Image Enhancement of Simplified Ultrasonic CT Using Frequency Analysis Method

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In this paper, a simplified ultrasonic CT system, which uses the information in three directions, that is, 90°, +45° and −45° about the inspection plane, is applied to the high strength steel, and the frequency analysis method for enhancing the C scan or CT image is developed. This frequency analysis method is based on the frequency response property of the material. By comparing the magnitudes in the frequency domain, the special frequency which shows a significant difference between the welded joint and base material was found and used to obtain a C scan or CT image. Experimental results for several kinds of specimens, having a welded joint by electron beam welding, a weld joint by arc welding, on a fatigue crack, showed that the obtained C scan or CT image has better resolution than the results of previous experiments using the maximum value of the received waveform.

Key Words : Simplified Ultrasonic CT (Computerized Tomography), C Scan Image, CT Image

1. Introduction

The sound attenuation in materials is one of the key parameters used for detecting and sizing flaws in ultrasonic non-destructive testing. The degree of attenuation is known to be dependent on distributed flaws, crystal grains and other micro structural non-uniformities. This suggests the possibility that micro structural properties could be characterized by analyzing the attenuation process. The sound attenuation of a material is usually quantified as the attenuation coefficient of an impulse wave having frequencies of narrow band and is determined from the decreasing rate of successive bottom echoes in the plate specimen (Birks, 1991 ; Matsumoto and Kimura, 1971).

Using this sound attenuation in material as a new measurement method to estimate the welded joint or change of material condition, a simplified ultrasonic CT system was developed (Kim, et al., 2001). The simplified ultrasonic CT system uses the information in −45° and +45° directions about the inspection plane as well as that in the perpendicular direction about the inspection plane. Performance of the simplified ultrasonic CT was confirmed through specimens with a simple defect and several specimens with a welded joint. While the obtained CT images were similar to the actual image, there is some problem, in resolution of the C scan or CT image. In the previous paper, the maximum amplitude of the first bottom echo was used to draw the C scan or CT image. Because the sound attenuation in the base metal and welded joint or defect part is different, the change of the maximum amplitude was used.

One of the ways to test materials of attenuation is to look at the frequency response of the plate

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specimen (Papoulis, 1987). In this paper, we applied this property to a simplified ultrasonic CT. The amplitude of a special frequency component which shows larger amplitude than another frequency component is first found and used to draw for the C scan or CT image. The theoretical basis is first introduced to evaluate the sound attenuation in the frequency domain due to crystal grains of a metallic material. It has been shown that this new method is sufficiently effective in enhancing the resolution of the C scan or CT image and may eventually be used to determine the micro structural properties such as the grain size in the high strength material.

2. Theoretical Background of Frequency Analysis

As in Fig. 1, we consider a system to measure attenuation due to microstructure in materials and will call it an attenuation system. In the system theory, if an input signal $f(t)$ in the time domain enters a system, the output signal $g(t)$ can generally be obtained by the following equation (Papoulis, 1987),

$$g(t)=\int_{-\infty}^{\infty} h(t)f(t-\tau)\,d\tau, \text{ or } g(t)=h(t)*f(t) \quad (1)$$

where $h(t)$ is the impulse response and mark $*$ designates the convolution integral. By Fourier transformation it can be expressed in the frequency domain,

$$G(\omega)=H(\omega)\cdot F(\omega) \quad (2)$$

where ω is the angular frequency, $\omega=2f\pi$. $H(\omega)$

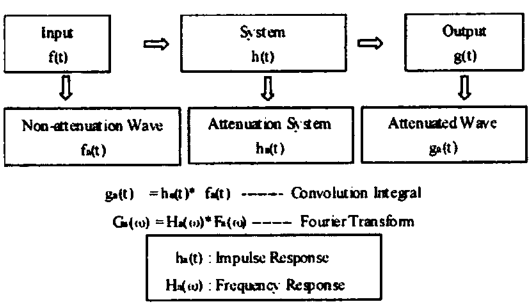


Fig. 1 Attenuation system

is called the frequency response or system function.

