Quantifying Performance of Ultrasonic Immersion Inspection Using Phased Arrays for Curvilinear Disc Forgings

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Abstract. Use of full-matrix capture (FMC), combined with the total focusing method (TFM), has been shown to provide improvements to flaw sensitivity within components of irregular geometry. Ultrasonic immersion inspection of aerospace discs requires strict specifications to ensure full coverage – one of which is that all surfaces should be machined flat. The ability to detect defects through curved surfaces, with an equivalent sensitivity to that obtained through flat surfaces could bring many advantages. In this work, the relationship between surface curvature and sensitivity to standard defects was quantified for various front wall radii. Phased array FMC immersion inspection of curved components was simulated using finite element modelling, then visualized using surface-compensated focusing techniques. This includes the use of BRAIN software developed at the University of Bristol for production of TFM images. Modelling results were compared to experimental data from a series of test blocks with a range of curvatures, containing standard defects. The sensitivity to defects is evaluated by comparing the performance to conventional methods. Results are used to highlight the benefits and limitations of these methods relating to the application area of aerospace engine disc forgings.

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INTRODUCTION

Ultrasonic phased arrays can be used to perform the total focusing method (TFM). The amplitude of A-scans from the full-matrix of element transmit and receive combinations is taken from each trace at the time of flight (ToF) corresponding to the location of a pixel in a scale image. These amplitudes are summed to give the brightness of the pixel, and this is repeated for each pixel to create a B-scan image.

An inspection incorporating media with different bulk wave propagation velocities must take these into account when calculating the ToF for a focused image. Furthermore, the shape of the interface will affect the ToF to each pixel location. The shape of the interface can be detected by first imaging it using water as the inspection medium, extracting the interface shape using raytracing to take the multiple media velocities and interface geometry into account. Using this interface, the corrected ToF for each pixel in the second medium can be calculated. A second TFM is performed using the calculated ToF, and the image of the flaw is then produced.

The use of TFM for imaging flaws through complex interfaces in immersion has been demonstrated, particularly for irregular weld caps. It would be desirable to have the ability to predict how the response to defects in the volume of a part degrades according to the interface geometry and positioning of the array. This would allow mapping of the expected signal for target defects in a component of a given shape, and provide the critical data required to predict its useful working lifetime.

This study looks at the specific case of radially curved geometries with centrally located flat bottomed holes (FBH) using surface-corrected 2D TFM with a linear phased array, as a first step towards reliably predicting coverage of complex curved parts.

BACKGROUND

Industrial Motivation

Full-matrix capture ultrasound (FMC) is an acquisition mode whereby each element is fired in turn, followed by all elements recording the resulting a-scan at each receiving element location. This produces n_{el}^2 A-scans where n_{el} is the number of array elements. This technique generates orders of magnitude more data relative to those which perform focusing at acquisition time, but enables to perform TFM, which produces an image focused at every point below the surface of the inspection media. The benefit of this ability, in the long term, outweighs the practical hurdles of FMC-TFM processes such as data-rate, calculation time of TFM and the efficient storage of FMC for future use – all of which are being addressed. There is an exciting opportunity to leverage this data to help with component registration, achieve better overall sensitivity to defects, provide positional feedback to robotic systems and streamline the design of forged components prior to inspection.

This work sets out to lay the foundations for the last goal – by quantifying how the surface geometry of a fine-grained steel component will affect the signal obtained from a FBH in immersion, after the FMC-TFM process has been applied. A way to reliably predict the performance of the technique, for a given flaw and component geometry, is key for deployment of TFM in industry. Unlike for a single element method inspecting a flat-sided part, there is no straightforward way to calculate the beam and infer the expected flaw signal –TFM does not have a beam shape in the traditional sense, as the ability to image the flaw cannot be ascertained by decoupling the properties of the probe from the imaging technique used. This means that in order to assess imaging capability over the whole component, the flaw response must be predicted.

Coverage maps are currently produced by using a combination of beam calculations and heuristics based on ultrasonic principles or experience, and they are corroborated with data from experimental trials. The results are used to determine the useful working lives of components, and also to determine the minimum mid-manufacture forging shape that can be reliably inspected. The ability of phased array ultrasound to retain similar sensitivity through curved surfaces is the key to new, smaller mid-manufacture forging designs. Exactly how close to net-shape these mid-manufacture stages can be machined relies directly upon the ability of FMC-TFM to correct for curvature. There are two major research questions that must be answered:

1. What are the most extreme interfaces through which a FBH can be satisfactorily imaged?
2. How much can the use of these interface shapes reduce the mid-manufacture component size, compared to machining the sides flat?

