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# Focus and frequency evaluation of acoustic lens type focused ultrasonic probe

音響レンズ型集束超音波探触子の焦点位置と周波数評価

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## 1. Introduction

Focused ultrasound probes are used for small defect detection in non-destructive inspection and medical ultrasound for treatment. Focusing of ultrasonic waves is performed by using an acoustic lens or a concave transducer, and a focal point is generated at an arbitrary position. In the case of an acoustic lens, the focal point is calculated in the same method as the optical refraction. However, in actual manufacture, the focal point is before the calculated value. In addition, depending on the shape, the focal point moves at frequency. This phenomenon was explained by the influence of direct wave and edge wave, and aperture angle. The frequency was evaluated by the inverse of the time [1]. This paper, it is described how it is appropriate to evaluate the received waveform by checking the difference in the focus position in the focus calculation value, simulation, and experiment.

## 2. Aperture angle and focal point moving

As shown in Fig. 1, the ultrasonic wave transmitted from the planer probe is a planar direct wave, and an edge wave is generated from a plane wave end portion. The outer edge wave is in phase with the direct wave, and the inner edge wave is in phase opposite to the direct wave. Since the inner edge wave is in opposite phase to the direct wave, it overlaps with the direct wave at a point where the propagation distance difference becomes a half wavelength, and the amplitude becomes large. The same applies to the focused ultrasound probe. As shown in Fig. 2, the inner edge wave overlaps with the direct wave to form a focal point. Here, the aperture angle θ is defined from the transducer widths and the curvatures of the lenses. In the plane, the aperture angle is 0°, and the focal point is affected only by the edge wave. Therefore, the smaller the aperture angle, the greater the influence of the edge wave. In the case of a plane, a direct wave and an edge wave overlap at $x_0$.

$$x_0 = \frac{1}{4}\left(\frac{D^2}{\lambda} - \lambda\right) \quad (1)$$

$D$: Transducer diameter
$\lambda$: Wavelength

Since the overlapping position changes depending on the wavelength, the focal point fluctuates depending on the wavelength when the influence of the edge wave is large.

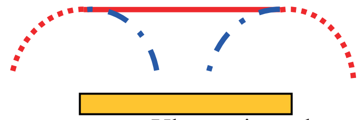


Fig.1 Direct wave and edge waves

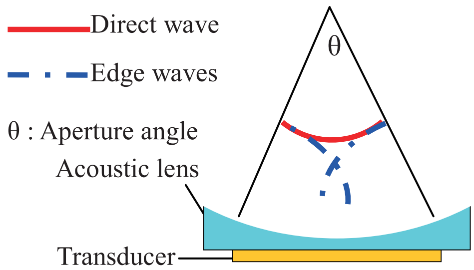


Fig.2 Focal formation and aperture angle

Here, the focal point of an acoustic lens type focusing ultrasonic probe with an aperture angle of 9.7° and 37.3° was investigated by calculation values, simulations, and experiment. The transducer diameters are 6.4 mm and the radius of curvature of the acoustic lens is 10 mm and 38 mm. The focal point is expressed by the following equation (2).

$$f = \frac{r}{1 - \dfrac{c_2}{c_1}} \quad (2)$$

$f$: Focal point
$r$ : Lens radius of curvature
$c_1$ : Acoustic velocity of acoustic lens
$c_2$ : Acoustic velocity of medium

The acoustic lens was epoxy with acoustic velocity of 2600 m/s, and the medium was water with acoustic velocity of 1500 m/s. In the simulators (eCompute, SWAN21), 1 cycle pulsed waves of 10 MHz and 5 MHz were applied to evaluate the amplitudes on the centre axes of the probes. In the experiments, a probe with a 5 MHz and 10 megahertz in water was used, and the focal point was evaluated by reflections of a 4 mm diameter stainless-steel sphere.

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Table 1 shows the respective focal point. In both simulations and experiments, the focal point position became closer than the calculated values. When the aperture angle was 9.7 ° and 10 MHz, the focal point fluctuated greatly with frequency. Also, since the expression (2) is not affected by the edge wave, the focus is greatly different when the aperture angle is small. Furthermore, the focal point was 9 mm different between the experiment and the simulation. This is considered from frequency evaluation.

