Time of flight diffraction imaging for double-probe technique

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Abstract

Due to rapid progress in microelectronics and computer technologies, the system evolving from analog to digital, and a programmable and flexible synthetic aperture focusing technique (SAFT) for the single-probe pulse echo imaging technique of ultrasonic nondestructive testing (NDT) become feasible. The double-probe reflection technique is usually used to detect the non-horizontal flaws in the ultrasonic NDT. Since there is an offset between the transmitter and receiver, the position and size of the flaw can not be directly read from the image. Therefore a digital signal processing (DSP) imaging method is proposed to process the ultrasonic image obtained by double-probe reflection technique.

In the imaging, the signal is redistributed on an ellipsoid with the transmitter and receiver positions as focuses, and the traveltime sum for the echo from the ellipsoid to the focuses as the traveltime of signal. After redistributing all the signals, the useful signals can be constructively added in some point where the reflected point is; otherwise the signals will be destructively added. Therefore, the image resolution of the flaw can be improved and the position and size of the flaw can be directly estimated from the processed image.

Based on the experimental results, the steep flaw (45°) cannot be detected by the pulse echo technique but can be detected by the double-probe method and the double-probe B-scan image of 30° tilted crack is clearer than the pulse echo B-scan image. However, the flaw image departs from its true position greatly. After processing, the steep flaw image can be moved to its true position. When the flaws are not greater than the probe largely, the sizes of the flaws are difficult to be discriminated in both pulse echo and double-probe B-scan images. In the processed double-probe B-scan image, the size of the flaws can be successfully estimated and the images of the flaws are close to their true shape.

I. INTRODUCTION

In the ultrasonic nondestructive testing (NDT), the single-probe pulse echo technique is the most commonly used method to detect flaws and to evaluate the physical properties of the materials. The synthetic aperture focusing technique (SAFT), time of flight diffraction (TOFD) and tomography are the modern methods of processing ultrasonic data for imaging the detected flaws. Due to rapid progress in computer technology, a programmable and flexible SAFT, TOFD and tomography for ultrasonic imaging becomes feasible. The system evolves from analog devices with delay line beamformers to digital beamforming system [1], [2].

A detailed theory of acoustic imaging can be found in textbooks [3]. A summary of the research of acoustic imaging made by IEEE is in [4]. An experimental synthetic aperture system combining holography and B-scan was designed for improving the medical image resolution [5]. The ultrasound holographic imaging method processing in frequency domain for enhancing the lateral resolution was used in ultrasonic NDT [6]. The earliest real-time digital imaging system was proposed in the early 80's. An image is obtained by drawing circles around the
individual probe positions with radii calculated from the first-arrival times of echoes reflected from the flaw by a computer [7]. A portable system for the reconstruction of the flaw image in near real time was devised and tested for ultrasonic NDT [8]. Ylitalo et al. introduced an ultrasound holographic B-scan imaging, which reconstructed the medical image by numerically backpropagating with correction for curvature distortion in the frequency domain [9]. A monostatic ultrasound synthetic aperture method reconstructed the medical image in the frequency domain using the FFT-algorithms that can improve considerably the image dynamical resolution [10]. The focus of the transducer is treated as a virtual source and the virtual source is assumed to produce approximately spherical waves over a certain aperture angle for synthetic aperture processing, which can improve lateral resolution beyond the focus of the transducer [11], [12]. If the flaw is not a horizontal planar flaw, the position and size of the flaw in the image may be incorrectly shown. The image resolution can be enhanced and the position and size of the flaw in the image can be estimated more accurately by the seismic migration methods [13], [14].

Since the beam width of the transducer is not wide enough to detect the steep flaw, in [13] and [14], the 30° tilted planar flaw images are noise and the 45° tilted planar flaw could not be detected by the single-probe technique. Also, the different size through holes could not be resolved in their original and processed pulse echo B-scan images [13]. Thus the double-probe ultrasonic techniques are used to detect the non-horizontal flaw [15]. But the position and size of the non-horizontal flaw can not be directly read from the image. Therefore the image must be further processed for improving the image resolution and estimating the position and size of the flaw.

