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Verification of Computational Fluid Dynamics Analysis of Sloshing for Investigating Seismic Safety of the Spent Fuel Pool

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1. Introduction

Nuclear power plant contains various fluid filled pools such as spent fuel pool. Fluid such as coolant shows various dynamic behaviors according to its depth [1]. Therefore, accurate investigation of the fluid dynamic behaviors is critical in the seismic evaluation of nuclear facilities.

Commercial computational fluid dynamic (CFD) software are widely used in the nuclear safety community [2]. These CFD software also could be effectively used in the accurate investigation of the behaviors of the fluid such like coolant. However, its validity should be verified with comparing to the experimental results prior to be used in the real seismic evaluation of the nuclear power plant. In this study, sloshing of the water in the scaled-down spent fuel pool was analyzed using experimental and computational approaches and the results of both approaches were compared with each other for the verification of the computational approach.

2. Methods and Results

Changes in water level and pressure on the wall surface of the pool during water sloshing were analyzed using experimental and computer simulation approaches. Then the results were compared with each other to verify CFD availability of CFD method for investigating sloshing phenomena.

2.1 Experiment

The rectangular tank was made of 35 mm thick acrylic glass (Fig. 1). Its height, width, and thickness were 815 mm, 520 mm, and 150 mm, respectively. The size of the tank was chosen based on the real spent fuel pool at South Korea's Hanul nuclear power plant. Four piezoelectric pressure sensors were attached to a side wall of the tank at the height of 120 mm, 235 mm, 615 mm, and 676 mm from the floor surface of the tank.

The tank was installed on the vibration table. The width and depth of the tank was aligned along the axis directions of the vibration table. Three different initial level of the filled water 230 mm, 420 mm, and 610 mm were adopted for the experiment. Excitation frequencies of 0.5 Hz, 1.0 Hz, and 5.0 Hz were used. Here, amplitude of the vibration was fixed to be 5 mm in all experimental cases. A digital camera was fixed in front of the vibration table to measure changes in the water level.

The table was excited during 10 second. Changes in free surfaces and pressures on the tank wall were measured for 15 seconds (10 seconds during excitation and 5 seconds after excitation).

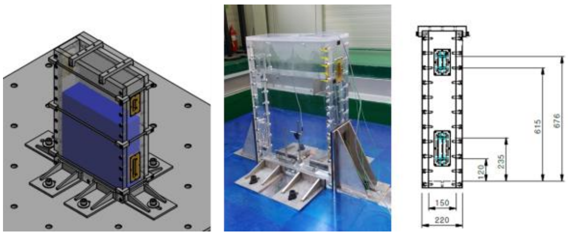

Fig. 1. Three-dimensional CAD model of the tank (left), real tank installed on the vibration table (middle), and the location of the pressure sensors (right)

2.2 CFD analysis

CFD model including water and air in the tank which has the same size with the experiment was developed [3]. The temperature of the water and air was assumed to be 25 ℃ and static pressure at the pressure outlet, which is the superior plane of the calculation domain, was set to be 0 Pa. The initial water level was varied from 230 mm to 610 mm, excitation with frequencies of 0.5 Hz, 1.0 Hz, and 5.0 Hz and amplitude of 5 mm were applied for 10 seconds same as the experiment. Here, commercial CFD software Ansys Fluent (Ansys Inc., Canonsburg, PA, USA) was used.

3. Results and Discussions

Fast Fourier Transform was employed to extract frequency content of changes in the pressure on the tank wall. In the experiments, the sensors which were exposed in the air could not measure the pressure correctly. Only sensor which located in the deepest location could measure the pressure in all cases. When the initial water level is 230 mm, no meaningful cycles of pressure changes were computed, however, the same frequency of the pressure changes with excitation frequency were computed in other cases.

In analytical approaches, When the initial water levels were 420 mm and 610 mm, the same frequency of the pressure changes with excitation frequency were computed. However, a frequency of 1.13 Hz was extracted with the excitation frequency in case that the initial water level is 230 mm. Previously published study have asserted that the sloshing frequency is very close to the first mode natural frequency of the water calculated by the linear wave theory [4]. The first mode natural frequency of the water when the initial water level is 230 mm is 1.22 Hz. Because the location at which the pressured was measured was not far from free surface when the initial water level is 230 mm, the sloshing frequency of the water 1.13 Hz seems to be extracted with excitation frequency (Table I).

Table I: Cycle of pressure changes on the wall surface measured at the height of 120 mm.

Excitation Frequency (Hz)	Initial water level (mm)	Computer simulation (Hz)	Experiment (Hz)
0.5	230	0.47, 1.13	-
	420	0.47	-
	610	0.47	-
1.0	230	1.00, 1.13	1.00
	420	1.00	1.00
	610	1.00	1.00
5.0	230	1.13, 5.00	4.98
	420	5.00	4.98
	610	5.00	4.98

The overall behavior of the water in study cases were very similar in both experimental and computational approaches, especially in the cases that 1 Hz of excitation frequency was used because the free surface was changed smoothly with slight splashed water (Fig. 2). However, the difference of the maximum water level of the computational results quite differed to the results of experiments when excitation frequency of 5 Hz was used. In this study, a normal digital camera was used. Thus, the exact maximum height could not be measured in the experimental results (Table II). In addition, image correction should be also necessary accurate measurement of free surface in the experiments.

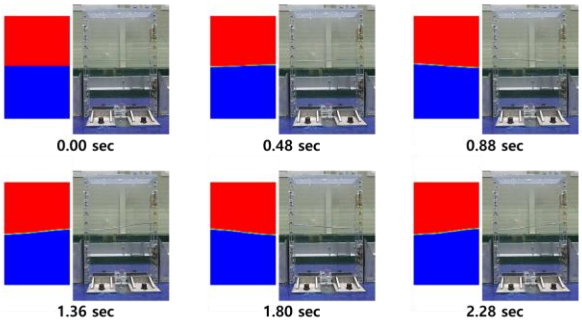

Fig. 2. Changes of water level in case that initial water level and was 420 mm and excitation frequency of 1 Hz was applied on the pool.

Table II: Maximum water level in 9 study cases

Excitation Frequency (Hz)	Initial water level (mm)	Computer simulation (mm)	Experiment (mm)
0.5	230	1.9	2.9
	420	0.0	2.8
	610	0.0	3.4
1.0	230	37.5	43.8
	420	24.5	25.1
	610	23.2	28.9
5.0	230	62.6	78.1
	420	127.9	64.2
	610	145.3	49.4

4. Conclusions

In this study, sloshing of the water in the scaled down spent fuel pool was investigated using both experimental and computational approaches. Different water levels in experiment and computer simulation were shown under high-frequency vibration because of inaccurate measurement of the water level in the experiments. However, water levels under low-frequency vibration and the cycle of pressure change predicted in the computer simulation showed good agreement with the results of the experiment.

The results of this study provide fundamental information of the dynamic behaviors of the water at various its depth in the pool. Furthermore, it would be concluded that the CFD could be effectively used in the investigation of the fluid sloshing for seismic evaluation of the nuclear facilities. The authors expect that changes in water level even under high-frequency vibration could be validated by performing accurate experiments with a high-speed camera in the future study.

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