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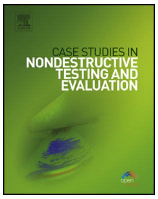

The inspection of curved components using flexible ultrasonic arrays and shape sensing fibres

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ABSTRACT

A novel inspection system which incorporates a low-profile flexible ultrasonic array and a shape sensing fibre is presented in this paper. The system is shown to be able to directly measure the location of the elements in the array as it conforms to a curved surface. This enables the accurate ultrasonic imaging and inspection of components with complex geometries for sub-surface defects. The system offers many significant advantages over other inspection approaches and is particularly applicable to *in situ* inspections where access is limited.

1. Introduction

Ultrasonic array probes are used frequently in industry to inspect components for sub-surface defects. Array probes are particular advantageous for *in situ* inspection as they offer the greatest inspection coverage from a single inspection location [1]. However, it is often necessary to perform inspections on components with curved surfaces and this can cause complications which lead to a reduction in defect detection sensitivity and an increased chance of false calls.

A number of inspection strategies have been developed to inspect components with a complex surface using ultrasonic arrays. One approach is to combine a flat array with a wedge that is specifically shaped to conform to the surface of the component [2]. However, this requires a bespoke wedge for every surface which becomes impractical for many applications where the surface profile of the component is not consistent. A more general approach is to combine a flat array with a flexible wedge [3] or with a water-filled chamber and flexible membrane [4]. In these cases, the data collected by the ultrasonic array can first be used to estimate the surface profile of the component. Once the surface profile is known the correct delay laws can be applied using Fermat's principle of least time [5] to correctly image the component. The major drawback with this method is that the offset of the probe must be carefully selected so that the repeat echoes from the front-surface of component do not interfere with the signals from sub-surface reflectors. This can make the probe relatively bulky and the method becomes unfeasible for inspections where *in situ* access may be limited.

An alternative approach is to use a flexible ultrasonic array that conforms to the curvature of the component. For example the Commissariat à l'Energie Atomique (CEA) and Imasonic SAS (Besançon, France) have developed flexible arrays which can be used for 2D and 3D imaging [6,7]. These probes incorporate a number of independent spring-loaded mechanical positioning sensors on the back of the ultrasonic array elements to measure the position of elements and allow the correct delay laws to be computed. The mechanical sensing system makes the probe large which again can be impractical when access is limited.

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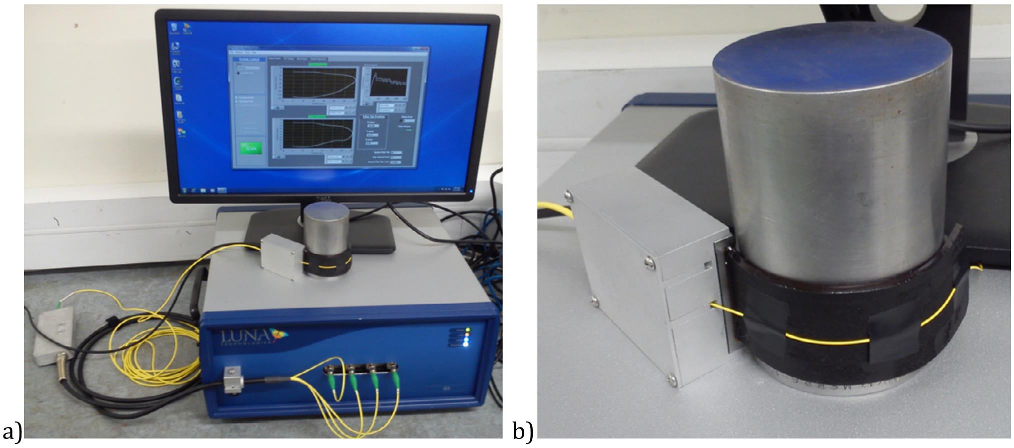

Fig. 1. Images of the flexible ultrasonic array probe with the shape sensing fibre system. a) The shape sensing system and b) a close-up of the (yellow) shape sensing fibre and the (black) flexible array on a cylindrical specimen.

