Theoretical and Experimental Study for the Remote Inspection of Cylindrical Structures Using an Ultrasonic Resonance Scattering

Sa-Hoe Lim, Young-Sang Joo, Jae-Han Lee
Korea Atomic Energy Research Institute, P.O.Box 105, Yuseong, Daejeon, Korea, 305-353, sahoe@kaeri.re.kr

1. Introduction

Reactor internals of a SFR (Sodium Fast Reactor) can not be visually examined owing to its opaque liquid sodium. The under-sodium evaluation technique using an ultrasonic wave should be applied for the inspection of reactor internals. There are many cylindrical structures (for example, fuel assembly of the core, reactor baffle, intermediate heat exchanger, upper internal structure and guide tubes) in a reactor and the continuous monitoring should be achieved for the these internal structures [1].

The resonance scattering problem of normally and obliquely incident acoustic waves by a structure immersed in a fluid has been discussed for the last several decades [2]. When some objects are insonified by acoustic waves, resonances are established at frequencies corresponding to the natural modes of a vibration of an object and scattered waves re-radiate in a fluid. The nondestructive evaluation technique utilizing the resonance scattering may be useful because a sensor is out of contact with the targets.

In this paper, the basic research for a remote inspection of cylindrical structures of reactor internals by using the resonance scattering technique is theoretically and experimentally studied.

2. Theoretical Investigation

The acoustic plane wave having wave number $\vec{k}$ is incident at angle α on a shell. The incident wave external to the scattering object is represented by

$$P_{inc} = \exp[i(k_z z - \omega t)]\sum_{n=0}^{\infty} \varepsilon_n i^n J_n(k_x r)\cos n\theta \,, \quad (1)$$

and the outgoing scattered wave can be written as

$$P_{sc} = \exp[i(k_z z - \omega t)]\sum_{n=0}^{\infty} \varepsilon_n i^n R_n H_n^{(1)}(k_x r)\cos n\theta \,. \quad (2)$$

In the above equations, $k_x = k\cos\alpha$, $k_z = k\sin\alpha$ and R_n are the scattering coefficients to be determined from the boundary conditions. $J_n(x)$ is the first kind Bessel function and $H_n^{(1)}(x)$ is the first kind Henkel function of order n. For each summation index n, seven parameters are to be found from the contact conditions:

on the outer surface of the shell

$$\tau_{rr}^{(1)} = -P \,,\; U_r^{(1)} = U_r \,,\; \tau_{r\theta}^{(1)} = 0 \,,\; \tau_{rz}^{(1)} = 0 \quad \text{at } r = a_1 \,, \quad (3\text{-}1)$$

and on the inner surface of the shell

$$\tau_{rr}^{(1)} = 0 \,,\; \tau_{r\theta}^{(1)} = 0 \,,\; \tau_{rz}^{(1)} = 0 \quad \text{at } r = a_0 \,. \quad (3\text{-}2)$$

From Eq. (2), the normalized far-field amplitude called a form function is given as

$$f_n(\theta,\eta) = \frac{2}{\sqrt{\pi i \eta}}\varepsilon_n R_n \cos n\theta \,, \quad (4)$$

where η is a normalized frequency ka_1.

The resonant part of each mode can be obtained by rejecting the acoustical background $f_n^{(b)}(\theta,\eta)$ from the normal mode components $f_n(\theta,\eta)$ according to the following equation:

$$f_n^{(reso)}(\theta,\eta) = \frac{2}{\sqrt{\pi i \eta}}\varepsilon_n (R_n - R_n^{(b)})\cos n\theta \,. \quad (5)$$

3. Experiments

The backscattering experiments are carried out for a Zr-4 cylindrical shell in a water tank. A diagram of the experimental setup is given in Fig. 1. The immersed specimen is insonified and its scattering signals are captured by broadband ultrasonic transducers. The transducers (central frequency: 0.5, 1.0, 2.25 and 3.5 MHz) are used. Backscattered signals are measured for the frequency of incident wave varying from 0.3 MHz to 4.0MHz, in the incident angle $0^{\circ} \le \alpha \le 40^{\circ}$.

4. Results and Discussion

The resonance spectra and form functions of a Zr-4 cylindrical shell are calculated for incidence angles varying from 0° to 40°, in the dimensionless parameter ka<100. The cylindrical shells are made of Zr-4 of density $\rho = 6.55 \; kg/m^3$, with longitudinal and transversal sound velocities of, respectively, $C_L = 4{,}600 \; m/s$ and $C_T = 2{,}360 \; m/s$. The ratio of the inner diameter and the outer diameter (ID/OD) of the shell is 0.89. The travel paths of all the waves propagated along the surface are helices, and the angle of each helix depends on the phase velocity of the corresponding surface wave [3, 4]. Fig. 2 shows complete resonance spectra computed with $\alpha = 0^{\circ}$ and 5°. As compared with the normal incidence, the additional wave modes excited by an obliquely incident acoustic wave propagate along helical paths in the cylindrical shell [5]. With an increase of α, all the resonance peaks are shifted up. Fig. 3 shows the calculated and measured backscattering spectral magnitude from the cylindrical shell, over a range of aspect angles from $\alpha = 0^{\circ}$ to $\alpha = 40^{\circ}$, in 1° increments.