This work made some progress towards answering question 1, whereas question 2 will be an optimization problem for a later study. The context and vision is important here however; a more advanced NDE technique, though perhaps more complex and expensive in itself, has the potential to dramatically reduce overall cost of the manufacture process by allowing the inspection of near net shaped components. An example would be ultrasonic inspection of aero-engine discs in a curvilinear form, as opposed to the current practice of the using an intermediate rectilinear disc form.

Phased array ultrasonic inspection for surface correction

For performing an inspection of a curved component using a single element probe in immersion, there are two options available for surface correction – adding a correction factor to account for curvature-related attenuation of the signal[1], or selecting a focused probe to counteract the focusing effect of the interface, and selecting an appropriate standoff to alter the focal point depth through the material created by the combination of interface and probe-wedge geometry.

For a complex component with many different curvatures, multiple wedges would be required to match the interface focusing effects, making the approach impractical for automated inspection procedures. The use of phased arrays to correct for surface geometry has been investigated for irregular and anisotropic welds[2,3], showing that TFM can correct for both the macrostructure and microstructure of a component. The maturity of this approach is shown by its implementation in commercial systems[4], highlighting the potential for other applications. Weld applications look to measure and correct as best as possible for deviations from a planar geometry, whereas in the application suggested by this study, the designers introduce a more challenging inspection geometry in order to create a more efficient manufacture process – it is therefore necessary to carefully quantify the effect of these curvatures on the TFM process.

The CAD profile of a suggested component part is known to a low tolerance, therefore it is possible to pre-calculate the focal laws in this case[5], however an immersion inspection may have more positional uncertainty than with a shaped wedge in contact. A study into automated crack detection [6] noted that a 0.5 mm undulation over a 100 mm surface could cause significant changes in ray path. In the case of positional uncertainty of this scale, it would be pragmatic to detect the exact surface using a primary TFM image of the surface in water before performing focusing, to ensure the surface used for focal law calculation is an accurate representation of the inspection setup.

This study uses software developed by the University of Bristol called BRAIN, in order to detect the interface geometry, and adjust the TFM focal laws. An initial TFM image is performed using the velocity of water to calculate ToF. From this, the peak signals along the interface are extracted and this is interpolated to form the measured surface in immersion, used as an input for the second stage of the TFM algorithm, where the refraction at the interface is taken into account. Ray paths from each array element to the pixel location are calculated by iterating the intersection point to fulfil Fermat's principle of least time. The minimum ToF ray path through both media is calculated then applied in the TFM equation to produce the corrected TFM image.

Path planning for automated inspection

Work on automating the delivery of ultrasonic phased array inspection has focused on optimising coverage speed[7], and flexible trajectory planning[8]. For a given complex geometry, it will be necessary to define the optimal probe positioning for coverage.

Using the fewest possible probe positions to achieve a certain sensitivity of coverage through the part volume will optimise the speed of the inspection for a required sensitivity level; ensuring that the scan step is not only determined by the surface normal of the component, but by the predicted sensitivity of the inspection.

FINITE ELEMENT MODELLING

The FE software PZFlex (Thornton Tomasetti, Cupertino, USA) was used to create a 2D model of FMC acquisition, in order to predict the drop-off in sensitivity induced by curved interfaces relative to a flat interface. The curvatures in this study are very large compared to the wavelength used, therefore the effects of diffraction could be said to be negligible, and a semi-analytical model could be applied. Future work on the industrial application looks at more complex and rough surfaces with deviation of the order of λ or below, therefore the FE approach was taken to preserve generality.

A model was developed to study the mesh size that should be used to maintain accuracy for the inspection. The leftmost element was used to transmit, and all element received. Each A-scan trace was compared to its counterpart using the highest mesh density simulated of $\rho_{\mathrm{mesh}} = 100$ where ρ_mesh $=\ \lambda/d_{\mathrm{el}}$ with λ as the longitudinal wavelength in water and d_{el} as the length of a square element side. An even structured mesh was used, approximating the curvature in steps. This was selected for computational efficiency, and was deemed appropriate as the radius of block curvature $\mathcal{R} \gg d_{\mathrm{el}}$.

For models of differing mesh density, one element was pulsed and 32 elements received. Each A-scan signal was compared for varying ρ_{mesh} , and the correlation coefficient was calculated from a window around the back wall reflection. Use of $\rho_{\mathrm{mesh}} = 25$ was found to achieve $C_{\mathrm{corr}} > 0.5$ for all elements, where C_{corr} is the Pearson Correlation Coefficient between the two windowed signals.

As the model was created in 2D, the FBH was represented by a notch in the infinite plane. Results from this approach are compared to experimental data in the results section.

