Investigation of the Sound Field of Phased Array Using the Photoelastic Visualization Technique and the Accurate FEM

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In this study, we tried to obtain an accurate ultrasonic sound field of the commercial phased array system. For this purpose, the experimental photoelastic ultrasonic visualization system was improved to evaluate a phased array system and the analytical special large-scale finite element method (FEM) code for ultrasonic transmission was applied.

As the results, an actual sound field of phased array system was much more complicate than that of the conventional industrial assumption based on a simple superposition. One of the causes of the difference might be the accuracy of the directivity for each element in the array transducer. Thus, the combination of photoelastic visualization method and FEM analysis was useful for the accurate sound field investigation of the phased array measurement. [doi:10.2320/matertrans.I-M2012806]

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1. Introduction

The phased array technique can easily control the ultrasonic sound field electrically by controlling the delay time of the excitation of each piezoelectric element in an array transducer. This technique realizes quick scanning and a focusing of ultrasonic propagation in industrial materials which allow an accurate and rapid imaging in the ultrasonic inspection.^{1,2)} According to the increase of the industrial applications of the phased array system, the more accurate sound field and the more appropriate setting of the phased array have been both required for more accurate sizing of the defects. The experimental observation has been applied mainly using the ultrasonic photoelastic visualization method.³⁻⁵⁾ This method can observe the ultrasonic wave in the glass model specimen and have also applied to phased array sound fields⁶⁻⁸⁾ for some limited applications. However photoelastic analysis has some limitations since the glass model specimen must be used for analysis for ultrasonic behaviors. Thus several analytical simulations have been also applied to analyze the ultrasonic sound fields, for example the finite element method (FEM), the boundary element method (BEM), and the FDTD method and so on. These methods also applied to the analysis of the sound field of phased array.^{9,10)} Though FEM analysis has been recognized as the most accurate, the accurate simulation using FEM for industrial problem, including the phased array sound field, was difficult due to the long calculation time up to now.

In this study, we applied the experimental photoelastic ultrasonic visualization system and the analytical finite element method (FEM).¹¹⁾

On the other hand, simple theoretical estimation of phased array directivity has been widely used in industry. But as the increasing of the requirement of accurate inspection some errors are actualized in the simple estimation.

Selfridge *et al.*¹²⁾ proposed a new estimation method pointing out that the error will cause by the directivity of small element. And according to this new estimation, other simple analysis¹³⁾ was applied to the sound field of phased array.

In this paper, we planed to investigate the accurate sound field of industrial phased array system to verify the availability of the conventional simple estimations. For this purpose, we used the experimental photoelastic ultrasonic visualization method³⁻⁵⁾ and the accurate large scale FEM analysis code for ultrasonic transmission¹¹⁾ to investigate the sound field of phased array.

2. Theory and Experiment

2.1 Phased array

The advantages of the phased array in industrial field were followings:^{1,2)}

- (1) Incident angle control
- (2) Focal point control
- (3) Electrical rapid scanning
- (4) Easy imaging of inspection results

Phased array transducer has the plural piezoelectric elements which can be driven independently. At the excitation of the piezoelectric elements, adequate time delays are added to each element due to the designed sound field. For example, no time delay makes a normal sound field like a one by monolithic piezoelectric element (Fig. 1). Only by controlling the time delays of each element of the array, the incident angles and the focal length are both controlled to change like an angle probe and a focal transducer, respectively (Fig. 2).

Table 1 shows the detail of the linear phased array used in this study. Nominal frequency is 4 MHz with 16ch elements. In this study, we planned to compare the ultrasonic visualization using photoelastic method and FEM analysis. For this purpose, glass model specimen was prepared. Table 2 shows acoustic parameter of the glass specimen used.

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Fig. 1 Transducer. (a) Normal transducer. (b) Phased array transducer.

Fig. 2 Phased array beam control. (a) Steering. (b) Focusing.

Table 1 Phased array parameters.

Element material	PZT
Element width	0.4 [mm]
Element pitch	0.5 [mm]
Number of Element	16
Frequency	4 [MHz]

Table 2 Glass specimen properties.