In this study a double-probe reflection ultrasonic NDT imaging technique, which is a digital signal processing (DSP) method, is proposed to process the ultrasonic data. This imaging method can improve the image resolution and move the anomaly image from its apparent position to its true position. In the following, the theory of the double-probe reflection imaging technique is explained. Then, the physical experiments are performed. Finally, a brief discussions and conclusions are given.

II. THEORY

Ultrasonic image can be processed in the time domain [2], [7], [12], [14] or in the frequency domain [6], [8]-[11], [13]. In the time domain, the processing is simple and less limited. On the other hand, in the frequency domain the processing is fast and efficient. In order to understand the imaging theory easily and to process the ultrasonic image facilely, in this study the time domain processing method is adopted to verify this double-probe reflection imaging technique.

If pulse echo technique is used to detect a point scatter in a homogeneous object, the possible locations of the point scatter will be located on a sphere using the probe position as center with radius calculated from the first-arrival time of the echo reflected from the scatter [7], [14]. When the double-probe reflection imaging technique is performed, the possible locations of the point scatter will be located on an ellipsoid with the transmitter position and receiver position as focuses and the traveltime sum for the echo from the ellipsoid to the focuses as the traveltime of signal [16]. Fig. 1 shows the concept of imaging. Transmitter 1 (T1) transmits and receiver 1 (R1) receives, and the possible locations will be located on the ellipsoid 1 (E1). Then the probes are moving forward, and transmitter 2 (T2) transmits and receiver 2 (R2) receives, and the possible locations will be located on the ellipsoid 2
and so on. Consequently the position of the point scatter will stand out in the image where the crossed point of the ellipsoids is.

In a Cartesian coordinate, the ellipsoid can be expressed as

\[(V \cdot t)^2 = (T(x, y, z) - S(x, y, z))^2 + (R(x, y, z) - S(x, y, z))^2 \quad (1)\]

where \(T(x, y, z)\) and \(R(x, y, z)\) are the positions of transmitter and receiver, respectively, \(S(x, y, z)\) is the possible locations of the point scatter, \(V\) is the longitudinal wave velocity of the object and \(t\) is the time.

In the ultrasonic tomography methods, the received signals are redistributed into the grided sub-area in order to get constructively or destructively added signals [17], [18]. In this study, a similar technique was adopted. During the processing, it is not necessary to pick the first arrival times of the signals. The target area of the point scatter is grided and we redistribute the received signals into the grided sub-area according Eq. (1). Since the signals are coherent and the noises are random, the signals in the grided sub-area can be constructively added if the point scatter is located in it, otherwise the signals will be destructively added [16].

Figure 2 shows a synthetic double-probe B-scan image for a point flaw and the processed image. Fig. 2a is the model of a point scatter located at depth 10 mm and is scanned by double-probe reflection technique. The offset between the probes is 10 mm and the longitudinal wave velocity of the object is 6356 m/sec. The echo diffracted from the point scatter is simulated with one cycle 5 MHz sine wave. If the echoes detected by the double-probe reflection technique are the waves reflected from the points, located at the middle points between the probes, then the time axis of the B-scan image can be transformed to depth axis. Fig. 2b is the synthetic B-scan image and its time axis has been transformed to depth axis. A point scatter shown in the synthetic B-scan image is a hyperbolic curve. The point scatter shown in the processed synthetic B-scan image (Fig. 2c) is more like a point and is located on X = 25 mm and depth = 10 mm, which is its true position. But the size of the point scatter in the image is about 2 mm, which is greater than the zero size of the point scatter. This is because the wavelet is one cycle 5 MHz sine wave, not infinitely small, and this size error effect can be improved using the deconvolution method [19] [20] for compressing the wavelet.

III. EXPERIMENTS

A schematic of the experimental system to detect a non-horizontal flaw using the double-probe reflection technique is shown in Fig. 3. Since the flaw is not a horizontal one, the echo reflected from the flaw will never come back to the transmitter. Therefore, double-probe method must be adopted to receive the reflected echo, in which the receiver is slightly offset from the transmitter. A pulse-receiver (Panametrics 5058PR) in pulse/echo mode is used to generate the 100 V monocycle pulse, which excites the transducer, and receives the signal. The received signal is displayed on a digitizing oscilloscope (Tektronix TDS20). The PC retrieves the digitized RF waveforms from the oscilloscope via IEEE-488 communications, stores, and processes them. A pair of 5 MHz and 3 mm diameter transducers (Panametrics V1091) are used to transmit and receive data.

