Development of 3D Dynamic Motion Model about Arbitrary Axis in the SPACE code

Byoung Jae Kim[1] and Seung Wook Lee[2]

[1]*Chungnam National University*
[2]*Korea Atomic Energy Research Institute*
E-mail: bjkim@cnu.ac.kr

1. Introduction

Lately, ocean nuclear power plants have attracted attention as one of diverse uses of nuclear power plants, and various efforts have been made to develop computer code that can be used to predict thermal hydraulics in large moving systems.

Most existing works usually adopted the rotation system based on the intrinsic Tait-Bryan angles[1-3]. A difficulty arises when dealing with a rotation around an arbitrary axis. It is common practice to specify the rotation vector in the fixed (or inertial) coordinates. Because the roll, pitch, yaw angles are expressed in the rotating coordinates, a complicated conversion process from the rotation specified in the fixed coordinates into the rotation in the intrinsic Tait-Bryan angles is required. In addition, the existing works considered only the rotations about one of axes of the fixed coordinates, so their verifications were not general.

The purpose of this study is to incorporate a three-dimensional rotation model about an arbitrary axis into the SPACE code. Various conceptual problems were tested to verify the dynamic motion model for general rotations.

2. 3D rotation about arbitrary axis

Figure 2 show a one-dimensional hydrodynamic component, such as a cell, in the inertial frame of reference. The direction of the component is expressed using the inclination angle (θ) and the azimuthal angle (ϕ), in the inertial reference frame.

Assume that the hydrodynamic component is rotated about an arbitrary axis in the inertial frame of reference. Let the rotation speed vector be $\mathbf{\Omega} = \Omega_X \mathbf{I} + \Omega_Y \mathbf{J} + \Omega_Z \mathbf{K}$. Then, the rotation axis direction unit vector is given by $(e_X, e_Y, e_Z) = (\Omega_X / |\mathbf{\Omega}|,\ \Omega_Y / |\mathbf{\Omega}|,\ \Omega_Z / |\mathbf{\Omega}|)$.

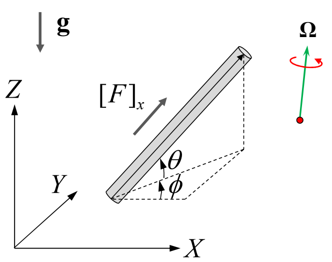

Fig. 1 A one-dimensional hydrodynamic component

The SPACE code adopted a rotation system based on the rotation matrix **R** by angle α around the rotation axis

$$\mathbf{R} = \begin{bmatrix} \cos\alpha + e_X^2(1-\cos\alpha) & e_X e_Y(1-\cos\alpha) - e_Z \sin\alpha & e_X e_Z(1-\cos\alpha) + e_Y \sin\alpha \\ e_Y e_X(1-\cos\alpha) + e_Z \sin\alpha & \cos\alpha + e_Y^2(1-\cos\alpha) & e_Y e_Z(1-\cos\alpha) - e_X \sin\alpha \\ e_Z e_X(1-\cos\alpha) - e_Y \sin\alpha & e_Z e_Y(1-\cos\alpha) + e_X \sin\alpha & \cos\alpha + e_Z^2(1-\cos\alpha) \end{bmatrix} \quad (1)$$

A code user only needs to specify the rotation vector and the point through which the rotation axis passes in the inertial frame of reference. This rotation matrix directly describes a three-dimensional rotation about an arbitrary axis. Once the component is rotated, the direction vector of the component is newly computed using the rotation matrix **R** . Subsequently, the inclination and azimuthal angles are updated based on the new direction vector, and the two-phase flow pattern is also updated based on the new inclination angle.

3. Results and discussion

3.1. Rotation of a 2D pipeline loop about a tilted angle

Figure 2 shows the two cases in which the rotation axes pass through the point (X, Y, Z) = (0.5 m, 0 m, 0 m) and are tilted 30° from the X-axis. In Fig. 2(a), the rotation speed is very small (Ω=2°/s) so that the motion of water is affected mainly by changes in the direction of gravity due to rotation. In Fig. 2(b), the rotation speed is relatively large (Ω=90°/s) and gravity is not applied. In this case, the final water distribution is determined only by the Centrifugal force. Figure 3 shows the code calculation results.

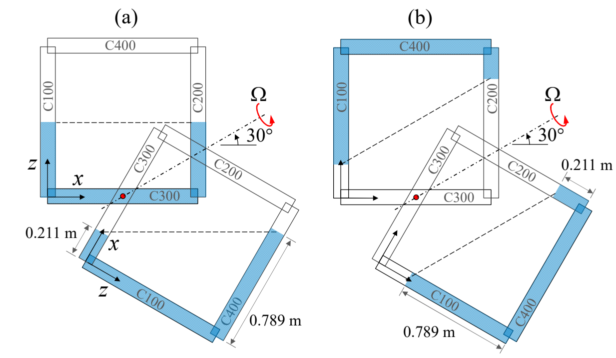

Fig. 2 Square manometer: (a) Ω=2°/s, (b) Ω=90°/s and gravity is not applied.

