ABSTRACT

The non-destructive inspection of components with irregular surface geometry can be very challenging. The performance of inspections using conventional rigid wedge ultrasonic transducers is limited because of inconsistent coupling and beam distortion. A novel approach using a membrane coupled conformable phased array device is under development to reduce these problems. This low-cost, robust device uses a standard phased array coupled to the component surface via a fluid-filled, low-loss polyurethane membrane. The performance of the membrane-coupled device has been improved to reduce the required coupling force, increase inspection speed and reduce probe noise. The evolution of the membrane-coupled device is presented and the performance improvements over previous designs are discussed. A comparison between the membrane coupled conformable phased array and conventional rigid wedge technology is then completed. This comparison demonstrates that the membrane device can theoretically be used to reduce inspection time by approximately a factor of three when compared to the single crystal approach. This significant time reduction is achieved whilst improving inspection coverage, flexibility and performance, as well as reducing the amount of user intervention.

INTRODUCTION

The inspection of components with complex surface geometry such as an undressed weld cap can be challenging and it is not always possible to achieve 100% test coverage using conventional inspection techniques. Unfortunately weld cap removal is an expensive, time-consuming task, which becomes even more difficult when the component is in service; the removal process can also compromise the integrity of safety critical pipe-work. It is often found when the weld cap is removed that due to the effect of the welding process the surface profile has been distorted. This irregularity in the component finish prevents complete scan coverage with conventional rigid wedge transducers. The target application component for this work is representative of this situation; a schematic diagram of the target application component is shown in Figure 1. The component is a section of large bore stainless steel pipe-work, which contains an austenitic weld. The inspection must be capable of detecting small defects with through-wall dimension of less than twice the wavelength of the inspection centre frequency. The pipe-work has a wall thickness of greater than 50mm, and defects can occur anywhere within the weld and Heat Affected Zone (HAZ) of the pipe-work; this limits the maximum inspection frequency. The variable radius of curvature in the elbow section prevents inspection of the weld using conventional rigid transducer technology from this direction. The inspection must be completed on the straight section of pipe from the outside only. Due to these access constraints, thorough inspection of the pipe-work is challenging.
In the current target application inspection the weld cap must be removed and multiple small-footprint rigid wedge single crystal transducers are then used in a complex raster scan to achieve the best possible scan coverage. However, due to distortion in the surface profile caused by the welding process, complete coverage cannot be achieved using this approach. The current inspection approach is a slow process requiring significant user intervention, which is an issue for in-service inspection in the nuclear environment. It is desirable to leave the weld-cap in place and rapidly complete a detailed, accurate inspection of the component.

Phased array transducers offer an alternative approach; a single phased array transducer can be used to replace multiple single crystal probes. Electronic scanning can then be used to reduce the amount of mechanical scanning required, which can also reduce inspection time significantly. However, with both single crystal and phased array transducers any mismatch between the base of the rigid transducer and the surface profile of the component under test causes an irregular coupling layer, which results in a deterioration in performance [1]. Researchers at Imperial College London and Rolls-Royce have developed a conformable membrane coupled phased array device. This cost effective approach uses a standard phased array coupled to the component surface via a fluid-filled, low-loss membrane. The rubber membrane conforms to the surface profile of the component under test to ensure that uniform coupling is maintained, even when the weld cap is left in place. A single phased array device is used to measure the surface profile and then complete the inspection. Surface profile measurement is used to update delay laws and ensure a high integrity inspection can be achieved [2].