Eq. (2) can be rewritten in terms of the amplitudes $G_0(\omega)$, $H_0(\omega)$ and $F_0(\omega)$, phases $p_g(\omega)$, $p_h(\omega)$ and $f_f(\omega)$.

$$G_0(\omega)\exp[ip_g(\omega)]$$
$$=H_0(\omega)\exp[ip_h(\omega)\cdot F_0(\omega)\exp[ip_f(\omega)]]$$

when, we consider the attenuation system composed of crystal grains in a metal plate, the frequency $H_a(\omega)$ of the attenuation system can be obtained as

$$H_a(\omega)=G_a(\omega)/F_a(\omega)$$

where $F_a(\omega)$ represents the input function to the system. $F_a(\omega)$ is equivalent to the output function of an ideal material where crystal grains are infinitely fine and no attenuation is observed. $G_a(\omega)$ is the output function of any material with any grain sizes, but it always has the same distance of sound propagation as the ideal one. The equation can be rewritten in terms of amplitude and phase, and we obtain a final expression :

$$H_{0a}(\omega)\exp[ip_h(\omega)]=\frac{G_{0a}(\omega)\exp[ip_g(\omega)]}{F_{0a}(\omega)\exp[ip_f(\omega)]} \quad (3)$$

It is considered that the frequency response is represented by the decrease of echo height in the ultrasonic attenuation measurement. The attenuation coefficient with respect to the frequency can be obtained as

$$\alpha_a(\omega)=\frac{20}{L}\log_{10}\left[\frac{1}{H_{0a}(\omega)}\right] \quad (4)$$

where $\alpha_a(\omega)$ is the attenuation coefficient(dB/cm) and L is the ultrasonic sound propagation distance(cm) in the test material.

3. The Simplified Ultrasonic CT and Specimen

Figure 2 shows the simplified ultrasonic CT system developed in a previous research (Kim, et al., 2001), and the position of the longitudinal sensor was on the opposite side of the shear sensor. However, in the present study, the positions of the longitudinal and shear sensor are on the same side so that the experiment can be performed on one side. This system is applied to evaluate high strength steel. First, in order to find the special frequency which shows a large difference in waveform between the welded joint and base material, the specimen was are welded as shown in Fig. 3 (a). This specimen is made of SM 50(JIS G 3106, 1999). Figure 3 (b) illustrates the specimen with the welded joint by electron beam welding. For the purpose of comparison, this specimen was made of SM 50 and NRIM (National Research Institute for Metals) Material No. 11 (Nakajima, 2000). Figure 3(c) shows the specimen with welded joint by electron beam welding having a fatigue crack. The original size of this specimen was 17 mm×17 mm×100 mm. After electron beam welding, the specimen was fatigued in MTS. After the fatigue experiment, this specimen was then cut to the same size with another specimen. This specimen was also made by SM 50(JIS G 3106, 1999) and NRIM(National Research Institute for Metals) No. 7 for comparison.

