Transactions of the Korean Nuclear Society Autumn Meeting
Jeju, Korea, October 21-22, 2010

Simulations of Propagation and Radiation of A_0-mode Lamb Wave in Ultrasonic Waveguide Sensor

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1. Introduction

As the sodium coolant of a sodium-cooled fast reactor (SFR) is opaque to light, a conventional visual inspection cannot be used for carrying out an in-service inspection of the internal structures under a sodium level. An ultrasonic wave should be applied for an under-sodium viewing of the internal structures in a reactor vessel. [1-2]. Recently, a new plate type ultrasonic waveguide sensor has been developed for the versatile applications in the under-sodium viewing application [3]. In the plate type ultrasonic waveguide sensor, the A_0 mode Lamb wave is utilized for the long distance propagation and the effective radiation capability in a fluid. And a radiation beam steering technique is presented which is capable of steering an ultrasonic radiation beam of a waveguide sensor without a mechanical movement of the sensor module [3].

In this paper, the numerical simulation of the propagation and radiation of A_0-mode Lamb wave in ultrasonic leaky wave generation from waveguide sensor is performed by using the finite element method (FEM). The objective of this research is to compare the previous theoretical and experimental results with its numerical simulation.

2. Ultrasonic Waveguide Sensor

Ultrasonic waveguide sensor consists of a thin strip plate, wedge and ultrasonic sensor, as shown Fig. 1. When the waveguide sensor is submerged in a liquid, the leaky waves create the longitudinal wave within the liquid by the mode conversion. The longitudinal ultrasonic beam resulting from the mode conversion is emitted at an angle θ to the waveguide normal, given as:

$$Sin\ \theta(fd) = \frac{V_L}{C_p(fd)} \tag{1}$$

where V_L is the longitudinal wave velocity in a liquid and C_p is the phase velocity of the Lamb wave.

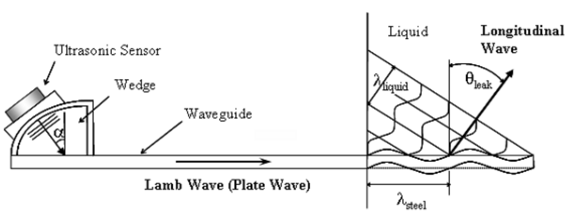


Fig. 1. Leaky Lamb wave propagation in the waveguide sensor and radiation in a fluid by a mode conversion.

In the waveguide sensor application, the zero-order anti-symmetric A_0 mode has been utilized for the single mode generation and an effective radiation capability. Fig 2 shows the dispersion curves of the phase and the group velocity for the A_0 mode Lamb wave in the SS304 plate.

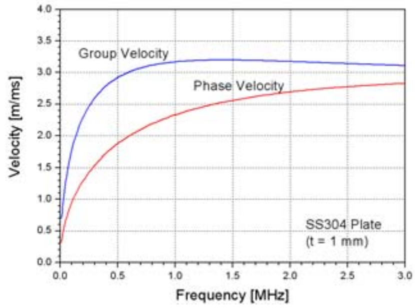


Fig. 2. Dispersion curves of phase and group velocity for A_0 mode Lamb wave in the SS304 plate.

3. FEM Numerical Modeling

The finite element method (FEM) is a numerical simulation method that has been widely and successfully utilized to solve the static and dynamic problems in mechanical, aeronautical and automotive industries. In the finite element analysis of elastic wave propagation, the explicit dynamic method is computationally efficient due to the relatively short dynamic response times and is widely used for analyzing transient dynamic problem [4]. The weak form for a plane harmonic elastodynamic problem obtained through the application of the principle of virtual work can be written using matrix notation as

$$\int_{\Omega} \delta\boldsymbol{\varepsilon}^T \boldsymbol{\sigma} d\Omega = \int_{\Gamma} \delta\mathbf{u}^T \mathbf{t}\sigma d\Gamma + \varpi^2 \int_{\Omega} \rho \delta\mathbf{u}^T \mathbf{u} d\Omega \tag{2}$$

where $\mathbf{u} = [u_x, u_y]^T$, $\mathbf{t} = [t_x, t_y]^T$, $\boldsymbol{\varepsilon} = [\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{xy}]^T$ and $\boldsymbol{\sigma} = [\sigma_{xx}, \sigma_{yy}, \sigma_{xy}]^T$.

