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Article

Evaluation of Interface Defects for Inaccessible Reactor Shrink Fit Nozzle Weld by Ultrasonic Wave

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Abstract: An effective method to inspect inaccessible nuclear power facility by interface wave which propagate along the shrink fit boundary of reactor head is proposed in this study. Reactor head is relatively thick to inspect from the outside of reactor by conventional ultrasonic testing. The proposed interface wave can propagate a long distance from the fixed transducer position. The inside of nuclear reactor is limited to access due to the high radiation, so transducers are located at outside of nuclear facility and interface wave propagates into the nuclear reactor for defect detection. The numerical simulation and experiments were carried out to validate the effectiveness of the proposed interface wave inspection method. Various defect cases simulating field failures are also presented with satisfactory detectability by the proposed technique with the features for defect classification.

Keywords: nuclear facility; ultrasonic interface wave; defect detection; nondestructive testing; finite element method; inaccessible nozzle

1. Introduction

It is very important to efficiently monitor the nuclear power plant condition and to detect defects for the safe operation of complex structure. In order to prevent failure situation, schedule-based maintenance has been performed to inspect nuclear power facility. This inspection scheme is moving toward from schedule-based maintenance to condition-based maintenance. For the condition-based maintenance inspection, proper diagnostic method should follow up for each component. The risk of failure with defects has been increased due to long-term use in the nuclear power plants and large industrial pipes. Moreover, the needs of the safety diagnosis and life prediction technology for main equipment of nuclear power plants such as jointing weld is growing for maintenance and extension of the life due to the aging of operated nuclear power plants.

In general, there are several ways of diagnosing the plant condition. First, diagnostic tests to classify the candidates of anomalies are repeated until an anomaly is identified. Second, an assumption for the detected anomaly is made and it is confirmed by diagnostic tests. Third, a standard set of diagnostic tests is applied and the anomaly is diagnostic [1]. Recently, nuclear power facility safety issues become great concern to people. Nuclear power plant has been built several decays since the first time generates electricity by nuclear source. Nuclear power plant components are specially designed for their purpose. Therefore, those components need a unique inspection method to achieve high safety demands. Nuclear power plant components inspection by Guided wave inspection method is presented such as nuclear power plant valves [2], pipes [3-5] and steam generator tube [6]. Nuclear power plants are inspected regular schedule based maintenance. Ultrasonic NDE is employed periodically on a nuclear power system to inspect the defects or defect growth. The need of continuous online monitoring has been increased for the stable safety check. Online monitoring is becoming all the more important with development of radiation hard materials and wireless communication. However, it has long way to go to achieve this purpose by online monitoring for the nuclear power component. In case of the reactor head nozzle, generally it is

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inspected by conventional ultrasonic testing (UT) during in-service inspection (ISI) period from the inside of nuclear reactor with remote robot system due to the high radiation [7,8]. Nuclear reactor head is relatively thick to be inspected by conventional UT accessing from outside of reactor head. The remote robot system is a solution for weld inspection on reactor nozzle. However, for condition-based maintenance, the remote robot inspection method is only possible during ISI, so alternative inspection method is proposed in this paper.

The penetrated nozzle on the reactor head is inspected by the pseudo interface wave which is propagating along the boundary between nozzle and reactor head. Through proposed inspection technique, the defects on the weld and its interface can be identified from outside of nuclear reactor head. The pseudo interface wave propagating characteristic on the nuclear reactor nozzle is presented [9]. It shows possibility of interface inspection method. However, for the quantitative defect identification model based study is performed in this study. The pseudo interface wave propagation characteristic and scattering from defect and weld at reactor nozzle is evaluated and experimentally validated.

2. Interface wave propagation theory

A variety of interface wave type is discussed in earlier literature. Rayleigh waves are one of the interface waves which travel in solid-vacuum half space. In isotropic solids the particle motion in elliptical and retrograde, for shallow depths, with respect to the propagation direction. The Stoneley wave which propagate the interface between solid-solid media is introduced by Stoneley [10]. Some surface wave applications can be found in earlier papers [11-13]. Surface wave propagates on half media and Stoneley wave propagates along the interface between to different solid material. The displacement of interface wave on the plate is defined in equation (1 a, b) [14].

