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DEVELOPMENT OF A 3D CODE FOR THE ANALYSIS OF FLUID-STRUCTURE INTERACTION IN THE LIQUID STORAGE TANK

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ABSTRACT

Based on the Physical Component – Boundary Fitted Coordinate (PCBFC) method, a 3D code was developed for the analysis of free surface flow, which effectiveness was confirmed by the seismic response experiment of liquid sloshing in the annular region formed by coaxial circular cylinders. The fluid–structure interaction phenomenon in a liquid storage tank was further simulated by this code after incorporating it with a structure module.

Keywords: PCBFC, Free surface, Sloshing, Fluid-structure interaction

1. INTRODUCTION

The main vessel of the tank-type fast reactor is a thin-wall vessel with a large volume of liquid sodium filled. In order to ensure its structural integrity in the seismic condition, it is necessary to evaluate the fluid–structure interaction phenomenon once observed in such liquid storage tank.

The numerical simulation of the free surface flow is a unique branch of computational fluid dynamics, where special meshes are needed to fit and trace the moving free surface. Meshes used in PCBFC method (Takizawa, Koshizuka and Kondo, 1992; Lu, Takizawa and Kondo, 1998) have these functions because PCBFC method is a boundary fitted coordinates (BFC) method established on the arbitrary Lagrangian-Eulerian (ALE) coordinates system, in addition it has fine numerical stability and high accuracy due to introduction of the physical components (PC). Based on the PCBFC method, a 2D code (Takizawa, Koshizuka and Kondo, 1992; Lu, Takizawa and Kondo, 1998) has already been developed for the analysis of 2D free surface flow. In order to solve the 3D free surface flow such as in the tank-type fast reactor, it is necessary to extend the PCBFC code from 2D to 3D.

Lu Daogang (1998) has developed the 3D PCBFC code by extending the space connection coefficients and Lie derivative. By this code, Gao Xiao'an (2000) has analyzed fluid–structure interaction phenomenon in a liquid storage tank after incorporating it with a structure module. This paper will give a brief introductions on above works.

2. METHOD

The PCBFC method is a BFC method having "physical component (PC)" as variables and "physical curvilinear space (PCS)" as analytical space. The PC is introduced to reduce the mesh sensitivities of the BFC method The PCS is a space congruent to the physical space having oblique coordinates that run along the analytical grids, as illustrated with other spaces in Fig.1. “Differential geometry of physical component (DGPC)” was formulated by applying the theorems of differential geometry and manifold theory to the PCS. The physical contra-variant is adopted for the definition of flow velocity. The governing equations for incompressible fluid are described using the DGPC as follows;

$$\nabla_{(i)}u^{(i)} = 0\,, \tag{1}$$

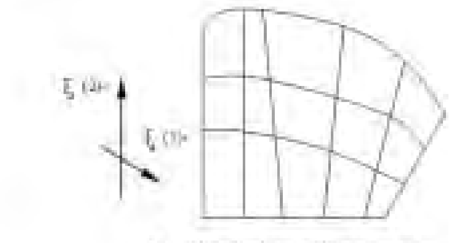
$$\frac{\partial u^{(i)}}{\partial t} = -u^{(j)}\nabla_{(j)}u^{(i)} - \frac{1}{\rho}g^{(ik)}\nabla_{(k)}p + \nu\nabla_{(j)}g^{(jk)}\nabla_{(k)}u^{(i)} + f_l g^{(ij)}\nabla_{(j)}x^l\,, \tag{2}$$

where u、p、ρ、ν and f are the velocity, pressure, density, viscosity and external forces respectively. The term $\nabla_{(j)}u^{(i)}$ is a covariant derivative in the PCS and defined as follows;

$$\nabla_{(j)}u^{(i)} = \frac{\partial u^{(i)}}{\partial \xi^{(j)}} + \Gamma^{(i)}_{(jk)}u^{(k)}, \tag{3}$$

where $\Gamma^{(i)}_{(jk)}$ is a connection coefficient in PCS, which is introduced to preserve the tensor character of the derivative in PCS. The term $g^{(ij)}$ is the inverse of matrix $g_{(ij)}$, which is a tensor related to the distance in PCS.

