Beam Pattern Analysis of the Plate-type Waveguide Sensor for Under-Sodium Viewing

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1. Introduction

Recently, the plate-type ultrasonic waveguide (WG) sensor for under-sodium viewing (USV) in a sodium-cooled fast reactor (SFR) has been developed [1, 2]. In the developed WG sensor approach, the A_0 mode Lamb wave is used and a thin beryllium layer is coated on the waveguide surface to improve the ultrasonic radiation ability in a sodium environment. In this work, the beam pattern radiated from the developed plate-type WG sensor is investigated analytically to understand and predict the ultrasonic beam radiation property of the WG sensor in a liquid. Analytic calculations to obtain beam patterns for two kinds of WG sensors with and without beryllium coating layers were carried out and the results were compared with those obtained by experiments.

2. Method and Results

2.1. Beam pattern analysis

Fig. 1 shows both the configuration of the plate-type WG sensor and the analytical model to calculate the ultrasonic beam pattern in a liquid. When the compressional wave is generated by an ultrasonic transducer, it propagates through a wedge and is converted into an A_0-mode Lamb wave in a strip plate. Then the A_0-mode Lamb wave propagating through the strip plate is radiated into a surrounding liquid by mode conversion to a leaky longitudinal wave. By measuring reflected waves from any obstacles, structures in a liquid can be inspected.

For efficient use of the WG sensor for USV, it should be important to understand the ultrasonic beam radiation property of the WG sensor in a liquid. To predict the ultrasonic beam pattern emitted from the plate-type WG sensor in a liquid, the far-field approximation was employed [3, 4]. That is, the distance (r) from the starting point (O) of the immersed section to the measurement point (P) is sufficiently large. In this condition, one can assume that all points in the immersed section of the WG sensor are equidistant from the measurement point P and all lines connecting P and all points in the immersed section are nearly parallel. Under these assumptions, the acoustic pressure at P can be expressed as

$$p(r,\theta,t) = \frac{Ab\hat{p}_0}{r} \times \int_0^a \mathrm{e}^{-\beta x} \cos\left[k_b x - \omega\left(t + \frac{x \sin\theta}{c_L}\right)\right] dx \quad (1)$$

where A is a constant, b is the width of the WG sensor plate, $\hat{p}_0$ is the amplitude at O, ω is the angular frequency, c_L is the velocity of sound in a liquid, and β and k_b are the attenuation coefficient of the A_0-mode Lamb wave and its wavenumber, respectively. From Eq. (1), the squared pressure amplitude at P which is the quantity of prime importance can be derived as

$$\hat{p}^2 = \left(\frac{Ab\hat{p}_0}{r}\right)^2 \cdot \frac{1 - 2\cos(k_\theta a)\mathrm{e}^{-\beta a} + \mathrm{e}^{-2\beta a}}{\beta^2 + k_\theta^2} \quad (2)$$

where k_θ is

$$k_\theta = k_b\left(1 - \frac{v_b}{c_L}\sin\theta\right). \quad (3)$$

Here, v_b denotes the phase velocity of the A_0-mode Lamb wave in the WG sensor. Using Eq. (2), the beam pattern of the leaky longitudinal wave emitted from the WG sensor in a liquid can be calculated.

Fig. 2 shows the calculated beam patterns of two kinds of WG sensors at 1 MHz by using Eq. (2):

Case 1: A 1 mm thick SS304 plate with 15 mm in width and 18 mm in immersion length.

Case 2: A 1 mm thick SS304 plate with 0.25 mm thick beryllium coating layers on both surfaces. The width and the immersion length are the same as Case 1.

From the results, one can see that two cases show different beam patterns and the radiation angle of the leaky longitudinal wave emitted from the WG sensor of Case 2 is less than that of Case 1. This is because the approach employing the thin beryllium coating layer can considerably increases the phase velocity of an A_0-mode Lamb wave (see [2] for details).

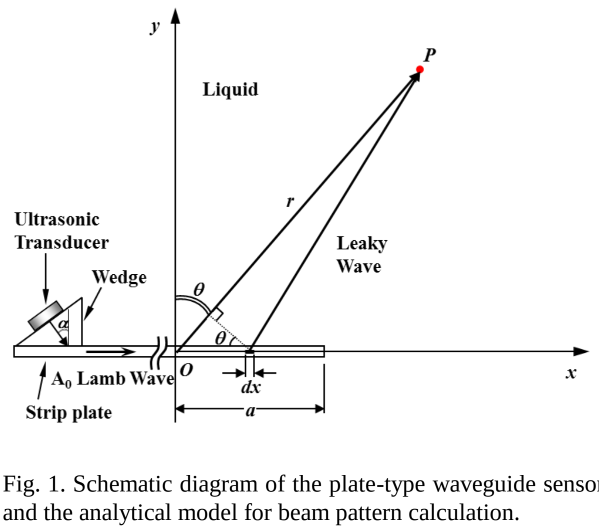

Fig. 1. Schematic diagram of the plate-type waveguide sensor and the analytical model for beam pattern calculation.

