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Estimation of Ultrasonic Beam Profile Radiated from a Plate-Type Ultrasonic Waveguide Sensor in Sodium

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1. Introduction

Development of the under-sodium inspection technologies using the ultrasound is necessarily required to examine the integrity of in-vessel structures in a Sodium-cooled Fast Reactor (SFR) because the liquid sodium coolant is optically opaque and is always preserved in the high temperature condition. Recently, a plate-type ultrasonic waveguide sensor has been developed for under-sodium viewing (USV) [1] and the performance of the developed waveguide sensor was successfully demonstrated through several under-sodium experiments [2].

In relation to the USV performance, meanwhile, the ultrasonic beam profile radiated from the developed waveguide sensor is the most important factor. And the estimation of the radiation beam profile using the numerical and analytical models can be the effective way to know under-sodium radiation characteristics because it is very difficult to experimentally measure the beam profile in a hot liquid sodium environment.

This paper deals with the radiation beam estimation of a plate-type ultrasonic waveguide sensor in sodium. The under-sodium radiation beams at different conditions were estimated by both FEM and semi-analytical methods [3, 4].

2. A Plate-Type Ultrasonic Waveguide Sensor

2.1 Features

A plate-type ultrasonic waveguide sensor mainly consists of a commercial ultrasonic transducer, a solid wedge, a waveguide of thin and long strip-type plate and a shielding tube. Especially for the use in liquid sodium, a thin beryllium layer is coated on the radiation section surface as shown in Figure 1.

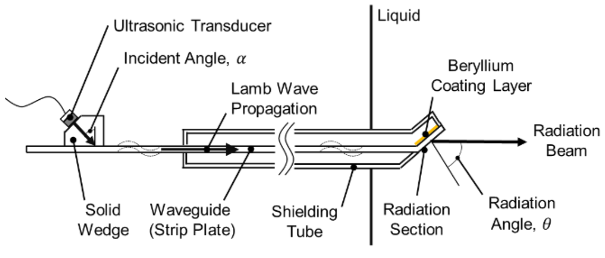

Fig. 1. A schematic diagram of the plate-type ultrasonic waveguide sensor.

In the waveguide sensor, the longitudinal wave that is converted from the A_0-mode Lamb wave in the waveguide is radiated into a surrounding liquid and the radiation angle (θ) can be calculated by Snell's law as follows.

$$\theta(fd) = sin^{-1}\left(\frac{V_{liquid}}{C_p(fd)}\right) \quad (1)$$

where V_{liquid} is the longitudinal wave velocity in the surrounding liquid and C_p is the phase velocity of the A_0-mode Lamb wave in the waveguide with a thickness of d at an excitation frequency of f. According to Snell's law, C_p must be greater than V_{liquid} for the beam radiation into the surrounding liquid.

2.2 Effects of the Beryllium Coating Layer

Figure 2 shows the dispersion curves of the A_0-mode Lamb wave in a stainless steel (STS304) plate with a thickness of 1 mm. The normal operating frequency range of the developed waveguide sensor is from 0.8 MHz to 1.7 MHz to use the almost non-dispersive group velocity and for the possibility of the radiation beam steering by varying the phase velocity. Area A and B indicate the frequency ranges where the ultrasonic wave cannot be radiated from the sensor into water and liquid sodium, respectively. This is because that C_p in Area A and B is smaller than V_{liquid}. And Area A is relatively far away from the operating frequency range whereas Area B is overlapped with that. From these characteristics, therefore, one can predict that it is not suitable to apply the waveguide sensor to the practical under-sodium inspection. Although the frequency range from approximately 1.3 MHz to 1.7 MHz seems to be able to use, the radiation beams in this range have large radiation angles which cannot be applied to the practical inspection.

Accordingly, the faster phase velocity should be necessary to solve this technical issue. The phase velocity could be increased by coating the beryllium (Be) layer on the waveguide surface [5]. Beryllium is a material widely known to have the fastest ultrasonic velocity among the nature and it has been revealed that its coating on the plate highly increases the phase and group velocities of the A_0-mode Lamb wave as shown in Figures. 3-a) and 3-b), respectively. Consequently, the beryllium coating layer on the plate surface makes the developed waveguide sensor to have two main advantages; the radiation beam at the decreased radiation angle and the reduced dispersion effect.

