Verification of dynamic motion model for ocean condition in MARS using conceptual problems

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1. Introduction

In an offshore plant or a maritime reactor, the motion of the platform can affect the thermal hydraulic behavior of the fluid system of the ship, which can change the regime of the two-phase flow or heat transfer phenomena [3]. Therefore, it is necessary to develop codes that can reflect the effects of these ocean conditions. In this regard, thermal-hydraulic analyses under ocean conditions using RETRAN were performed in Korea and Japan [4, 5].

Meanwhile, the dynamic motion model related to ocean condition had been implemented in the MARS (Multidimensional Analysis of Reactor Safety) code. It is a safety analysis code for a nuclear power plant developed by the Korea Atomic Energy Research Institute (KAERI) [1] based on the RELAP5 / MOD3 code [2] and has been used for safety analysis and licensing of land-based nuclear power plants. Extension of the simulation capability of MARS to the ocean condition would be beneficial as it has been validated for licensing of land-based plants in Korea. However, after the implementation of the dynamic motion model, a systematic validation result for the model has not been published in an open literature. Thus, in this study, the existing dynamic motion model in the MARS code was verified by analyzing conceptual problems.

2. Review of the dynamic motion model in MARS

In MARS, the dynamic motion with six degrees of freedom is input as a boundary condition, and the change in the body force due to the motion is reflected in the momentum equation. In general, the motion in the ocean consists of three linear motions (surging, swaying and heaving) and three rotational motions (rolling, pitching and yawing) as shown in Fig. 1. As boundary conditions for the ship motion in MARS input file, a user can choose two options, sinusoidal function and user-supplied table. One can use sinusoidal function for acceleration value of linear motion and the angular value of rotational motion expressed in equations (1) and (2) as,

$$\text{Acceleration} : a_{x,y,z} = \mathrm{A}\sin\left(\frac{2\pi t}{T} + \phi\right) + a_0, \quad (1)$$

$$\text{Angle} : \theta^\circ = \mathrm{A}\sin\left(\frac{2\pi t}{T} + \phi\right) + wt + \theta_\circ, \quad (2)$$

where A is the amplitude of oscillation, T is the period of oscillation, ϕ is the phase angle for acceleration, a_0 and θ_0 are the initial acceleration and angle and w is the initial angular speed. In the other option, one can set the time dependent acceleration value for six motions using user-supplied table.

During the dynamic motion calculation, updated coordinates by rotation are obtained as shown in Fig. 2. At every time step, the distance from the center of rotation to the center of the node is updated. Next, the acceleration for the X, Y, and Z axes is calculated as

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} \dot{\phi}_z^2 + \dot{\theta}_y^2 & \ddot{\phi}_z & -\ddot{\theta}_y \\ -\ddot{\phi}_z & \dot{\phi}_z^2 + \dot{\xi}_x^2 & \ddot{\xi}_x \\ \ddot{\theta}_y & -\ddot{\xi}_x & \dot{\xi}_x^2 + \dot{\theta}_y^2 \end{bmatrix} \begin{bmatrix} R_x \\ R_y \\ R_z \end{bmatrix}, \quad (3)$$

$$\text{NetGrav} = a_x \times Dirn_x + a_y \times Dirn_y + a_z \times Dirn_z , (4)$$

where $a_{x,y,z}$ is the body acceleration in X/Y/Z-direction, $\dot{\xi}_x/\dot{\theta}_y/\dot{\phi}_z$ is the roll/pitch/yaw speed, $\ddot{\xi}_x/\ddot{\theta}_y/\ddot{\phi}_z$ is the roll/pitch /yaw acceleration, $R_{x,y,z}$ is the X/Y/Z-coordinate of center of volume, 'NetGrav' is the net body force along volume direction, and $Dirn_{x,y,z}$ is the X/Y/Z-component of volume direction unit vector. Finally, they are applied in momentum equation as an additional acceleration term.