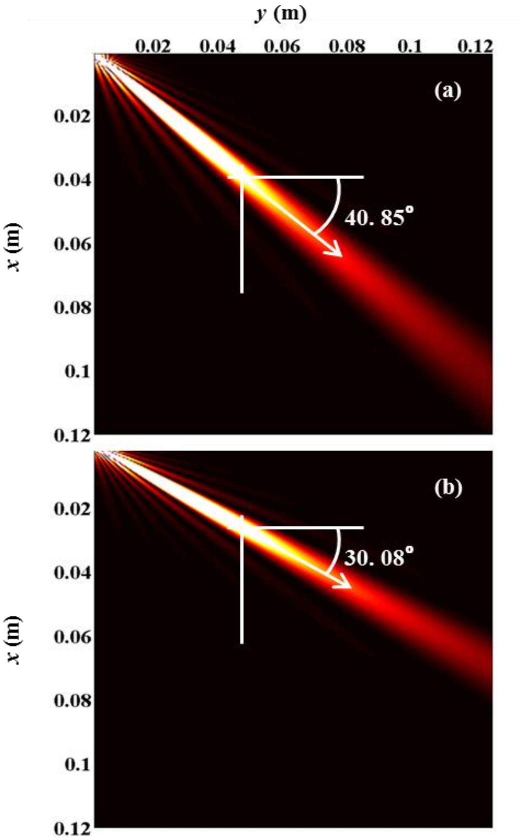

Fig. 2. Calculated beam patterns for (a) Case 1 and (b) Case 2.

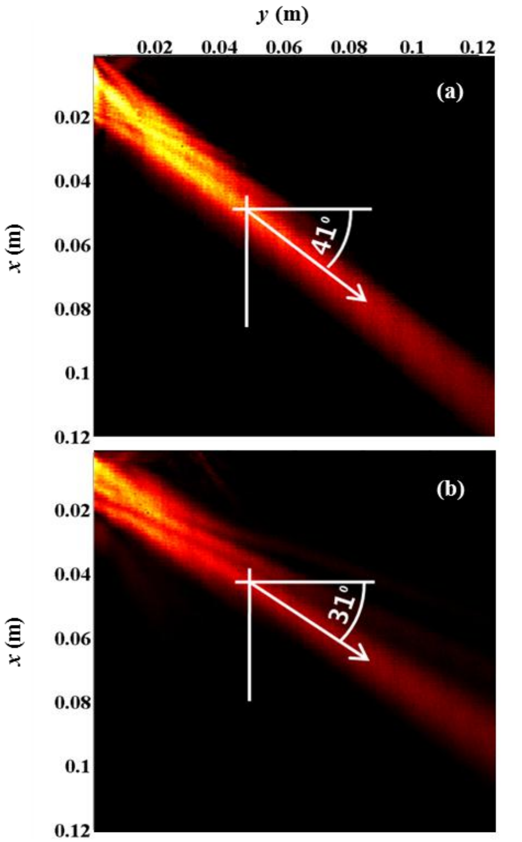

Fig. 3. Experimentally obtained beam patterns for (a) Case 1 and (b) Case 2.

2.2. Experimental verification

To verify the analytical results, experiments to obtain beam patterns for above two cases were conducted. A needle-pin hydrophone (ONDA HNR-0500, Ø 2.5 mm) was used to receive acoustic signals radiated from the WG sensor into water and scanned with a step of 0.3 mm in *x-y* plane over the predetermined area (120 × 120 mm^2) in front of the WG sensor. Fig. 3 shows experimentally obtained beam patterns at 1 MHz (the counterpart of Fig. 2). Comparing the results in Figs. 2 and 3, the near field distributions of ultrasonic energy in analytically and experimentally obtained results are noticeably different. This is because the analytic calculation is based on the far-field approximation. Nevertheless, angles of ultrasonic beam radiation obtained by the analytic calculation are well agreed with those obtained by experiments.

3. Conclusions

In this work, the beam pattern of the plate-type WG sensor for USV was investigated analytically. Employing the far-field approximation, the acoustic response at a given measurement position was calculated for the plate-type WG sensors with and without beryllium coating layers. The beam patterns of WG sensors were predicted by the analytic calculation and the corresponding experiments were carried out. The results showed that the far-field beam pattern radiated from the plate-type WG sensor could be well predicted by an analytic calculation. The radiation beam angles obtained by the analytical calculation were in good agreement with those obtained by experiments.

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