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Automated Implementation of Selective Matrix Capture using Laser-Induced Phased Arrays for Large Area Inspection

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Abstract: In-process non-destructive evaluation (NDE) is critical for the widespread adoption of additive manufacturing (AM) in high-value industries. Existing inspection methods struggle to cope with the high deposition rates and complex geometries from processes such as wire arc additive manufacturing (WAAM). Laser-induced phased arrays (LIPA) offer a remote, couplant-free ultrasonic inspection technique capable of imaging subsurface features in optically opaque components. While full matrix capture (FMC) has previously been used for data acquisition, its reliance on a large number of array elements results in prohibitively long inspection times. Selective matrix capture (SMC) is a novel data acquisition method designed to enhance inspection efficiency [1]. This paper presents the automation of SMC, a two-stage process that first locates the presence of a defect using a sparse array, then uses an optimised array to image and classify the defect.

Keywords: Selective Matrix Capture, Laser-Induced Phased Arrays, Non-Destructive Evaluation, Additive Manufacturing, Automated Inspection

Background

Ultrasonic testing (UT) is widely adopted across industries such as aerospace, civil engineering, and renewable energy for non-destructive evaluation [2]. It enables real-time, non-invasive imaging of internal structures, making it particularly valuable in safety-critical applications. With the advancement of manufacturing technologies, such as additive manufacturing (AM), there is a demand for high-resolution, in-process inspections [3]. Laser ultrasound (LU) has been identified as a technology that can address the requirements for in-process inspection because it is a remote, couplant-free technique suitable for extreme heat and restrictive access environments of manufacturing processes [4]. Laser-induced phased arrays (LIPAs) have a strong potential to address the shortcomings of conventional ultrasonic transducer arrays in such extreme environments, because they offer high-quality ultrasonic imaging.

LIPAs are based on the principle of laser ultrasonics, where the excitation and detection of ultrasound is done using lasers. The ultrasonic excitation beam from a pulsed laser generates ultrasound, and the ultrasonic detection beam of a continuous wave laser detects it. The two lasers are scanned on the surface of the inspected component, acquiring data in a series of positions, synthesising an array where the array generation and detection elements are the corresponding laser positions. Full-matrix capture (FMC) is a data acquisition methodology where ultrasonic signals from all possible combinations of generation and detection elements are captured. The FMC data are then used with a variety of imaging algorithms, including the total focusing method (TFM), which yields high-quality ultrasonic imaging, and this has been demonstrated with LIPAs [5]. The mechanical scanning of the laser beams introduces a long data acquisition time, which compromises the implementation of LIPAs for in-process inspection.

Lukacs et al. have proposed a novel data acquisition method referred to as selective matrix capture (SMC) [1]. SMC is an adaptive methodology based on the concept that not all signals from FMC are information-rich, making it ineffective to acquire signals uniformly across the inspected region. Instead, SMC aims to capture only information-rich signals, without compromising ultrasonic imaging quality using a two-stage data acquisition process. The first stage is the agnostic stage, where the location or absence of any region of interest (ROI) is unknown. A sparse LIPA is synthesised with the minimum amount of array elements required to provide a reliable answer to the following two questions: a) Is there an ROI? and if the answer is “yes”, then b) where is the ROI? The first stage yields a series of low-resolution ultrasonic images, and if an ROI has not been identified, the scanning process ends. If an ROI is identified, then SMC enters the second stage: the optimisation stage.

During the second stage, the information for the location of the ROI is used to synthesise a new LIPA with optimum element configuration (array element number, distribution and aperture) to inspect the ROI. Two array optimisation strategies have already been suggested in the literature [1].

SMC has been shown to reduce the time for data acquisition by an order of magnitude [1]. The SMC with LIPAs is well suited for automation and consequently for large area inspection: the lasers can be mounted onto robotic platforms and inspection can be achieved through automated scanning of fibre-coupled beams. For full automation, a robust criterion is needed to translate the inspection from the first to the second stage of the SMC, and one such criterion has been proposed to be the pixel intensity distribution of the low-resolution ultrasonic images resulting from the first stage of FMC. Previously, this criterion was used while the sparsity of the synthesised LIPA was iteratively decreased, until an ROI was found. Therefore, the criterion was designed to signal the presence of an ROI, but was not able to declare a region defect-free. It is important for a fully automated SMC-based system that the methodology is developed to ensure reliability that the region is defect-free when sparse arrays are used for imaging. The present paper addresses this point by introducing a pre-inspection study of the probability of detection (POD) and the false positive rate (FPR) to identify a suitable degree of array sparsity for a reliable threshold for the shift of the pixel intensity distribution that would signal a ROI. This study is based on the worst-case scenario for defect detection, identifying the minimum defect size expected at the largest depth required for inspection. These parameters are dependent on the NDE application and can be adapted accordingly.

SMC Methodology

The SMC data acquisition methodology has been described in the literature [1]. This section presents: a) the pixel intensity distribution as a criterion for transitioning to the second stage of the SMC; b) the pre-inspection study, to identify the parameters for automated implementation of the SMC.