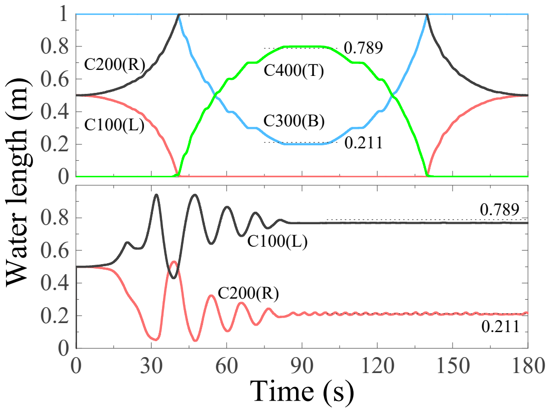

Fig. 3 Results: (a) Ω=2°/s, (b) Ω increases linearly to 90°/s for the first 100 s and then remains at 90°/s.

3.2. Rotation of a 3D pipeline loop about a tilted angle

Figure 4 shows a schematic diagram of the three-dimensional pipeline loop. The first test was conducted at a rotation speed of -2°/s about the axis with $\theta = 45°$ and $\phi = 30°$. The rotation speed is so small that the motion of water is determined mainly by changes in the direction of gravity due to rotation. The second test was performed at a rotation speed of -90°/s about the axis with $\theta = 30°$ and $\phi = 75°$, and the gravity was not applied. In this condition, the final water distribution was determined only by the Centrifugal force.

To validate the code calculation results, we also performed multi-dimensional CFD simulations based on the approach suggested by [4]. Figures 5 and 6 compare the code calculation results with the CFD results.

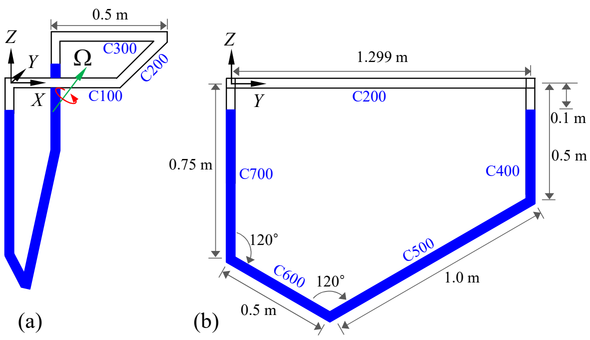

Fig. 4 Initial water distribution in the the three-dimensional pipeline loop: (a) Isometric view, (b) YZ-plane view.

4. Conclusion

The code results for the 2D pipeline loop with a tilted rotation axis showed good agreement with theoretical predictions. The code results for the 3D pipeline loop with a tilted rotation axis also agreed well with the multi-dimensional CFD results.

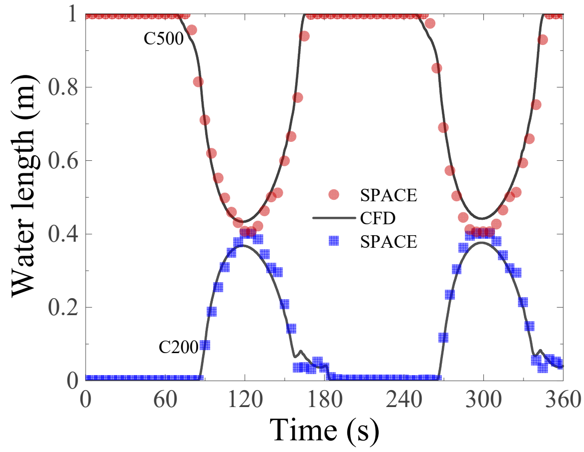

Fig. 5 Result for the rotation axis ($\theta = 45°$, $\phi = 30°$) and $\Omega = -2° / s$.

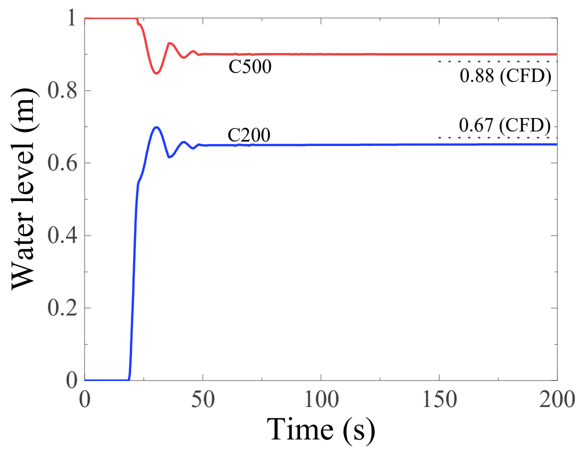

Fig. 6 Result for the rotation axis ($\theta = 30°$, $\phi = 75°$), $\Omega = -90° / s$, and no gravity.

ACKNOWLEGMENTS

This work was supported by National Research Foundation of Korea grants funded by the Ministry of Science and ICT (No. NRF-2017M2A8A4016738 and No. NRF-2021M2D2A1A02039565).

REFERENCES

[1] H.-K. Beom, G.-W. Kim, G.-C. Park,H.K. Cho, Verification and Improvement of Dynamic Motion Model in Mars for Marine Reactor Thermal-Hydraulic Analysis under Ocean Condition, Nuclear Engineering and Technology 51 (2019) pp.1231-1240.
[2] G.L. Mesina, D.L. Aumiller, F.X. Buschman,M.R. Kyle, Modeling Moving Systems with Relap5-3d, Nuclear Science and Engineering 182 (2016) pp.83-95.
[3] B.H. Yan,L. Yu, The Development and Validation of a Thermal Hydraulic Code in Rolling Motion, Annals of Nuclear Energy 38 (2011) pp.1728-1736.
[4] B.J. Kim, M.H. Kim, S.W. Lee,K.D. Kim, Two-Fluid Equations for Two-Phase Flows in Moving Systems, Nuclear Engineering and Technology 51 (2019) pp.1504-1513.