SEOUL NATIONAL UNIVERSITY

NuTHEL
Nuclear Thermal Hydraulic Engineering Lab.

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Extension of MARS-KS motion model to MULTID component modifying volume connection information for marine reactor simulation

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Contents

1 Introduction

- Background
- MARS-KS motion model
- History of MARS-KS motion model

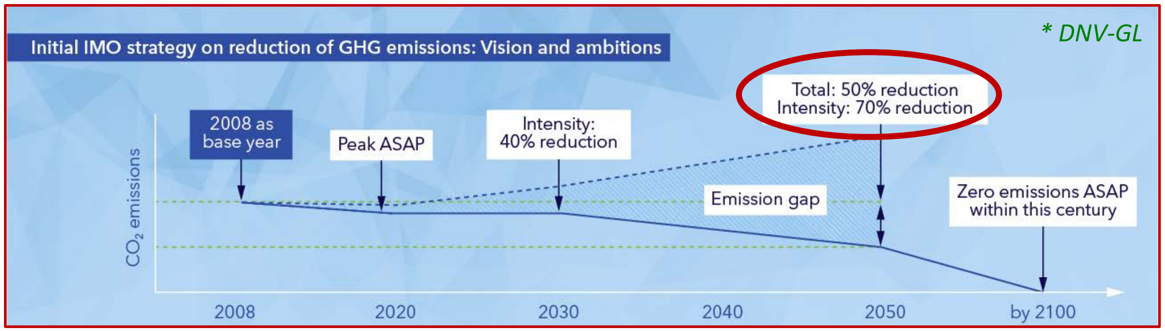
Background

a. https://edition.cnn.com/2019/06/28/europe/russia-arctic-floating-nuclear-power-station-intl/index.html
b. http://www.okbm.nnov.ru/en/business-directions/reactors-plants-for-small-and-medium-sized-npps/
c. https://corepower.energy/regulatory/
d. I.H. Kim et al., Development of BANDI-60S for a floating nuclear power plant, Transactions of the Korean Nuclear Society Autumn Meeting, 2019.
e. Modular Reactors, Ulsan, Korea, July 3, 2019.

Reducing GHG (Greenhouse gas) emissions from ships

** IMO: International Maritime Organization*

- CO_2 emissions from ships is responsible for 2-3% of all global GHG emissions.
- IMO* adopted a resolution on 'Initial IMO strategy on reduction of GHG emissions from ships' in 2018.
  - The aim is to reduce total emissions from shipping by 50% in 2050 compared to 2008.

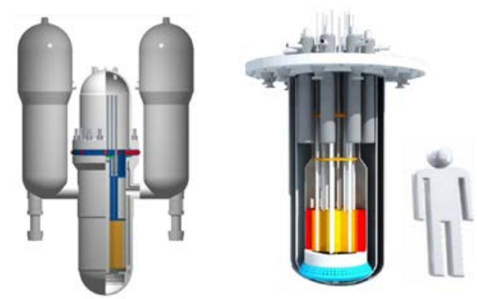


Utilization and development of marine nuclear power

- Nuclear powered ship to reduce ship's GHG emissions and use its efficiency

Akademik Lomonosov, Russia (2020-) [a]

CORE-POWER MSR, UK-US (Planned) [c]



BANDI-60s [d] / MicroUranus [e]

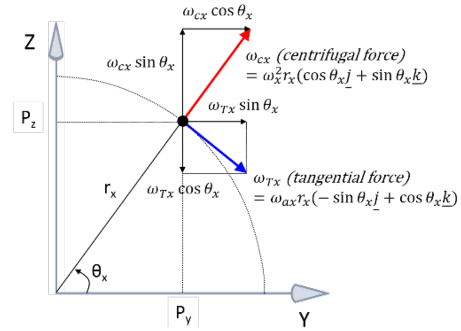
MARS-KS motion model

MARS-KS motion model for marine reactor

- General form of momentum equation under the motion condition

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}\right)=-\nabla p+\mu\nabla^2\mathbf{u}-\rho\mathbf{g}-\rho\left(\frac{d^2\mathbf{R}}{dt^2}+\boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\mathbf{r})+\frac{d\boldsymbol{\Omega}}{dt}\times\mathbf{r}\right)$$

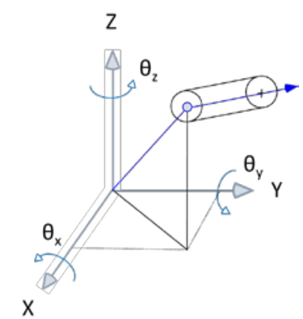
Translational acceleration — *Centripetal acceleration* — *Tangential acceleration*



- Net rotation matrix

$$[M_t]=[M_Z][M_Y][M_X]$$

$$=\begin{bmatrix}\cos\theta_z & -\sin\theta_z & 0\\ \sin\theta_z & \cos\theta_z & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\cos\theta_y & 0 & \sin\theta_y\\ 0 & 1 & 0\\ -\sin\theta_y & 0 & \cos\theta_y\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta_x & -\sin\theta_x\\ 0 & \sin\theta_x & \cos\theta_x\end{bmatrix}$$



- Motion condition for MARS-KS motion model
  - Type 1: sinusoidal function

Translational motion $a_{x,y,z}=A\sin\left(\frac{2\pi t}{T}+\phi\right)+a_0$

Angular motion $\theta^\circ=A\sin\left(\frac{2\pi t}{T}+\phi\right)+wt+\theta_0$

A : Amplitude *T : Period* *a_0 : Initial acceleration*
Ø : Phase angle *w : Initial angular speed* *ϑ_0 : Initial angle*

  - Type 2: User-supplied table

Time (s)	Roll/pitch/yaw acceleration (deg/s^2)	X/Y/Z acceleration (m/s^2)
…	…	…

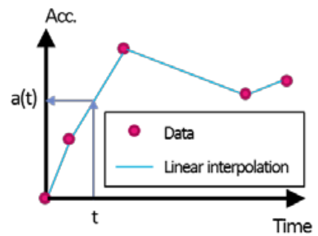
History of MARS-KS motion model

Status of MARS-KS motion model modification (SNU, 2017 ~ 2018)

- Implementation of user-supplied table [a]

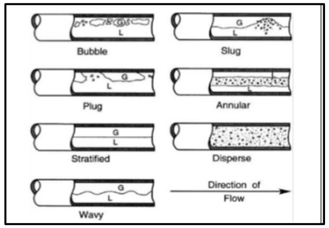
Time (s)	Rotational acc. (deg/s^2)			Translational acc. (m/s^2)		
	x	y	z	x	y	z
…	…	…	…	…	…	…

< User-supplied table >

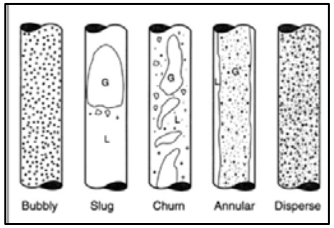


< Linear interpolation >

- Modification of flow regime determination under inclination [a]