Pixel intensity distribution criterion

The pixel intensity distribution criterion is based on the assumption that the TFM image of an area in the absence of any defects will have a certain pixel intensity distribution, which is due to incoherent noise only (e.g. due to electric or instrumentation noise). When the imaged data has coherent signals from a defect, above the noise floor, then these signals will correspond to TFM pixels with intensity higher than the noise pixel intensity distribution. Therefore, these pixels will cause a shift in the characteristic pixel intensity distribution of the noise floor. Identifying the location of the pixels that cause the shift leads to the identification of the ROI. On the contrary, if no defect is present (and there is no other source of coherent noise, such as artefacts from reflections or undesired ultrasonic modes), there will not be a shift of the characteristic pixel intensity distribution of the noise floor. The peak of the pixel intensity distribution is a convenient point of reference to measure this shift. If this peak shifts beyond a predefined threshold, then it signals the presence of an ROI. Otherwise, the area is considered defect-free. The following study was conducted to identify this threshold.

Pre-inspection study

The pre-inspection study was based on a worst-case NDE inspection scenario: the minimum size of defect expected to be reliably detected was set to be a 1 mm diameter side drilled hole (SDH), which is an omnidirectional scatterer, optimal for detection with a 1D LIPA. The inspected component was a rectangular aluminium sample with a total thickness/depth of 38 mm. The SDH was located at the maximum targeted depth of 13 mm below the surface. A total of 123 LIPAs with 64 elements and 0.4 mm pitch were synthesised across the sample surface, and the full matrix was captured. The aperture (25.6 mm) of each 64-element LIPA was shifted relative to the next by 0.4 mm (with a 98.4% overlap), and the total area covered by LIPA was 74.4 mm. The SDH was located at the centre of this scanned region. These data sets were then undersampled and used to synthesise LIPAs of 32, 16 and 8 elements of the same aperture (25.6 mm) and pitch of 0.8 mm, 1.2 mm and 1.6 mm, respectively, to identify the minimum number of array elements for a sparse LIPA, suitable for the first stage of the SMC. TFM images using the shear-shear wave mode arrival, with a digital filter centred at 4 MHz and a bandwidth of 100%, were produced from each dataset [4]. The shift of the pixel intensity distributions of the TFM images was analysed with respect to the ground truth (presence or absence of the SDH) as shown in Fig. 1. Then, the POD and FPR were calculated using the method shown in the literature [6], and the results are shown in Tab. 1 and Tab. 2.

Discussion

The presence of the SDH (ground truth) is expected in TFM images from arrays No. 61-123. Fig. 1 shows that the peak of the noise intensity distribution for arrays No. 61-123, with 64 and 32 elements, is at <-24 dB, but the peak in the noise remains >-24 dB for all arrays with 16 and 8 elements. The peak of

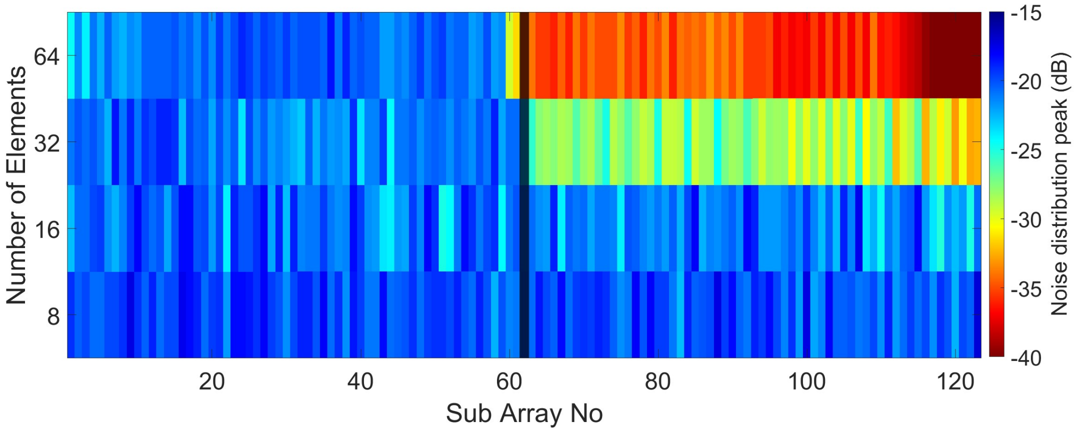

Fig. 1: Noise distribution from 123 arrays with an increasing number of elements. The defect is known to be present in all TFM images from arrays No. 61-123 (to the right of the black vertical line)

the noise distribution does not demonstrate a shift for the arrays No. 1-60, with 64, 32, 16 and 8 elements, in agreement with the ground truth, as the SDH is absent in these TFM images.

The results in Tab. 1 and Tab. 2, show how a 32-element array and a threshold of -24 dB correspond to a POD of 97% and FPR of 2%. These were seen to be the optimal parameters and were used in the automated first stage of the SMC.