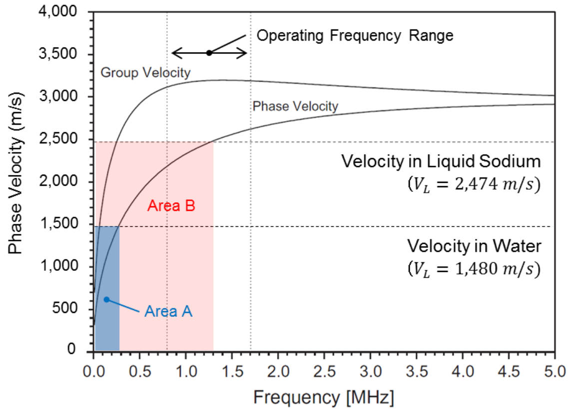

Fig. 2. Dispersion curves of the A_0-mode Lamb wave in a 1 mm thick STS304 plate.

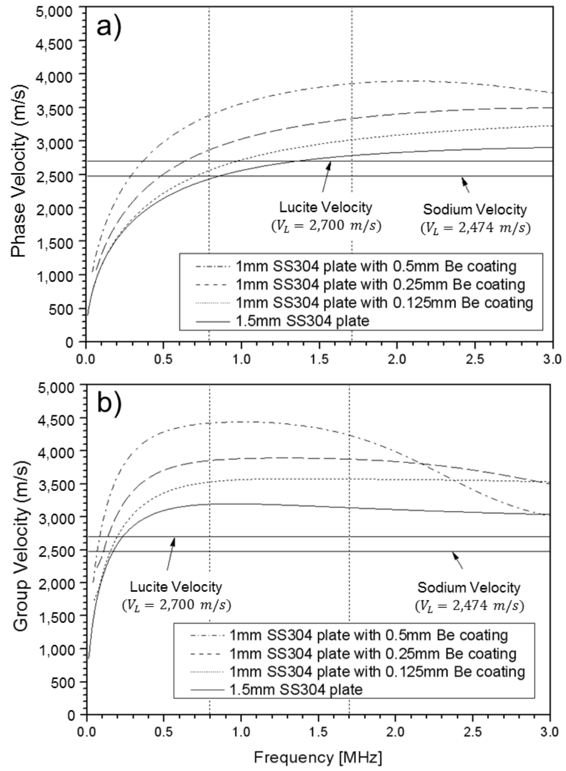

Fig. 3. Dispersion curves of the STS304 plate with the different thicknesses of the beryllium coating layers [5].

3. Estimation Models for Radiation Beam

Recently, FEM and semi-analytical estimation models for the ultrasonic radiation beam from the waveguide sensor have been proposed by authors [3, 4]. The semi-analytical model was developed based on the Rayleigh-Sommerfeld Integral (RSI) method which is one of representative methods for the acoustic field modeling whereas a commercial software ANSYS [6] was used for the FEM model as shown in Fig. 4.

Figure 5 shows the under-water ultrasonic radiation beam profiles obtained from experiments and analyses using FEM and semi-analytical models conducted for a

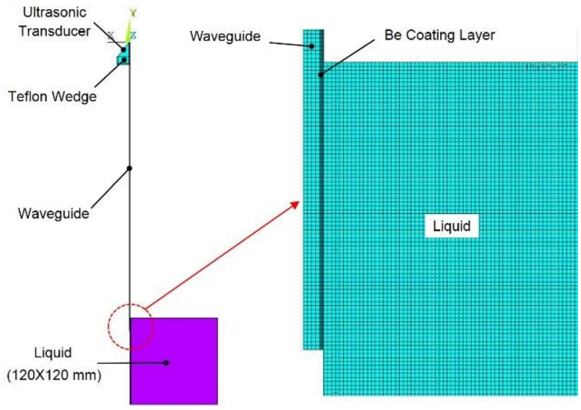

Fig. 4. FEM model for the radiation beam estimation of the waveguide sensor.

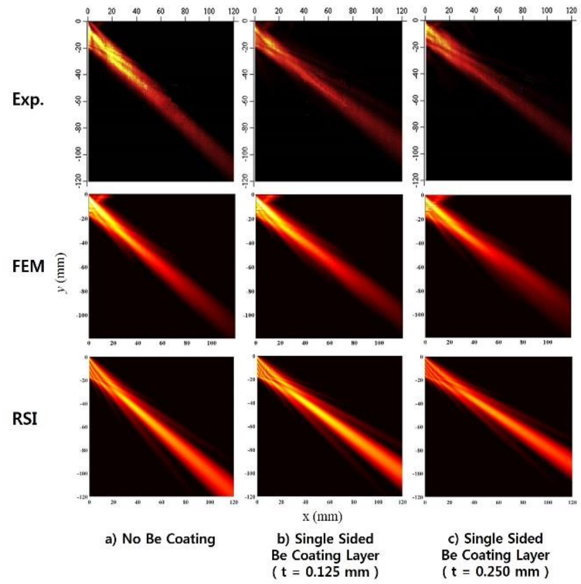

Fig. 5. The radiation beam profiles obtained from experiments and analyses.