EXPERIMENTAL WORK

C-scans were performed on a series of convex and concave curved blocks, with radial interfaces from 10 mm to 40 mm, and the common dimensions are shown in Figure 1. The arrangement of all blocks, with differing radii, is shown in Figure 2. These were constructed of FV535, a high chromium martensitic stainless steel. A 32 element 10 MHz Imasonic phased array probe was used for the array scan and a 10 MHz GE 8” spherically focused probe was used for the single element scan. Calibration for position, gain and gate settings was performed using a flat test block with the same metal path and flaw diameter. C-scans of each block were produced using each method. For the single element inspection, encoded A-scans were gated according to the target flat depth, and the maximum amplitude in this gate was recorded at each x-y position. For the array scan, at each probe position, a corrected TFM B-scan was produced and gated as shown in Figure 3. C-scans produced from these methods are shown in Figure 4. The peak signal from the FBH C-scan was measured, as was the peak signal using the same settings for the flat-interface calibration block. This was repeated for the concave blocks, with results shown in Figure 5.

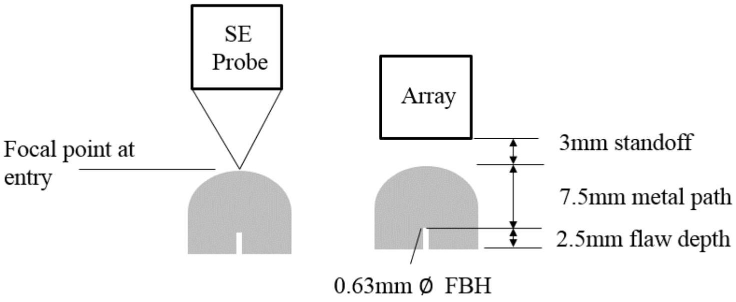


Figure 1- C-scan inspection setup

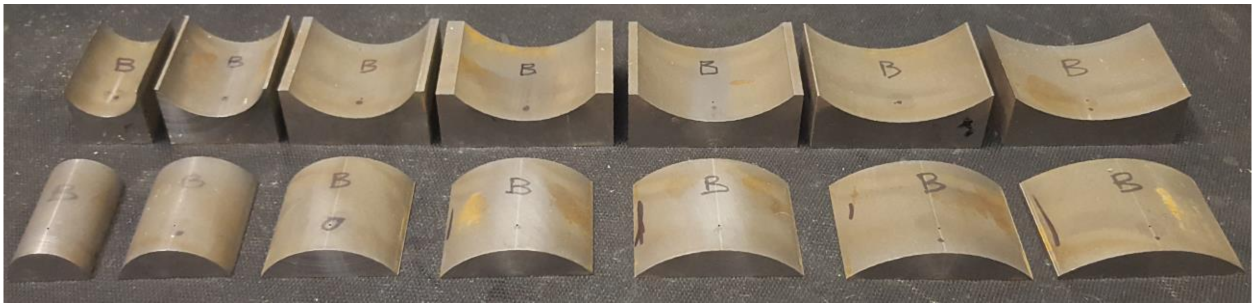


Figure 2 - Concave and Convex blocks

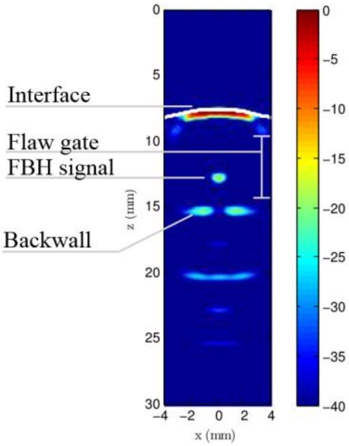
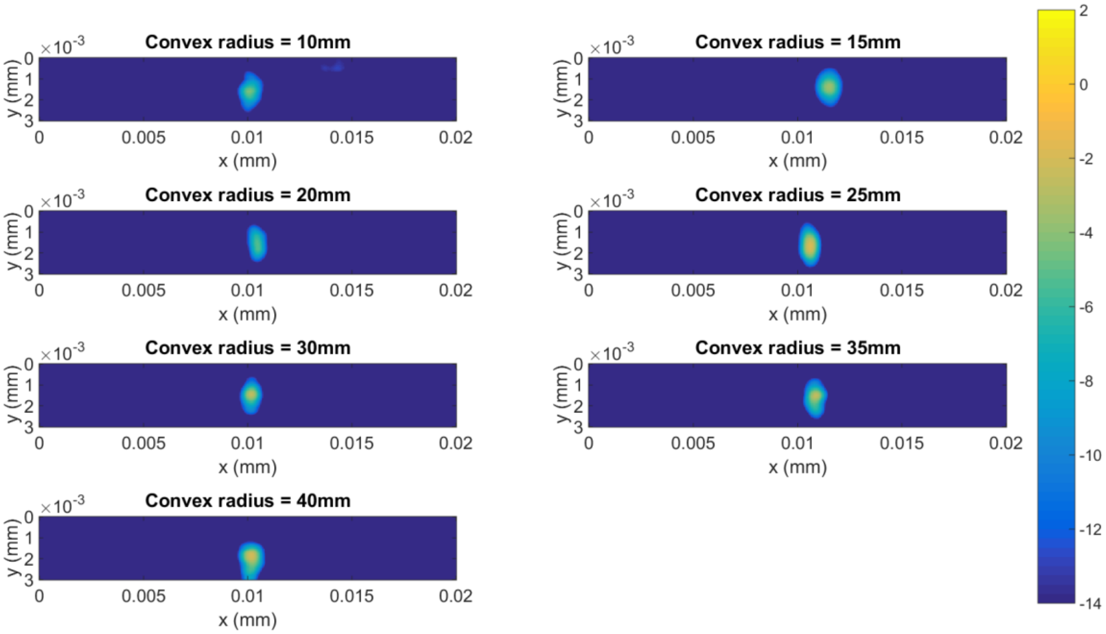