$$u = \mathrm{u}(z)e^{ikx}, w = \mathrm{w}(z)e^{ikx} \qquad (1\text{ a, b})$$

where u and w is the displacement in the x and z directions. The term $e^{i\omega t}$ has been omitted here and after. The coordinate system is shown in Figure 1. Unknown amplitude u(z) and w(z) can be define as equation (2)

$$\mathrm{u(z)} = [(\mathrm{A}e^{-k\alpha z} + Be^{k\alpha z}) - \beta(\mathrm{C}e^{-k\beta z} - De^{k\beta z})]e^{ikx} \qquad (2\text{ a})$$

$$\mathrm{w(z)} = i[\alpha(\mathrm{A}e^{-k\alpha z} - Be^{k\alpha z}) - (\mathrm{C}e^{-k\beta z} + De^{k\beta z})]e^{ikx} \qquad (2\text{ b})$$

where $\alpha^2 = 1 - \frac{c^2}{c_L^2}$, $\beta^2 = 1 - \frac{c^2}{c_T^2}$, $\mathrm{c} = \frac{\omega}{\mathrm{k}}$

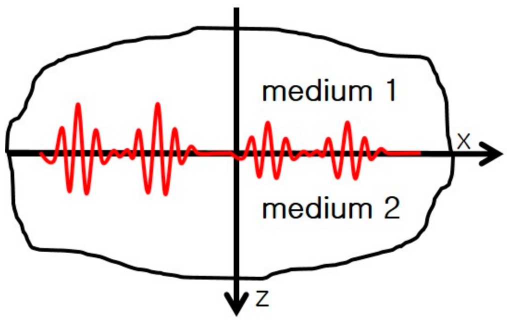

Figure 1. Coordinates of interface medium 1 and medium 2.

The stress component is derived as equation (3 a, b)

$$\sigma_z = i\mu[-\mathrm{k}(1+\beta^2)(Ae^{-k\alpha z} + Be^{k\alpha z}) + 2k\beta\big(Ce^{-k\beta z} - De^{k\beta z}\big)]e^{ikx} \qquad (3\text{ a})$$

$$\sigma_{xz} = \mu[-2\mathrm{k}\alpha(Ae^{-k\alpha z} - Be^{k\alpha z}) + k(1+\beta^2)(Ce^{-k\beta z} + De^{k\beta z}]e^{ikx} \qquad (3\text{ b})$$

The boundary condition on the interface between medium 1 and 2 can be set as below

$$u^{(1)} = u^{(2)}, w^{(1)} = w^{(2)}, \sigma_z^{(1)} = \sigma_z^{(2)}, \sigma_{xz}^{(1)} = \sigma_{xz}^{(2)}$$

where superscript (1) and (2) indicate medium 1 and 2, respectively.

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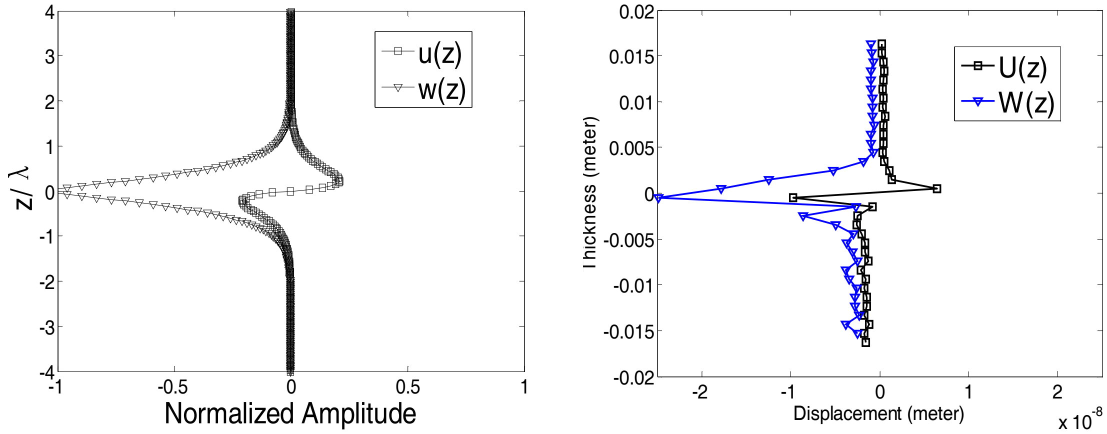
To satisfy boundary condition, when z=0, the system equation (4) have a nontrivial solution when determinant is zero.