**Membrane coupled phased array device development**

The 1st generation membrane coupled phased array device is shown in Figure 2a [3]. This device was designed for handheld inspection and uses a standard linear 32 element, 1.5mm element pitch, 2MHz centre frequency transducer. It was coupled to the component outer surface via a water path and a commercially available low-loss rubber. This device was used to successfully test a number of test-pieces containing a simulated weld cap and artificial defects. However, the membrane material was only available in a limited range of thicknesses, which either reduced flexibility and hence the conformability of the device, or led to rapid wear and potential issues of unacceptable damage. The device used a constant volume design; the unit was sealed using a relatively complex plastic housing and demineralised water was introduced into the device via a non-return valve. The constant volume design required significant force to ensure good coupling to the component under test.
The 2\textsuperscript{nd} generation membrane coupled phased array is shown in Fig 1b [3, 4, 5]. This device uses a linear 80 element, 1.25mm pitch, 2MHz centre frequency transducer. The bespoke transducer design from Imasonic [6] was modified to include an extended flange, which was used to improve the seal between the array and the probe housing, and ensure no leakage from the device during operation. A castable polyurethane was used to create the membrane. This extremely robust material allows thinner, more flexible sheets to be used in the device. A “picture frame” approach was adopted to seal the device, where the membrane is clamped to the base of the device using a metal frame. This design again helps to provide an improvement in the water tight seal, over the 1\textsuperscript{st} generation device, and reduces the time required should the membrane require replacement. The 2\textsuperscript{nd} generation design also used a constant pressure approach; a constant head of demineralised water is used to maintain the pressure within the device. This reduces the amount of force required to ensure good coupling between the membrane coupled device and the component under test.

The 2\textsuperscript{nd} generation membrane coupled device represents a significant improvement over the earlier design. Successful testing was completed on two flat plate non-welded testpieces that contained a weld cap representative of that found in the target application [4]. This testing demonstrated that it was theoretically possible to perform a thorough inspection of the target application component. Results also demonstrated that the measurement of the surface profile of the component under test could be accurately completed and that this data could be used to update the required phased array delay laws. However, when considering the overall inspection of the target application a significant noise signal was observed that corrupted the inspection data and reduced the effectiveness of the inspection. There were two major sources of internal noise within the 2\textsuperscript{nd} generation membrane coupled device; the grating lobe noise and the beam spread internal noise [5].

The 3\textsuperscript{rd} Generation membrane coupled device

Recent development work has focused on a number of improvements to the membrane coupled device performance. In the latest membrane coupled device a linear 128 element, 0.75mm pitch, 2MHz centre frequency transducer is used. A photograph of the 3\textsuperscript{rd} generation membrane coupled device is shown in Figure 3. The 2\textsuperscript{nd} and 3\textsuperscript{rd} generation arrays are approximately the same physical size and the device design has the same sized footprint. This approach allows reuse of the same picture frame and membrane sizes. Grating lobes are a characteristic of any phased array transducer and depend on element pitch, frequency and bandwidth [7]. In order to eliminate grating lobes under all operational conditions an element pitch of $\lambda/2$ must be adopted [8]. This is a limitation of the membrane coupled device approach; the wavelength at the centre frequency of the array in water is approximately 0.75mm, in order to achieve the $\lambda/2$ a very fine pitch array is required. An array of this type would have a small footprint, which would significantly increase the amount of required axial scanning to provide complete inspection coverage. This would in turn increase the time required to complete the inspection and reduce some of the benefits associated with the membrane device approach. A compromise is taken in the design of the 3\textsuperscript{rd} generation device; the footprint of the array is kept as
large as possible to allow rapid scanning and a long focal length, but reduced to a point where the effect of the grating lobes becomes negligible. The grating lobe noise [5], which was a significant issue in some inspections using the 2nd generation device, is therefore reduced to an acceptable level.

Figure 3 - Photograph of the 3rd generation membrane coupled conformable phased array device.

The beam spread noise identified using the 2nd generation device is still present within the 3rd generation approach. This source of noise continues to be the most significant within the membrane probe. It is due to the beam that is generated by an aperture within the array not being perfectly collimated, some beam spread occurs due to the effects of diffraction. Some energy at the edge of the generated beam occurs at the correct angle to reflect from the component outer surface, back up to the phased array. It impinges normally on the phased array and then follows the same path in reverse back to the active aperture. This reflection path is shown schematically for a simple 0° longitudinal wave inspection using the membrane probe in Figure 4.