Three specimens are fabricated and scanned, and the images are processed for verifying this imaging technique. The offset between the probes is 10 mm. In order to compare the double-probe B-scan image with the pulse echo B-scan image, the same probe was also used to perform the pulse echo B-scan. The scanning interval in space is 1 mm in the following experiments. The longitudinal wave velocity of the specimens (duralumin) is 6356 m/sec and the scan is done by hand.
1. **30° tilted crack**

A duralumin block 30 mm in height, 30 mm in wide and 150 mm in length, with a 30° tilted planar crack cut at the center, is shown in Fig. 4a. The pulse echo B-scan image is shown in Fig. 4b and the formula “depth = traveltime/2. × velocity” is used to transform the time axis into the depth axis. For a double-probe B-scan image, if we do not know the crack previously and assume the echoes we detected are the waves reflected from a horizontal planar crack, the time axis of the B-scan image can be transformed to the depth axis. The double-probe B-scan image is shown in Fig. 4c and the time axis has been transformed to the depth axis. The image (Fig. 4c) is clearer than Fig. 4b and those reported using pulse echo technique [13][14]. The dashed line in the image is the true position of crack. The multi-reflections, which reflect between the top surface of the specimen and the crack, can be seen below the crack image (Fig. 4b and 4c). The processed image is shown in Fig. 4d and the crack image has been perfectly moved to its true position. Since all the signals in the double-probe B-scan image are redistributed on ellipses and they cannot be destructively added everywhere especially for the area above the crack image, there are weak concentric ellipses present in the background of the processed image. The multi-reflections do not follow the equation of ellipse of the reflected waves from the flaw; therefore they can be focused and they are very weak in Fig. 4d.

2. **45° tilted crack**

A 45° tilted planar crack cut at the center of the specimen is shown in Fig. 5a. The pulse echo B-scan image is shown in Fig. 5b. Since the beam width of the transducer is not wide enough, the 45° tilted planar crack could not be detected in Fig. 5b and in [13][14] by pulse echo technique. In Fig. 5b, only the back-wall echoes reflected from the bottom of the hanging-wall of the crack are observed. But it can be seen in the double-probe B-scan image (Fig. 5c). In Fig. 5c the time axis has been transformed to depth axis. The dashed line is the true position of crack. The position of deeper part of the crack is more departed from the true crack position than the shallower part of the crack. In addition, the contrast between the apparent position and true position of the crack in the image will be enlarged when the tilted angle is increased when comparing Figs. 4c with 5c. The multi-reflections can be still seen in Fig. 5c. The processed image is shown in Fig. 5d and the crack image has been exactly moved to its true position. The multi-reflections are weakened and there are weak concentric ellipses background in the processed image.

3. **Different size flaws**

If the size of the flaw is smaller than the wavelength of the echo and the size of the transducer, the flaw in the B-scan image will be like an “umbrella”. It is the waves diffracted from the flaw. The size of the flaw is not always correlated to the size of the "umbrella". Therefore, it is difficult to estimate the size of the flaw from the B-scan image directly [13].

A specimen with 5 through-holes and their diameters are 5, 4, 3, 2 and 1 mm, respectively, and with depths of the center of the holes 10 mm (Fig. 6a) was scanned. The pulse echo and double-probe B-scan images are shown in Fig. 6b and 6c, respectively. In both images, the time axes have been transformed to the depth axes. The Fig. 6c looks noisier than the Fig. 6b and the “umbrellas” in Fig. 6c extend for a longer distance than those in Fig. 6b. This means that the pulse echo technique can only show detail of the top area of the holes, and the more information of the hole can be obtained using the double-probe technique than the pulse echo technique. The reflected echoes in Fig. 6c are lower frequency than those in Fig. 6b. Even though the
diameters of the through-holes are different, the sizes and curvatures of the 5 “umbrellas” are almost the same in the images except that the echoes reflected from the smallest hole are weakest than the others. Therefore it is difficult to evaluate the sizes of the holes from the B-scan images directly as in the case [13]. The multi-reflections, which reflect between the top surface of the specimen and the holes, can be seen below the main “umbrellas”. The difference in traveltimes between the main “umbrellas” and multi-reflections becomes larger, and the amplitudes of the multi-reflections turn into smaller as the hole is smaller.