## 3. Frequency evaluation

The amplitude of ultrasonic increases when the propagation distance difference of the direct wave and the edge wave is half a wavelength. As shown in Fig. 3, at a short distance, the direct wave and edge wave are separated and overlapped at a focal point position to form 1.5 wavelengths ultrasonic. At this time, since the direct wave and the edge wave overlap each other with a half wavelength shift, the wavelength of the peak signal at the centre can be obtained from the time difference between the peak signals A and B. Since the wavelength is represented by the product of the sonic velocity and the period, the wavelength is obtained by multiplying the time difference between A and B by 2 and multiplying the sonic velocity.

$$\lambda = cT \quad (3)$$

$\lambda$: Wavelength $T$: A cycle time
$c$: Acoustic velocity

However, in JIS Z 2350:2002, the frequencies are evaluated by FFT results of the reflected signals from the flat plate. Table 2 shows frequency calculated by FFT and frequency of the time difference between the peaks. These frequency calculated from reflected signal of the glass plate and the stainless steel sphere using a probe with aperture angle of 9.7° and 10 MHz. The FFT of the glass-plate reflected signal have a centre frequency of 9.2 MHz, while the time-difference between the peaks is 12.2 MHz. The frequency from the peak-to-peak time-difference in the simulation is 9.4 MHz, and the experiments are 2.8 MHz higher than the simulation. Table 3 shows the focal points when the frequencies obtained from the time difference between peaks in simulation and experiment are matched. The focal points of simulations and experiments are aligned, it is appropriate to calculate the frequency for obtaining the wavelength using the reciprocal of the period. Assuming that the frequency calculation result of the FFT is frequency A and the frequency obtained from the reciprocal of the period is frequency B, the wavelength is calculated by Equation 4.

$$\lambda = \frac{c}{f_B} \quad (4)$$

$\lambda$: Wavelength $f_B$: Frequency B
$c$: Acoustic velocity

The frequency A is preferably not used for wavelength calculation. Therefore, any focal point of probes can be designed by matching frequencies B at simulations and experiments.

## 4. Conclusion

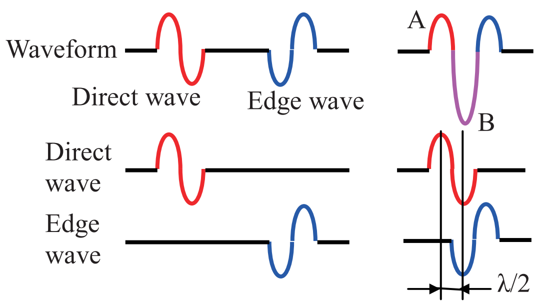
The focal point of the acoustic-lens type focusing ultrasonic probe was examined from the evaluations of the aperture angle, the effect of the edge wave, and the frequency, and it was described that the focal point position fluctuated with the frequency when the aperture angle was small.

## Reference

[1] Y. Tanaka et al: Acoustic imaging kennkyuukai **AI-2018-24(2018)**. [in Japanese]

Table 1 Comparison of focal points

| Aperture angle [deg] | Frequency [MHz] | Facal point (Simulation) [mm] | Facal point (Experiment) [mm] | Eq. (2) [mm] |
|---|---|---|---|---|
| 9.7 | 10 | 43 | 52 | 90 |
| (R38[mm]) | 5 | 30 | 31 | 90 |
| 37.3 | 10 | 21 | 20 | 24 |
| (R10[mm]) | 5 | 21 | 20 | 24 |




(a) Before focal point (b) Focal point

Fig. 3 Overlapped direct wave and edge wave at central axis

Table 2 Each situation frequency of probe with 9.7 degree aperture angle

| [MHz] | | Glass plate reflection | Stainless ball reflection |
|---|---|---|---|
| FFT | Peak | 8.4 | 11.4 |
| | Centre | 9.2(JIS) | 11.2 |
| Peak to peak time difference | | 9.3 | 12.8 |

Table 3 Focal point and frequency B of probe with 9.7 degree aperture angle

| | Experiment | | Simulation | |
|---|---|---|---|---|
| Facal point[mm] | 43 | 52 | 43 | 52 |
| Frequency B[MHz] | 9.8 | 12.8 | 9.4 | 12.7 |