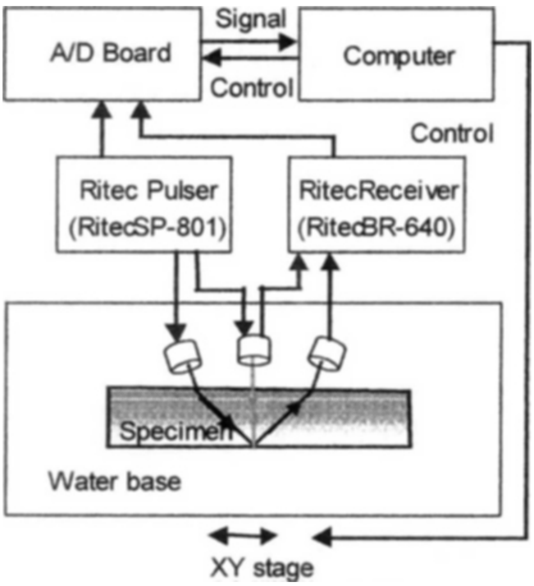


Fig. 2 The construction of simplified ultrasonic CT system

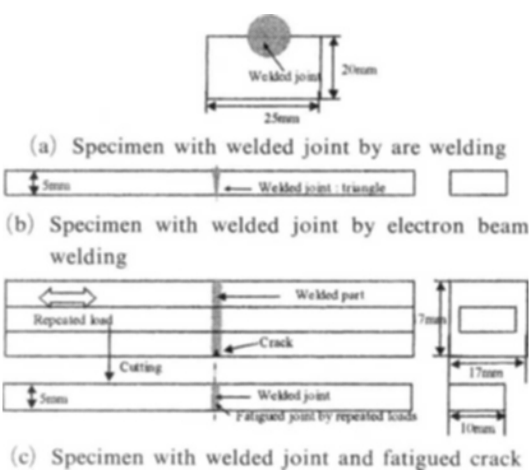


Fig. 3 Specimens with welded joint

4. Selection of Proper Frequency and Application to High Strength Steel

4.1 Selection of special frequency

In order to search for the frequency at which the amplitude change is large, the Fourier transformation of the received waveform at base material and welded joint of the specimen with welded joint by arc welding of Fig. 3(a) was conducted, and the result is illustrated in Fig. 4.

In this case, the maximum value in the Fourier

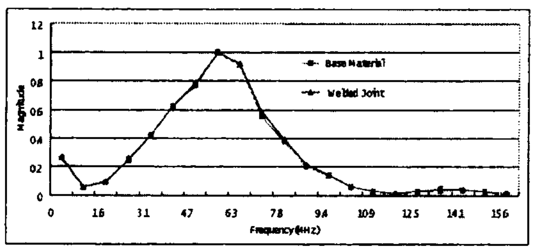


Fig. 4 The Fourier transformation of a received waveform at the base material and welded joint

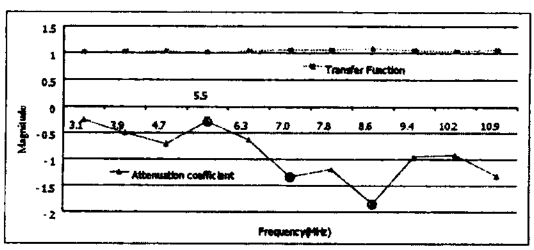
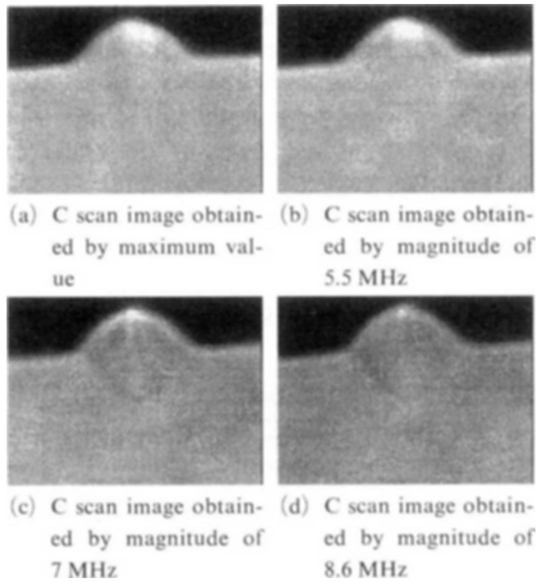


Fig. 5 The transfer function and attenuation coefficient between the welded joint and base material

transformation domain was normalized for comparison. The magnitude of Fourier transformation at the welded joint is larger than that at the base material over the range of 6-9 MHz because the grain size at the welded joint is larger than that at the base metal. In order to confirm this relation, the transfer function and attenuation coefficient in the frequency domain of Eq. (4) were obtained as shown in Fig. 5.

We assume that the first echo received from the base material of the specimen with the welded part by arc welding of Fig. 3 (a) is input signal $f_{0a}(t)$ and the first echo received from the welded joint of the same specimen is output signal $g_{0a}(t)$. Since the frequency at which the amplitude is maximum is found from Fig. 5, the magnitude of this frequency component is used to draw a C scan or CT image. In this case, the attenuation coefficient becomes a minus value because all values in the frequency domain are normalized by a maximum value.



