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ARTICLE

Ultrasonic propagation analysis for new water level measurement method using clamp-on ultrasonic transducers

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Water level gauges using differential pressure are widely used for reactor pressure vessels (RPV). However, if a severe accident occurs and the water in the reference plane evaporates, the water level cannot be measured. To solve this problem, we have developed a new method to measure water level by measuring the magnitude of the ultrasonic echo signal. Two clamp-on ultrasonic transducers are installed on the RPV surface and the signals emitted from one of the ultrasonic transducers are received by the other transducer via the RPV with reflection. In addition to experimental verification of this method, we conducted ultrasonic propagation simulations. The calculated results show that as the water level drops, the magnitude of the received echo signal increases due to the effect of acoustic impedance. If this measurement method can be improved and applied to RPVs made of carbon steel with thick walls, water levels can be measured appropriately during a severe accident.

Keywords: ***water level of RPV; simulation of ultrasonic propagation; reflection of ultrasonic; acoustic impedance***

1. Introduction

A differential pressure gauge is used to measure the water level in the containment vessel of a nuclear power plant. However, if a severe accident occurs and water evaporates in the piping on the gauge reference side, as shown in **Figure 1**, the differential pressure between the water level in the vessel and the water level in the piping in the reference vessel becomes small. As a result, the water level is erroneously recognized as normal even though it is decreasing, which will greatly affect operation of the plant. We have devised a new method of measuring the water level by using ultrasonic waves to ensure that it can still be measured normally even in the event of a severe accident.

An ultrasonic transducer (TDX) is clamped to the vessel surface as shown in **Figure 2**, so that under normal conditions, ultrasonic waves can be transmitted from a

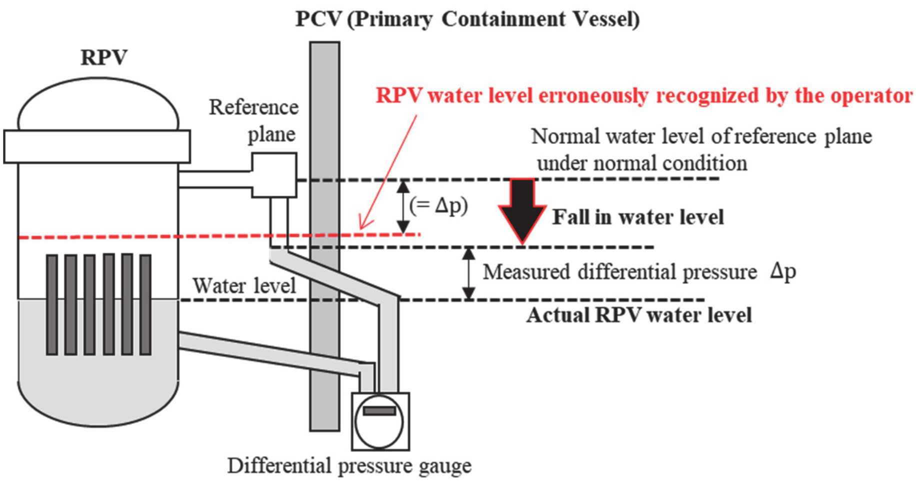

Figure 1. Schematic diagram of differential pressure gauge.

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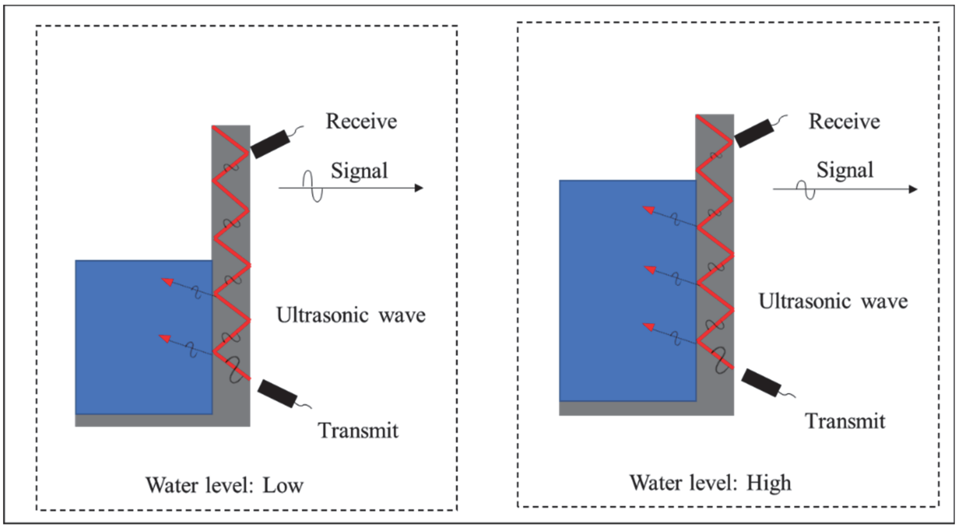

Figure 2. Schematic diagram of ultrasonic clamp-on water level gauge.

low (or high) water level position and received at a high (or low) water level position. Ultrasonic waves transmitted from one TDX are received by another TDX while being reflected multiple times within the vessel material. The magnitude of the received signal increases as the water level decreases, enabling the water level to be determined from the magnitude of the received signal. Since there is no measuring instrument inserted inside the vessel, installation is simple and the instrument is not affected by the inside of the vessel.