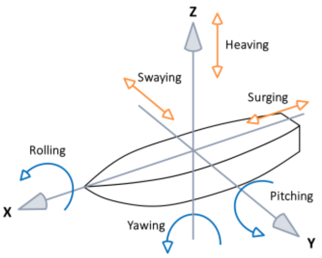
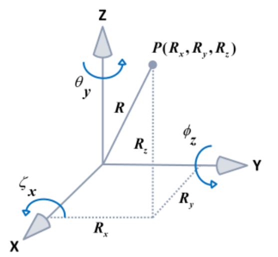


Fig. 1. Six degrees of freedom of ship motions (MARS coordinate)



Rotmat = $\mathbf{T_z T_y T_x}$

$$\begin{pmatrix} \cos\phi_z & -\sin\phi_z & 0 \\ \sin\phi_z & \cos\phi_z & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\zeta_x & -\sin\zeta_x \\ 0 & \sin\zeta_x & \cos\zeta_x \end{pmatrix}$$

Fig. 2. Three-dimensional coordinates with rotation (MARS)

3. Analysis of conceptual problems with MARS

In this section, the dynamic motion model of MARS was verified through solving the conceptual problem in order to confirm whether MARS can accurately predict the thermal hydraulic effect under the ocean motion. The three conceptual problems were chosen such as manometer moving problems with angular and linear motion cases and closed loop rotation problem with mild rolling condition. The details of boundary conditions of the dynamic motions are summarized in Table I. For comparison with the analytical solution, it was assumed that there was no wall friction and energy loss.

Table I: Geometry information and boundary conditions of three conceptual problems

Parameters	Problem 1	Problem 2	Problem 3
	Manometer		Closed loop
	Case 1.	Case 2.	
Length	10m (5m for water)		1m (0.5m for water)
Pitch	4.5m		1m
Diameter	0.254m		0.254m
Pressure	atmospheric		atmospheric
Temp.	323K		323K
Motion Option	Rolling motion - Amplitude : 45° - Period: 600s	Linear motion - Acc. : $10m/s^2$	Rolling motion - Amplitude : 180° - Period : 200s

3.1 Manometer

Two conceptual problems were analyzed regarding the manometric fluid behavior caused by the dynamic motion. The schematic figure of the problem 1 and 2 and their MARS nodalization were shown in Fig. 3. Calculation was carried out for two different motion conditions using the same geometry and boundary condition except for the motion conditions.

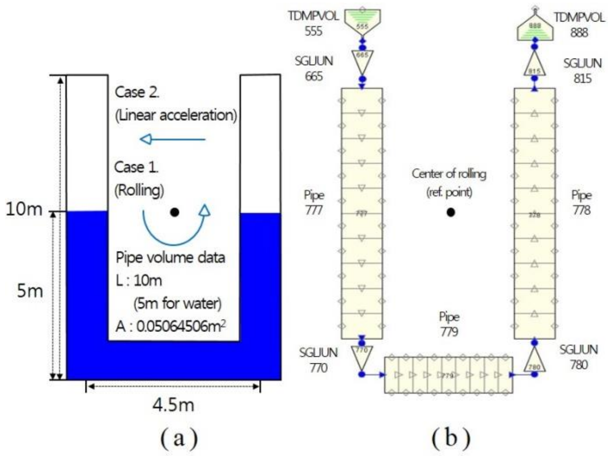


Fig. 3. (a) Concept of manometer problem (b) Nodalization for MARS calculation

3.1.1 Manometer under rolling motion

First, we confirmed that the MARS can accurately calculate the water column height of the manometer through a rolling motion with a slow period of 600 seconds. The manometer maintains the Z-axis height (water level) of 5 m regardless of rolling motion when the rolling speed is slow as shown in Fig. 4. The MARS calculation results are shown in Fig. 5. The variation in the water column height of the manometer was visualized as the volume liquid fraction value using a SNAP environment as shown in Fig. 5. (a). One can see that the water level of manometer remains constant during the rolling motion. As shown in Fig. 5. (b), at 150 and 450 seconds of the 600 seconds cycle, the maximum amplitude reached 45 degrees, with the difference between the water column height of both pipes of the manometer being 4.5 m in analytic solution and 4.504 m in MARS. In addition, to calculate the water level value through z-axis in MARS, the following equation (4) was applied as

$$Z_0 + (y \sin\theta - \ell \cos\theta), \qquad (4)$$

where Z_0 is the initial water column length, y is the half of the pitch, ℓ is the water column height variation according to the angle calculated by MARS. If the value of ℓ calculated by MARS is correct, then $y \sin\theta - \ell \cos\theta = 0$ and the Z value should be 5 m which is the initial value. As a result, the predicted value of the water level showed good agreement with the analytic solution within ±0.011 m(0.22%) error.