(a) C scan image obtained by maximum value (b) C scan image obtained by magnitude of 5.5 MHz (c) C scan image obtained by magnitude of 7 MHz (d) C scan image obtained by magnitude of 8.6 MHz

Fig. 6 The C scan image for the specimen with welded joint by arc welding

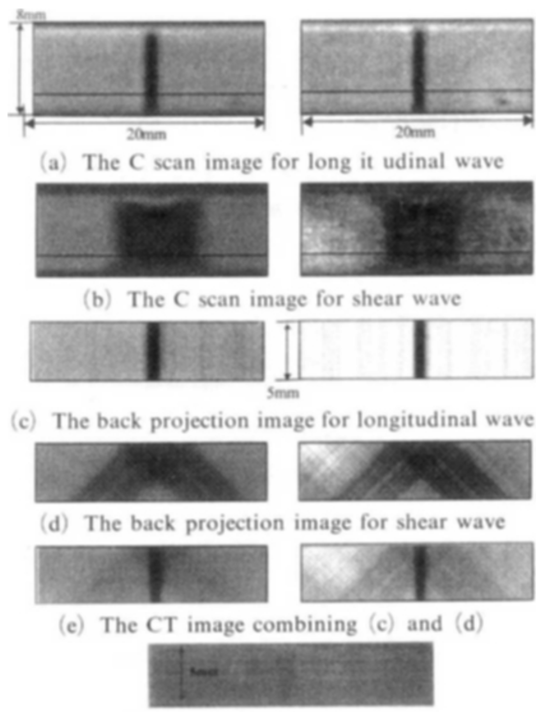
4.2 C scan image using the selected frequency

In order to confirm that this selection method is useful, three arbitrary frequencies including the selected frequency were used to make the C scan image. In Fig. 5, these frequencies are marked by circles.

In Fig. 6, (a) shows the result of previous research which used the maximum amplitude; (b), (c) and (d) show the C scan image using the frequency component of 5.4, 7 and 8.6 MHz, respectively. Since the best CT image is obtained at the selected frequency, the amplitude at 8.6 MHz is used to draw the C scan or CT image of high strength steel.

4.3 Application to high strength steel

Experimental results for specimens of Figs. 3 (b) and (c) were obtained and they are shown in Figs. 7～10. Figure 7 shows the experimental result for the specimen with the welded joint by electron beam welding of Fig. 3 (b).



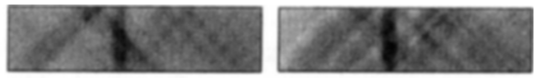
(a) The C scan image for long it udinal wave
(b) The C scan image for shear wave
(c) The back projection image for longitudinal wave
(d) The back projection image for shear wave
(e) The CT image combining (c) and (d)
(f) The photo of specimen

Fig. 7 The experimental result for specimen with welded joint by electron beam welding (SM50)

Figures 7 (a) and (b) show the C scan image or projection image for longitudinal and shear wave, respectively. In (a) and (b), the horizontal

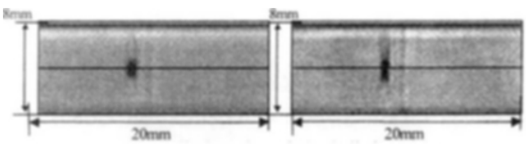
(a) The CT image using information in 3 directions (Previous result) (b) The CT image using information in 3 directions (New result)

Fig. 8 The experimental result for specimen with welded joint by electron beam welding (NRIM material No. 11)

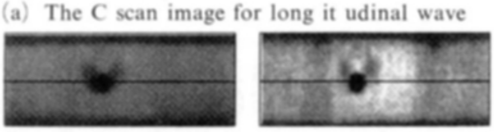


(a) The CT image using information in 3 directions (Previous result) (b) The CT image using information in 3 directions (New result)

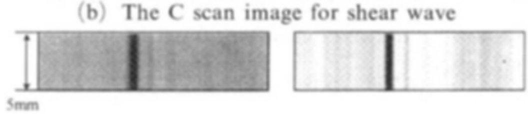
Fig. 10 The experimental result for the specimen with welded joint by electron beam welding and fatigued crack (NRIM material No. 7)