A Physical space B Curvilinear space



C Physical curvilinear space

Fig.1 Spaces related to BFC method

The velocity and the pressure after the grid movement are assessed by using the Lie derivative as follows;

$$u^{(i)}_a = u^{(i)}_b + L_V u^{(i)} \cdot \Delta t \tag{4}$$

$$p_a = p_b + L_V p \cdot \Delta t \tag{5}$$

where “a” and “b” denote“after” and“before”. $L_V u^{(i)}$ is the Lie derivative of $u^{(i)}$ in V direction and is expanded as follows;

$$L_V u^{(i)} = V^{(j)}\nabla_{(j)}u^{(i)} - \Gamma^{(i)}_{(tj)}u^{(j)} \tag{6}$$

where t and $\Gamma^{(i)}_{(tj)}$ are time and a time connection coefficient, respectively.

In the expansion from 2D to 3D, the space connection coefficients $\Gamma^{(i)}_{(jk)}$ are expanded from 8 to 27，and Lie derivative is made to trace the grids in 3 directions instead of 2 directions.

3. VALIDATION OF THE 3D CODE

An experiment (Fujita, Ito and Okada, 1985) performed by Mitsubishi was chosen to verify the effectiveness of the 3D code, in which the seismic response of liquid sloshing in the annular region formed by coaxial circular cylinders is measured.

3.1 Sloshing in A Cylinder

A cylinder (radius 88cm) is filled with water in depth 196.2cm. As shown in Fig. 2, the first mode wave shape of the free surface is set up in the initial. The time histories of the water levels in the right side（A）, left side（B）and center（C）are calculated after the free sloshing starts. The first mode natural frequency is measured.

As shown in Fig. 3, if the free surface is excited by 3 sine waves with the natural frequency of the first mode sloshing in the cylinder, the resonant sloshing of the free surface is produced, and the maximum wave height after 3 waves is measured from the time histories.