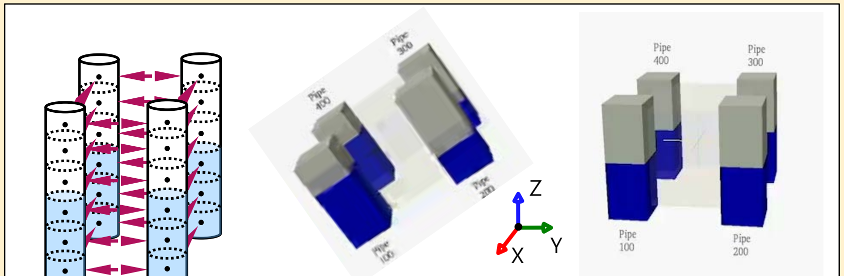
Horizontal flow regime map (0˚ ~ 45˚)



Vertical flow regime map (45˚ ~ 90˚)

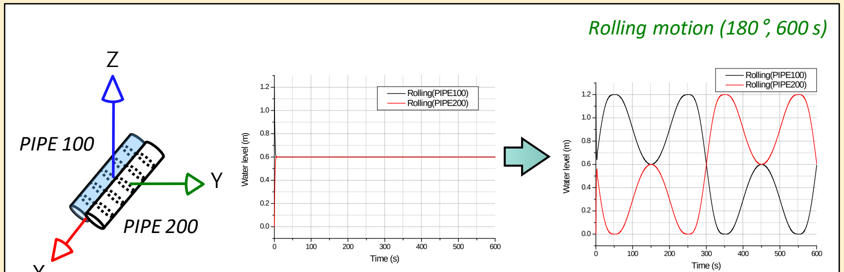
Status of MARS-KS motion model modification (SNU, 2018 ~ 2019)

- Improvement of cross-flow in MARS-KS [b, c]



< 30° Inclination > < 30° Rolling motion >

- Extension of cross-flow model to horizontal pipe [d]



< Before modification > < After modification >

a. H.K. Beom, G.W. Kim, G.C. Park, H.K. Cho, Improvement of dynamic motion model in MARS-KS for downcomer modeling of a maritime reactor with cross-junction connection, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 23-24, 2019.
b. 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, Vol.51, p.1231-1240, 2019.
c. H.K. Beom, G.W. Kim, G.C. Park, H.K. Cho, Improvement of dynamic motion model in MARS-KS for downcomer modeling of a maritime reactor with cross-junction connection, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 23-24, 2019.
d. S.W. Park, G.W. Kim, H.K. Cho, Status of MARS-KS modification for thermal-hydraulic analysis of a marine reactor, Korean Society for Fluid Machinery summer conference, Pyeongchang, Korea, Aug. 24-26, 2020.

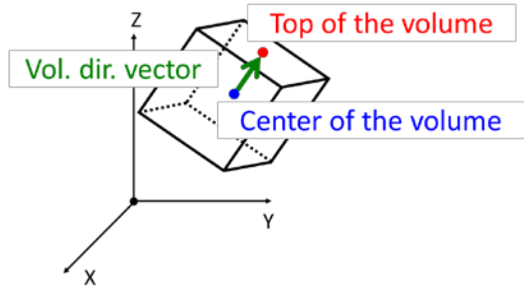
2 Modification of MARS-KS motion model

- Auto-generated volume direction unit vector
- Calculation of pressure head by each axis
- Modification of volume connection information
- Updating the junction property
- Extension of MARS-KS motion model to MULTID component

Modification of MARS-KS motion model

❖ Modification ①: Auto-generated volume direction unit vector

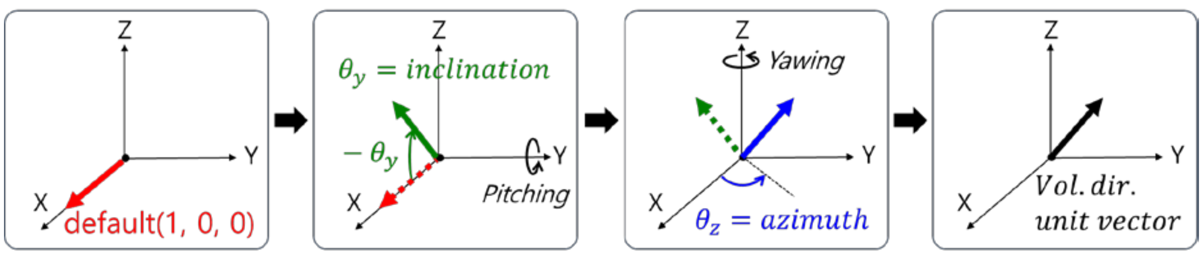
- The volume direction unit vector indicating the flow direction of the volume
- Limitation in the existing method of generating a volume direction unit vector
  - A user should input the coordinates for center and top points of all volumes.



* rolling motion						
0.0	0.0	0.0				
27	x	y	z	x	y	z
555010000	0.0	-2.25	5.5	0.0	-2.25	5.0
777010000	0.0	-2.25	4.5	0.0	-2.25	4.0
777020000	0.0	-2.25	3.5	0.0	-2.25	3.0
Volume number	Center of the volume			Top of the volume		

MARS-KS motion model input file

- Auto-generated volume direction unit vector using three-dimensional rotation matrix
  - Only the center coordinates of the volume are needed to generate the volume direction unit vector.
  - It helps users to reduce input preparation time and human errors when generating input files.



Calculation procedure of auto-generated volume direction unit vector

* rolling motion			
0.0	0.0	0.0	
27	x	y	z
555010000	0.0	-2.25	5.5
777010000	0.0	-2.25	4.5
777020000	0.0	-2.25	3.5
Volume number	Center of the volume		

MARS-KS motion model input file

Modification of MARS-KS motion model

❖ Modification ②: Calculation of pressure head by each axis

- Modification of acceleration and length terms to reflect the pressure head by each axis

$$\textbf{Pressure head} = \textbf{Density} \times \textbf{Acceleration} \times \textbf{Length}$$

Before

$$dP = -\rho \cdot NetG \cdot Length_z$$

$$NetG = a_x \cdot Dirn_x + a_y \cdot Dirn_y + a_z \cdot Dirn_z$$

⇩

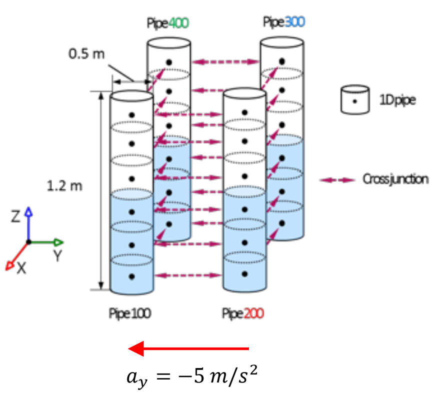
After

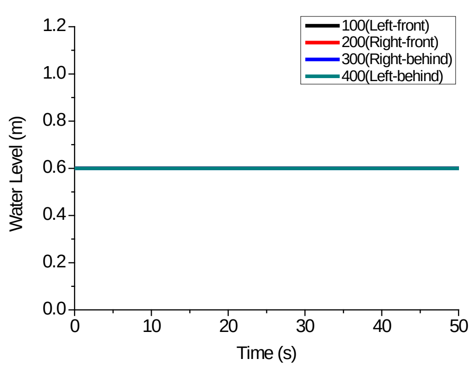
$$dP = -\rho \cdot (a_x \cdot Length_x + a_y \cdot Length_y + a_z \cdot Length_z)$$