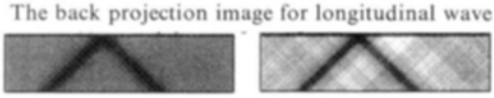
(a) The C scan image for long it udinal wave



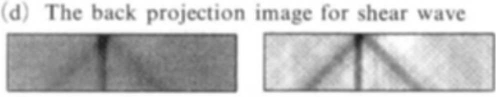
(b) The C scan image for shear wave



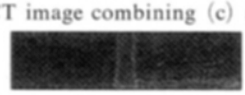
(c) The back projection image for longitudinal wave



(d) The back projection image for shear wave



(e) The CT image combining (c) and (d)



(f) The photo of specimen

Fig. 9 The experimental result for the specimen with the welded joint by electron beam welding and fatigued crack (SM 50)

line shows the line to make the back projection image of (c) and (d). Furthermore, (c) and (d) show the back projection image of (a) and (b), respectively. Also, (e) shows the CT image which is made by combining the image in (c) and (d). In Fig. 7, the C scan image and CT image obtained by the previous method, which uses the maximum value(left), is shown to compare with that by the new method(right). The result using the amplitude of the special frequency is more distinct in the resolution. For its applicability to high strength material, this method is applied to the NRIM material No. 11 which has similar electron beam welding to the one in Fig. 7. Figure 8 shows the experimental result.

Figure 8 (b) shows the condition of electron beam welding and is very similar to Fig. 7. It is thus confirmed confirm that the proposed method using the frequency analysis method is effective in drawing a C scan or CT image.

The experimental result for the specimen with the welded joint by electron beam welding and fatigue crack of Fig. 3 (c) is shown in Fig. 9.

In Fig. 9(b), the thick line at the center shows the welded joint, which is faintly represented. The fatigued part is seen near the border line of the welded joint. The degree of fatigue seems to be high in the upper part. Comparing with the previous method, the fatigue part is observed more clearly by the present method. Figure 10 shows the experimental result for the specimen made of the NRIM material No. 7 which has similar electron beam welding and a fatigue crack to the one in Fig. 9.

Similarly, the shape of the fatigued part is detected more clearly by this method.

From these results, the method using the special frequency at which the amplitude is maximum, is a very effective way of obtaining better images.

5. Conclusion

The simplified ultrasonic CT was modified so that the positions of the longitudinal and shear sensor are on the same side.

In order to enhance the image of the simplified ultrasonic CT, we checked the Fourier transformation of first bottom echo. We know that the magnitude of the Fourier transformation of the first bottom echo changes according to the frequency and the component of material. This amplitude change between the base material and the welded part was maximum, not in central frequency but in special frequency. In order to obtain a large contrast, we selected one frequency which had the biggest difference in amplitude.

The selected frequency was used to make the C scan image. The obtained CT image using the magnitude at the selected frequency produced a better image than the image obtained by the previous method or the image obtained using other frequencies.

From the experimental results using high strength steel, we have learned that the method using the special frequency at which the amplitude is maximum is very effective in getting a better image than the previous method which uses the maximum value of the received waveform. This new method may eventually be used to determine the micro structural properties such as the grain size in high strength material.

References

Birks, A. S., 1991, *Nondestructive Testing Handbook 7 : Ultrasonic Testing*, ASNT.

JIS G 3106, 1999, *Rolled Steels for Welded Structures*.

Kim, K. C., Fukuhara H. and Yamawaki, H., 2001, "The Development of Simplified Ultrasonic CT System and its Application to the Evaluation of Weld Metal," *KSME International*, Vol. 15, No. 1, pp. 52～60

Matsumoto, S. and Kimura, K., 1971, "Relation Between Grain Size and Attenuation Coefficient of Austenitic Stainless Steel and Iron," *J. JSNDI*, Vol. 20, pp. 283～291 (In Japanese).

Nakajima, H., 2000, "Tensile and Impact Properties of Low Ferritic Ultrafine-Grained Steels," *Current Advances in Materials and Processes-Report of the ISIJ Meeting*, Vol. 13, p. 454 (In Japanese).

Papoulis, A., 1987, *The Fourier Integral and its Applications*, Mc Graw-Hill, p. 81.