6 MHz was performed before processing the signals using the TFM algorithm. The TFM image was processed using the shear wave mode.

SAW SUPPRESSION METHODS

Amplitude Thresholding

The thresholding method uses the simple approach of amplitude thresholding the ultrasonic signals. However, this technique has the disadvantage that any bulk wave signal from a possible reflector with an amplitude above the set threshold is thresholded and hence the SNR of the image is reduced.

Phase Coherence Imaging

Phase coherence imaging (PCI) [12, 13] uses phase in order to determine a weighing factor for each signal arriving from each pixel in an image. In contrast, in TFM, the amplitude of the signals are added up irrespective of whether they arrive in phase or out of phase. A simple approach of phase coherence imaging is to perform a deviation check on the phases of the signals. A bulk wave reflected from defects inside the bulk, will arrive with small phase differences between them. If this phase deviation is only a few degrees, then these signals have a higher probability of being reflections from actual defects and so a higher weighing factor is assigned to them. If a SAW cross-talk is present, which is due to a SAW arriving at the detector at the same time as the expected bulk wave, it will arrive significantly more out of phase compared to signals from the bulk. In this case the phase deviation is several degrees, and a lower weighing factor is assigned to them. Hence, PCI is implemented by calculating the weighing coherence factor which will then be multiplied to the TFM data to formulate the final image. Thus, the SAW cross-talk is suppressed when a TFM image is generated using a bulk wave mode.

Frequency-Wavenumber Filtering

The frequency-wavenumber filtering method considers the constant velocity curve of the SAW on the frequency-wavenumber (f-k) spectrum. Each row of the Full matrix provides the spatially sampled data to perform a two-dimensional fast Fourier transform to obtain the frequency-wavenumber spectrum of the data. SAW suppression is performed by creating a bandstop filter in the f-k domain and multiplying the filter with the f-k data . The filtered data is inverse transformed and populated in the Full matrix to be processed using the TFM algorithm.

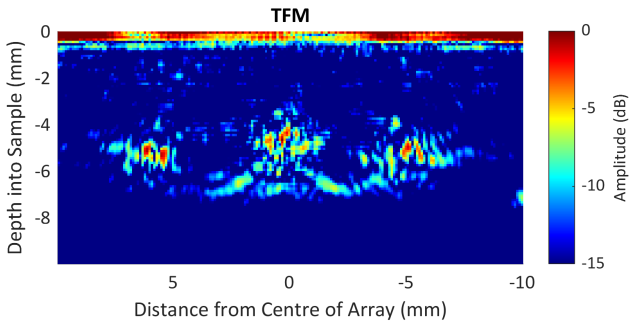


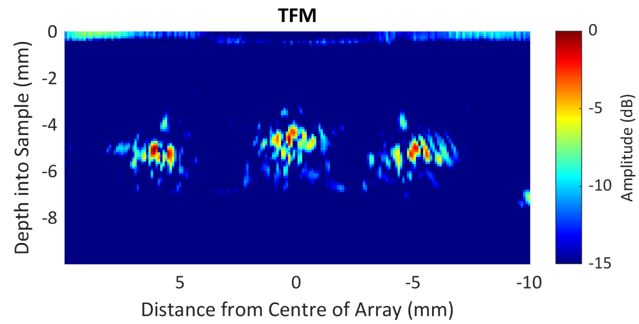
FIGURE 3. TFM IMAGE BASED ON SHEAR WAVE MODE FROM FULL MATRIX CAPTURE DATA CONTAINING 161 ELEMENTS AND PITCH OF 0.155 MM. THE ULTRASONIC SIGNALS WERE BANDPASS FILTERED AT 6 MHz PRIOR TO PROCESSING USING TFM. THE THREE HOLES CLOSER TO THE SCAN SURFACE ARE EMBEDDED WITHIN THE SAW CROSS-TALK.

RESULTS AND DISCUSSION

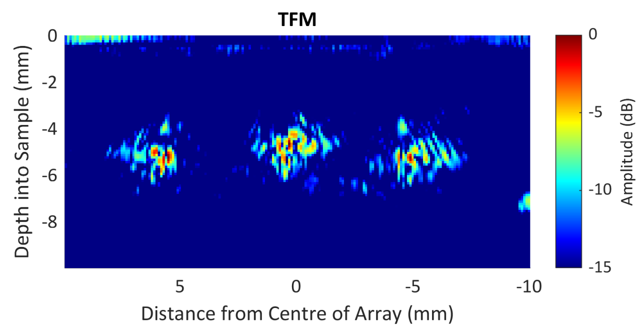
Figure 3 shows the original TFM image giving indications of the three holes. It is observed that the SAW cross talk is present up to a depth of 7 mm from the scan surface. Hence, any feature up to a depth of 7 mm is affected by the SAW cross-talk. The SAW cross-talk exhibits a semi-circular pattern on the TFM image. In figure 3, it can be observed that there are indications between (and below) the hole indications on the left and the center and also between (and below) the hole indications on the right and the center. In the case where the defects are not known beforehand, the SAW cross-talk can give rise to artifacts which can misrepresent a defect-free region as a defective region.

The three methods discussed in the previous section is used to suppress/remove the SAW cross-talk. Two parameters are used to assess the performance of the signal processing methods tested. The first parameter is the signal to noise ratio (SNR) and the second parameter is the array performance indicator (API). The array performance indicator is a useful metric for quantifying the TFM image resolution [5] and hence can be used to compare the performance of the same array for the different methods used. Ideally, the SNR should be high and the API should be low for better performance of the imaging method. The SNR and the API of the original TFM image was computed as 23.3 dB and 1.65 respectively.