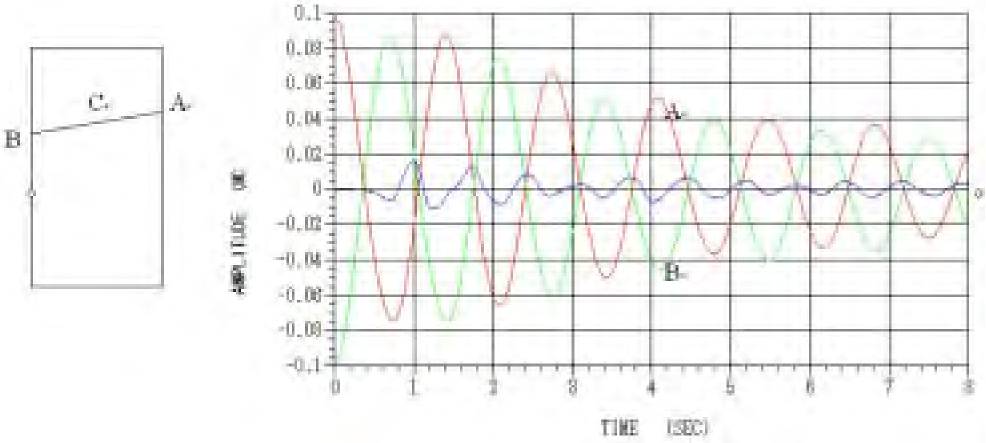


Fig. 2 Initial wave shape and time histories of the water levels in a cylinder

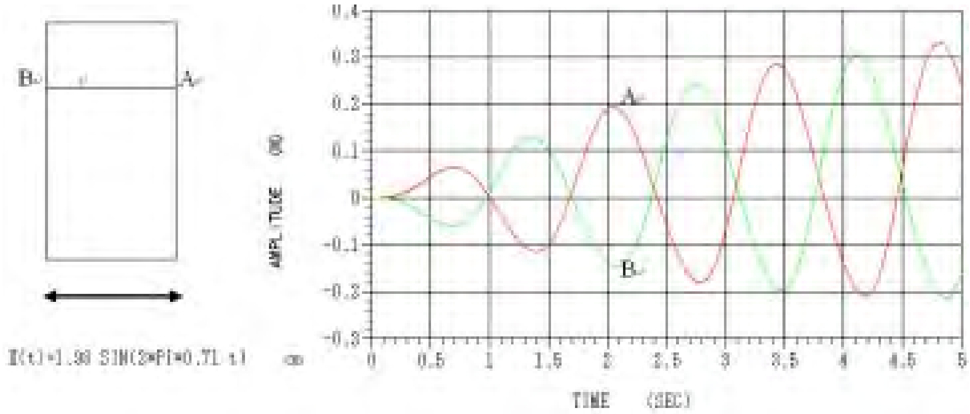


Fig. 3 Sloshing response in a cylinder excited by 3 sine waves

The numerical results by PC-BFC are list in Table 1 together with the analytical ones and the experimental ones. The numerical ones are in good agreements with the experimental ones.

Table 1 Natural frequency and wave height in a cylinder

	1st mode Natural frequency (Hz)	Maximum wave height after 3 sine wave (cm)
Experimental	0.71	34.8
Analytical	0.72	28.4
PCBFC	0.72	33.0

3.2 Sloshing in An Annular Region

An annular region formed by coaxial circular cylinders (outer radius 88cm and inner radius 82.5cm) is filled with water in depth 74.5cm. As shown in Fig. 4, the first mode wave shape of the free surface is set up in the initial. The time histories of the water levels in the right side （A） and left side （B） are calculated after the free sloshing starts. The first mode natural frequency is measured.

As shown in Fig. 5, if the free surface is excited by 3 sine waves with the natural frequency of the first mode sloshing in the annular, the resonant sloshing of the free surface is produced, and the maximum wave height after 3 waves is measured from the time histories.