Material	Quartz glass
Longitudinal wave velocity	5570 [m/s]
Shear wave velocity	3510 [m/s]
Density	2.7×10^3 [kg/m ³]

2.2 Theory of directivity for phased array

Up to now, the directivity of the phased array sound fields was proposed to calculate. But as many calculations considered the continuous wave, these directivities were different from the one by pulse wave. For the directivity of the continuous wave followings were proposed.¹⁴⁾

First, the single element directivity $Re(\theta)$ is estimated by

$$Re(\theta) = \frac{\sin X}{X}, \text{ where } X = \frac{\pi}{\lambda} e \sin \theta. \quad (1)$$

Fig. 3 Ultrasonic visualization system using photoelastic method.

Second, phased array directivity $Ra(\theta)$ which consists of non-directional elements is written by

$$Ra(\theta) = \frac{\sin(nY)}{n \sin Y}, \text{ where } Y = \frac{\pi p}{\lambda} (\sin \theta - \sin \theta_0). \quad (2)$$

Thus finally, phased array directivity $R(\theta)$ can be expressed by

$$R(\theta) = Re(\theta)Ra(\theta), \quad (3)$$

where element width e , wave length λ , number of elements n , pitch p , steering angle θ_0 .

Though eq. (3) have been widely used for industrial use, Selfridge *et al.*¹²⁾ pointed out that the actual directivity of the single narrow element was different from the eq. (1). Thus we compared the conventional directivity of the eqs. (1) and (3) for industrial phased array system with the one by photoelastic method and by the FEM analysis.

2.3 Directivity measurement using photoelastic visualization of ultrasonic propagation

2.3.1 Photoelastic visualization method

Photoelastic method has been used as a stress analytical method. It uses birefringence due to the stress state of transparent materials. As the ultrasound is a stress wave, ultrasound can be also visualized by photoelastic method only adding the stroboscope. Figure 3 shows the schematic diagram of ultrasonic visualization system using photoelastic method for phased array measurement.

The photoelastic visualization of phased array can be synchronized with external trigger from the phased array system to the photoelastic visualization system. We add the special digital timing generators to a delay unit to increase the general versatility for many commercial ultrasonic pulser including the phased array system.

Since this system uses the circular polarization, the brightness of the visualized image I is written by eq. (4).

$$I = a^2 \sin^2(\delta/2) \quad (4)$$

Where a is the constant, δ is the function of the difference of principal stress.

2.3.2 Directivity measurement using photoelastic visualization for phased array

Figure 4 shows the procedures of the directivity measurement using the photoelastic visualization image.¹⁵⁻¹⁷⁾

Fig. 4 The Procedures of the directivity measurement using the photoelastic visualization image.

The directivity is the relationship between sound pressure and an ultrasonic propagation angle from a sound source. To obtain the directivity from the visualization image following procedures were employed. The center of array probe was decided as a sound source and the two circles of radius of r_1 and r_2 were supposed. The maximum amplitude of the sound pressure between two circles was plotted according to the ultrasonic traveling angle θ . Using these procedures, the directivities of the ultrasonic wave can be obtained from the dependence between the angle θ and the maximum brightness value.

Since the stress of the ultrasonic and δ are small enough, the brightness of the visualized image I can be considered to proportion to the square of intensity of the sound pressure [eq. (4)].

Then using the procedures, we can obtain the accurate sound pressure distribution of the phased array experimentally.

2.4 Directivity measurement using large scale FEM analysis

2.4.1 Large scale FEM code used

FEM (Finite Element Method) recognizes as the most accuracy analysis method even for the simulation of the ultrasonic wave propagation. However, we need large number of mesh, at least tens of millions meshes for example, to obtain an accurate FEM simulation because 1/20 to 1/30 of wave length mesh size for MHz range frequency and the dynamic analysis is both required. Then accurate FEM analysis has been difficult to apply widely to the industrial problem because of the long calculation time. Recently, the large scale FEM code specialized to ultrasonic propagation only which optimize to memories of the computer to use the voxel FEM mesh¹⁸⁾ has been developed. The 'voxel' is a term in the field of computer graphics to indicate a 'volume pixel', which geometrically is regular hexahedron.¹⁸⁾

In this study, we use this FEM code¹¹⁾ to apply for the phased array sound pressure analysis by using an inexpensive cluster PC.

