Development of Flaw Visualization Technique at Near Field of Phased Array Probe*

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Abstract
Ultrasonic flaw detection and sizing is an important issue for ensuring structural reliability of industrial plants. The ultrasonic phased array technique is one of the most effective tools for visualizing the flaws in structural components. It is important to enhance the spatial resolution of phased array images to clearly visualize flaws; however, the spatial resolution of phased array images needs more research. A high spatial resolution phased array probe was designed as the first stage of this study. To investigate the spatial resolution of the phased array probe, acoustic analysis was conducted utilizing the Rayleigh-Sommerfeld Integral. The spatial resolution was investigated by changing the total aperture of the probe. As a result, the large-aperture phased array probe achieved high spatial resolution. Next, ultrasonic testing was simulated by the finite differential method using conventional and specially designed phased array probes. For the conventional probe, the flaw could be visualized but the shape was not clear enough. On the other hand, for the specially designed large-aperture probe, extensive noise appeared in the image and the flaws could not be visualized. Because of mode conversion, Rayleigh waves are generated at the contact surface between the transducer and testing material. The amplitude of Rayleigh waves are much higher than the diffraction echoes, hence the Rayleigh waves disturb the visualized image at the near field of the probe. Consequently a new technique for flaw visualization at the near field of the phased array probe was developed by eliminating detrimental waves. As a result the flaws could be clearly visualized using this technique.

Key words: Non-destructive Testing, Ultrasonic Testing, Phased Array, Flaw Visualization, Fatigue Crack, Stress Corrosion Cracking

1. Introduction

Stress corrosion cracking (SCC) and fatigue cracking have recently been observed in austenitic stainless steel components of Japanese nuclear power plants. To ensure structural reliability and predict the remaining life of such plants, flaw size measurement and flaw type distinction are both important issues. Though the ultrasonic phased array technique is one of the most effective tools for flaw visualization, the spatial resolution of the visualized image is not satisfactory. Therefore the development of a flaw visualization technique with high spatial resolution has been anticipated. There are several research projects using beam focusing or steering of the phased array probe. For example, Wooh et al. investigated the effect of beam steering for the linear phased array probe utilizing acoustic analysis. Azar et al. studied the beam focusing behavior of linear phased arrays. They mentioned the effect of a grating robe or sound pressure at the focal point, though the...
quantitative information about spatial resolution of the probe was not clear. Initially in this study the conventional ultrasonic phased array technique was applied to an austenitic stainless steel specimen with SCC. As a result the SCC echo observed though the spatial resolution was not too high. Subsequently a high spatial resolution ultrasonic phased array transducer was designed using acoustic analysis. The effectiveness of this specially designed phased array transducer was investigated by numerical simulation utilizing the synthetic aperture focusing technique. However, due to extensive noise, the flaw in the simulation model was not visualized at the near field of the phased array probe. Therefore a new flaw visualization technique at the near field of the phased array probe was proposed.

2. SCC visualization using the conventional phased array system

First, conventional ultrasonic testing was conducted to investigate the effectiveness of the conventional phased array system. Figure 1 shows the schematic illustration of the specimen used for this experiment. The material is made of type 316 austenitic stainless steel. The SCC was introduced in a high-pressure and high-temperature water environment in the heat-affected zone of this specimen (shown to the left in Fig.1).

A sector scan using the conventional phased array system was conducted for flaw visualization. The center frequency of the phased array probe was 5 MHz, the element number was 32, the total length of the entire array was 15.9 mm and the element size was 0.4 mm. The right hand image of Fig. 1 shows the sector scan of the SCC. Though both the back wall echo from the bottom of specimen and the SCC echo were observed at the marked area, the detailed shape was not clearly visualized. Therefore the examiner needs a high degree of skill to accurately measure the flaw size and distinguish the flaw type. Consequently, to conduct ultrasonic testing more easily, greater high spatial resolution is needed.

Fig. 1 Type 316 stainless steel specimen (left) and its flaw visualization (right)

3. Estimation of spatial resolution by ultrasonic acoustic analysis

It was necessary to use the high spatial resolution phased array probe to visualize the detailed shape of the flaws. To estimate the spatial resolution of the phased array transducer, ultrasonic acoustic analysis was conducted by using the following Rayleigh-Sommerfeld Integral equation (12):

\[
p(r, \omega) = \frac{k \rho c v_0 \exp(-i\pi/4)}{2} \int_0^\infty \frac{1}{kr} \exp(ikr)dr
\]

where \( r \) is the distance from the center of the transducer to the analytical point, \( k \) is the wave number, \( \rho \) is the density, \( c \) is the acoustic speed and \( v_0 \) is the velocity at \( z=0 \). Since the calculation assumes type 304 stainless steel, the acoustic speed of the longitudinal wave
was set as 5790 m/s and $k$ was calculated using this value and frequency of the ultrasonic beam. Though this equation is for a 2-D model, the result matches well in the case of the linear phased array transducer. Figure 2 shows a phased array transducer model, where $M$ is the transducer element number, each of width $2b$, with pitch $s$ and the total length of the entire array is $2B$. The element number $M$ must be set as a sufficient number for beam focusing and steering. The ultrasonic sound radiation can be calculated by synthesis of Eq. (1) for each transducer element.

