The ultrasonic inspection of non-planar surface components using Full Matrix Capture

So Kitazawa¹, Hidetaka Komuro² Kenichi Otani²
1 Hitachi, Ltd., Research and Development Group, 7-2-1 Omika, Hitachi, Ibaraki 319-1221, Japan, so.kitazawa.yd@hitachi.com
2 Hitachi-GE Nuclear Energy, Ltd., 3-1-1 Saiwai, Hitachi, Ibaraki 317-0073, Japan

Abstract
The applicability of the full matrix capture and the total focusing method has been examined for objects with non-planar surfaces. The presented combination of the low-cost sensor configuration and algorithm allows for a fast and accurate inspection of pipe weld that has the curved geometry of a weld bead. In the proposed configuration, a linear array transducer is mounted on a ring-shaped plastic wedge that is circumferentially set over the welded joint. In addition, the transducer can be circumferentially moved freely on the wedge. With regard to the TFM calculation, the refraction at two interfaces was taken into account. The refractive points for each propagation path can be found by exploiting Fermat’s principle of least time followed by verifying whether the angle of incidence is less than the critical angle based on Snell’s law. The obtained TFM images showed an echo reflected at a notch on the inner wall of a pipe specimen, indicating correct focussing through the curved refraction interfaces.

1. Introduction

The full matrix capture (FMC) is a data acquisition strategy that utilises the capture of every possible transmit-receive combination for a given array transducer. The acquired data can be visualised with the total focusing method (TFM) which is a primary algorithm to reconstruct images from FMC waveform data (1). Although a variety of techniques regarding FMC and TFM for the inspection of objects with non-planar surfaces have been reported last few years, most of them are based on the immersion method in which testing parts are fully or partially immersed in liquid such as water, or the direct contact method by the use of a flexible array transducer capable of conforming to curved geometry. However, the applicability of these methods is sometimes limited from a practical point of view; some parts are not allowed to be immersed in water and/or inspection processes need to be performed as low-cost as possible. The aim of this study is to establish an efficient ultrasonic testing technique that enables fast and accurate inspection of objects that possess non-planar surfaces, and moreover, with as simple a sensor configuration as possible. As the first attempt, an application of FMC and TFM to welded pipe inspection was examined.

2. Theoretical Background

2.1 Sensor configuration for FMC pipe inspection
The schematic of the sensor configuration being developed in this study is shown in Figure 1. The diagram illustrates a configuration in the case of a butt welded joint between pipes. During inspection, a linear array transducer is mounted on a ring-shaped plastic wedge that is circumferentially set over the welded joint. In addition, another plastic jig is between the transducer and the wedge, so that the transducer can be circumferentially moved freely on the wedge along a guide groove. The gap between the ring-shaped wedge and welded joint surface is filled with gel as contact medium. In the FMC acquisition, an ultrasound wave is transmitted on one element and received on all elements; this process repeats until all elements have transmitted.

2.2 Propagation path calculation based on Fermat’s principle

As shown in Figure 2, most of the propagation paths of ultrasound waves in the sensor configuration in Figure 1 pass through three different parts: wedge, contact medium and pipe wall, with each part typically corresponding to plastic, gel and steel, respectively, in terms of material.

Thus, refraction at two interfaces between those materials is required to be taken into account in the TFM calculation. The refractive points at the material boundaries for
each propagation path can be found by exploiting Fermat’s principle of least time followed by verifying whether the angle of incidence is less than the critical angle based on Snell’s law (2). For each transmitter-receiver element pair, the propagation time $t_{ij}$ is given by

$$t_{ij} = \frac{d_{T1}}{c_1} + \frac{d_{T2}}{c_2} + \frac{d_{R3}}{c_3} + \frac{d_{R2}}{c_2} + \frac{d_{R1}}{c_1}$$

(1)

where $c_n$ is the sound speed in the $n$th layer, and $d_{Tn}$ and $d_{Rn}$ are the propagation distances in the $n$th layer along the transmission and receiving path, respectively. In this study, the refractive points were obtained by solving optimisation problem with the boundaries approximated as analytic functions. In addition, the TFM algorithm used here consists of two steps. At first, a curved profile of the weld part surface is extracted from a temporary TMF image reconstructed by using known information, i.e. the curved geometry of the wedge and sound speeds of the wedge and contact medium. In other words, only the refraction between the wedge and contact medium is considered in the first step. A complete TFM image can be successively obtained with taking into account not only the first refraction boundary but also the second one between the contact medium and pipe metal. The surface profile of the weld part obtained in the first step is utilised in the second step.

3. Experimental

In this work, a stainless steel pipe butt-welded joint with an outer diameter of 60 mm was used as shown in Figure 3. It has a notch produced by electrical discharge machining (EDM) on its inner wall in the heat-affected zone. The size of the notch was 5 mm length $\times$ 1 mm width and its depth was 0.5 mm. The transducer was a KGK 24 element linear array probe with 0.3 mm pitch and 10 MHz central frequency.

![Figure 3. Pipe specimen that has an EDM notch on its inner wall near butt-welded joint.](image)

4. Results
Figure 4 shows the longitudinal mode TFM images reconstructed from the FMC data recorded with the probe set just above and off the notch. Comparing Figures 3(a) and (b), an echo reflected at the top of the notch was clearly observed just above the back wall echo from the inner surface of the pipe in (a), while only a back wall echo was found in (b). The height of the notch was estimated at 0.5 mm, which agrees with the actual value, showing correct focusing through the curved refraction interfaces.

![Figure 4. TFM images reconstructed from FMC data recorded (a) above and (b) off a notch on the inner wall of the pipe specimen.](image)

5. Conclusions

The applicability of the FMC and TFM has been examined for objects with non-planar surfaces. The presented combination of the low-cost sensor configuration and algorithm allows for a fast and accurate inspection of pipe weld that has the curved geometry of a weld bead, while the conventional direct-contact phased array method would be problematic in terms of the contactability of an array probe with a non-planar surface.

References