Figure 4 - Schematic diagram of the beam spread noise signal in simple case where main beam steered to normal incidence

In the 3rd generation design the beam spread noise reflection is carefully controlled by adjusting the array stand-off so that it does not interfere with the signals of interest from the component under test. A comparison of the beam spread noise signal from the 2nd generation and the 3rd generation devices is shown in Figure 5 using the 0° longitudinal wave inspection approach discussed above. In the results provided in Figure 5 the membrane device water wedge is represented in blue and the stainless steel
component is shown in green, the area in black is the region interrogated by the membrane device in each case. These results, and all those shown later, have been produced using the full matrix capture (FMC) approach to data acquisition [9]. In each case the FMC data is then displayed using bespoke processing software developed by Long et al [10]. In these results an aperture of 30mm is used, this corresponds to 24 elements in the 2\textsuperscript{nd} generation device and 40 elements in the 3\textsuperscript{rd} generation. Appropriate time delays are applied to the individual elements within the array to generate the 0° beam with no focusing. In the 2\textsuperscript{nd} generation device the beam spread noise occurs at a time corresponding to the 2\textsuperscript{nd} backwall reflection, this effect is shown in Figure 5a. In the 3\textsuperscript{rd} generation device the noise signal occurs much earlier at a time corresponding to the 1\textsuperscript{st} backwall reflection, which is shown in Figure 5b. The angle of the internal noise signal relative to the backwall reflection is related to the angle of the array, X in Figure 4. The angle of the 3\textsuperscript{rd} generation device has been reduced in order to decrease the time interval over which the beam spread noise signal is an issue; this again helps to improve the inspection performance of device.

![Figure 5 - 0° longitudinal wave inspection results using (a) the 2\textsuperscript{nd} generation and (b) the 3\textsuperscript{rd} generation membrane coupled conformable phased array devices.](image)

A number of mechanical improvements have also been made to the 3\textsuperscript{rd} generation device to improve the inspection performance. These changes simplify the membrane replacement process and decrease the time associated with completing this task. The 3\textsuperscript{rd} generation design also includes an integrated irrigation system. All testing using the 1\textsuperscript{st} and 2\textsuperscript{nd} generation designs requires immersion testing, or the use of a gel couplant. Both of these approaches are typically impractical in the nuclear environment and cannot be used with the target application component. The integrated irrigation system is isolated from the fluid encapsulation of the membrane device. This approach ensures that if coupling is lost to the device then the membrane probe does not need to be reconfigured. The irrigation water feed is inserted into the front of the device, this feeds into eight narrow bore tubes that are used to deliver water to the base of the array. The thickness of the metal picture frame has been increased to allow these tubes to be inserted. Water is then injected through the picture frame, this ensures sufficient fluid to provide good coupling and allows any mechanical scanning that is required to be completed. The design of the integrated irrigation system will be further refined and updated in future developments of the membrane device approach.
EXPERIMENTAL RESULTS

Comparison testing was completed in order to quantify the performance improvement of the 3rd generation membrane probe over the 2nd generation device, and conventional rigid wedge single crystal transducers. Experimental testing has been completed on a flat plate, non-welded test-piece that is designed to replicate the target application. On the top surface of the test-piece a series of welds were laid to produce a realistic weld cap profile. A number of defects were embedded into the test-piece; surface breaking defects were produced using an electro-discharge machining (EDM) technique and mid-wall defects were produced by inserting flat bottomed holes (FBH) at the required depth and orientation. Results from the inspection of a range of defects using the 2nd generation device have been reported previously [4]. In this study, a single defect not included in the initial study is considered. This defect simulates an approximately mid-wall lack of side-wall fusion defect on the near fusion face of the weld. The defect is inserted at 25º to the backwall normal and is a 5.6mm diameter flat-bottomed hole; this has an equivalent area to a 4mm x 8mm elliptical defect, which is the minimum postulated defect of interest. The primary technique used to inspect this type of defect is a Transverse-Longitudinal (TL) skip technique. In this inspection the phased array delay laws are suitably controlled to generate a 65º longitudinal wave and the associated shear wave at approximately 29º. The shear wave preferentially mode converts to a longitudinal wave upon reflection with the backwall. The mode-converted longitudinal wave reflects specularly from the defect of interest, and provides an appropriate detection technique for this type of defect. This inspection technique is shown schematically using the membrane probe approach in Figure 6.