Table 3 FEM calculation condition.

Mesh size	0.02 [mm]
Number of meshes	About 32 million
Courant number	0.8
Time step	About 2.87 [ns]
Required calculation time	About 80 [min] (6CPU parallel)

Fig. 5 Photoelastic visualization image using a single element.

Fig. 6 FEM visualization image using the single element.

2.4.2 Directivity measurement using large scale FEM analysis for phased array

The model of the FEM analysis was constructed as the same as the experimental conditions, glass specimen and 16ch array as shown in Tables 1 and 2. In addition, the FEM calculation condition is shown in Table 3.

In addition, the directivity from the FEM analysis could be obtained using the same procedures as in the case of the analysis of the photoelastic image (Fig. 4).

3. Results and Discussion

3.1 Directivity of a single element

Ultrasonic visualization images using a single array element by photoelastic method and by FEM analysis were shown in Figs. 5 and 6, respectively. In the FEM analysis in Fig. 6, only longitudinal wave was shown in a sound pressure expression.

To compare the directivities in Figs. 5 and 6, the directivity of a single element by photoelastic visualization image and

Fig. 7 Comparison of the FEM, photoelastic and theory for a single array element.

Fig. 8 Photoelastic visualization image of steering angle 30°.

FEM was shown in Fig. 7. The theoretical estimation is obtained by eq. (1).

The directivity by photoelastic and the one by FEM agree well nevertheless the lack of dynamic range in experimental method. Some experimental variation can be observed in photoelastic curve similar to Lemon and Posakony's report measured by a hydrophone.¹⁹⁾

However, conventional estimation had a large gap compare with the photoelastic and the FEM directivities of the single element. This difference is a similar tendency of Selfridge's report.¹²⁾

3.2 Steering directivity

Next, we focused on a steering directivity using same method. In this case, the theoretical estimation is obtained by eq. (3). Figure 8 shows photoelastic visualization image of phased array measurement with the steering angle of 30° which was the angled plane wave using 16 elements. Figure 9 shows the FEM visualization image of the longitudinal wave at the same experimental setting of the photoelastic method. The steering directivities of 30° for longitudinal wave were shown in Fig. 10. The steering directivities of 60° for longitudinal wave were shown in Fig. 11 similarly. Although slight differences were existed three estimations agree well. There is a possibility that phase alignment of maximum sound pressure from single elements affect the steering directivity. So we consider that there is no great distinction between the traditional theory and the photoelastic, the FEM analysis.

Fig. 9 FEM visualization image of steering angle 30°.

Fig. 10 Comparison of the FEM, photoelastic and theory for the steering directivity of 30°.

Fig. 11 Comparison of the FEM, photoelastic and theory for the steering directivity of 60°.

In addition, theoretical estimation had many side lobes due to the continuous wave and others had main lobe only. Then we considered that the photoelastic visualization method and the FEM analysis were effective enough to evaluate the commercial phased array systems quantitatively as a first step. In addition, we checked the availability of this method by other phased array systems.

4. Conclusion

In this study, we investigate phased array sound field using the photoelastic visualization technique and the accurate FEM analysis. Obtained directivities were compared with the conventional simple theory for the phased array. In case of the ultrasonic propagation from a single element, theoretical estimation had a large gap from the one by photoelastic and/or by FEM. The actual directivity of the single element was

narrow. As to the steering of the incident echo, although slight differences were existed depending on a continuous wave and pulse wave, three estimations agree well. Thus, the photoelastic visualization method could observe the sound fields of actual phased array nevertheless its limited dynamic range. The FEM analysis could also estimate the accurate ultrasonic behavior after the fairly long calculation time. According to these investigations, the combination of the photoelastic method and FEM analysis will be useful for the accurate investigation of sound field of the phased array.

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