Calibration of Ultrasonic Phased Arrays for Industrial Applications

M. Ingram*, A. Gachagan*, A. J. Mulholland*, A. Nordon*, J. Dziewierz*, M. Hegarty†, E. Becker†
*University of Strathclyde, Glasgow, UK
†BP Chemicals Ltd, Hull, UK
E-mail: m.ingram@strath.ac.uk

Abstract—This paper investigates the consistency in phased array element performance by extracting information from the Full Matrix Capture (FMC) of a reflection from a planar interface. The purpose of this work is to generate a robust methodology for tracking phased array performance over time, therefore, ensuring the reliability of measured data. To achieve this, a calibration method has been developed that quantifies the pulse length, sensitivity, bandwidth and phase error for each element in the array. This paper will highlight the variation across individual array elements and the experimental variation across FMC replicates. Finally, to illustrate the impact of the element performance variation, the phase error is included within the Total Focussing Method imaging algorithm, resulting in an 8% increase in ultrasonic image resolution.

Keywords—calibration; linear phased array; ultrasound, FMC, TFM.

I. INTRODUCTION AND MOTIVATION

Ultrasonic phased arrays are well-established in the field of non-destructive evaluation (NDE) for imaging into optically opaque structures, for example, these images can be used for the identification and characterisation of defects in steel [1]. In recent years, industrial uptake of phased arrays has increased, because the precise positioning of the active array elements permits accurate imaging of the load material.

This technology is based on an underlying assumption that the hardware, comprising of the phased array and the Phased Array Controller (PAC), behave as designed and that experimental error is negligible. Therefore to ensure reliability in measured data, it is important to understand how the array performance varies from its design specification, and in doing so, provide an understanding of the uncertainty in NDE measurements.

In this paper, the maximum quantity of data is obtained for the phased array by acquiring time-domain signals (A-scans) corresponding to every transmit ($T_x$)-receive ($R_x$) element combination. This approach is known Full Matrix Capture (FMC) [2]. In this paper, a method for linear array calibration has been developed that takes multiple replicates of the FMC of a back wall reflection as an input and calculates the pulse length, sensitivity, bandwidth and phase error for each element in the array. For this method, the thickness and wave speed in a calibration sample block are known.

Using the FMC data to perform the calibration enables the results to be based purely on the integrity of the hardware, because it decouples error associated with the hardware from that in the beam forming delays [3]. Previously, array calibration has assessed purely the consistency of element performance in terms of the variation between elements [3]. In this paper, the spread in element performance due to positional error has also been investigated by acquiring multiple FMC replicates of the sample under identical experimental conditions.

II. METHODOLOGY

A. Data Acquisition

The procedure for array calibration is demonstrated using a 128 element linear phased array (Vermon, France), where the number of transmitting elements $nT_x$ is identical to the number of receiving elements $nR_x$, and these were controlled using the FIMarkbox (Diagnostic Sonar Ltd, UK). The calibration method was applied to linear arrays across a frequency range of 1 - 10 MHz. Results from a 5 MHz device are shown in this paper. The array was mounted onto a glass test block 50 mm thick, as shown in Fig. 1. A crown glass sample was chosen because it permits visual inspection, reducing the uncertainty of there not being a clear path to the back wall. Water was used to couple the ultrasonic path between the array and the sample, and the sample was placed on two blocks so that the back wall had an air load, creating a high mechanical impedance mismatch, leading to a large reflection coefficient. The wave speed in the sample was measured as 5680 $\text{m s}^{-1}$ and this was assumed to be homogeneous throughout the sample. Using all available elements, FMC data were acquired five times where the array was unmounted, cleaned and remounted in the same position between each FMC replicate. The array was removed between FMC replicates to establish a realistic degree of experimental error due to the operator; such an error is typically assumed to be negligible.

B. Signal Processing

The signal processing of the FMC data is outlined below, which was performed in MATLAB (R2016b, The MathWorks Inc). Before estimating the array characteristics, the part of

![Fig. 1: Apparatus for linear array calibration.](image-url)
the time domain signal that contained the interaction of the wave with the back wall was isolated for each signal. This was achieved by plotting every A-Scan from each FMC replicate on one plot and identifying the beginning and end points of interest. Therefore, interference from the initial main bang or any lateral wave modes across the array were minimised. It should be noted that for the array performance characteristics, only the subset of the FMC data pertaining to the same element transmitting and receiving (the diagonal of the FMC data set) has been used; this corresponds to a vertical ray path for the propagating wave. These results have the lowest degree of uncertainty because error associated with discretisation of the array element locations is minimised [4].