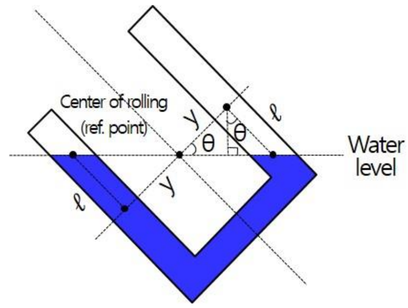


Fig. 4. Concept to calculate water level using MARS data

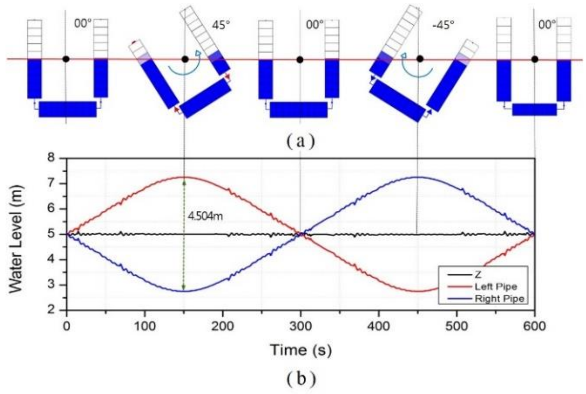


Fig. 5. Result of MARS calculation under rolling motion

3.1.2 Manometer under linear acceleration

If the manometer is given a linear acceleration in the horizontal direction, a height difference should occur as shown in Fig. 6. In order to simulate this, the acceleration of 10 m/s^2 was applied to the Y axis of the manometer constantly, and the amount of water level change in both pipes was confirmed by MARS and visualized using SNAP environment.

The results of the water level calculation in the analytic solution are as follows. By analyzing the acceleration component, the acceleration of X-direction is zero, Y-direction is '-accy' and Z-direction is '-g' for gravity. Then, one can get the analytic solution after the substitution into equilibrium equation as

$$\mathrm{Xdx} + \mathrm{Ydy} + \mathrm{Zdz} = 0\ , \qquad (5)$$

$$-\mathrm{accydy} - \mathrm{gdz} = 0,\ \ \mathrm{dz} = -\frac{accy}{g}dy, \qquad (6)$$

$$\therefore \mathrm{z} = -\frac{accy}{g}y = -4.589\ [\mathrm{m}]. \qquad (7)$$

On the other hand, the water level difference of the manometer was 4.583 m in MARS calculation within 0.001m (0.6%) error of the analytic solution. Therefore, it was concluded that MARS code well predicts the thermal hydraulic behavior of manometer under dynamic motion including rotational and linear one.

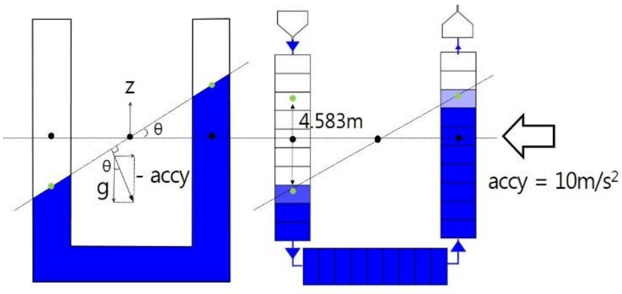


Fig. 6. (a) Concept of problem 2
(b) Result of MARS calculation

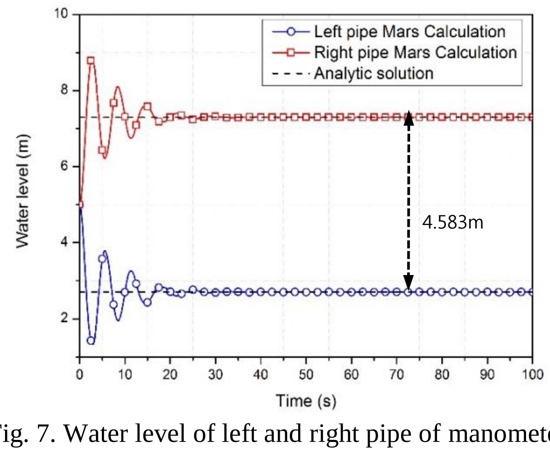


Fig. 7. Water level of left and right pipe of manometer

3.2 Rotating closed loop

The rotating closed loop problem aimed to confirm whether MARS can simulate the phase separation in harsh rolling condition with amplitude of 180 degrees, namely rollover case. To do this, nodalization was performed as shown in Fig. 8. Water column height variation was confirmed by volume liquid fraction in the pipe over time using SNAP. As a result, as shown in Fig. 9 and 10, MARS appropriately simulated the water movement inside the pipe due to the rolling motion.