$$a_x = R_x\dot{\phi}_z^{\,2} + R_x\dot{\theta}_y^{\,2} + R_z\ddot{\theta}_y - R_y\ddot{\phi}_z - a_{x,0}$$
$$a_y = R_y\dot{\zeta}_x^{\,2} + R_y\dot{\phi}_z^{\,2} + R_x\ddot{\phi}_z - R_z\ddot{\zeta}_x - a_{y,0}$$
$$a_z = R_z\dot{\zeta}_x^{\,2} + R_z\dot{\theta}_y^{\,2} + R_y\ddot{\zeta}_x - R_x\ddot{\theta}_y - a_{z,0} - g_z$$

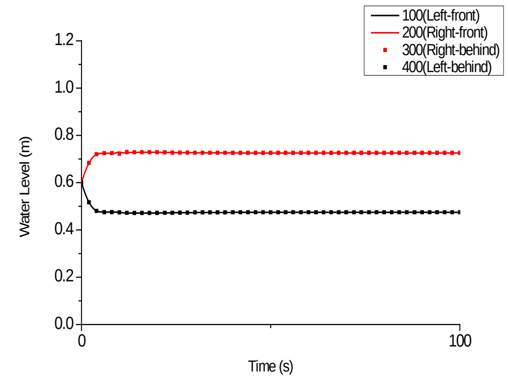
❖ MARS-KS analysis result

- Linear acceleration motion ($-5\ m/s^2$ *along the y axis*)





Before modification

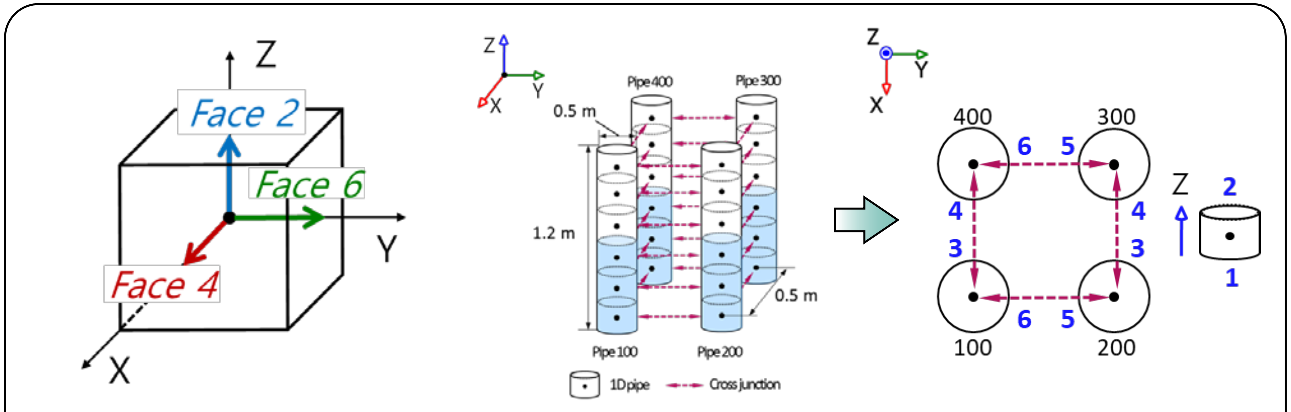


After modification

Modification of MARS-KS motion model

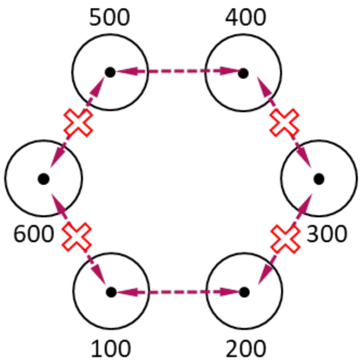
❖ Modification ③: Modification of volume connection information

- Limitation in the existing volume connection information based on the face number
  - Cross-junction connection restricted to the direction of the face number



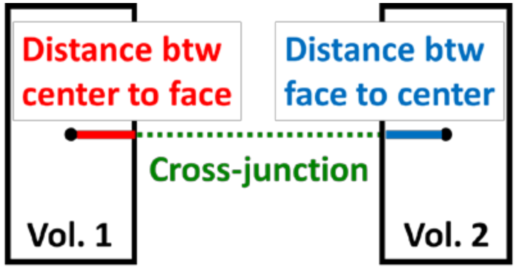
Concept of face number

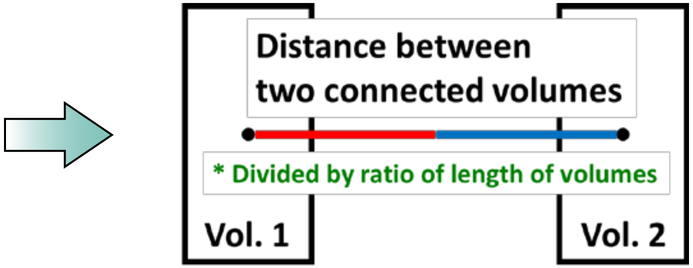
MARS-KS nodalization



Limitation

- Improved procedure evaluating the volume connection information
  - The distance and direction between the connected volumes are calculated.