$$\begin{bmatrix} \sigma_z^{(1)} - \sigma_z^{(2)} \\ \sigma_{xz}^{(1)} - \sigma_{xz}^{(2)} \\ u^{(1)} - u^{(2)} \\ w^{(1)} - w^{(2)} \end{bmatrix} = \begin{bmatrix} -(1+\beta_1^2) & -2\beta_1 & (1+\beta_1^2)g & -2\beta_2 g \\ 2\alpha_1 & (1+\beta_1^2) & 2\alpha_2 g & -(1+\beta_2^2)g \\ 1 & \beta_1 & -1 & \beta_2 \\ -\alpha_1 & -1 & -\alpha_2 & 1 \end{bmatrix} \begin{bmatrix} B_1 \\ D_1 \\ A_2 \\ C_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

Figure 2 shows wave amplitude distributions on the thickness direction. The interface wave amplitude distributions on the thickness direction are calculated by analytic approach by wave equation on the Figure 2 (a) and finite element numerical approach on the Figure 2 (b). Displacement u(z) is in-plane displacement and w(z) is out-of-plane displacement. The out of plane displacement on the interface is the maximum while getting far from the interface out of plane displacement becomes zero. In the case of this research, two layered structure has similar material property as stainless steel 316..



(a) (b)

Figure 2. Wave amplitude distributions on the thickness direction (a) theoretical analysis and (b) finite element numerical analysis. Square symbols indicate u(z) and triangle symbols present w(z).

3. Nuclear reactor head nozzle model

On the integrated small nuclear reactor system as illustrated in Figure 3, the control element drive mechanism (CEDM) installs through nuclear reactor head. In the structure, the interface of reactor head and nozzle pipe are attached with shrink fit condition and welded at the end of shrink fit boundary. On the connection part of CEDM nozzle and reactor head, special shape of weld such as J-groove weld is employed for prevention of radiation leakage. The proposed interface wave inspection method is applied for the monitoring of J-groove weld.

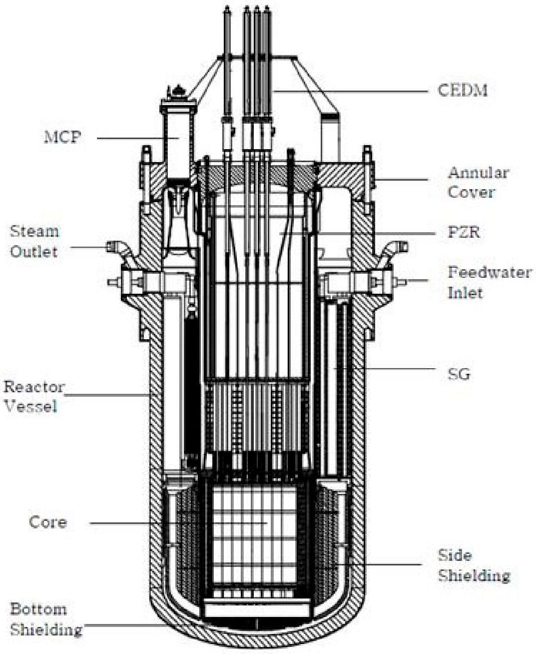


Figure 3. Schematic of integrated small modular reactor system

3.1. Finite element model analyis for reactor nozzle

Finite element modeling is performed to verify interface wave propagation pattern and reflection signal analysis. Commercial finite element modeling package ABAQUS/CAE 6.12 is employed for model analysis. The detail specification of CEDM nozzle model is shown in Figure 4 and mesh information is listed on Table 1. The material of this model is Stainless steel 316 for reactor head and nozzle. The excitation frequency is 1 MHz and the wave length is 0.0027 m for the interface wave. The mesh size is set as 1/10 of wave length to indicate proper wave propagation characteristic in the numerical model. The edge of nozzle and reactor head is set as absorbing boundary to eliminate unexpected reflection from the boundary.

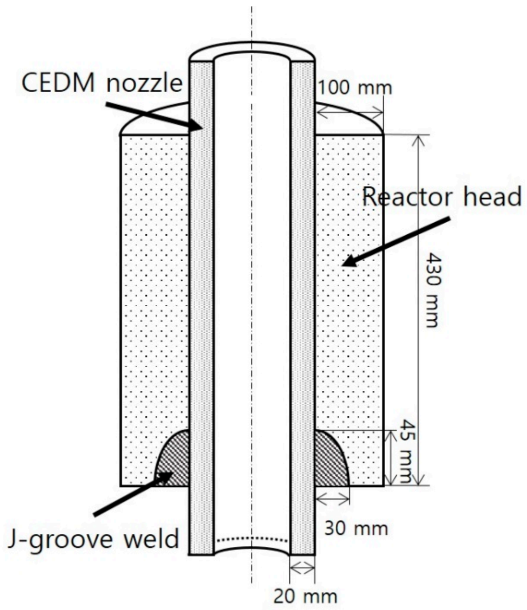


Figure 4. Interface wave propagation model on CEDM nozzle model.

