A CALIBRATION ROUTINE FOR FULL MATRIX CAPTURE (FMC)

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ABSTRACT
When phased array probes are used for ultrasonic inspection it is necessary to ensure that consistent performance is achieved. If Full Matrix Capture (FMC) is used to record inspection data the most appropriate way of doing this is to assess transducer performance on an element by element basis rather than assess a specific beam. The rationale for this approach is that FMC allows any beam to be synthetically produced, including the re-analysis of old inspection data using different beams or imaging algorithms. To take advantage of this flexibility requires a method of probe calibration not coupled with a particular beam.

This paper presents the development of a calibration routine based on this philosophy, including the selection of acceptable limits for element performance. The routine incorporates probe checks, distance amplitude correction, and the setting of inspection sensitivity.

INTRODUCTION
Phased array technology is now widely used across industries for Non-Destructive Evaluation (NDE) [Error! Reference source not found., Error! Reference source not found.]. However, it is currently standard practice to use arrays to emulate the performance of a number of monolithic transducers. Calibration is performed by carrying out direct measurement on the beams produced by the array, using standard reflectors to ensure beam integrity. These procedures have been inherited from standards written for monolithic transducers, e.g. BSEN 12668:2-2010 [Error! Reference source not found.], as there are currently no completed standards for the calibration of array probes agreed by the British, European, or American national standards committees. As there are no centrally agreed standards in place the calibration procedures used for arrays vary from operator to operator and may include the calibration of a single beam for each array, the calibration of the lowest and highest angled beams the array is required to produce, the calibration of every beam, or something in between. The development of Full Matrix Capture (FMC) technology and associated methods, e.g. the Total Focusing Method (TFM) [Error! Reference source not found.], makes this approach impractical as one of the main benefits of FMC is that data can be processed at any time after data has been collected. Using the existing approach would mean that the usable results from an inspection would be limited to those beams calibrated at the beginning of an inspection. Instead a calibration procedure is proposed that measures the performance of each element of an array to ensure it is within a certain tolerance. By ensuring each element is functioning within specification inspection performance can be guaranteed when beam forming is subsequently carried out.

This paper introduces a probe check procedure for phased arrays based on measurements of individual element performance, a Distance Amplitude Correction (DAC) methodology for FMC, and experimental examples.

PROBE CHECK PROCEDURE
The checking and calibration of single element probes is performed using calibration reflectors to measure beam performance. This approach is inappropriate for phased arrays used with FMC. The approach recommended for phased arrays recording FMC data instead focuses on the integrity of the transducer. Practically this can be achieved by monitoring the parameters of the array elements that dictate their
performance. Analysis of array systems shows that performance is dictated by the following parameters: relative sensitivity, relative phase, and element directivity pattern.

The directivity pattern of a transducer is a function of the element shape and frequency, and experimental measurements have demonstrated that there is very little variation between elements in the same array regardless of relative sensitivity. Hence, by measuring the sensitivity, relative phase (or firing delay) of each element in an array, and monitoring the number of non-functioning (dead) element in the array it is possible to ensure that the array is functioning correctly without time consuming beam measurements being carried out. For this approach to be adopted acceptance criteria need to be decided upon based on evidence of the effects that they have on the ultrasonic field produced by an array. Other aspects of equipment calibration such as time base and amplifier linearity checks would be conducted using methods applied to single element transducers [Error! Reference source not found., Error! Reference source not found.].

Experimental measurements using 10 arrays have been carried out by placing the arrays on 60 mm slip gauges which are sat on a high precision granite surface plate, and placing the whole assembly in immersion. Pulse-echo signals are recorded on each element and by comparison of the maximum recorded amplitude and zero crossing point of each element the relative sensitivity and firing delay of each element is recorded. Each array was measured three times apart from two arrays that were measured 20 times, in order to quantify the systematic error of the system when measuring firing delay. Figure 1 present a diagram of the experimental setup, and an example time trace. The results of the experimental trials are shown in Figure 2. The two histograms show the variation in relative sensitivity and firing delay across all the arrays. Analysis of the systematic error of the system showed that it is less than the error due to the sample period, +/- 5 ns at 100 MHz.