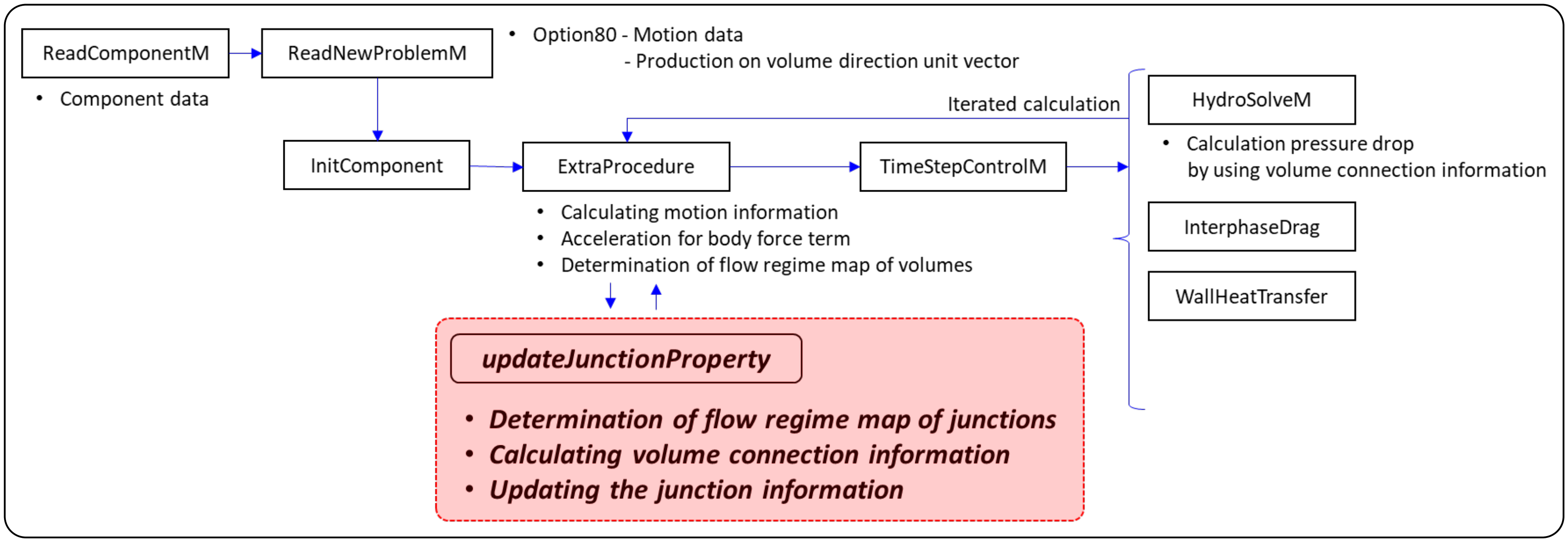




Modification of MARS-KS motion model

❖ Modification ④: Updating the junction property

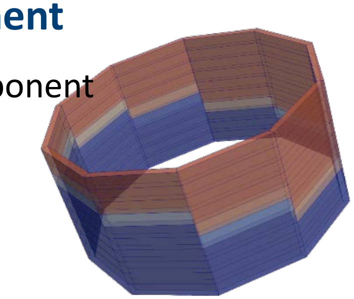
- Adding a procedure for the updating the junction property



Calculation procedure of MARS-KS motion model

❖ Modification ⑤: Extension of MARS-KS motion model to MULTID component

- Modification of MARS-KS motion model applicable to both One-D and MULTID component
- Modification of post-processing function for the MULTID component



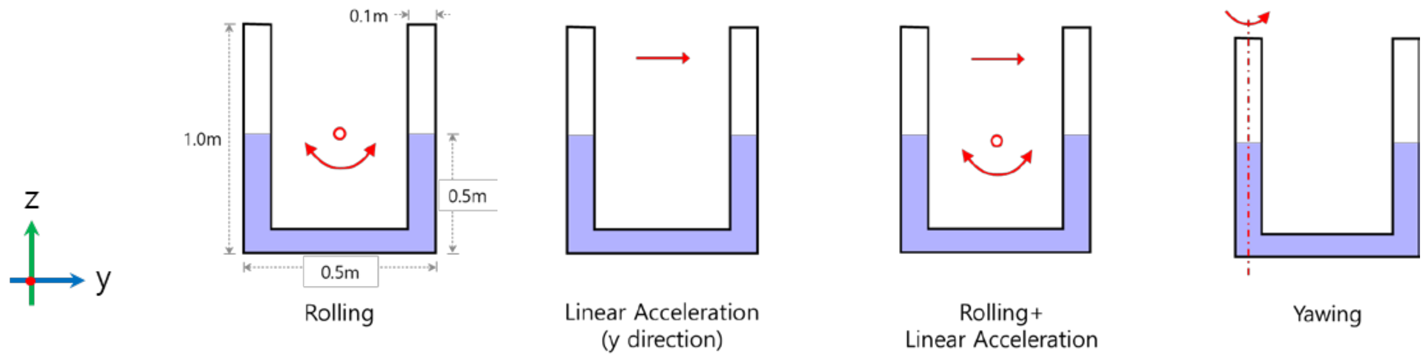
3 Verification of MARS-KS motion model

- 1-D conceptual problems
- Cross-flow problems
- MULTID component problems

Verification of MARS-KS motion model

1-D conceptual problems

- Quantitative evaluation by comparing with analytic solution

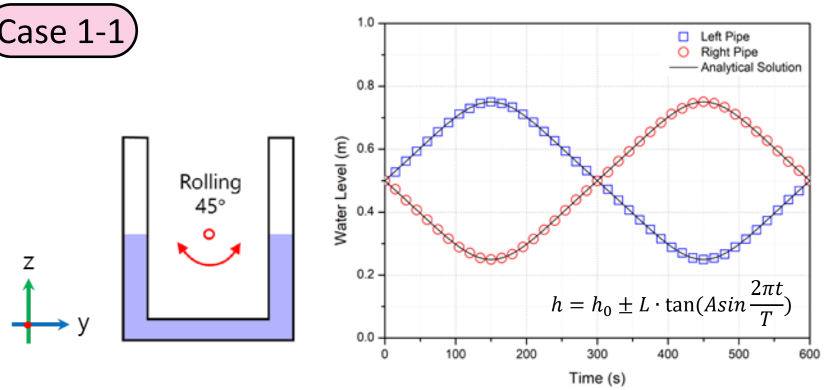


Parameters	Manometer			
	Case 1-1	Case 1-2	Case 1-3	Case 1-4
Length	1 m (0.5 m for water)	1 m (0.5 m for water)	1 m (0.5 m for water)	1 m (0.5 m for water)
Pitch	0.5 m	0.5 m	0.5 m	0.5 m
Diameter	0.1 m	0.1 m	0.1 m	0.1 m
Motion condition	**Rotational motion along the x-axis** - Amplitude: 45° - Period: 600 s	**Linear acceleration along the y-axis** - Acc.: 10 m/s^2	**Linear acceleration along the y-axis** - Acc.: 5 m/s^2 **Rotational motion along the x-axis** - Amplitude: 30° - Period: 600 s	**Rotational motion along the z-axis** - Angular speed : 360°/s

Verification of MARS-KS motion model

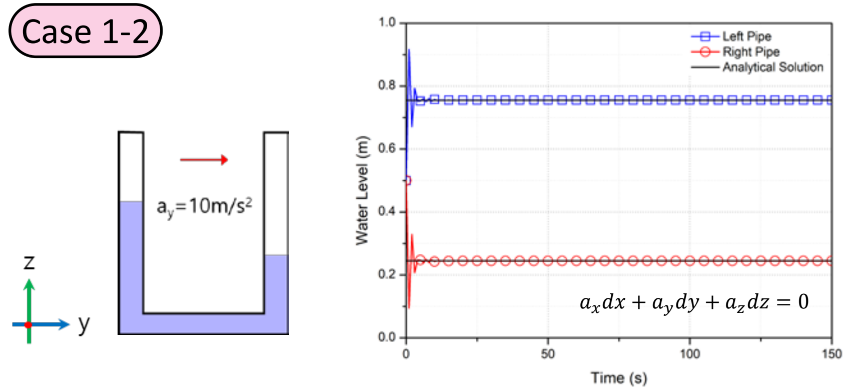
❖ **MARS-KS simulation results of 1-D conceptual problems (Max. error: 0.752 %)**