The purpose of this study is to confirm the effectiveness of a new ultrasonic water level measurement method by simulating ultrasonic propagation in a small 10 mm wall thickness aluminum vessel model, and to apply this method to RPVs in the future.

2. Ultrasonic reflection

If there is water in the vessel, when ultrasonic waves are reflected inside the vessel, some of the waves enter the water, thus reducing the energy reflected. Therefore, the higher the water level, the lower the magnitude of the received signal.

When water (material 2) is inside the vessel (material 1), the reflectance R_p and transmittance T_p of sound are given by the following equations:

$$R_p = \frac{Z_2 - Z_1}{Z_1 + Z_2} \tag{1}$$

$$T_p = \frac{2Z_2}{Z_1 + Z_2} \tag{2}$$

where Z_1 is the acoustic impedance of material 1 (vessel) and Z_2 is that of material 2 (water).

In the absence of water in the vessel, the reflectance of ultrasonic waves $R_w \approx 1$, and the signal displacement ratio is as follows:

$$\frac{R_p}{R_w} \approx R_p \tag{3}$$

Using the difference in reflectance at the pipe boundary with and without water, TDXs for transmitting and receiving are placed diagonally by clamping on the vessel in the direction of the height of the vessel. The reflectance of ultrasound propagating diagonally from material 1 to material 2 is denoted by R_m. When the water level is full, the signal is reflected n times at the boundary with the water inside the vessel before reaching the TDX for receiving. When the water level decreases and the signal is reflected k times at the boundary with the water, the ratio is as follows:

$$\frac{R_m^k}{R_m^n} = R_m^{(k-n)} \tag{4}$$

The lower the water level, the smaller k becomes, and since $R_m < 1$, the lower the water level, the larger the received signal.

3. Ultrasonic propagation simulation

3.1. Calculation method

To investigate the applicability of using ultrasound to measure water level, finite element method (FEM) propagation analysis using a two-dimensional simplified model was performed to evaluate the magnitude of the received signal. The analysis code used was ComWAVE®, which can efficiently analyze ultrasonic wave propagation [1,2].

The vessel was made of aluminum, and ultrasonic waves with a frequency of 2 MHz were transmitted from a TDX with an external diameter of 10 mm. Aluminum was used in this study because the acoustic impedances of aluminum and carbon steel for longitudinal waves are, respectively, about 12 times and 30 times larger than that of water. Therefore, when the vessel is aluminum, the

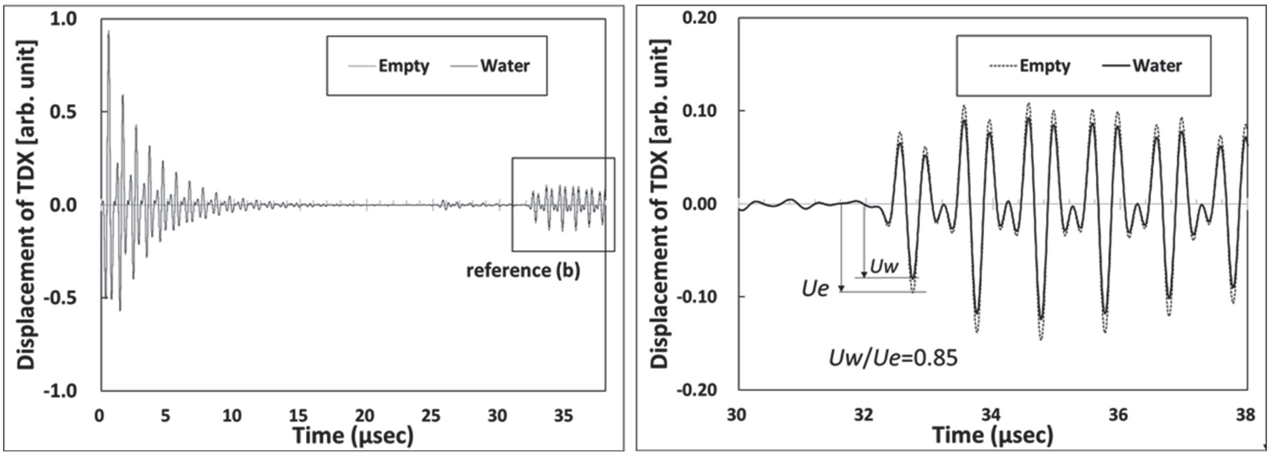

Figure 3. Waveforms of received signals when ultrasonic waves are injected perpendicularly to the vessel.

transmission of ultrasonic waves to water is larger and the reflection is smaller than that of carbon steel, the main material of the RPV. Therefore, the effect of the water level is significant, making it easier to evaluate the magnitude of the ultrasonic signal in a small-scale experimantal model. In the actual model, the distance between the two transducers can be made larger. As a result, the number of ultrasonic reflections increases, and we estimate that the effect of water level on the echo signal is also larger in carbon steel vessels.