Figure 1. The experimental arrangement used to measure element performance a) two elements excited above a granite reflector b) the resulting pulse-echo time traces.
A specification for element performance

The influence of element performance has been investigated via the use of a bespoke array beam model to perform Monte Carlo simulations. The system is modelled in 2D plain strain. The array is modelled using Huygens’ Principle and ray tracing is used to compute the contribution of each element to the ultrasonic field in the inspection material. A more detailed discussion of the model can be found in Duxbury et al [Error! Reference source not found.]. The Monte Carlo simulations were performed by using a normally distributed random number generator to assign variations to element sensitivity, and phase. The maximum change in each parameter was fixed, referred to as the Maximum Variation (Mv), and 1000 realisations of the model were computed to form a simulation group. A number of simulation groups were produced by using a range of Mv values. In each case a simulation is performed using a uniform array in order to establish baseline performance for each model configuration.

Variation in the directivity pattern of the array elements was not investigated as experimental measurements using a number of arrays has shown that this parameter exhibits little variation and will not vary with time. The effect of dead elements was investigated using a non-statistical approach, as the occurrence of a contiguous group of dead elements was found to be the worst case. Instead, for each model configuration simulations were performed with an increasing number of contiguous dead elements, and in each case every possible location of the dead elements in the array was tested, and the worst case recorded.

The model was used to simulate three different beams using a variety of arrays, steering angles, focusing, and transverse and longitudinal beams; details can be seen in Figure 3. The model was used to calculate the ultrasonic field along a line of computation points normal to the beam axis. This produces a variation in amplitude commonly referred to as an echodynamic. All simulations were repeated for three different array centre frequencies; details can be seen in Table 1.

The echodynamics produced from the simulations have been analysed on the basis of the largest amplitude unwanted feature, or artefact, introduced as a result of variation in element performance. Examples of beam artefacts include enlarged or additional side lobes, and raising of the noise floor of the echodynamic. The analysis is completed by comparing each echodynamic with the baseline echodynamic for that model configuration. This process is explained graphically in Figure 4, a). The results from all simulation groups are then plotted using the standard deviation of the varied element parameter across the
whole array and the maximum amplitude change, referred to as background level. An example result for firing delay is presented in Figure 4, b). Each colour in the scatter plot represents a different simulation group. A profile is then fitted to the results by plotting the mean standard deviation of each simulation group against the 99% confidence interval of the groups cumulative distribution function calculated using the Kaplan-Meier estimate \[ \text{Error! Reference source not found.}, \text{Error! Reference source not found.}, \] including a confidence bound \[ \text{Error! Reference source not found.}. \] In practise this results in less than 1% of the outlying results being excluded.

To decide upon a specification for element properties the worst tolerable deterioration in beam quality must be decided upon. A minimum amplitude separation of 8 dB in the free field, or 16 dB pulse echo, between any beam artefact and the main beam has been selected. This approach is inline with the methodology outlined in BSEN 12668-2:2010 \[ \text{Error! Reference source not found.}. \] for single element probes. This standard requires an amplitude separation between the main beam and side lobes of 10 dB in the free field.

![Figure 3. Details of the model configurations used for the Monte Carlo Simulations](image)

**Table 1.** Details of the array specifications used during the simulations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array centre frequency (MHz)</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
</tr>
<tr>
<td>Bandwidth (%)</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Element pitch (mm)</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td>Element gap (mm)</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
</tr>
</tbody>
</table>

![Comparison of echodynamics limited to this region](image)

![Background level (dB)](image)
Table 2. A summary of the limits of maximum variation in element parameters before the background level reaches 4 dB for the three beam types: plane zero degree longitudinal (0LP), focused zero degree longitudinal (0L), and focused 45 degree transverse (45T).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Beam</th>
<th>Centre frequency (MHz)</th>
<th>2.0</th>
<th>5.0</th>
<th>7.5</th>
<th>Mean</th>
</tr>
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<tbody>
<tr>
<td>Relative sensitivity</td>
<td>0LP</td>
<td>0.74</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0L</td>
<td>&gt; 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45T</td>
<td>&gt; 1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Dead elements (% of aperture)</td>
<td>0LP</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0L</td>
<td>14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45T</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Firing delay: (t_0) (ns)</td>
<td>0LP</td>
<td>50</td>
<td>19</td>
<td>13</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0L</td>
<td>95</td>
<td>33</td>
<td>26</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>45T</td>
<td>93</td>
<td>36</td>
<td>24</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Firing delay: (Bt_0) (×10^{-3})</td>
<td>0LP</td>
<td>49</td>
<td>49</td>
<td>49</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0L</td>
<td>95</td>
<td>82</td>
<td>96</td>
<td>91</td>
<td>89</td>
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<td></td>
<td>45T</td>
<td>93</td>
<td>90</td>
<td>88</td>
<td>90</td>
<td>90</td>
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</tbody>
</table>

