ADVANCES IN ULTRASONIC FLAW CHARACTERISATION

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Introduction

This paper will discuss the progress of techniques for the ultrasonic characterisation of flaws over the last 40 years and describe in more detail one of the most recent studies performed by AMEC in an attempt to validate characterisation for small (~3 mm in through-wall extent) flaws using a combination of an updated objective flaw characterisation software and post-processing algorithms for linear phased array Full Matrix Capture data.

Background

The principles of good ultrasonic inspection design are based on an understanding of the interaction of ultrasound with defects are now well established within the nuclear industry. As long ago as the 1970’s (Reference 1) it was recognised that accurate sizing and characterisation of manufacturing and service induced defects in major nuclear reactor pressure vessels and piping posed particular problems for conventional code defined ultrasonic inspection methods. Improved techniques were required to provide meaningful and reliable location, through-wall and length sizing and characterisation (planar or volumetric) information on manufacturing and service induced defects to support plant structural integrity assessments. Research and development programmes were underway in Europe and the USA investigating improved ultrasonic inspection technologies, some of which are now in common use worldwide, others which have been largely discarded.

Reference 1 summarised 1970’s research being performed in the areas of

- Improved probe designs (large focused and transmit-receive longitudinal probes) and optimised inspection parameters for specific components and materials based on physical understanding of ultrasound propagation and defect interaction characteristics
- Signal processing techniques for enhancing defect signal to noise ratios and defect discrimination (including adaptive learning networks)
- Defect imaging and sizing using ultrasonic holographic techniques
- Defect length and through-wall sizing using ultrasonic time of flight diffraction (TOFD) and synthetic aperture processing (SAFT) techniques
- Defect characterisation using ultrasonic spectroscopic and multi-parameter regression techniques
- Defect sizing based using Ultrasonic phased and sequential arrays.

It was concluded that more quantitative information was required from defect sizing and characterisation programmes on the relative merits of both conventional and advanced characterisation techniques for specific defect types.

Quantitative information regarding the capabilities of research and best practice industrial ultrasonic inspection techniques for nuclear reactor pressure vessel and piping components emerged (Reference 2) in the 1980-90’s from international round robin inspection programmes (DDTs, PISC II and III) in and supporting national experimental and theoretical modelling research programmes. In the UK, the good performance of the multi-probe pulse echo and TOFD/SAFT methods (Reference 3) in the DDT and PISCII round robin tests led to their specification for use in the manufacturing and pre/in-service inspection programmes for the Sizewell B PWR.

885
In parallel, the benefits of a formal demonstration of the capabilities of the ultrasonic inspection techniques, systems and personnel in circumventing the thorny issue of quantifying overall inspection reliability were recognised and led to the establishment of the UK Inspection Validation Centre (Reference 2). This was mirrored sometime later by the establishment of the European Network for Inspection Qualification and the Performance Demonstration Initiative (PDI) programme in the USA.

The widespread adoption of formal Inspection Qualification as the preferred means of demonstrating the capabilities of nuclear NDE systems, procedures and personnel is evidenced by the large number of technical papers on specific qualification exercises and reviews of national Inspection Qualification programmes presented in recent Conferences (References 4 and 5). Additionally, some of the recognised best practice ultrasonic methods for the detection, sizing and characterisation of defects are now captured in national codes and standards (References 6, 7 and 8).

The status of current best practice defect sizing and characterisation techniques

Almost without exception, Inspection Qualification target defect sizes are based on either structural integrity defect tolerance and crack growth assessments, with an allowance of a reserve factor, or established knowledge of best practice inspection capability in the component in question. This usually ensures that the target qualification defect sizes are large with respect to known inspection capability and hence can be achieved with high reliability. Where this is the case, the current approach to Inspection Qualification is considered fit for purpose. Concerns regarding the existing limitations of existing ultrasonic techniques for sizing and characterising defects, and the lack of a complete theoretical understanding of the processes involved, are of only limited concern.

Emerging requirements for improved small defect sizing and characterisation techniques

Current best practice inspection qualification approaches are challenged when the required qualification target defect sizes for defect detection approach the defect detection limit. This may be the case when refinements to component design, unexpected degradation of component material properties or up-rating of plant service demands lead to smaller start of life tolerable defect sizes. Pressures to minimise intrusive in-service inspection or the impracticality of routine ISI over long operational periods (Reference 9) would also demand further improvements in ultrasonic defect detection, sizing and characterisation capabilities for small start of life defects. For such applications, a reliable capability to discriminate between small crack-like and volumetric manufacturing flaws in new and replacement nuclear plant components is needed. This in turn places extra demands for the use of realistic flaw types in test specimens used for inspection capability, reliability and qualification programmes (References 10 and 11).