Case 1-1



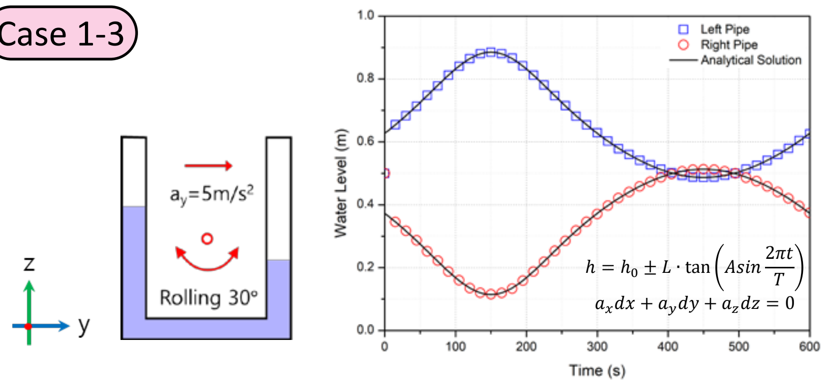
Rotational motion along the x-axis (45°, 600 s)

Case 1-2



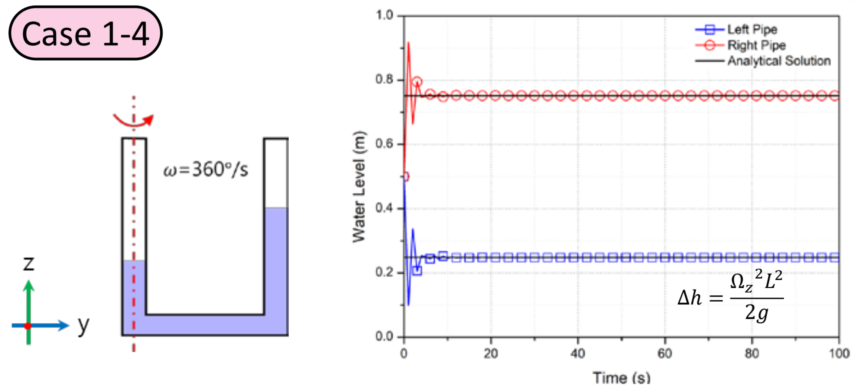
Linear acceleration along the y-axis (10 m/s²)

Case 1-3



Complex motion

Case 1-4

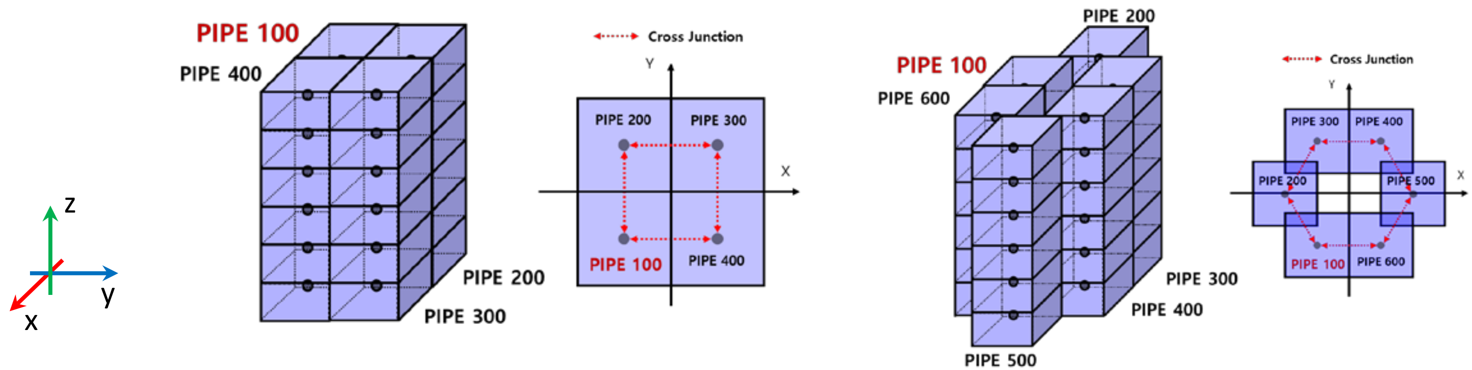


Rotational motion along the z-axis (360°/s)

Verification of MARS-KS motion model

❖ Cross-flow examples

- Quantitative evaluation by comparing with analytic solution

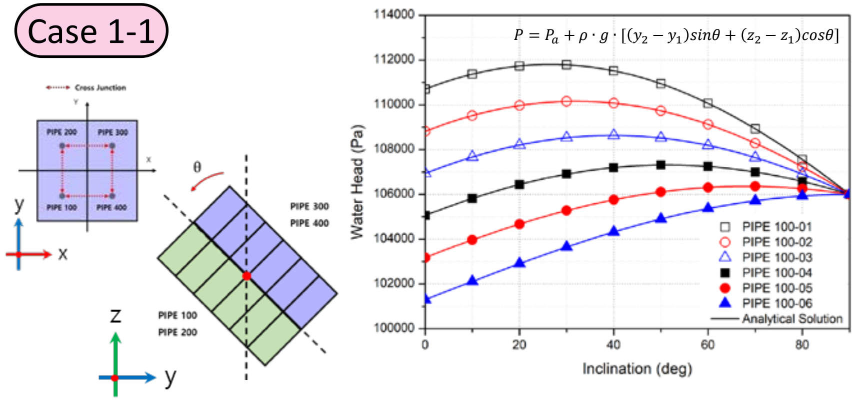


Parameters	Problem 1		Problem 2	
	4 PIPEs connected using cross-junction		6 PIPEs connected using cross-junction	
	Case 1-1	Case 1-2	Case 2-1	Case 2-2
Phase	Single-phase	Single-phase	Single-phase	Single-phase
Length	1.2 m	1.2 m	1.2 m	1.2 m
Diameter	0.5 m	0.5 m	0.5 m	0.5 m
Motion condition	**Inclination along the x-axis** - Angles: 0 ~ 90°	**Rotational motion along the x-axis** - Amplitude: 90° - Period: 600 s	**Inclination along the x-axis** - Angles: 0 ~ 90°	**Rotational motion along the x-axis** - Amplitude: 90° - Period: 600 s

Verification of MARS-KS motion model

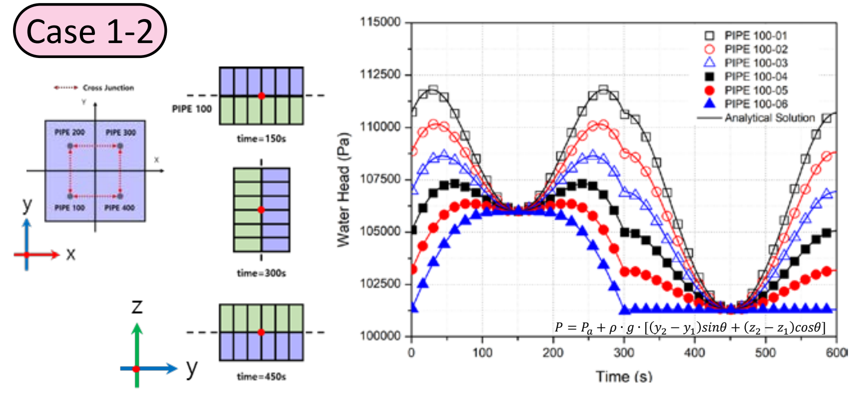
❖ **MARS-KS simulation results of cross-flow problems (Max. error: 0.0 %)**