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Table 1. CEDM nozzle modeling specification

Frequency	1MHz
Wavelength	0.0027m
Mesh size	0.00027m
Element type	CPE4R(Plane strain condition)

The interface wave propagates with strong directivity and less distribution on circumferential direction [15]. Finite element model of CEDM nozzle interface wave propagation and reflection is depicted in Figure 5. Interface wave energy is concentrated on the interface and it propagates along the axial direction. The propagation distance of interface wave is 430 mm from the excitation location and it reflected from the boundary of weld and the end of reactor head.

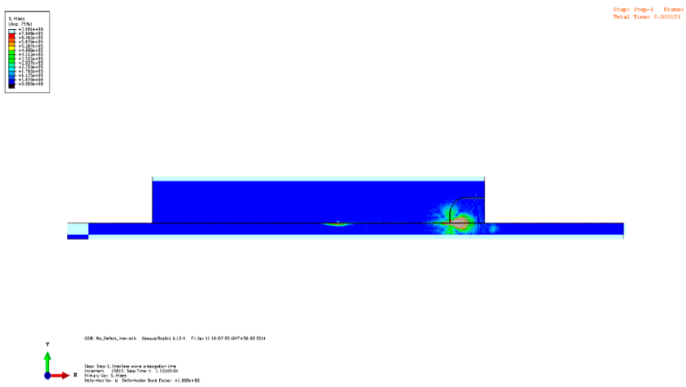
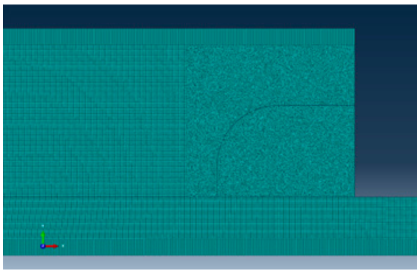
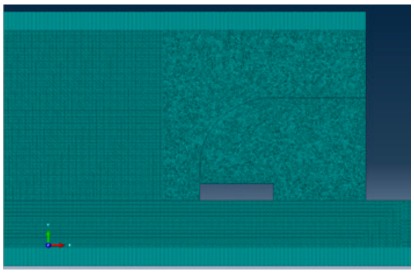


Figure 5. Interface wave propagation model on CEDM nozzle model of finite element analysis

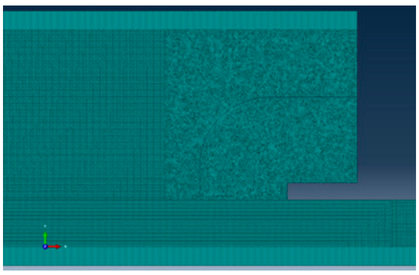
The FEM model of defects in nozzle weld are depicted on Figure 6. J-groove weld is modeled at the end of nozzle and it is attached with reactor head. The interface wave propagates along the boundary of nozzle and reactor head. Three different defects are modeled to investigate the reflection from the boundary of weld and the end of structure. These defect locations are chosen based on the possibility of defect initiation at the manufacturing process and operation.



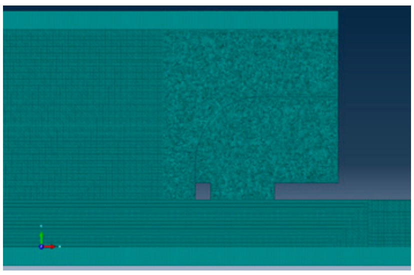
(a) Intact model



(b) Anomaly #1



(c) Anomaly #2



(d) Anomaly #3

Figure 6. Nozzle weld model (a) Intact model, (b)~(d) anomalies

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For analysis convenience, each parts of model components are set with different mesh type. It can help computing time and memory. Interface wave is generated on the outside of reactor head and it propagates along the interface and reflects from weld and defect. The reflected signals from weld and defects are depicted on Figure 7. It shows the weld and defect reflection signal at each location. Because of two dimensional models, once interface wave reflected from the defect, the most of wave energy is scattered from the defect. These model analysis indicates the existence and the location of defects.