1 mm thick STS304 plate with different thicknesses of single sided Be coating layers. The results show good agreements between experiments and analyses in terms of the radiation beam characteristics such as the radiation angle and beam pattern although there are a few minor discrepancies which might be caused by assumptions used in analyses; some factors that do not significantly affect the radiation beam characteristics, such as the actual shape of the input signal, were neglected in analyses.

4. Estimations of Under-Sodium Radiation Beam

Since it is not easy to experimentally measure the under-sodium radiation beams in hot liquid sodium, the numerical or analytical method is one of effective ways to know the under-sodium radiation characteristics of the waveguide sensor. Hence, the under-sodium radiation beam from the waveguide sensor were estimated using

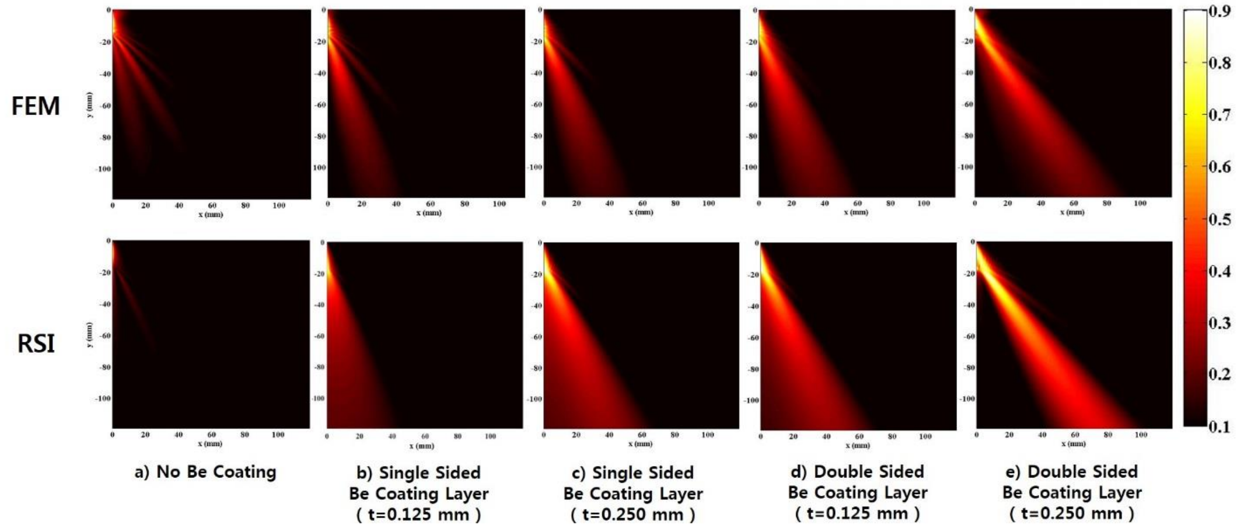

Fig. 6. Estimated under-sodium radiation beam profiles by FEM and RSI models.

the developed FEM and RSI models which had been validated through the previous under-water case.

Figure 6 shows the estimated under-sodium radiation beam profiles obtained by the developed FEM and RSI models. Analyses were conducted for a 1 mm thick STS304 plate with different thicknesses of single and double sided Be coating layers and each result was normalized by its maximum amplitude. The results show that both models have good similarities in terms of the radiation beam characteristics such as the radiation angle and beam pattern although there are still a few minor discrepancies caused by different modeling descriptions; e.g. the dispersion effect based on all frequency components was not considered in the RSI model unlike the FEM model. And one can also see that both models give quite reasonable estimation results representing under-sodium radiation characteristics as mentioned in previous sections; there are no main radiation beams without Be coating layers and radiation angles decrease as thicknesses of Be coating layers increase.

5. Conclusions

In this work, the ultrasonic beam estimations radiated from the plate-type ultrasonic waveguide sensor in liquid sodium were performed by using the FEM and RSI models which had been validated through under-water ultrasonic beam estimations. The results showed that two models had good similarities in terms of the radiation beam characteristics and they could give highly reasonable estimation results. From these results, therefore, one can expect that the introduced FEM and RSI models can be valuable tools for the optimal design of the waveguide sensor.

Acknowledgements

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