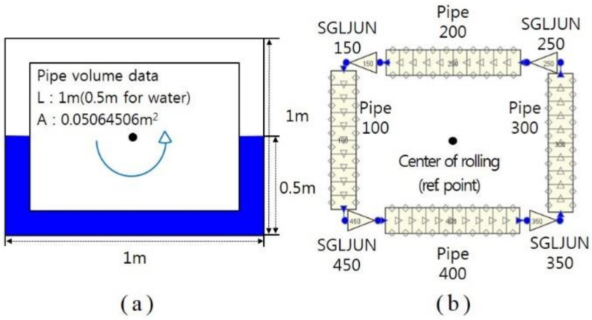


Fig. 8. (a) Concept of closed loop problem
(b) Nodalization for MARS calculation

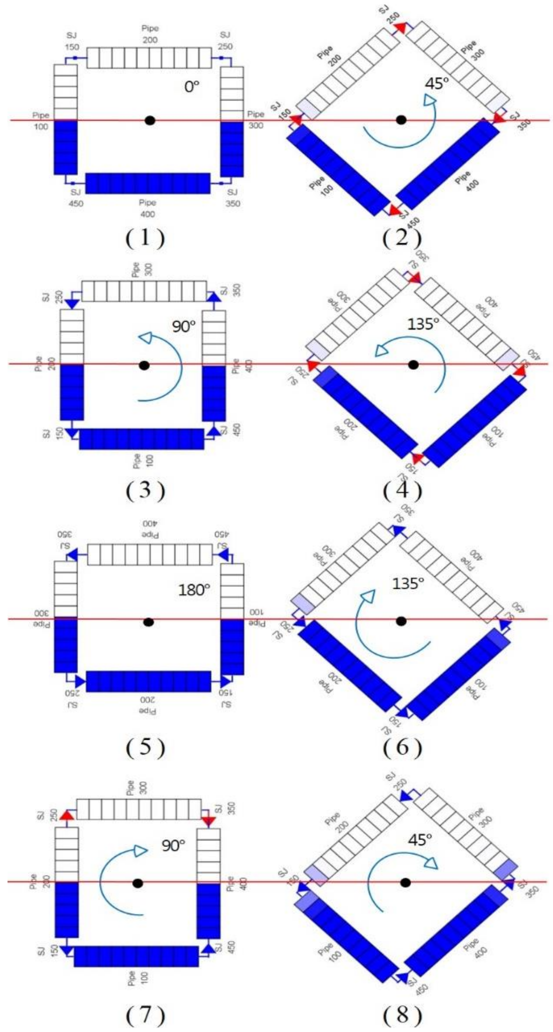


Fig. 9. Distribution of water in closed loop under rolling motion

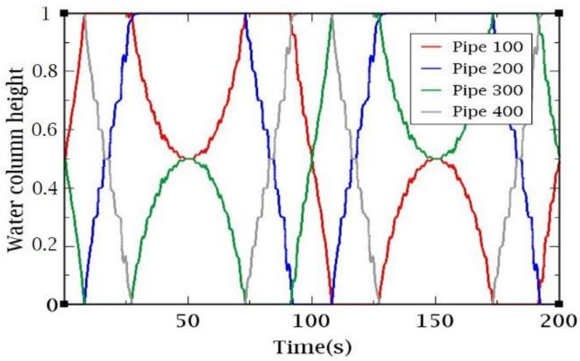


Fig. 10. Variation of water column height in the left and right pipes of manometer

4. Conclusions

MARS calculates the body force with the input acceleration and angle of dynamic motion and reflects it into the momentum equation, so that motion condition can be applied to thermal hydraulic analysis. In this study, the verification of the dynamic model was carried out by solving three kinds of conceptual problems to confirm whether MARS accurately performs thermal hydraulic analysis by motion conditions. For the manometer, the variation of water column height and the water level were observed under rolling motion and constant acceleration, respectively. The water level of closed loop under rolling motion is observed with a large amplitude of 180 degrees slowly. As a result, all of the three cases confirmed that MARS was properly calculating the motion condition.

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