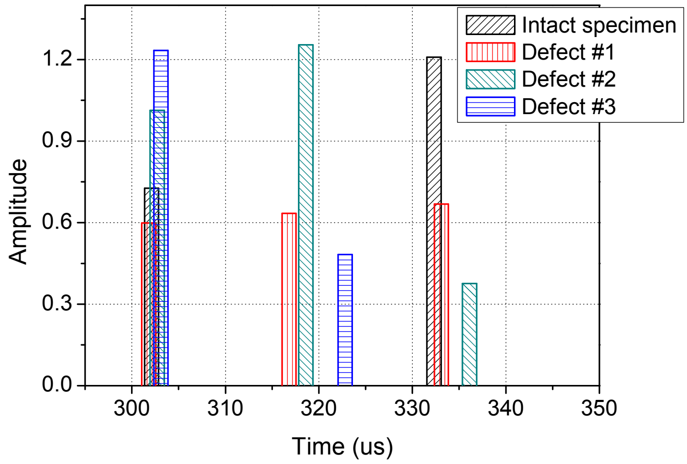

Figure 7. Finite element model analysis signals

As it is shown on Figure 7, the interface wave can propagate along the shrink fitted structure and the interface wave can identify defects inside of weld at the interface of structure.

3.2. Experimental setup and specimen

The interface waves propagate along the shrink fit interface condition and reflect from defect and reactor head end. The experimental setup is illustrated on Figure 8 The excitation frequency is 1 MHz with 4 cycles of tone burst wave signal.

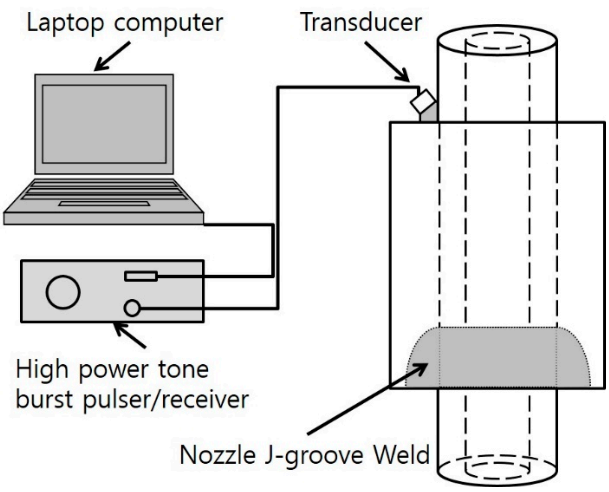

Figure 8. CEDM nozzle inspection system

The specimen is manufactured with shrink fit condition as part of nuclear reactor. One side of boundary is J-groove welded. Figure 9 shows the picture of CEDM nozzle specimen with J-groove

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welded. The specimen is simplified for the purpose of this study. The complicated inner structures are excluded due to the interface wave propagation characteristic.

Figure 9. CEDM nozzle specimen with J-groove weld

The specification of CEDM nozzle specimen is listed on Table 2. The thickness of reactor head is 430 mm and outer diameter of nozzle is 340 mm and 20 mm thick. Material of this specimen is Stainless steel 316. The interface on reactor head and CEDM nozzle is made of shrink fit condition.

Table 2. The specification of CEDM nozzle specimen

Specimen dimension	Distance (mm)
Inner radius	50
Attached layer radius	70
Outer radius	170
Length	430

To verify interface wave propagation, the defect is manufactured at the interface of nozzle and reactor head. Detail defects information are listed on Table 3. Defect location and size is shown on Figure 10. There are five defects on the specimen at every quarter part. Two defects are on the same axial line to check interface wave resolution. Dashed line on the right hand side in Figure 10 indicate J-groove weld.

Table 3. The defect information of CEDM nozzle specimen

Defect	Axial size (mm)	Circumferential size (mm)	Radius size (mm)
#1	20	20	1
#2	20	20	1
#3-1	3	5	1
#3-2	15	10	1

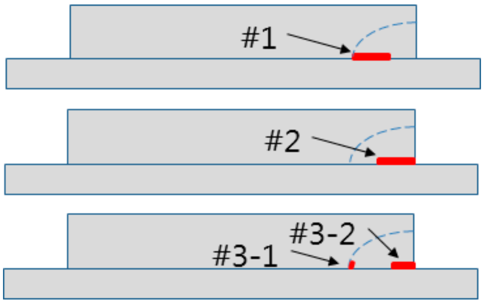


Figure 10. Defect location and shape on a lateral view of specimen

The interface wave inspection is performed on this specimen. The experimental result shows on Figure 11.