Case 1-1



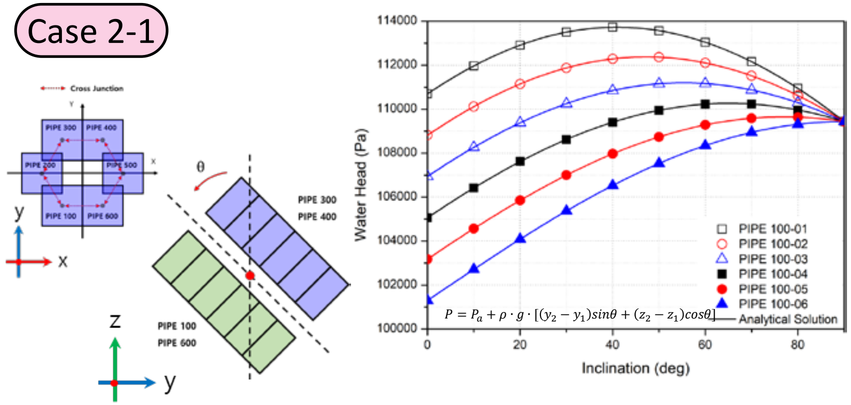
Inclination along the x-axis (0 ° ~ 90 °)

Case 1-2



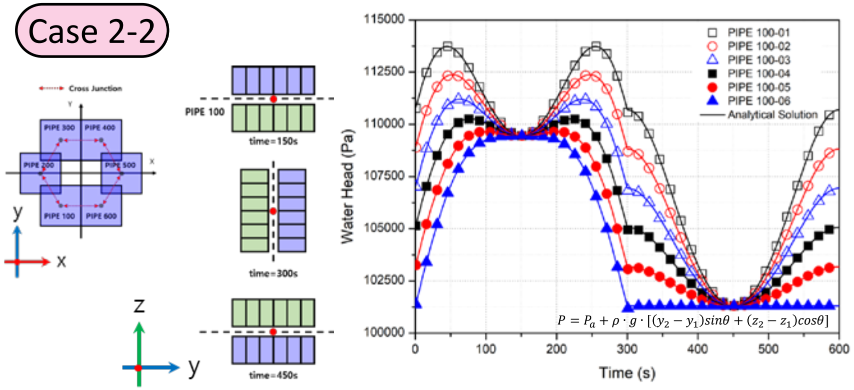
Rotational motion along the x-axis (90 °, 600 s)

Case 2-1



Inclination along the x-axis (0 ° ~ 90 °)

Case 2-2

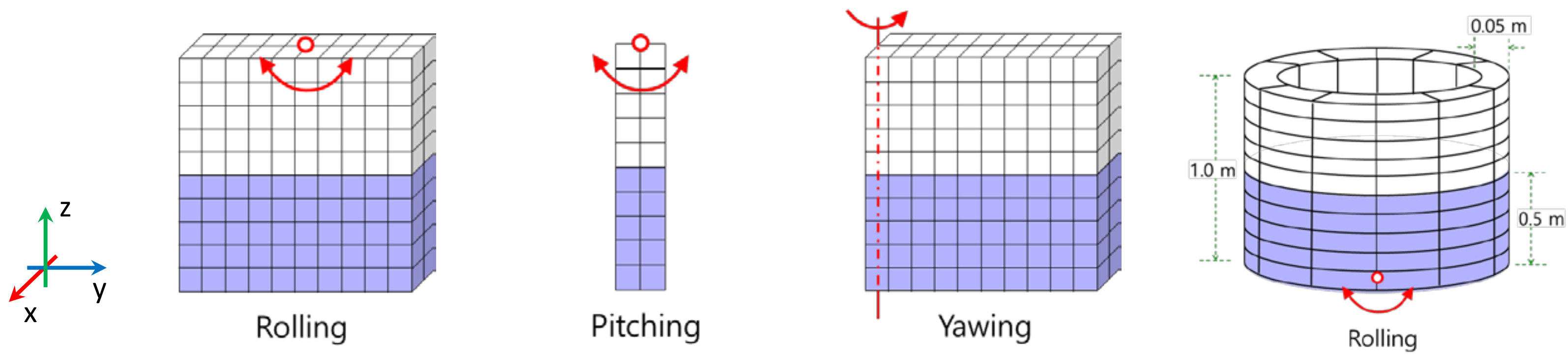


Rotational motion along the x-axis (90 °, 600 s)

Verification of MARS-KS motion model

❖ MULTID component examples

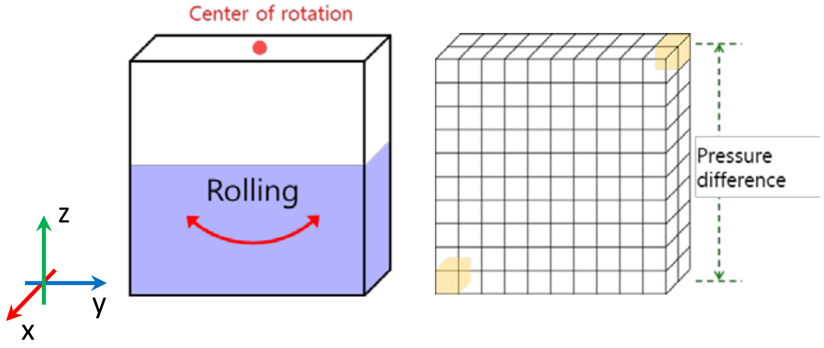
- Quantitative evaluation by comparing with analytic solution



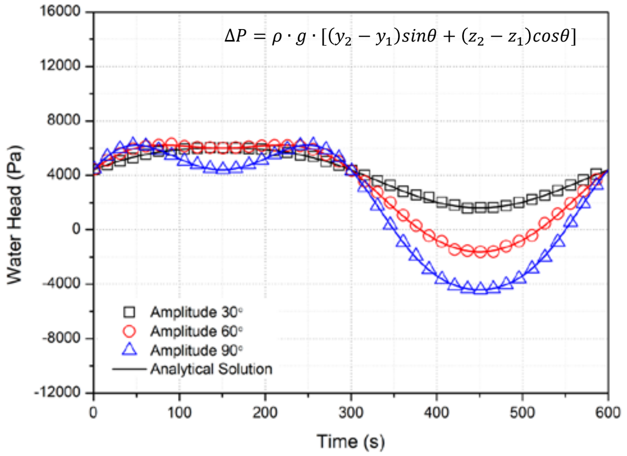
Parameters	Problem 1			Problem 2
	Slab consisted of 200 volumes			Cylindrical MULTID
	Case 1-1	Case 1-2	Case 1-3	
Phase	2-phase	2-phase	2-phase	2-phase
Length	1.0 m	1.0 m	1.0 m	1.0 m
Diameter	0.2 m × 1.0 m	0.2 m × 1.0 m	0.2 m × 1.0 m	2.0 m
Motion condition	**Rotational motion along the x-axis** - Amplitude : 30, 60, 90° - Period: 600 s	**Rotational motion along the y-axis** - Amplitude : 30, 60, 90° - Period: 600 s	**Rotational motion along the z-axis** - Angular speed : 60, 360°/s	**Rotational motion along the x-axis** - Amplitude: 30° - Period: 600 s