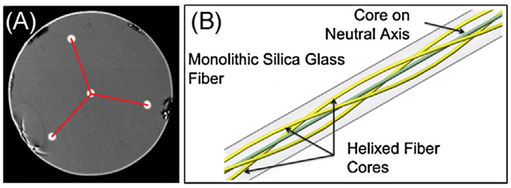

Fig. 2. Images showing the composition of the shape sensing fibre a) in the cross-section of the fibre and b) down the length of the fibre. Images courtesy of Luna Inc.

A number of methods have been developed that enable flexible arrays to be used without position sensing systems [8,9]. In general these methods use data processing on the collected ultrasonic data to estimate the position of the array elements. This requires *a priori* knowledge of the sub-surface geometry of the component such as the position of point-like reflectors or the location of the back wall of the component.

In this paper, a new approach to inspect curved components with an ultrasonic array probe is presented. Here a low-profile flexible array probe is combined with a fibre optic shape sensing device which measures the position of the elements along the array. This design means the overall size of the probe can be kept to a minimum which is advantageous for many inspection scenarios. In addition, no prior knowledge of the component geometry is required making this a very generic and robust approach.

2. Details of the shape sensing fibre and flexible ultrasonic array

The flexible array probe and shape sensing fibre is shown in Fig. 1. The shape sensing fibre is manufactured by Luna Inc. (Virginia, USA). The shape sensing fibre operates on the principle of optical frequency domain reflectometry (OFDR) [10]. In conventional OFDR a fibre Bragg grating is utilised which is a grating pattern manufactured into a short section of an optical fibre. When light is transmitted down the fibre, the wavelength of light reflected from the grating is relative to the periodicity of the grating. If the fibre is strained, the periodicity changes and therefore the wavelength of the reflected light is also changed enabling the strain to be measured. Alternatively, OFDR can also use the Rayleigh scattering from the inherent defects present in the fibre. In this way OFDR can measure the strain distributed along the length of the fibre rather than at the discrete point where a grating is located. It is this latter method that is used in the Luna shape sensing fibre.

The shape sensing fibre has an overall diameter of 250 µm and comprises four OFDR 9 µm diameter cores. One core is located on the centre of the fibre (neutral axis). The remaining three cores are helically wound down the length of the fibre at equally spaced 120° azimuths at fixed radii from the centre of the fibre, as shown in Fig. 2. The cores measure the strain profile acting along their individual lengths as the fibre is curved. The shape of the fibre can be computed from the four strain profiles [11]. In this way the position of the fibre can be measured to an accuracy of 1% of its length, although the exact accuracy is also a function of the fibre curvature.

The shape sensing fibre was incorporated in to a low-profile flexible ultrasonic array by simply attaching the fibre with electrical tape along the length of the array. The array was supplied by Phoenix Inspection Systems Ltd (Warrington, UK). The probe has a centre frequency of 5 MHz, 64 elements with a 1.0 mm element pitch. The ultrasonic elements are manufactured from a 1–3 PZT composite bonded on to a flexible polyimide film containing the electrical connectors. The probe is backed with neoprene which gives a total probe height of 2 mm.

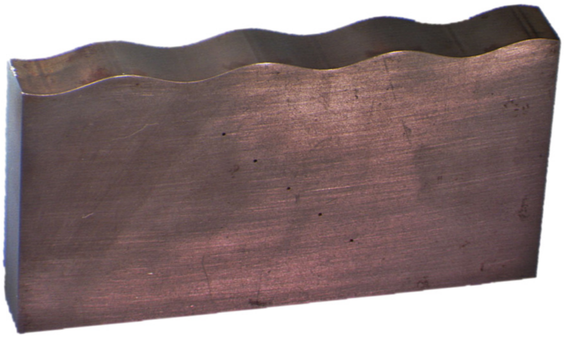

Fig. 3. The mild steel test specimen used for the experimental work.