Figure 4 shows the TFM image generated after amplitude thresholding at two different values. The threshold for each ultrasonic signal is based on the rms value of the same ultrasonic signal. Hence, for every ultrasonic signal there is a corresponding threshold value rather than a global threshold. Two instances of threshold are considered for this work. In the first instance, the threshold is set equal to the rms value of the ultrasonic signal (Fig. 4(a)). In the second instance, the threshold is set equal to half the rms value of the ultrasonic signal (Fig. 4(b)). It is observed that in both the cases the holes are reasonably separated from the SAW cross-talk and the artifacts have been suppressed. The SNR and API of the TFM image with threshold set at rms was computed as 22.9 dB and 1.65 respectively and of the TFM image with threshold set at 0.5 rms was computed as 26.1 dB and 1.69 respectively. It is to be noted that thresholding at rms has



(a)



(b)

FIGURE 4. TFM IMAGE OBTAINED AFTER THRESHOLDING THE ULTRASONIC SIGNALS AT (a) RMS; (b) 0.5 RMS.

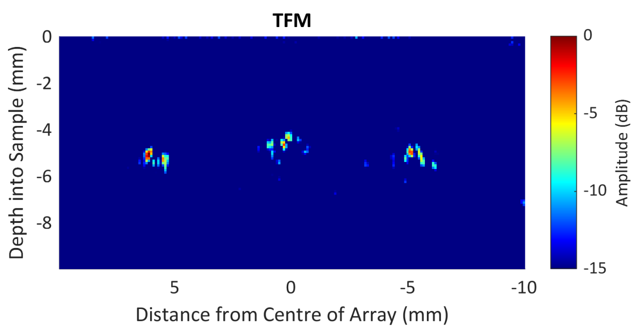


FIGURE 5. TFM IMAGE OBTAINED AFTER PERFORMING PHASE COHERENCE IMAGING.

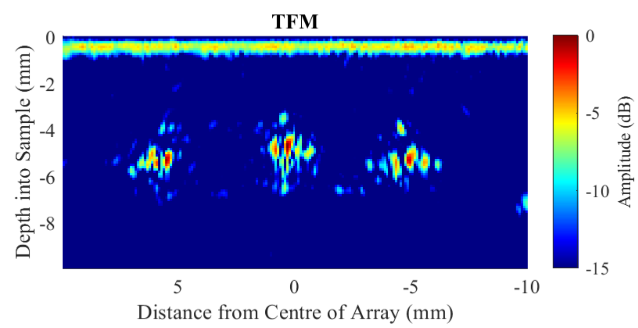


FIGURE 6. TFM IMAGE OBTAINED AFTER FREQUENCY-WAVENUMBER FILTERING.

reduced the SNR by 0.4 dB compared to the original TFM image whereas the API remains unchanged. However, for a threshold at 0.5 rms, the SNR and API has increased by 2.8 dB and 0.4 respectively.

Figure 5 shows the TFM image generated after phase coherence imaging. It is observed that the SAW cross-talk is completely suppressed and the only remaining indications are that of the three holes. It is to be noted that the PCI approach also removes the noise from the image and hence increases the SNR of the image. The SNR and the API of the PCI image was computed as 37.9 dB and 0.56 respectively. There is an increase in the SNR by 14.6 dB and a drop in API by 1.09 compared to the original TFM image.

Figure 6 shows the TFM image generated after frequency-wavenumber filtering. It is observed that the hole indications are reasonably separated from the SAW cross-talk and the artifacts have been suppressed, however, significant SAW-cross-talk exists closer to the scan surface to a depth of 1 mm. The SNR and API of the f-k filtered TFM image was computed as 23.5 dB and 1.39 respectively. It is to be noted that the increase in SNR compared to the original image is only 0.2 dB, however, the API has dropped by 0.26 which indicates a better array performance compared to the original TFM image.

Table 1 gives a summary of the SNR and API of the three methods tested. The three methods discussed (i.e. amplitude thresholding, phase coherence imaging and frequency-wavenumber filtering) have been able to suppress the SAW cross-talk in the TFM image making it possible to detect near-surface defects within the SAW cross-talk region.

TABLE 1. PERFORMANCE COMPARISON: AMPLITUDE THRESHOLDING, PHASE COHERENCE IMAGING AND FREQUENCY-WAVENUMBER FILTERING

Method	SNR (dB)	API
Original TFM image	23.3	1.65
Amplitude Thresholding at rms	22.9	1.65
Amplitude Thresholding at 0.5 rms	26.1	1.69
Phase Coherence Imaging	37.9	0.56
Frequency-Wavenumber Imaging	23.5	1.39

SUMMARY AND CONCLUSIONS

Surface Acoustic Wave cross-talk is present in TFM imaging when used with laser ultrasonic data. This is due to the fact that all wave modes are excited simultaneously in laser ultrasonics. Due to the high amplitude of SAW in laser ultrasonics, the SAW cross-talk adversely affects near-surface defect detection during bulk wave imaging.

Three signal processing methods (amplitude thresholding, phase coherence imaging and frequency-wavenumber filtering) were implemented on the LIPA ultrasonic data for SAW suppression. Two parameters (SNR and API) were used to compare the performance of the three methods used. It is observed that, of the three methods tested, the PCI method outperforms the other two methods by giving an improvement in SNR by 14.6 dB and a drop in API by 1.09 while successfully suppressing the SAW cross-talk.

In addition, we have demonstrated an ultrasonic testing method that is non-contact, capable of remote operation, does not use couplant, and capable of inspecting non-polished surfaces - all of which are features suited for harsh environments, for example welding or additive manufacturing. The optical scanning feature of this method can enable faster and automated inspection. The ultrasonic generation system can be fibre coupled making this method suited for places of restricted access. The whole setup can be fitted inside a box and can also be oriented vertically which makes it attractive for additive manufacturing and weld inspection – which highlights the portability of the method.

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