The calculations were performed on a two-dimensional model, with a mesh size of 0.05 mm square and a Courant number of 0.7. All models were assumed to be at room temperature and atmospheric pressure.

3.2. Basic calculation

In order to understand the propagation characteristics of the magnitude of the received signal with and without water in the vessel, a simulation was conducted in which a longitudinal wave signal was emitted and received by one ultrasonic TDX perpendicular to the vessel. The thickness of the vessel was 100 mm.

The received signal displacements in each case are shown in **Figure 3(a)** shows the displacement data for the time period from transmission to reception, and **(b)** is a magnified image of the area around the time of reception of the main signal. The displacement ratio of the received signal near the time of reception was 0.85 for an aluminum–water reflectance $R_p = 0.846$, which is close to the value given by Eq. (3). Ultrasound is attenuated by diffusion, but the ratio of this displacement is not affected by the water level in the vessel. In ultrasonic transducers, volumetric strain of the transducer element generates a voltage signal that is proportional to the volumetric strain, and the displacement is proportional to this strain. These results make it possible to measure the water level by measuring the amplitude ratio of the TDX's signals.

3.3. Relationship between water level and ultrasound signal magnitude

The analysis for ultrasonic measurement of water level

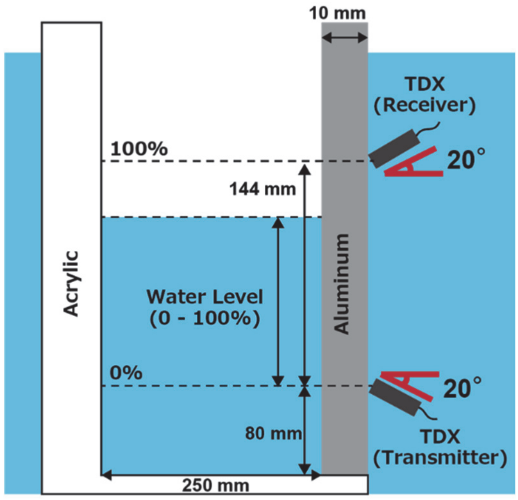

Figure 4. Schematic diagram of the experimental equipment used in the analysis.

was performed by modeling the schematic diagram of the experimental apparatus shown in **Figure 4**. The TDX for transmitting is mounted at an angle so that longitudinal ultrasonic waves are propagated from the TDX for transmitting and only transverse waves are propagated through the vessel material. The TDX for receiving is placed at the position where the propagated wave is reflected multiple times by the piping and reaches the surface of the vessel.

In this model, the distance between the transmitting and receiving TDXs is approximately 144 mm, the mounting angle is 20°, and the vessel wall thickness is 10 mm. In this model, the transmitted ultrasonic waves are reflected seven times inside the vessel before reaching the receiving transducer. In the simulation model, the outside of the vessel is also filled with water. This is the same condition as in the experimental model. In the actual plant, couplant (contact medium) is applied to eliminate the air layer between the TDX or TDX fixture and the container surface when the TDX is fixed to the container, but the condition of the couplant causes variations in the ultrasonic wave propagation. The effect of the TDX's installation condition on the measured values will need to be studied in the future. Simulation and experimental results at five different water levels are shown in **Figures 5(a)** and **5(b)**. In the experiments, ultrasonic waves were transmitted from the TDX by giving a 2 MHz burst wave voltage signal, the received waveform was measured 20 times consecutively at the same water level by an A/D converter, and the average waveform was used to evaluate the echo height. Compared to the simulation, the changes in echo signal in response to changes in water level were smaller. It is assumed that this is because ultrasonic waves leak outside from the fixture of the TDX, and the ultrasonic waves propagating from the TDX to the vessel material, which are affected by the water level, have become smaller. Therefore, the signals received by the TDX contain signals unaffected by water level, so changes due to water level are small. The conversion characteristics of the received echoes from volumetric strain to electrical signals at the TDX should also be investigated in the future.

In both cases, the maximum echo height was normalized by the value at 0% water level. The lower the water level, the greater the magnitude of echo, and compared to the full water level, the signal was approximately five times greater at no water level in the simulation and 1.6 times greater in the experiment.

Thus, the relationship between the water level and the received signal was confirmed by simulation and experiment.

4. Conclusions

Simulations and experiments on ultrasound propagation were conducted using a model of a 10-mm-thick aluminum vessel to determine the displacement of the received signal. We confirmed that the lower the water level, the greater the echo signal, and thus demonstrated the effectiveness of this method. In the future, we plan to conduct verifications using the same material as an actual plant.

References

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