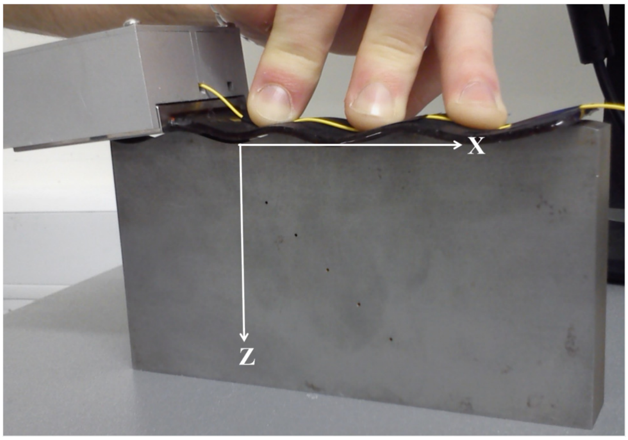

Fig. 4. Image showing the flexible array and shape sensing fibre on the test specimen.

3. Experiments and results

To test the capability of the array and shape sensing fibre, practical experiments were performed on the test specimen shown in Fig. 3. The test specimen was a $160 \times 80 \times 20$ mm mild steel block that contained five 1 mm diameter side-drilled holes (SDHs) at varying depths. The top surface of the specimen had a sinusoidal profile with a period of 40 mm and amplitude of ±2 mm.

The array and shape sensing fibre were placed on the sinusoidal profile with the active elements over the SDHs as shown in Fig. 4. The probe was forced down onto the specimen to ensure the probe conformed to the curvature and the elements were in contact with the surface.

The array was connected to a Peak NDT Ltd (Derby, UK) Micropulse MP5PA array controller. The full-matrix capture (FMC) approach was used to collect the ultrasonic data using a sampling frequency of 50 MHz. The FMC data is collected by pulsing on one element in the array and receiving on all others. This is repeated for every transmit–receive combination [12]. The Total Focusing Method (TFM) was used for imaging. In TFM, the FMC data is post-processed in the time-domain to synthetically focus ultrasonic energy at every pixel in the image field and offers excellent imaging performance.

To compute the intensity of a pixel in the TFM image, the time-of-flight of the ultrasonic wave as it propagates from the transmit element to the pixel and back to a receive element must be calculated. To do so, the group velocity of the component and the position of elements must be known. For this component an isotropic longitudinal velocity of 5895 m/s was used. However, for anisotropic materials the group velocity profile must be used [13].

The positions of the elements were estimated using the shape sensing fibre. The fibre was connected to a Luna Inc. FORM G3 Interrogator Prototype. The FORM G3 measured the 3D position of the fibre with a measurement resolution of 40 μm with a refresh rate of 40 Hz. The measured positions were computed along the length of the fibre which was longer than the active area of the ultrasonic array. Therefore, the positional data was clipped to the active area and then translated so that the origin was aligned to the first element of the array. The data was then rotated so that the Cartesian coordinates were aligned to the test specimen, as shown in Fig. 4. Finally, the positional data was resampled to 64 points to compute the coordinates of individual array elements.

Fig. 5 shows the positions of the elements in the array as measured by the shape sensing fibre against the nominal machined surface profile of the test specimen. The graphs show that, in general, the position of the measured elements matches closely to the nominal profile. However there are discrepancies of up to 0.37 mm in the Z-axis and 0.64 mm in the

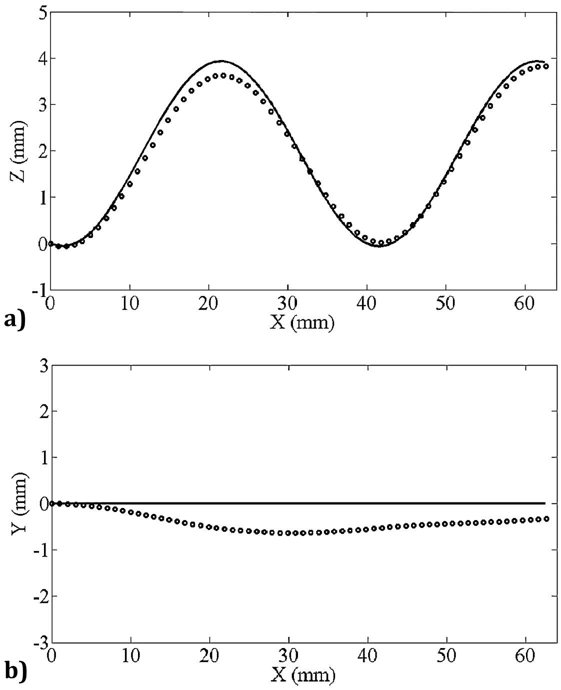

Fig. 5. The position of the array elements as measured by the shape sensing fibre (circles) compared to the nominal machined surface (solid line) for a) the X–Z plane and b) the X–Y plane.