Progress in phased array based small defect sizing and characterisation

The major technological advances (in computer processing power, mathematical modelling, sensor technology (composite transducers, and phased arrays) over the last 20 years have not in themselves led to comparative improvements in defect sizing and characterisation performance. They have enabled inspection optimisation for complex geometry components and fast collection, storage and processing of large full RF waveform A-scan data files with the potential for further refinement of defect detection, sizing and characterisation capabilities. However, they have mainly re-confirmed the capabilities achieved with less technologically advanced best practice inspection techniques and systems in the 1980-90’s. In particular, the known limitations regarding the detection, sizing and characterisation of small defects evident with earlier best practice inspection design have remained.
Significant advances have been made recently (References 12-15) through academic research into the use of ultrasonic phased arrays for improved small defect sizing and characterisation. Full matrix capture (FMC), Total Focusing Method (TFM), scattering coefficient matrices (SCM) (References 12-14) methods, supported by hybrid modelling of the interaction of ultrasound with rough cracks (Reference 15), have been studied in depth. The potential and limitations of amplitude based, scattering coefficient matrices based and image based techniques for sizing small misoriented crack-like defects of height \( h \) have been assessed support by limited experimental trials. In summary, amplitude based techniques appeared most applicable for \( h \leq 0.2 \lambda \) (\( \lambda = \) ultrasonic wavelength), scattering coefficient matrices techniques for \( 0.2 \lambda < h < 1.4 \lambda \), and imaged based techniques for \( h > 1.4 \lambda \). These finding regarding very small and large defects are largely consistent with current ultrasonic best practice but the applicability of scattering coefficient matrix technique to realistic defects in engineering components has not been tested.

**Objective flaw characterisation (OFC) methods**

In the early 1980-90’s, objective ultrasonic physically-based pattern recognition techniques (References 16 and 17) were developed to aid reliable discrimination between crack-like and volumetric flaws/defects. Ultrasonic full RF waveform data files were collected from raster scans over a suspect defect volume using immersion pulse echo with a variety of inspection angles. Three physically based numerical features derived from the ultrasonic signal amplitude variation with incidence angle (amplitude ratio), the ultrasonic waveform peakedness (kurtosis) and ultrasonic signal volume distribution (sphericity) in three dimensional space are calculated for each suspect flaw volume. These features were stored in a large diverse flaw feature database and plotted in a three dimensional feature space. A clear separation of purely crack-like and purely volumetric defects was evident in the feature space. Calculated features from an unknown flaw could then be plotted in this feature space to determine the flaws relative crack-like or volumetric characteristics within defined confidence limits. The size range of flaws studied in References 16 and 17 were generally larger than those of current interest.

**Current study**

In the study reported here, we have sought to extend the objective flaw characterisation (OFC) method to smaller flaws by including additional evidence derived from phased TFM images and SCMs.

A series of rectangular (600mm x 600mm x 57mm) ferritic test specimens containing implanted small (\( \geq 3 \)mm through wall extent) geometric and realistic weld defects were examined using multi-probe pulse echo techniques and a new small flaw feature database constructed. FMC phased array inspections were then performed over identified flaws from which TFM images and SCMs of each defect were produced.

The multi-probe pulse echo data were collected using 10 mm single crystal diameter 4 MHz (0°, 45°, 60°, 70° and 45° tandem) probes and the Micropulse 5PA automated flaw detector running MIPS and GUIDE data collection and processing software. The RF waveforms were collected with a sample rate of 50 MHz on a raster grid of 0.5 mm by 0.25 mm. FMC phased array inspections were performed with 5MHz 64 element probes.

A procedure for assessing the evidence on flaw character from the OFC features (amplitude ratio, kurtosis and sphericity), TFM images and SCMs was then developed and described in a written technical justification of the approach.

The resulting capability was tested in a blind trial performed on an additional ferritic test specimen containing implanted defects. The results from this blind trial are summarised here.

One test specimen was destructively examined to determine the true nature of the implanted defects. A comparison of the ultrasonic and metallographic evidence from four of these defects are presented in images below.
Results

Figure 1 presents a typical plot of two of the flaw features from the flaw feature database.

![Figure 1](image1.png)

Figure 1 The Amplitude ratio (AM) against the Kurtosis (KU) for the original flaw database and the newly collected results.