The B-Scan results obtained in the inspection of the defect of interest using the single crystal approach and the 2nd and 3rd generation membrane coupled phased array devices are shown in Figure 7. Single crystal results are generated using the British Energy GUIDE platform, whereas the phased array data is once again presented using the Imperial College processing software. This inspection approach is used to detect defects of this type along the entire 25º fusion face. It is therefore not practical to complete the single crystal inspection using focused transducers. A large number of different probes would be required which would make the inspection time using this approach very inhibitive. However, inspection using phased array transducers and FMC data acquisition allows multiple beams to be generated using different delay laws with a single device. It is therefore possible to rapidly complete a focused inspection at multiple depths within the component. The single crystal transducer used in this study was a ½” diameter 2.25MHz Krautkramer device. Calibration of the single crystal transducer demonstrated that a beam of 67º is generated. This illustrates a second limitation of the single crystal approach because it is not possible to optimise the beam for the defect orientation.
Testing has been completed with both the 2\textsuperscript{nd} and 3\textsuperscript{rd} generation membrane coupled devices. To allow direct comparison between the two approaches an aperture of 30mm has once again been used. In each case the delay laws have been controlled to provide single depth focusing at a depth which approximately corresponds to the centre of the defect.

In each case the main TL response associated with the defect is observed, along with an additional Transverse-Longitudinal-Longitudinal (TLL) signal. This TLL signal occurs due to the beam spread of the main beam and is not optimally aligned for this type of defect. It is therefore observed at a lower signal amplitude. The effect of the beam spread internal noise signal in the 2\textsuperscript{nd} generation device is clearly visible in Figure 7b. This internal noise signal significantly corrupts the inspection data. Even when the focused beam is used, it would still not be possible to reliably isolate the defect from the noise signal. In the 3\textsuperscript{rd} generation device the internal noise signal has been removed from the inspection region of interest, a high quality inspection can now be completed.

In order to demonstrate the high level of performance of the 3\textsuperscript{rd} generation phased array device when using the integrated irrigation system, testing was completed with the device in immersion and in irrigation. A comparison of the results is shown in Figure 8. Some very slight differences between the two data sets can be observed but the signal to noise ratio of the two images is the same. There are some minor discrepancies between the two results but these are all minor and the result demonstrates that the performance of the 3\textsuperscript{rd} generation device is maintained when using the irrigation system.

**CONCLUSION**

The long-term goal of this development work is to provide a reliable alternative inspection approach to conventional single crystal transducers using the membrane coupled conformable phased array device. The motivation for this work is that even when the weld cap has been removed from the
target application component complete inspection coverage is not achievable. Inspection is currently completed using multiple single crystal transducers that are mechanically scanned over the component.

![Image](a) ![Image](b)

Figure 8. TL inspection results for the defect of interest using the 3rd generation membrane coupled phased array in a. immersion, and b. irrigation.

The inspection angle is fixed for each probe and provides no flexibility to variable defect tilt and focusing is impractical. A 3rd generation membrane coupled device has been developed which delivers a number of improvements over previous versions. The new device provides improved beam forming, reduced internal noise and has an integrated irrigation system. Using the membrane coupled device it is possible to achieve complete inspection coverage in a limited number of circumferential scans without the need to remove the weld cap. Electronic scanning is completed to generate a wide range of beam angles and focal depths. A theoretical study demonstrates that the potential inspection time can be reduced by approximately two-thirds by using the membrane device instead of single crystal techniques.

**REFERENCES**

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