\[
\text{Total length} : 2B \\
\text{Element length} : 2b \\
\text{Element pitch} : s \\
\text{Element number} : M \\
\text{Total length} : 2B
\]

\[\text{Fig. 2 Schematic illustration of phased array probe model}\]

Initially the spatial resolution of the conventional phased array probe used in Section 2 was investigated. The value of $2b$ was set as 0.4 mm, $2B$ was set as 15.9 mm and $M$ was set as 32. It should be noted that the high-frequency ultrasonic beam provides high spatial resolution. However, in the case of ultrasonic testing of the austenitic stainless steel weld zone, the high-frequency ultrasonic beam causes high scattering and attenuation at the weld zone and the heat affected zone. For example, in Fig. 1, noise echoes appeared all over the image, especially at the boundary of the weld metal and base metal. To avoid the scattering, the use of a low-frequency ultrasonic signal is usually effective. In addition to the 5 MHz signal, a 2 MHz signal was also investigated.

To estimate the spatial resolution, the half-value width of ultrasonic beam intensity was utilized. For example, Fig. 3 shows the relationship between angle and ultrasonic beam intensity at $r=20$ mm when the ultrasonic beam is focused at $x=0$ mm, $z=20$ mm in the case of the 5 MHz probe. In this case, the half-value width is estimated as 5.27 degree (0.0919 radian) then the spatial resolution is calculated as 1.84 mm by multiplying 20 mm and 0.0919 radian.

\[\text{Fig. 3 An example of ultrasonic sound radiation (focused at } x=0 \text{ mm, } z=20 \text{ mm)}\]

Figure 4 shows the calculated spatial resolutions for the 5 MHz and 2 MHz conventional probes. It is clear that the 5 MHz probe has a higher resolution compared to the 2 MHz probe. For example, at $(x, z) = (0 \text{ mm, } 30 \text{ mm})$, the calculated spatial resolution is 2.68 mm and 6.78 mm for the 5 MHz and 2 MHz probes, respectively. However, as previously mentioned, the high frequency causes high scattering by the crystal grains. Therefore, it is important to enhance the spatial resolution when using a low-frequency
ultrasonic beam.

It should be noted that the aperture length of transducer \(2B\) is strongly related to the spatial resolution. Consequently new probes using a 2 MHz ultrasonic beam were designed and their spatial resolutions were investigated. As previously mentioned, the element width \(2b\) of the conventional 5 MHz probe was 0.4 mm. Therefore, the \(2b\) of the new probe was set as 1.0 mm in order to generate a similar acoustic field as the conventional probe. The element number \(M\) must be set at a sufficient number for beam focusing and steering. The \(M\) was set at 19 in order to satisfy this purpose. When using the above parameters, the spatial resolution was investigated by changing \(2B\) from 31 mm to 91 mm.

![Fig. 4 Calculated spatial resolutions of conventional probes (5 MHz and 2 MHz)](image)

Figure 5 shows the spatial resolutions contour maps for \(2B=31\) mm, \(51\) mm, \(71\) mm, and \(91\) mm. In the case of a small \(2B\), the spatial resolution of the transducer is lower than 3 mm at the far field and it is not enough to visualize the detailed flaw shape. On the other hand, where \(2B=91\) mm, the spatial resolution is higher than 2.0 mm over all the significant area. At \((x, z) = (0\) mm, 30 mm\) the calculated spatial resolution is 1.76 mm. This value is 1.5 times better than the conventional 5 MHz probe. In addition, the phased array provides high spatial resolution at the near field of the probe. However, the maximum value of each result for Fig. 5 did not vary much. For example, the maximum resolution values were 1.17 mm, 1.13 mm, 1.12 mm and 1.11 mm for \(2B=31\) mm, \(51\) mm, \(71\) mm and \(91\) mm case, respectively. The high resolution area is enhanced by using the large-aperture probe but the maximum value of resolution may be fixed by the ultrasonic frequency. Considering the above, 91 mm was adopted as the total length of the entire array.
4. Numerical simulation and flaw visualization

To investigate the effectiveness of the specially designed phased array transducer, numerical simulation by the finite difference method (Wave2000, CyberLogic, Inc.) was used for simulating ultrasonic wave propagation. Figure 6 shows the simulation models for this study. The model assumes a homogeneous isotropic elastic body, but the effects of weld metal or heat affected zone were not taken into account. The flaws that simulate SCC and fatigue flaws were implemented in the model. The gaps in the flaws of each model are vacuum-filled and do not propagate any ultrasonic waves. The infinite boundary conditions were set on the left and right sides. According to the discussion in Section 3, two types of probe were used in the model. Probe A consists of 32 ultrasonic oscillators (0.4 mm width, 0.5 mm pitch) and probe B consists of 19 oscillators (1 mm width, 5 mm pitch) on the surface of the specimen. The arrangements of probe B for the SCC model and the slit model are shown in Fig. 6. For the incident wave, 2 MHz longitudinal Gaussian sine pulse beams defined by the following equation were generated by each oscillator as displacement for each simulation.