The results from the Monte Carlo simulations have been analysed using a reference amplitude that is 12 dB lower than the peak amplitude of the main beam. This means that there is an 8 dB amplitude separation between artefacts and main beam when the background level reaches 4 dB. The profile fitted to all the simulation groups is then linearly interpolated to predict a maximum variation in each parameter that results in a 4 dB change. The results from analysing all model configurations are shown in Table 2.

The results for element sensitivity show that an array generating focused beams is tolerant to any variation in element sensitivity, but plane beams are limited to a change of 0.74. These values are extreme relative to the experimental results presented earlier, and such a large change in element sensitivity is likely to be indicative of a faulty element. Instead a limit of 50 % variation in relative sensitivity is suggested; this limit is significantly higher than those suggested previously. Elements outside of the 50 % limit are considered dead.

The dead element results again shows that plane beams have a much lower tolerance to variations in element performance than focused beams. This appears intuitive as plane beams are always reliant on a small number of elements to generate each part of the wave front, while focused beams use all elements to resolve the beam at a particular point in space. As a result a limit of 9 % dead elements in an aperture is suggested.

The results for firing delay have been expressed as the maximum possible firing delay between each element and the aperture mean. The limit decreases with increasing transducer centre frequency, and the limit for the plane beam is much lower than the focused beam. The results are also expressed as the product of transducer bandwidth and firing delay (\(Bt_0\)); this produces a dimensionless parameter proposed by Steinberg. This parameter should remain constant across different centre frequencies, as Steinberg suggests that the sensitivity of an array system to phased changes is defined by the range of frequencies that the system operates over. The results demonstrate that this is true for the range of frequencies considered, and the value of \(Bt_0\) should be above 0.05 and 0.09 for plane and focused beams respectively.
INSPECTION CALIBRATION

To maintain the flexibility of FMC inspection it is necessary to adopt an alternative approach to inspection calibration. In this approach a detailed FMC scan of a suitable calibration test-piece containing a series of known reflectors is completed to fully characterise the transducer used during the inspection. Each inspection beam used in the actual testing is then calibrated in post-processing. This process allows all of the standard phased array and single element inspection techniques typically used to be reproduced using FMC data acquisition. It also allows appropriate calibration of more novel inspection techniques to be completed. This inspection calibration procedure includes the production of Distance Amplitude Correction (DAC) curves. This capability is demonstrated by the results provided in Figure 5. This data has been produced using a 48 element, 1.25 mm pitch, 2 MHz array mounted on a ~22º Rexolite wedge. A 10 element aperture generating a 45º plane shear wave has been mechanically scanned along the top surface (Z = 0 mm) of a stainless steel calibration block containing 4 Side Drilled Holes (SDHs) at different depths. The data is displayed in the British Energy/EDF software Graphical Ultrasonic Inspection Data Evaluation (GUIDE) [Error! Reference source not found.], and the SDH locations have been superimposed on the data. The four direct shear wave responses from the SDH targets are labelled in Figure 5; along with a fifth signal which is due to a skip shear-shear wave reflection from the underside of the deepest hole. In Figure 5 (a) signals from all four SDH targets are clearly observed, but the amplitude of the individual responses varies with depth. In Figure 5 (b) DAC is applied to the data and the three deepest SDH responses appear at the same amplitude; the signal from the first SDH is partially masked by the front wall echo.

This method is entirely automated and allows a separate DAC curve to be recorded for each aperture location in the array. This allows B-scans formed via the use of electronic scanning to be presented at constant sensitivity. The amplitude of the SDH reflections is also used to set inspection sensitivity. In the image presented in Figure 5 b) the colour scale is plotted relative to amplitude of the shallowest SDH response.