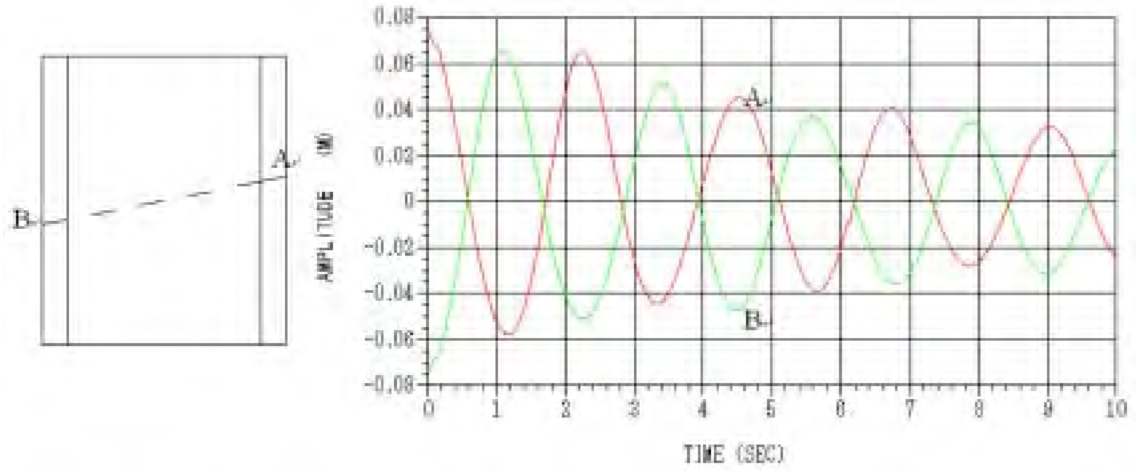


Fig. 4 Initial wave shape and time histories of the water levels in an annular

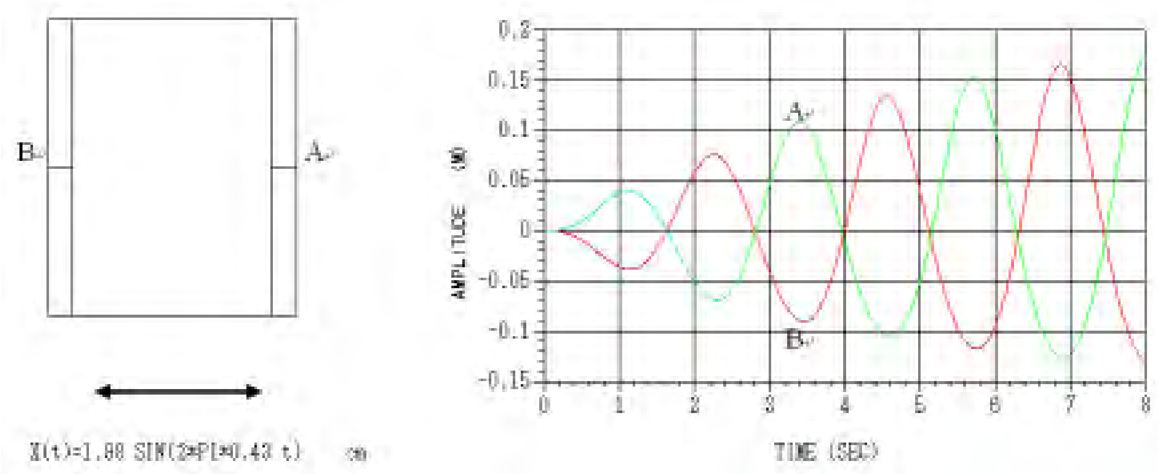


Fig. 5 Sloshing response in an annular excited by 3 sine waves

The numerical results by PC-BFC are list in Table 2 together with the analytical ones and the experimental ones. The numerical ones are in good agreements with the experimental ones.

Table 2 Natural frequency and wave height in an annular

	1^{st} mode Natural frequency (Hz)	Maximum wave height after 3 sine wave (cm)
Experimental	0.43	11.0
Analytical	0.45	12.9
PCBFC	0.44	12.6

4. FLUID–STRUCTURE INTERACTION PHENOMENON IN A LIQUID STORAGE TANK

Du Jianbin (1999) has analyzed the fluid–structure interaction phenomenon in a cylindrical liquid storage tank excited by sine wave. Fig. 6 shows the liquid storage tank fixed in the bottom. The sine waves are input in the horizontal direction from the bottom. The main parameters for the fluid and the structure are given as follows: fluid density ρ_f=1000kg/m^3, gravity g=9.8m/s^2, structure density ρ_s=2400kg/m^3, Young's modulus E=2.2932×10^{10}N/m^2, Poisson ratioμ=0.3. Two natural frequencies of the coupled system were found. The lower one is 0.36Hz, which is close to the first order natural frequency of the sloshing; and the higher is 24.9Hz, which is close to the first order natural frequency (beam mode) of the structure.