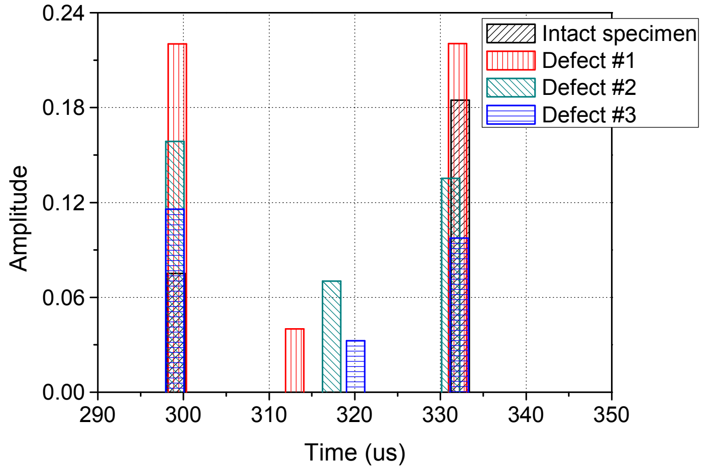
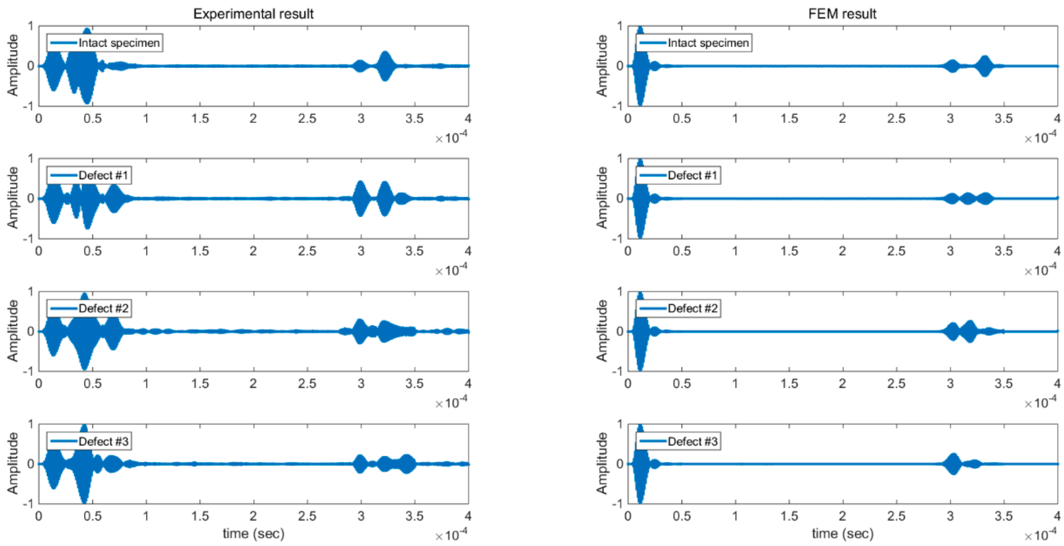


Figure 11. CEDM weld specimen inspection signal

Finite element model analysis result and experimental results are compared in Figure 12. FEM model analysis show good agreement with experimental results. Both of FEM and experimental results have two peaks from the boundary of weld and the end of outer structure. From the each defects the reflection ratio between first and second peaks are much different compared to defected case and non-defect case.



(**a**) (**b**)

Figure 12. Comparison between experimental results (a) and numerical modeling results (b)

4. Discussion

The nuclear reactor nozzle J-groove weld defect investigation is performed by numerical finite element method and experimental approach via interface wave in this paper. The interface boundary is modeled by finite element method and it is analyzed the wave propagation characteristic of reflection signal. The interface wave propagates along the interface and reflected from weld and

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defect. The reflected signal pattern shows good agreement on numerical analysis and experimental validation.

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Author Contributions: Jaesun Lee designed the methodology, implemented the simulations and experiments, and wrote the manuscript. Younho Cho prepared the specimen for the experiment, and gave guidance and helped to improve the quality of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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