\[ P(t) = A \exp\left\{ -\frac{(t - d/2)^2}{a^2}\right\} \sin(2\pi ft) \]  

(2)
where $A$ is the amplitude, $t$ is the time scale, $d$ is the duration, $a$ is the time constant and $f$ is the center frequency. In this simulation, $A$ was set as 50, $d$ was set as 2.0 $\mu$s, $a$ was set as 0.3 $\mu$s and $f$ was set as 2.0 MHz. The waveform and its frequency component are shown in Fig. 7. Since the simulation model assumes type 304 stainless steel, the acoustic speeds of the longitudinal and shear waves were set as 5790 m/s and 3180 m/s, respectively. Though the center frequency of the incident wave is 2 MHz, higher frequency components up to 4 MHz also exist. The wavelength of the shear wave at 4 MHz is 800 $\mu$m, the finite difference grid element size was set as 40 $\mu$m for resolving 800 $\mu$m by 20 points to provide a good approximation (13). The time step for simulation was set as 5.75 ns to avoid instability. The displacements of each oscillator were recorded as the ultrasonic waveforms. The 1024 (32×32) and 361 (19×19) ultrasonic waveforms obtained for the model with probes A and B were reconstructed to generate images of flaw shapes using the Synthetic Aperture Focusing Technique (SAFT)\textsuperscript{(14), (15)}. 

Fig. 6 Ultrasonic simulation models with SCC (upper) and slit (lower)

Fig. 7 Waveform and its frequency component of incident wave
Figure 8 shows the visualization result for the SCC and slit model with probe A. The color corresponds to the intensity of synthesized echoes using SAFT. For the SCC model, the flaw tip is observed in the Figure, though the detailed shape is unclear. For the slit model, the flaw tip is also observed, though the flaw tip echo is not very sharp. Moreover, the large amplitude noise echo appears at the near field of probe. Hence the maximum value of the color scale was manually set as 20% of the noise intensity because the flaw tip intensity is five times weaker than the noise.

![Flaw visualization results for SCC and slit models with probe A](image)

Fig. 8 Flaw visualization results for SCC and slit models with probe A

On the other hand, Fig. 9 shows the visualization result for the SCC model with probe B. The flaw shape could not be visualized due to excessive noise in the Figure. Among the signals received, besides the flaw echo, the lateral wave, Rayleigh wave and back wall echoes are visible as shown in Fig. 10. For example, the black line in Fig. 11 shows an example of signals obtained by numerical simulation. The “L”, “B1”, “B2”, and “R” correspond to the lateral wave that propagates along the surface of the specimen, the first and second back wall echoes and Rayleigh wave, respectively. Though the echoes from flaws appear between the lateral wave and the back wall echo, the amplitude is usually weaker than these echoes. As the velocity of the Rayleigh wave is lower than the longitudinal wave and its intensity is much higher than the flaw tip echo, it distorts the image construction of the SAFT at the near field of the phased array probe. Though the noise also appears in Fig. 8 at the near field of the probe, the flaw can be separated from the noise. On the other hand, for probe B, due to the large aperture of the probe, the flaw exists relatively close to the probe. Hence the flaw is buried in the noise.

The arrival times of the lateral wave, back wall echo and Rayleigh wave do not depend on the flaw size or location but could only be calculated from the relative locations of the transmitters and the velocity of each wave. Consequently these waves could be canceled out in the signals received by considering arrival times and the duration of incident waves as shown by the red line in Fig. 11. Figure 12 shows the results of flaw visualization for each simulation model by using modified received signals. As shown in the Figure, the detailed shape of the SCC could be approximately reconstructed. On the other hand, in the case of
slit model, only the top of the flaw could be sharply visualized. The results are different from each other and so the flaw types could be distinguished when visualizing the results. Moreover, the flaw size can be measured by following the top echo of each flaw. If the surface is not flat or the thickness of the specimen is not constant, the arrival times of each wave may be a little different from the expected times. In this case, if the duration time for canceling is set longer than the duration of the incident wave, the noise may be canceled successfully. However, because the canceled waves may contain flaw tip echoes, this approach may reduce the spatial resolution of the visualization result.

Fig. 9 Flaw visualization result for SCC model with probe B

Fig. 10 Schematic illustration of harmful echo paths

Fig. 11 An example of a received signal (transmitter: No.5, receiver: No.15)
Fig. 12 Modified flaw visualization results for SCC and slit models with probe B

5. Conclusion

In this study we carried out fundamental research to generate high spatial resolution images of flaws in structural components. A high spatial resolution phased array transducer was designed using acoustic analysis. Numerical simulation was then conducted to investigate the effectiveness of the designed transducer. Flaw shape visualization was conducted using the Synthetic Aperture Focusing Technique. However, excessive noise was apparent in the visualization result. Subsequently the lateral waves, back wall echoes and Rayleigh waves were canceled out in the received signals and the SAFT used again. As a result the detailed flaw shapes were clearly visualized and the flaw types could be distinguished using the specially designed ultrasonic phased array transducer.

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