Tab. 1: Experimentally obtained, FPR calculated for a range of thresholds. The highlighted value was chosen for 1^st^ stage of SMC.

Threshold	Number of Elements			
	8	**16**	**32**	**64**
-16	100%	100%	100%	100%
-18	93%	95%	100%	100%
-20	40%	60%	80%	72%
-22	2%	20%	18%	8%
-24	0%	7%	2%	3%
-26	0%	0%	0%	2%
-28	0%	0%	0%	2%
-30	0%	0%	0%	0%

Automated implementation of SMC

Using the parameters identified, five sparse 32-element LIPAs with an aperture of 25.6 mm, pitch of 0.8 mm and overlap of 2.3% (0.6 mm) were synthesised across the surface of the sample as shown in Fig. 2. A total surface area of 125 mm was scanned. A known defect of 1 mm diameter SDH was located at the centre of the scanned area, 13 mm below the surface. In accordance with the ground truth, the pixel intensity distribution of LIPA No. 3 crossed the pre-determined -24 dB threshold, indicating the presence of a ROI, while LIPAs 1,2,4 and 5 did not present a sufficient shift in the pixel intensity distribution as shown in Fig. 3, indicating defect-free regions. In addition, the location of the ROI was successfully localised based on the corresponding TFM pixel presenting the maximum pixel intensity in the distribution.

Tab. 2: Experimentally obtained POD calculated for a range of thresholds. The highlighted value was chosen for 1^st^ stage of SMC.

Threshold	Number of Elements			
	8	**16**	**32**	**64**
-16	100%	100%	100%	100%
-18	90%	94%	100%	100%
-20	51%	86%	100%	100%
-22	5%	24%	98%	100%
-24	0%	8%	97%	100%
-26	0%	0%	86%	100%
-28	0%	0%	54%	100%
-30	0%	0%	14%	100%

Conclusion

This study demonstrated a data-driven approach for calibrating sparse LIPAs as part of the first stage of SMC. An automated methodology was developed and validated through a pre-inspection study, identifying the minimum array configuration required to reliably detect a 1 mm SDH at a depth of up to 13 mm in aluminium. A 32-element sparse array with a -24 dB threshold was used for the automated first stage of the SMC. This threshold enabled the system to distinguish between defect-present and defect-free regions. The use of five, sparse 32-element LIPAs in the large area

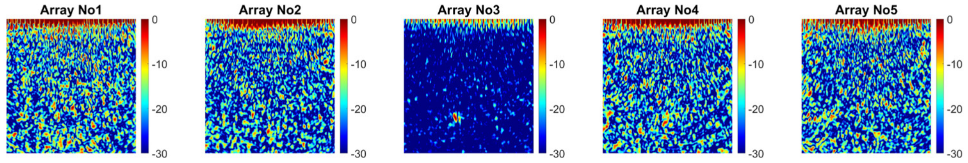

Fig. 2: Five TFM images obtained using 32-element arrays, showing how no ROI were present in Arrays No. 1,2,4 and 5. Array No. 3 shows the presence of a small ROI at the bottom left corner.

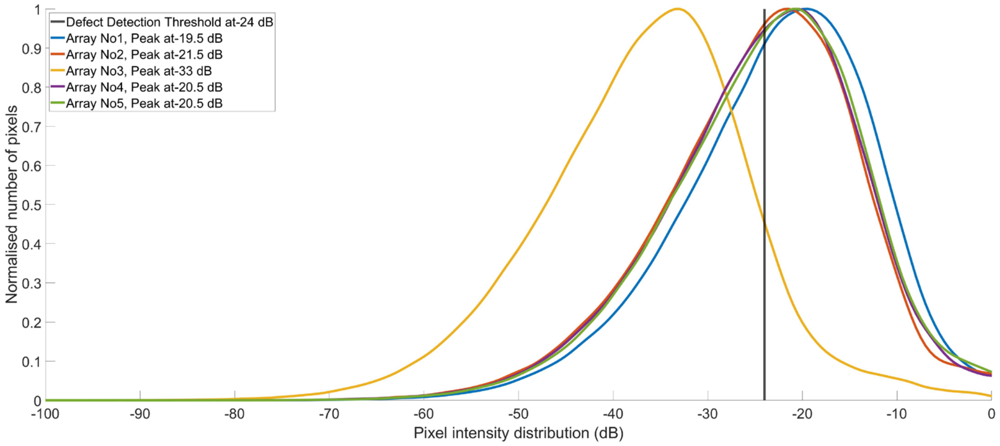

Fig. 3: Graphs showing the pixel intensity distributions for the five arrays. Array No. 3 crosses the pre-determined threshold of -24 dB.

inspection corresponded to a data acquisition time of 15 minutes, compared to a data acquisition time of just over an hour for five, dense 64-element LIPAs, corresponding to 75% faster data acquisition. The resulting ROI can then be used to guide the design of optimised stage-two arrays, forming the basis for a fully automated SMC workflow.

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