Y-axis. This could be due to a number of factors including: errors due to how the fibre was attached to the array; errors in the coordinate rotations and the inherent inaccuracies of the shape sensing system.

The TFM images from the collected array data are shown in Fig. 6. All of the imaging and data processing was performed using MATLAB 7.11.1 (The MathWorks Inc., Massachusetts, USA). The same raw data has been used for all three images but they have been computed using different element positions. Fig. 6(a) shows the TFM image produced assuming that the array elements were flat (*i.e.* all elements were positioned at $Z = 0$). The indications from the SDHs and back wall can be seen to be significantly distorted. Fig. 6(b) shows the TFM image computed using the nominal surface profile. In this case the individual SDHs can be seen to be imaged as point-like reflectors located at their correct positions. Also, the back wall is imaged as a flat line at a depth of 80 mm. Fig. 6(c) shows the TFM image computed using the element position as measured by the shape sensing fibre. It can be seen that this image very closely matches the result in (b), with only a slight degradation of image quality (the most obvious example of the degradation is the slightly irregular amplitude from the back wall).

4. Concluding remarks

A new system that has incorporated a shape sensing fibre with a low-profile flexible ultrasonic array probe has been presented in this paper. This system has been shown to successfully measure the positions of the element in the array, enabling accurate imaging to be performed on a component with a curved surface.

Inaccuracies were observed in the positional data, however. The error due to the position of the fibre relative to the array element could be minimised by accurately imbedding the fibre in the array during the manufacturing process. Errors due to the coordinate translation and rotation process could be minimised by using a rigorous calibration and normalisation procedure. These errors and the inherent inaccuracies in the shape sensing method should be researched further to improve the fundamental understanding and ultimately determine how they affect the inspection reliability and repeatability.

A linear array was used in the example presented in this paper but the method is also applicable to flexible matrix arrays. However, it should be noted that although the commercially available flexible array probes are able to conform to a 3 mm radius of curvature, the shape sensing fibre can only measure down to a radius of curvature of 10 mm which does limit the applicability of this system to certain components.

The results presented in this paper are very preliminary and a significant amount of further work is required before the system could be used for in-service inspections. However, it has been shown that the method is feasible and offers many significant advantages over other approaches.

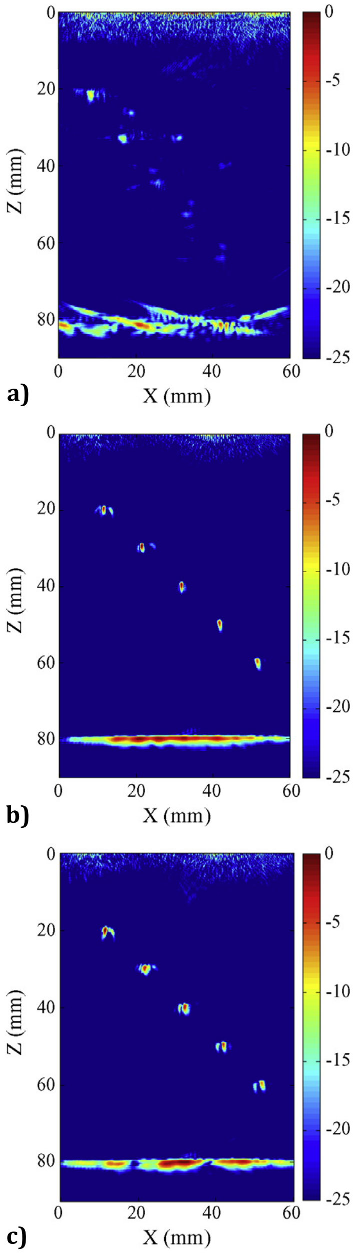

Fig. 6. TFM images of the test specimen computed when a) assuming a flat array, b) using the nominal surface profile of the specimen and c) using the element positions measuring by the shape sensing fibre. All images are shown using the dB scale with 0 dB set to the maximum signal in each image.

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