The processed image is shown in Fig. 6d. The sizes of hole image decrease from left to right that is in accordance with their sizes. Since the wavelet used in this study is not a spike, they cannot be focused on a point but an area. However, the sizes of hole image can more truly associate with their sizes except the 1 mm diameter hole image.

**IV. DISCUSSIONS**

The computer is not fast enough to process the ultrasonic data real time in this study, a processing step is needed before the processed image is obtained. But the optical focusing technique [5][6][21] can be useful for real time displaying of the flaw image. However, the reconstruction of flaw image in real time (or near real time) using a computer may be available soon with the rapid progress in computer technology.

If the transducer has a narrow sound beam, only a few area beneath the transducer can be illuminated and only a small portion of the signal reflected from the area will be included in the imaging. Therefore the amount of summation in each grided sub-area is too small to add the signals constructively and to add the noises destructively. In the extreme case, if the sound beam is a line thus a point scatter will be a point in the image, and then the point image will be processed as a half of ellipse in the processed image using this imaging technique, which means that this imaging technique cannot achieve good lateral resolution if the sound beam is narrow.

On the other hand, if the sound beam is broad, then not only the double-probe method but also the pulse echo method can detect the tilted reflectors. That means that the ultrasonic energy is distributed over a wide angular range and a lot of information beneath the probes can be received, although the information may be very weak, complex and not easy to use. Owing to the fast advancement in DSP and computer technology, it becomes possible for us to process the weak and complex signal transmitted and received by broad sound beam transducers. After processing, the image resolution can be enhanced.

The quality of the pulse echo B-scan image for detecting the horizontal flaw (or near horizontal flaw) will be better than the double-probe B-scan image because the dominant ultrasonic energy radiated from the transducer usually propagate along the axis of the transducer. A comparison between the pulse echo and double-probe B-scan images for a 15° tilted crack (not show in this paper) is consistent with this conclusion but the 15° tilted crack can be still seen in the double-probe B-scan image. The apparent position of a near horizontal crack in an image is close to its true position, therefore it is not necessary to do further processing for correcting the crack image. Nevertheless, the diffracted waves diffracted by the tips of the crack can be removed to the tips of the crack in the image after processing that is useful for estimating the size of the flaw.

The angle beam probe can be used to detect the steep flaw, but this method is not so good for detecting the horizontal (or near horizontal) flaw and the tilted flaw
with a tilted angle as the beam probe. The various types of flaws may exist in a sample, or for reconnaissance in previously untested sample, the double-probe with a broad sound beam technique will has higher probability for successful detecting the flaws than the pulse echo and angle beam probes techniques. If the type of the flaw has been known before testing, then the appropriate techniques can be adopted for getting the maximum reflected energy from the flaw and the associated imaging methods can be used to do further processing.

The value of offset, which is the distance between the probes, used in the scanning depends on the tilted angle of the flaw (or curvature of the flaw), beam width of the probe and the depth of flaw. The conception is sketched in Fig. 7, where T is the transmitter. Two offsets (O1 and O2) of double-probe technique are used to scan a sphere flaw; the reflected points on the sphere for the echoes to receiver 1 (R1) and receiver 2 (R2) are P1 and P2, respectively. The figure shows that the larger offset method can detect the deeper part of the sphere. This is the same for the tilted flaw, the steeper flaw need using a larger offset method to detect. The angle of beam spread of the transducer is 24° reported by Panametrics and the offset is 10 mm used in this study, these are enough to detect 5-30 mm depth, 30°-45° tilted flaws and 10 mm depth, 1-5 mm diameter through holes.