Figure 1 shows several results with high Kurtosis values which places these particular results away from the other results in 3D space. On closer examination, these results were usually vertical planar defects and the parameters were calculated using the data collected by the tandem technique, which was only introduced during this current project and not in the original OFC program.

The next set of figures show the comparison of a small smooth planar defect with a complex nature; a mix between volumetric and planar. The figures show the automated multi-probe pulse echo, TFM, SCM and the metallographic images. These defects are from the specimen that was destructively examined.

Figure 2 B, C and D scan for a small (3.7 mm TWE) smooth planar defect.

![Figure 2](image2.png)

Figure 2 shows the ultrasonic response in three projections for the specified lack of fusion defect indicating a smooth planar defect.
The nature of the defect can also be clearly seen with the TFM image in Figure 3. From observation of the image, a smooth planar shape with an even distribution of amplitude would indicate a smooth planar defect.

The SCM plot (Figure 4) for the lack of fusion flaw shows a maximum amplitude at approximately 60°, indicating that the defect is orientated at 60° from the horizontal. The shape and amplitude of this distribution also can be used to determine whether the defect is planar or volumetric. In this case a narrow peak and a large amplitude with respect to a side drilled hole indicates a planar defect. A broad peak with a similar amplitude to a side drilled hole would indicate a volumetric defect.

Figure 5 Cross-sectional view of the lack of fusion defect under an optical microscope
Figure 5 shows a smooth lack of fusion defect as expected from the specification of this defect. The OFC software characterised this defect as a planar defect with 100% confidence and the evidence from TFM and SCM compliment this result.

Figure 6 B, C and D scans for a small (3.1 mm TWE) rough heat affected zone defect

The ultrasonic response in Figure 6 is indicative of a rough defect and at this size it is difficult to make an interpretation as to the type (volumetric or planar) of the defect.

Figure 7 TFM image of the rough heat affected zone defect

The TFM image in Figure 7 shows two large amplitude indications (red) with some surrounding artefact signals. As with the automated pulse echo data it is difficult to determine the true nature of this defect from this image.

Figure 8 SCM image for the rough heat affected zone defect
The SCM image (Figure 8) again shows a high amplitude peak around 60° indicating a planar defect.

![Image](image.png)

Figure 9 Small mixed characteristic defect

The true nature of the defect is shown in Figure 9 which appears to be a mix between a volumetric and a planar defect. The OFC programme characterised the small smooth planar defect as planar with high confidence but mis-classified the small mixed characteristic defect as volumetric (with lower confidence). However, using a combination of the alternative methods (TFM, SCM) an overall decision with higher confidence can be made.

- After complete destructive examination of this test specimen, it was found that:
- Two defects correctly classified with 100% confidence were smooth planar.
- Two of the defects correctly classified but at lower confidence were planar defects with non-uniform orientation.
- The remaining two defects were misclassified as volumetric with less than 100% confidence and were more complex, with volumetric features.
- The OFC code alone was unable to discriminate between volumetric defects and mixed planar/volumetric defects. However, it was found that the routine was able to provide the data interpreter with a level of confidence, by backing up the original assessment from GUIDE data (or indicating when something has gone wrong).

The TFM and SCM algorithms were able to provide complimentary information, to aid in the characterisation of defects. SCM provided a measure of the scattered amplitude due to the defect as a function of beam angle (thereby allowing an estimate of defect tilt to be calculated), while TFM provided an image focussed at every point, providing a visual guide as to the shape of the defect.

For smaller defects (<4 mm), the SCM technique was particularly useful, as it allowed a determination to be made of both the defect character (planar/volumetric) and the defect tilt (if applicable).

The overall conclusions of the study were -
- OFC classified 88% (150 out of 170) of the current defects in the database correctly.
- OFC classified seven out of the eight blind trial defects correctly.
- SCM performed well on the defects that were misclassified by OFC and on small defects (less than 4 mm extent).
On the defects that were destructively examined, TFM images showed characteristics that were evident in the defect macrograph e.g. non-uniformly orientated defects had areas of high amplitude along the defect in the TFM image.

Some defects do not fall into one of the three distinct categories used within OFC. However, the analysis procedure defined in the inspection procedure combining OFC and TFM and SCM information reduces the likelihood of misclassification.

**Proposed way forward**

Where further improvements in defect sizing and characterisation capability for small defects are needed over and above that achievable by best practice ultrasonic inspection design and inspection qualification methods, an approach based on combined analysis of OFC, TFM and SCM methods offers the potential for significant progress. In this project a start has been made in subjecting some of the more recent phased array based methods to the rigorous capability assessments performed on existing best practice ultrasonic techniques in the 1980-90’s.

**References**

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