Figure 3 - TFM Corrected B-scan example for 20 mm convex interface


Convex radius = 10mm

Convex radius = 15mm

Convex radius = 20mm

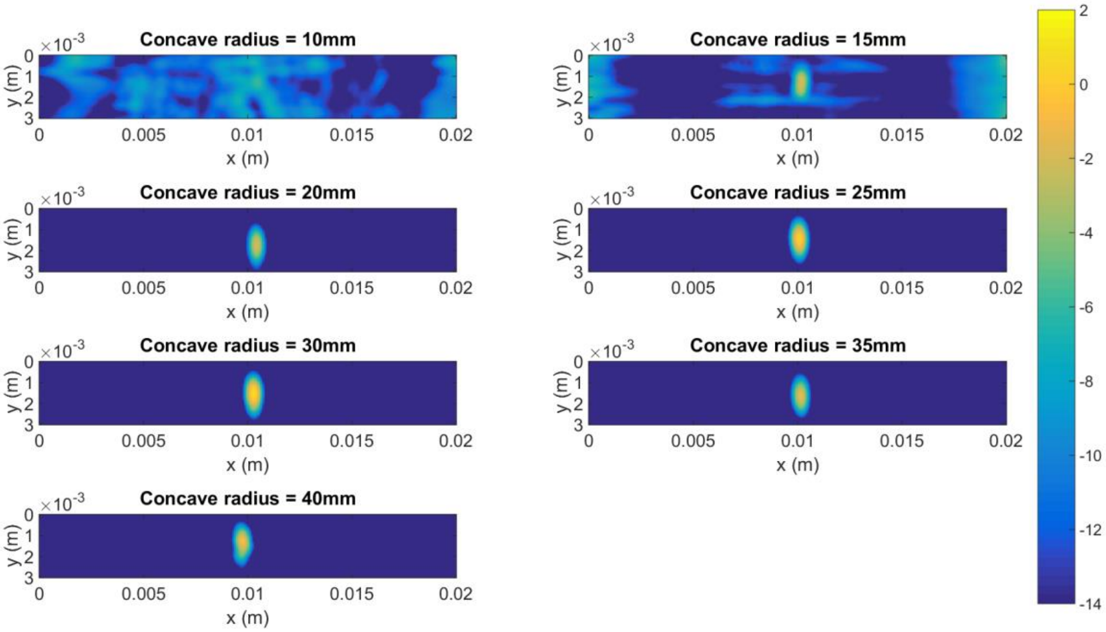
Convex radius = 25mm

Convex radius = 30mm

Convex radius = 35mm

Convex radius = 40mm

Figure 4 - C-scans of blocks with radially curved convex interface


Concave radius = 10mm

Concave radius = 15mm

Concave radius = 20mm

Concave radius = 25mm

Concave radius = 30mm

Concave radius = 35mm

Concave radius = 40mm

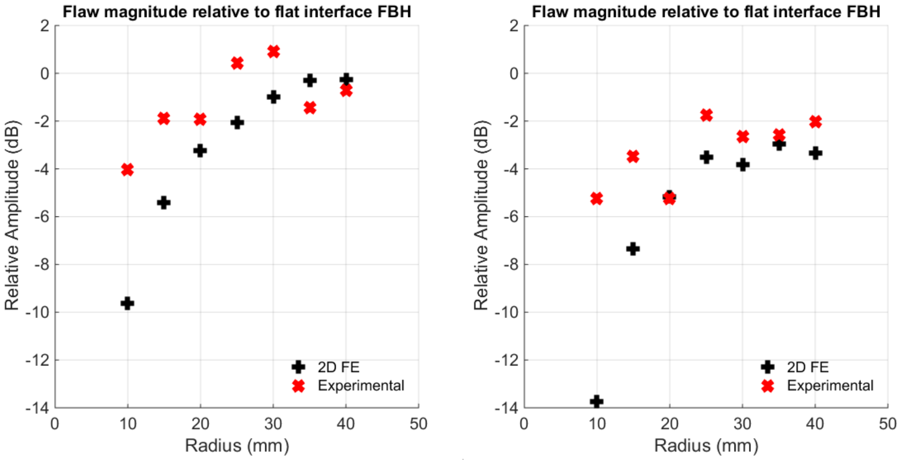
Figure 5 - C-scans of blocks with radially curved concave interface

RESULTS

The peak signal from the C-scan of each test piece was taken and normalized against the peak signal from a flat sided calibration block. Plotting the signal obtained against surface curvature, the effect of interface curvature on a given technique was quantified.

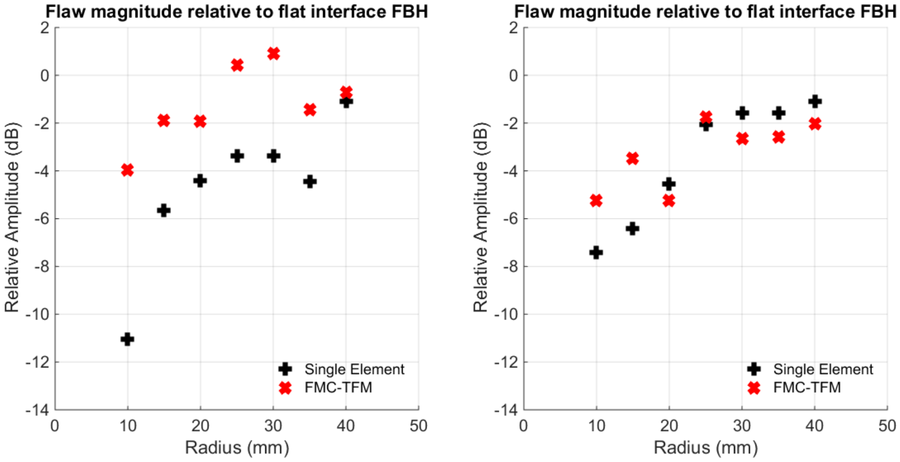
Use of the 2D FE model did not produce accurate results for radii tighter than 20 mm, as shown in Figure 6, so whereas the technique produced TFM images that were qualitatively very similar (B-scans looked almost identical, only with a different intensity at the centre of the flaw), a different approach should be taken to estimate accurately the signal strength vs. curvature relationship for a FBH.

The signal strength for TFM degraded less severely than that for the single element technique with tightening curvature, as shown in Figure 7. Note that the difference between the magnitude of improvement between the concave and convex plots is due to the focusing and defocusing of the beam at depths closer and farther from the FBH location in each block. A better representation of the signal change of centrally located flaw strength would be obtained with measurements using multiple metal paths.



a) Concave *b) Convex*

Figure 6 - Comparison of signal obtained from flaw beneath curved interface vs. signal obtained from same flaw through a flat interface, for 2D FE simulated and experimentally determined values.



a) Concave *b) Convex*

Figure 7- Comparison of signal obtained from flaw beneath curved interface vs. signal obtained from same flaw through a flat interface, for surface-corrected FMC-TFM inspection and single element probe inspection.

CONCLUSIONS AND FUTURE WORK

This work shows that a technique to detect and correct for radially curved interface geometry can be applied to FBH target defects, through curvatures from 10-40 mm. The relationship between signal strength and curvature cannot be reliably predicted using a 2D element finite element model for curvatures less than 20 mm in radius, and therefore another technique must be used, such as a 3D model that better represents the geometry of the FBH. Imaging of the FBH using TFM processes was shown to degrade less rapidly as interface curvature increases, compared to a spherically focused single element probe of the same frequency.

More experimental results, with a varying metal path and standoff, will better define the relationship between inspection parameters and performance. Development of a more accurate model will allow prediction of flaws in the entire region below the interface, helping to plan for coverage of a component. Further experimental studies using off-centre defects will be required to validate this coverage mapping approach.

ACKNOWLEDGEMENTS

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