The algorithm can also extract DAC curves for mode converted beams as well as direct beams. For example, it is common practise to use high angle compression wave probes to inspect austenitic welds. The probe produces a high angle longitudinal wave that is used to scan the weld volume and far fusion face, and a transverse wave is also generated. The transverse wave mode converts to a compression wave at the backwall of the component, and can be used to scan the near fusion face of the weld. If a DAC curve can be recorded for both the direct and mode converted compression waves both waves can be imaged at equal sensitivity. Figure 6 shows how the two DAC curves are measured, and displays two example DAC curves. A separate DAC curve is produced for each aperture location in the array, and the mean and maximum amplitude values from each SDH are plotted.
Figure 5. FMC Inspection of calibration block containing four SDH defects using a conventional 48 element array generating a plane 45° shear wave. A 10 element aperture has been mechanically scanned along the calibration block (left to right in the images), (a) without DAC, and (b) with DAC applied. All data is plotted by GUIDE [Error! Reference source not found.] using a RGB colour scale with a 26 dB dynamic range.

Figure 6. a) The method used to record direct and mode converted DAC curves b) example DAC curves for a direct and mode converted 65 degree longitudinal beams (65L and 65TL respectively). The DAC curves were recorded using 3 mm SDHs and a 2 MHz 128 element array in immersion utilising 20 elements.

Example experimental result

The DAC algorithm can be demonstrated using FMC data recorded on a welded test piece containing an artificial lack of fusion defect. A photograph of the test piece is shown in Figure 7, and demonstrates the primary detection techniques for the defect using a direct and mode converted 65 degree longitudinal beam (65L and 65TL respectively). The defect is nominally 12 × 8 mm (length × through wall extent). Scanned FMC data has also been collected on a calibration block, and DACs recorded in line with the method described in the previous section.

FMC data has been collected using a 2 MHz 0.75 mm pitch 128 element array in immersion,
positioned with the first element 8 mm above the top surface of the test piece with the array inclined at 7 degrees. 40 elements in the array have been used to generate the 65L and 65TL beams using the Almost Total Focusing Method (ATFM) [Error! Reference source not found.]. This method focuses the beam in transmit and receive at a number of depths in the image, thus allowing the advantages of a focused beam without the reduced sensitivity away from the depth of focus. Electronic scanning has also been used to generate a fully focused B-scan with fixed beam angle.

Figures 8 and 9 displays the B-scan images generated from the FMC data after processing for the direct and mode converted ATFM beams. The TL data has been plotted upwards after the mode conversion at the backwall. DAC has been applied to the two sets of data. The specular response from the fusion face defect for the 65L beam can clearly be seen at Ø3 mm SDH sensitivity + 12 dB (15 dB signal-to-noise ratio ignoring the probe echo). However, there is significant noise due to scatter from the austenitic weld as well as an internal probe echo.

The response from the 65TL beam is 4 dB above Ø3 mm SDH sensitivity (35 dB signal-to-noise ratio). There is little noise in the image as the wave propagates in the parent plate. The specular TL response is correctly plotted on the weld preparation lines superimposed on the image, and other mode converted signals can be seen in the image.

CONCLUSIONS
This paper has presented a methodology for phased array transducer checks and calibration when recording FMC data. This approach moves away from existing approaches which rely on measurements of the beams used in an inspection. Instead this method focuses on ensuring probe performance by monitoring the essential parameters of each array element. These checks are straightforward to carry out, and better suited to the inherent flexibility of FMC data.

Specifications for acceptable variations in element performance have been proposed on the basis of results from using an array beam model to conduct Monte Carlo simulation. The results demonstrate the deterioration in inspection performance caused by variations in element sensitivity and phase, and the presence of dead elements.

The second aspect of this paper is the setting of inspection sensitivity and the application of DAC. A method has been proposed that allows DAC curves to be automatically extracted from scanned FMC data. This method records DAC curves for each aperture location in the array, and allows DAC extraction for mode converted beams. The affect of applying such methods has been demonstrated on experimental data.

Figure 7. The test piece used to collect the experimental data
Figure 8. The image produced from the 65L ATFM results after the application of DAC curves, the colour scale is in decibels. 0 dB represents Ø3 mm SDH sensitivity.

Figure 9. The image produced from the 65TL ATFM results after the application of DAC curves, the colour scale is in decibels. 0 dB represents Ø3 mm SDH sensitivity.

REFERENCES

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5) British and european standard: Non-destructive testing - characterization and verification of ultrasonic examination equipment - part 1: Instruments (BSEN12668-1:2010)