The theoretical backscattering spectra show resonances of 3-types of helical waves: Stonely, circumferential and transversal waves [4]. The resonance frequency of the waves increases when the incidence angle increases. Behaviors of two wave modes are distinguishable. T_0 waves do not appear anymore beyond the second critical angle ($\alpha^{2nd.}_{critical} = \sin^{-1}(C/C_T) = 38.9^{\circ}$). In the experimental results, a splitting of the resonances of the T_0 waves is observed under the influence of a finite cylindrical shell. In a range from $\alpha = 0^{\circ}$ to the first critical angle ($\alpha^{1st.}_{critical} = \sin^{-1}(C/C_{plate}) = 21.5^{\circ}$), S_0 waves have helical waves feature. With increasing incident angles, the S_0 waves have a meridional waves feature the same as the plate wave.

5. Conclusion

There are many cylindrical structures in the reactor internals of a SFR and an integrity assessment of these structures must be carried out. A remote inspection by utilizing an ultrasonic resonance scattering may be useful because a sensor is out of contact with the targets. The acoustic scattering of obliquely incident plan acoustic waves by a cylindrical shell immersed in a fluid was researched. A comparison between theoretical and experimental results reveals a good agreement. Ray analysis of these backscattering amplitudes may be useful to measure elastic properties or material damage of cylindrical structures.

ACKNOWLEDGEMENT

This study was supported by the Korean Ministry of Science & Technology through its National Nuclear Technology Program.

REFERENCES

[1] Y. S. Joo, et al., Proceedings of the KNS, May 2005
[2] L. Flax, et al., JASA, 63, 723-731, 1978.
[3] S. F. Morse, et al., JASA, 103, 785-794, 1997.
[4] A. Nagl, et al., Wave Motion , 5, 235-247, 1993.
[5] F. Leon, et al., JASA, 91, 1388-1397, 1992.

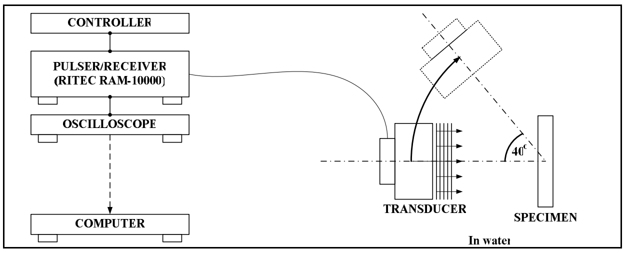

Fig. 1 Experimental setup

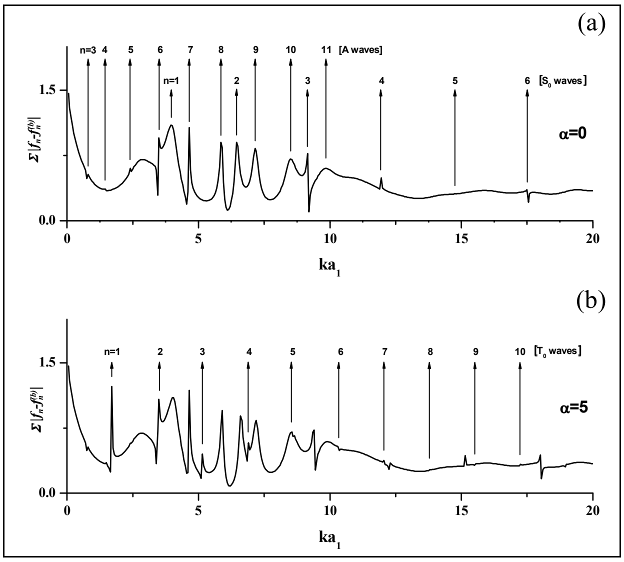

Fig. 2 Complete resonance form functions for (a) normal ($\alpha = 0^{\circ}$) and (b) oblique incidence ($\alpha = 5^{\circ}$).

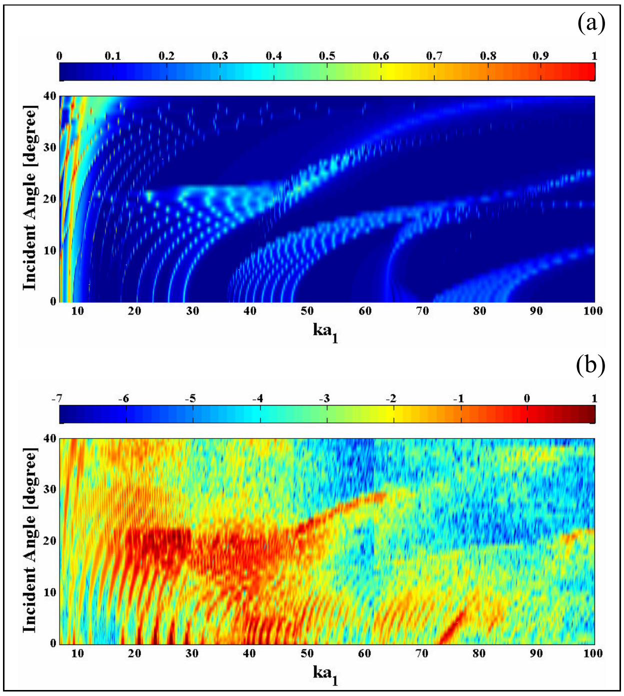

Fig. 3 Backscattering spectral magnitude as a function of frequency and aspect angle: (a) calculation and (b) measurement spectrum.