Abstract
This paper proposes a three-dimensional (3-D) image reconstruction method for minute internal flaws. In this method, the transit times of flaw echoes obtained by scanning a highly point-focused ultrasonic beam are measured and used to synthesize the flaw image. The procedure of the method is as follows. Before scanning the point-focused transducer, the transit times of the echo from a point-reflector set through the vicinity of the transducer are computed theoretically as a function of the point-reflector position relative to the transducer position. This computation considers the size and curvature of the transducer. The actual transit times are then measured while scanning the transducer. After scanning, a 3-D flaw image is reconstructed from the measured transit times by reference to the computed function. This method was applied to acquire 3-D images of flaws (50μm-300μm) in steel sheets, and accurate images were successfully obtained.

Keywords: flaw imaging, three-dimensional image, focused ultrasonic beam, transit time, scanning

1. Introduction

In some types of steel products, such as bearing steels and steel sheets for can-making, even small internal flaws (100μm in diameter and below) are harmful. It is important not only to detect the flaws but also to evaluate their shapes, because the shape of the flaw has information on the cause of the flaw. Therefore, a 3-D shape evaluation technique for minute internal flaws is needed.

A widely-used conventional evaluation technique in this technical field is a C-scan imaging by using an ultrasonic focused beam. Though the flaw image obtained by the C-scan imaging, however, contains the information on the shape of the flaw, the 3-D shape of the flaw cannot be obtained by C-scan imaging. Although the use of the ultrasonic C-scan imaging is necessary for detecting the minute internal flaw, the technique is not enough for the evaluation of the internal flaw.

Another evaluation technique applicable to 3-D imaging is the synthetic aperture focusing technique (SAFT), but the conventional SAFT cannot be combined with the focused ultrasonic beam as described in the section 2.

Other signal processing methods have also been proposed [1],[2]. Although the latter method [2] proposed a synthetic aperture focusing technique combined with a weakly focused ultrasonic beam, the objective of the proposed technique is to improve the two dimensional resolution in the ultrasonic testing of large cast steel roll.

Therefore, the authors attempted to develop a new three-dimensional (3-D) image reconstruction method for minute internal flaws by use of a highly focused beam. This paper describes the new method with reference to the conventional SAFT, the procedure of the new method, and the experimental results.
2. Unapplicability of Conventional SAFT

Figure 1 illustrates the problem with applying the conventional SAFT to the image reconstruction using a highly focused beam. In the procedure of the conventional SAFT, each transducer is assumed to be a point signal source and a point detector. In the ultrasonic testing using the highly focused beam, however, the focused ultrasonic transducer does not work as the point transducer as shown in Figure 1. When the size of the flaw is much smaller than the diameter of the transducer and there are multiple paths of flaw echoes, the conventional SAFT cannot be applied.

![Figure 1. Problem with applying the conventional SAFT to the image reconstruction using a highly focused beam](image)

3. Procedure

Figure 2 shows the outline of the three-dimensional (3-D) image reconstruction method with a highly focused beam. In this method, before scanning of the ultrasonic transducer, the echo signal from the point reflector is computed on the basis of experimental setup. This computation considers the size and the curvature of the transducer. The transit time of the echo is obtained from the computed signal. Repeated computations are then made while changing the transducer position relative to the point-reflector. The upper row in Figure 2 shows results of this computation.

After the computation, the ultrasonic echo signals from a test piece are gathered by scanning the transducer, and the transit times of the flaw echoes are detected. The middle row in Figure 2 shows this procedure.

Finally, a flaw image is reconstructed using both the computed transit time 3-D profile and the measured transit times. The lower row shows this image reconstruction process.
3.1 Computation of transit time

Figure 3 shows a schematic diagram of the transit time computation method. Prior to the computation, the transducer is divided into many tiny elements virtually. The sizes of these elements need to be much smaller than the wavelength of the ultrasound transmitted and received by the transducer. Then, the acoustic field at the point-reflector is computed by computing the acoustic fields generated by each element of the transducer and superimposing them. The echo signal from the point-reflector is then obtained by computing the echo signals received by each transducer element and synthesizing them. Finally, the transit time is detected from the computed echo signal.
Figure 3. Transit time computation method
3.2 Reconstruction of flaw image

Figure 4 shows the outline of the flaw image reconstruction method. Before starting the reconstruction procedure, a virtual 3-D test block which is used to project the flaw image and is divided into many small volumetric elements is prepared. The 3-D virtual test block is allocated in a PC memory and each volumetric element can be referred by the inherent memory-address of it. Each memory is used as a counter which is used to show the probability that the element is the part of the outer surface of the flaw and is initialized to zero.

For each actual measured value of transit time, an appropriate transit time 3-D profile is determined on the basis of actual measured value of the transit time and 1 is added to the counters of the elements that are involved in the determined transit time 3-D profile. After the whole procedure, the flaw image is reconstructed by using the counted values.

Figure 4. Flaw image reconstruction method
4. Experimental results

Figure 5 shows a schematic diagram of the experimental system. A transducer, 50 MHz in frequency, 6 mm in diameter, and 12 mm in focal length was used. The sampling frequency of the A/D converter was 1 GHz.

Figure 6 shows the image reconstruction results of a side drilled hole 300μm in diameter in a carbon steel sheet 5mm in thickness. The figure shows that the developed image reconstruction method provides an accurate image of a minute flaw. Figure 7 shows the results of applying this method to the 3-D imaging of minute flaws which exist in actual carbon steel slabs. As the figure shows, the images reconstructed by the developed method corresponded roughly to the optical micro-graph images.

![Figure 5. Schematic diagram of experimental system](image)

![Figure 6. Results of image reconstruction](image)
5. Conclusions

A three-dimensional (3-D) image reconstruction method for minute internal flaws using the highly focused ultrasonic beam has been developed. Experiments were performed with flaws in steel products, demonstrating that this method is effective for 3-D imaging of minute flaws. As a future work, the authors are planning to apply this method to evaluating internal flaws in various steel products.

References