Verification of MARS-KS motion model

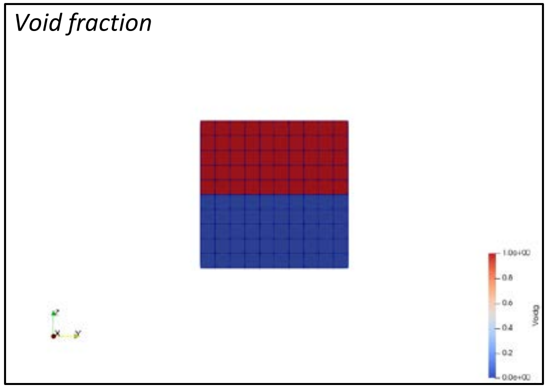
❖ **Problem 1: 2-phase slab under motion condition (Rolling motion)**



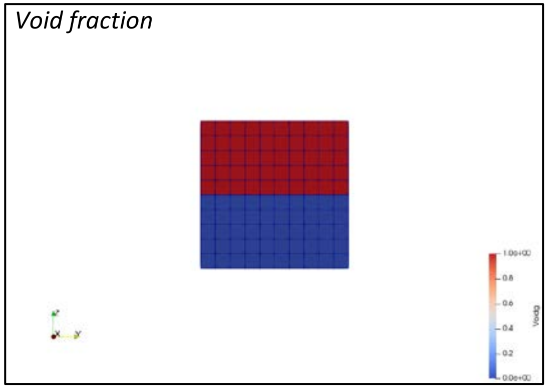
MARS-KS nodalization



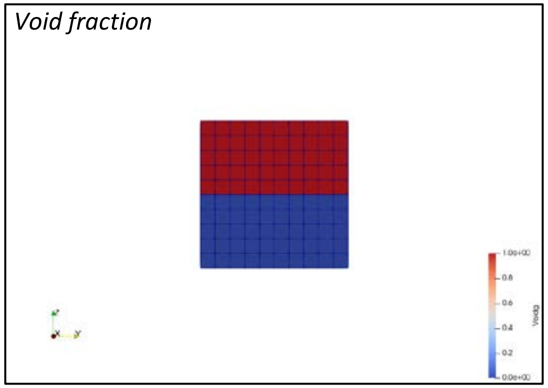
Simulation result



30° rolling motion



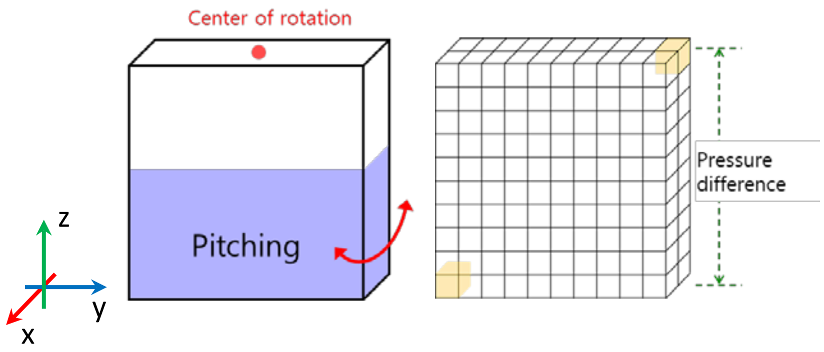
60° rolling motion



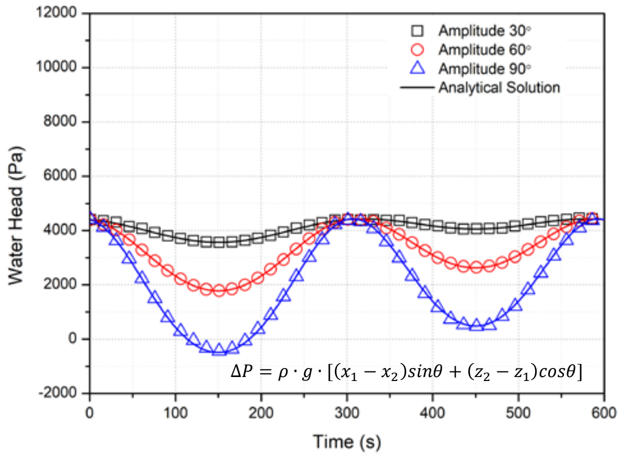
90° rolling motion

Verification of MARS-KS motion model

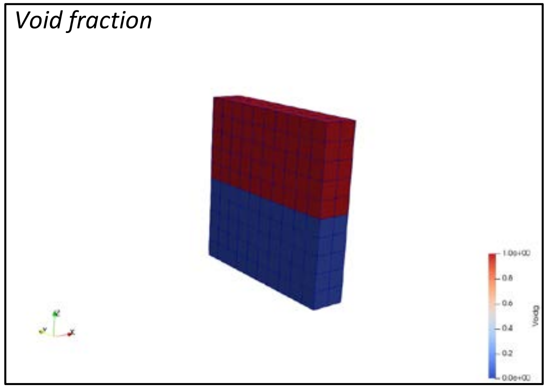
❖ **Problem 1: 2-phase slab under motion condition (Pitching motion)**