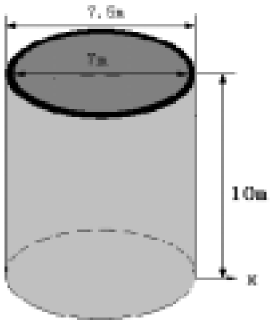


Fig. 6 Liquid storage tank

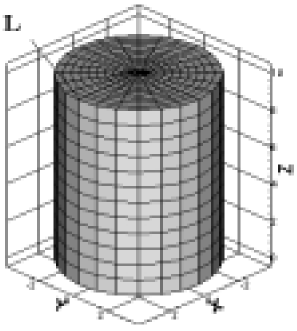


Fig. 7 Meshes of fluid

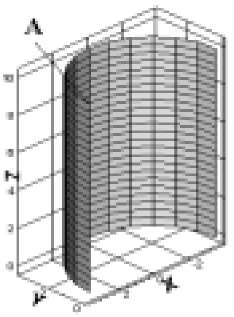
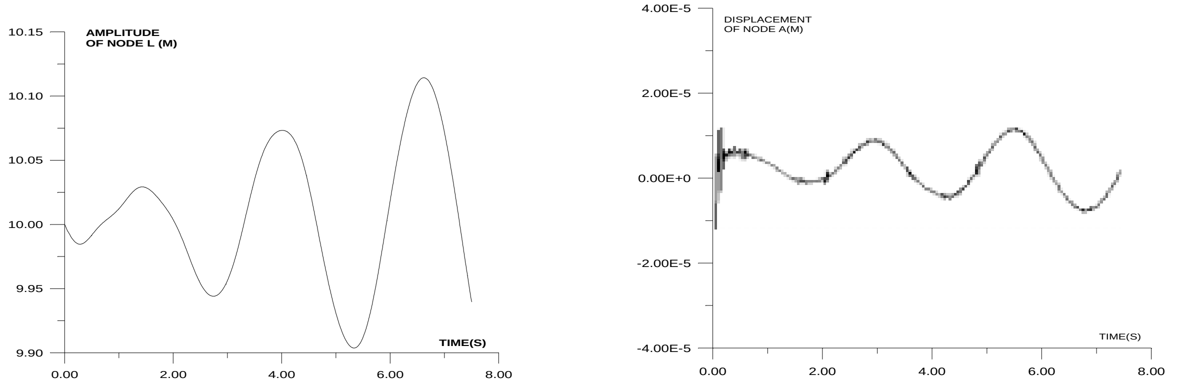


Fig. 8 Meshes of structure

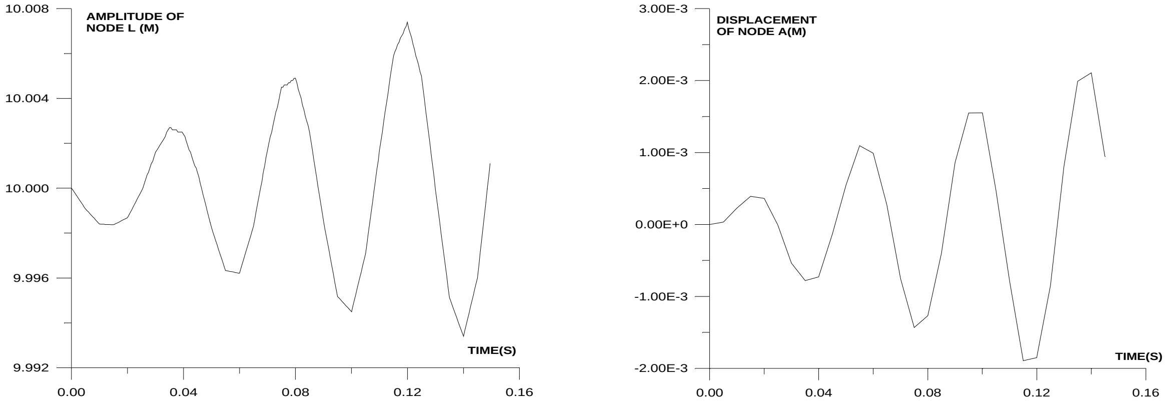


Time history of wave height（L point）

Time history of structure displacement (A point)

Fig. 9 Resonant responses in Lower frequency

Above problem was also analyzed using the 3D PCBFC code. Fig. 7 and Fig. 8 show respectively the meshes of the fluid and the structure adopted in the analysis. Fig. 9 and Fig. 10 show respectively the resonant responses of the fluid and the structure in lower frequency (0.36Hz) and those in higher frequency (24.9Hz). It is observed that the amplitude of sloshing in the case of the lower frequency is much larger than that in the case of the higher frequency, while the amplitude of the structure vibration in the case of the lower frequency is much smaller than that in the case of the higher frequency. The present results in the case of the lower frequency is almost in agreement with Du's (1999).



Time history of wave height（L point） Time history of structure displacement (A point)

Fig.10 Resonant responses in Higher frequency

5. CONCLUSIONS

A PCBFC based code has been extended from 2D to 3D. Its effectiveness is also verified by the analysis on an experiment. The fluid–structure interaction phenomenon in a liquid storage tank has been simulated using the newly developed code, and some characteristics in this phenomenon were discovered.

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