In array imaging, weighting the individual elements is known as apodization. In the synthetic aperture, the hyperbolic curvature compensation method is usually used to compensate for the amplitudes of the echoes diffracted from a point scatter in the B-scan image [9], which is a DSP apodization. The apodization has not been used in this preliminary study. The amplitudes of the echoes reflected from the deep part of tilted crack are weaker than those reflected from the shallow part and the amplitudes of the echoes diffracted from the point scatter in B-scan image are very different. Therefore the image resolution may be further improved if the apodization is applied in processing especially for the deep part of the tilted crack and the small diameter through hole.

The mono-offset method scans the flaw in each depth using a shooting angle, however, the multi-offset method uses multi-shooting angles. Consequently the flaw in a certain depth can be more clearly estimated by the multi-offset method. But it is still impossible to figure out the shape of the hole completely from finite shooting angles except if one uses in addition of the information of the sound paths between probes, back-wall and flaw. Especially for the reflection method, only the top area of hole can be illuminated. Therefore in the image (Fig. 6) only the top area of the hole can be figured out.

V. CONCLUSIONS

In this study a double-probe reflection ultrasonic NDT imaging method is proposed to detect the non-horizontal flaws and to process the image, and this method is verified and tested by laboratory experiments.

The tilted crack images (30° and 45°) can be moved to their true positions after processing. The sizes of through holes are difficult to estimate in the B-scan image but they can be evaluated in the processed image, and the hole images in the processed image are more similar to their true shape than those in the B-scan image, which are “umbrellas”.

REFERENCES


FIGURE CAPTIONS

Figure 1 Double-probe reflection imaging technique for detecting the non-horizontal flaw by intersection of ellipsoids. Transmitter 1 (T1) and receiver 1 (R1) are the double-probe pair. T2 and R2 are the same pair but move forward. E1 and E2 are the ellipsoids using T1, R1 and T2, R2 as the focuses, respectively.

Figure 2 Numerical model of a point scatter for testing the double-probe reflection imaging technique. (a) point scatter model, (b)synthetic B-scan image, (c) processed synthetic B-scan image.

Figure 3 Block diagram of the experimental system for detecting the non-horizontal flaw. T is the transmitter and R is the receiver.

Figure 4 The 30° tilted crack specimen was fabricated and scanned, and the double-probe B-scan image was processed using the double-probe reflection imaging technique. The dashed lines are the true positions of crack. (a) configuration of the specimen, (b) pulse echo B-scan image, (c) double-probe B-scan image, (d) processed double-probe B-scan image.

Figure 5 The 45° tilted crack specimen was fabricated and scanned, and the double-probe B-scan image was processed using the double-probe reflection imaging technique. The dashed lines are the true positions of crack. (a) configuration of the specimen, (b) pulse echo B-scan image, (c) double-probe B-scan image, (d) processed double-probe B-scan image.

Figure 6 The 1-5 mm diameters through holes specimen was fabricated and scanned, and the double-probe scan image was processed using the double-probe reflection imaging technique. (a) configuration of the specimen, (b) pulse echo B-scan image, (c) double-probe B-scan image, (d) processed double-probe B-scan image.

Figure 7 A concept of a large offset for detecting the deeper part of the sphere and a steep flaw. O1 and O2 are the offsets for transmitter (T) to receiver 1 (R1) and receiver 2 (R2). P1 and P2 are reflection points on a spherical flaw for the echoes reflected to R1 and R2, respectively.
(a) Diagram showing transducers and point scatter with dimensions labeled in mm.

(b) Graph showing depth versus X (mm) with a central focus point.

(c) Graph showing depth versus X (mm) with a series of concentric circles indicating point scatter.
personal computer

IEEE 488

oscilloscope
(Tektronix TDS420)

pulser/receiver
(Panametrics 5058PR)

flaw

R

T
(a) Diagram showing a cracked object with transducers at 30° and a unit of mm.

(b) Graph showing depth vs. X (mm) with a linear trend.

(c) Graph showing a 30° crack with transducers at 30°.

(d) Graph showing another 30° crack with transducers at 30°.

Unit: mm
(a) Diagram showing a 45° crack with transducers and unit: mm.

(b) Plot showing depth vs. X (mm) with a linear trend.

(c) 3D representation of a crack with depth vs. X (mm).

(d) Another 3D representation showing a crack with depth vs. X (mm).
transducers
through holes (diameters 5, 4, 3, 2, 1 mm)

(a)

(b)

(c)

(d)