Prior to estimation of the array performance characteristics the following peak detection method was performed for each $T_x$-$R_e$ combination in the FMC data subset and for each sample replicate. First the signals were normalised relative to the voltage and gain of the PAC. Then, these signals were filtered to remove low-frequency noise using a zero-phase highpass Butterworth filter of order eight. Accurate knowledge of the time-of-flight (TOF) is critical in NDE because the time-domain FMC data are used to generate Total Focussing Method (TFM) [2] images of an inspected sample. So, for the time-domain array performance characteristics the Hilbert Transform was applied to the filtered signals and the absolute value plotted to generate a clear peak corresponding to the back wall as shown in Fig. 2, where a single A-Scan is shown in the region of interest. The time-domain array characteristics were then estimated from these post-processed A-scans.

**Sensitivity:** The sensitivity ($V_o/V_i$) of each element corresponds to the ratio between the the detected signal voltage ($V_o$) at the peak maximum and the input signal voltage ($V_i$).

**Pulse Length:** The time difference between the first and last data points that were greater than -3 dB was defined as the pulse length as shown in Fig. 2.

**Phase:** The TOF was given by the time corresponding to the peak maximum in the post-processed A-Scans. Given that the straight line path to the back wall is known, the theoretical TOF can be calculated for the path length between each $T_x$-$R_e$ combination. The error in phase between the theoretical and observed peak times can then be determined by taking the difference between the two. In addition, the relative phase error was calculated as the ratio of the phase error difference to the theoretical TOF. Typical FMC data acquisition assumes the phase of the firing elements corresponds to a given start time that is the same for all elements, however given that a phase error is observed, this is not exactly true.

**Bandwidth:** To estimate the frequency bandwidth of each element, the filtered signals were transformed into the frequency domain. The first ($f_1$) and last ($f_2$) points of the peak greater than -3 dB were used to indicate the beginning and end points of the frequency domain response of the back wall reflection, shown in Fig. 3. Note, the glass block frequency-dependent attenuation was ignored for this experiment; this assumption could be verified by executing the data acquisition over two different paths. The bandwidth for a given element was then determined as the percentage of the frequency difference ($f_2 - f_1$) relative to the centre frequency ($f_{centre}$), where the centre frequency was determined as the midpoint between the first and last points greater than -3 dB.

### III. Results

For the linear array calibrated in this paper, the sensitivity, pulse length, phase and bandwidth were estimated for each element in each data set replicate. The mean and standard deviation across the five data sets were then determined for each array performance parameter, outlined in Fig. 4. The results show there is a high degree of consistency across the elements in every performance characteristic. However, element 100 is consistently observed as an outlier in each performance characteristic and across the sample replicates, indicated by the low spread in performance characteristic values for this element. To validate that this element is an outlier and is not in fact an artefact of the PAC, the same procedure was performed under the same conditions using another PAC (Dynaray, Zetec, Canada), this showed that the same element consistently under performs. Following this secondary assessment, this element was deemed to be an inactive element. This highlights the potential of this array calibration tool to track the deterioration of phased array performance over time.

Finally, to illustrate the impact of the element variation, the relative phase error has been included within the TFM imaging algorithm. A single FMC data set was acquired from a steel NDE test block with a 1 mm diameter side-drilled hole using the phased array calibrated above. The relative phase error corresponding to each transmitting element was used to weight the time delays in the TFM imaging algorithm. By weighting the time delays with the relative phase error, uncertainty created by different wave speeds in the calibration and test blocks is removed. The result of applying this phase-weighted TFM algorithm to the FMC data set are shown in Fig. 5, where the actual location of the side-drilled hole is indicated by the white circle. The improvement in image quality is evident.
resolution is seen as an increase in the positional accuracy of the defect, which is of the order of a radius of this side-drilled hole. For NDE applications, this could lead to a significant improvement of the TFM images used for locating defects. To quantify the improvement in image resolution, the area of the side-drilled hole (estimated from pixels greater than -6 dB) expressed as a percentage of its actual area shows that an improvement from 29.3% to 37.3% is observed in this case. Although this is only a small improvement, this is partly because the array has not deteriorated significantly from its initial state. This tool will prove more useful in the future after the array has deteriorated further from its current state, permitting correction for this deterioration. However, the degree of image enhancement varies depending on the array and PAC.

IV. CONCLUSION

An easy to use calibration tool for ultrasonic linear arrays has been developed, which requires two user inputs alongside FMC data of a back wall reflection. The results from this calibration show a clear indication of inactive elements and illustrate the spread in the performance across the array in terms of sensitivity, pulse length, phase and bandwidth. The variation in phase for each element was included in the TFM imaging algorithm showing an 8% increase in image resolution. The impact of this calibration tool will be most useful for applications requiring consistency of measured data and for improving image resolution, for example in biomedical diagnosis and defect detection in NDE.

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