Let us consider a homogeneous plate of thickness 2h under plane wave as shown in Fig 3. In order to reproduce the structure of Lamb waves, trial functions $\mathbf{u}$ corresponding to plane harmonic waves propagating in the x direction and towards x→ $-\infty$ are used [5].

$$\mathbf{u}(x, y, t) = \hat{\mathbf{u}}(y) e^{i(kx+\omega t)} \tag{3}$$

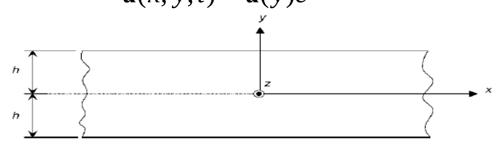
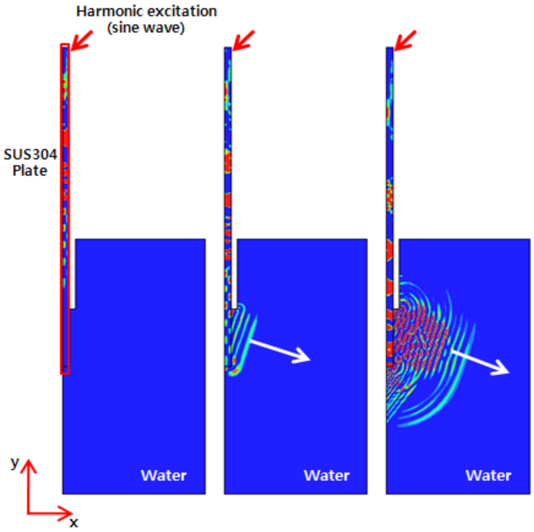


Fig. 3. Geometry of a plate of thickness 2h.

4. Simulation and Results

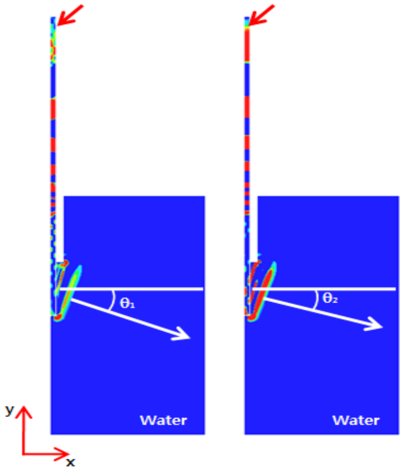
The common FEM program ANSYS that is explicit dynamic analysis code was used in this numerical simulation [4]. For the simulation of the propagation and radiation of A_0-mode Lamb wave in the ultrasonic waveguide sensor, the 1.5 mm thick and 400mm long SS304 plate and the water were modeled together, using Solid164 element type. The Solid164 element is used for the explicit 3-D modeling of solid structures. The element is defined by eight nodes having the following degrees of freedom at each node translations, velocities, and accelerations in the nodal x, y, and z directions. An excitation force in the xy-direction with the time dependence $F(t) = A\sin(2\pi \cdot t)$ for four periods (t<4/f) was applied to the right of top line at the plate model part.



(a) t=10μs (b) t=20μs (c) t=30μs

Fig. 4. Simulation results of the propagation and radiation of A_0-mode Lamb wave in the ultrasonic waveguide sensor submersed in water.

Material parameters (Young's modulus E=2.1×10^{11} N/m^2, Poisson ratio 0.33, density 7800 kg/m^3 and mass damping coefficient 0.001) were chosen appropriate for SUS304 plate. A transient (time dependent) analysis was performed using a step size of 1/10f. The mesh sizes of simulations were chosen to give a maximum element size of 0.5 mm, resulting in approximately 177,000 elements. Fig. 4 shows the numerical calculation results of the propagation of the A_0-mode Lamb wave in the plate and the radiation of the leaky wave in water at the various transient times (t = 10, 20 and 30μs) in the case of the 1MHz frequency excitation. The radiation angle of the leaky wave emitted from the ultrasonic waveguide sensor has been simulated according to the excitation frequency. As shown in Fig. 5, the simulation results show the angle of the radiation beam can be changed by the excitation frequency tuning. This simulation results show a good agreement with the previous experimental result [6].



(a) 0.8MHz (b) 1.5MHz

Fig. 5. Simulation results of the radiation beam steering according to the excitation frequency (θ_1 : at 0.8MHz, θ_2 : at 1.5MHz).

5. Conclusion

The FEM modeling and simulation of the propagation and radiation of A_0-mode Lamb wave in the ultrasonic waveguide sensor has been performed. The simulation results show that the radiation beam angle of the ultrasonic waveguide sensor can be steered by the frequency tuning of excitation pulse. The simulation and experimental results are found to be good agreement. The obtained good agreement demonstrates the validity and applicability of the radiation beam steering technique in ultrasonic waveguide sensor. The various detailed modeling of the ultrasonic waveguide sensor including a wedge and layered plate will be carried out in the further study.

ACKNOWLEDGEMENT

This study was supported by the Korean Ministry of Education, Science & Technology (MEST) through its National Nuclear Technology Program.

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