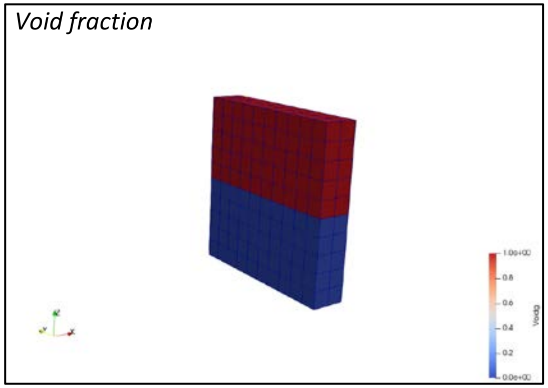
MARS-KS nodalization



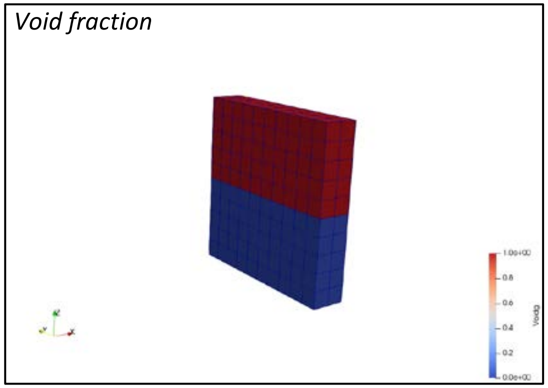
Simulation result



30° pitching motion



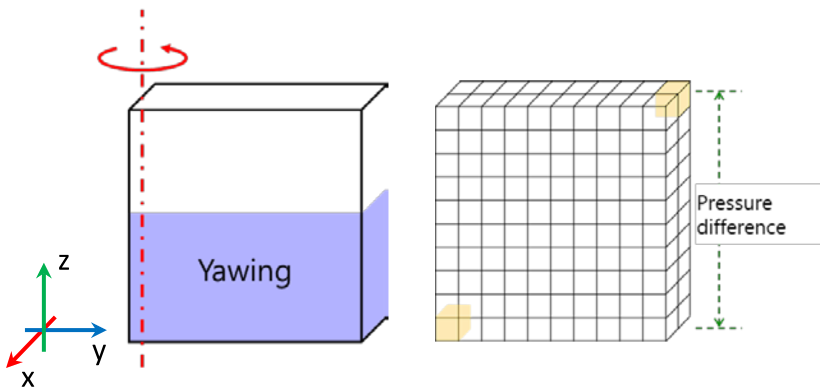
60° pitching motion



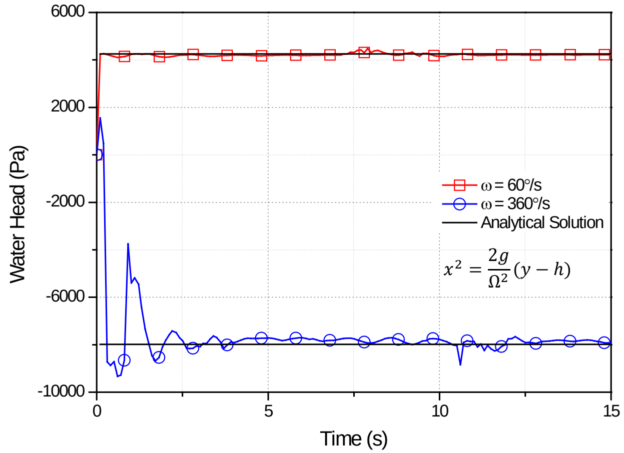
90° pitching motion

Verification of MARS-KS motion model

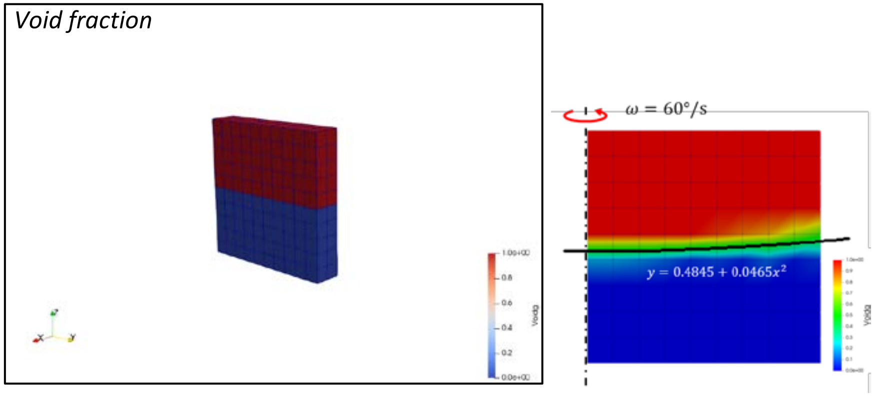
❖ **Problem 1: 2-phase slab under motion condition (Yawing motion)**



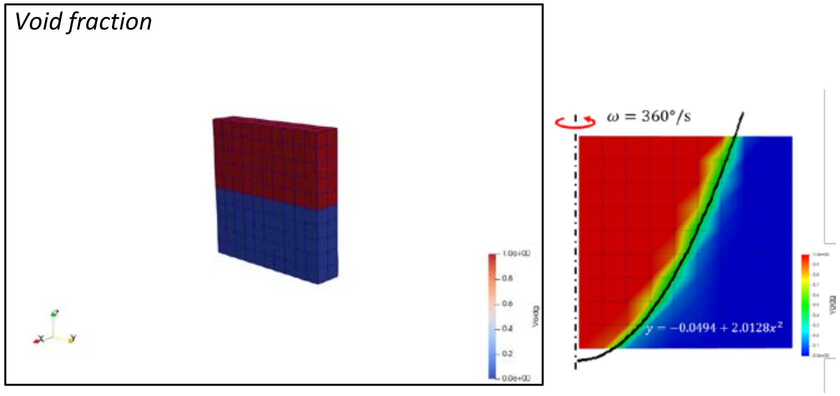
MARS-KS nodalization



Simulation result



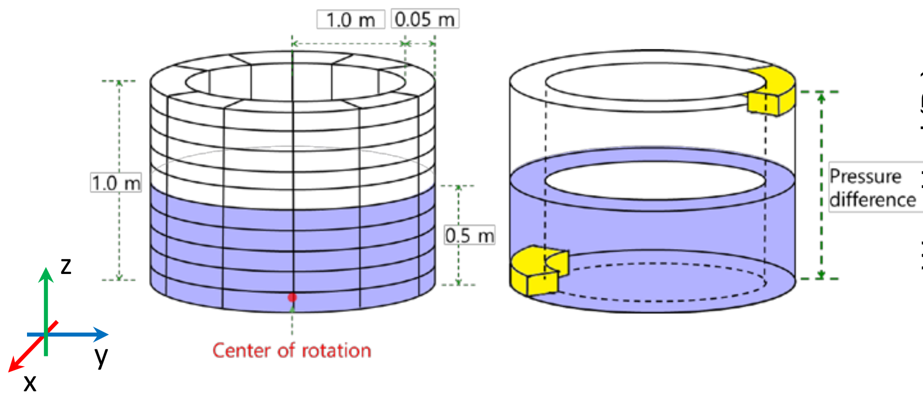
60 °/s yawing motion



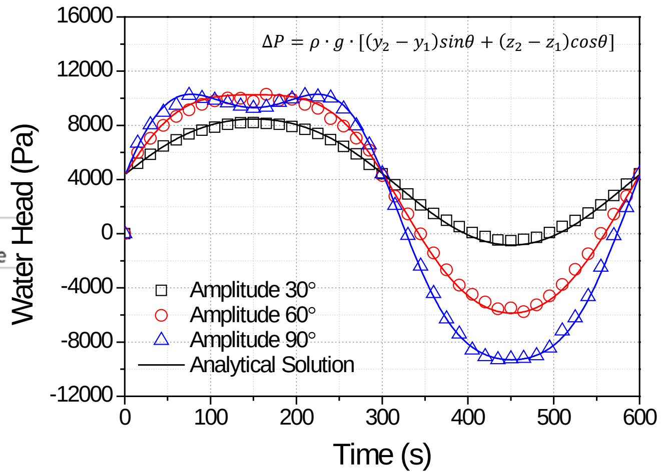
360 °/s yawing motion

Verification of MARS-KS motion model

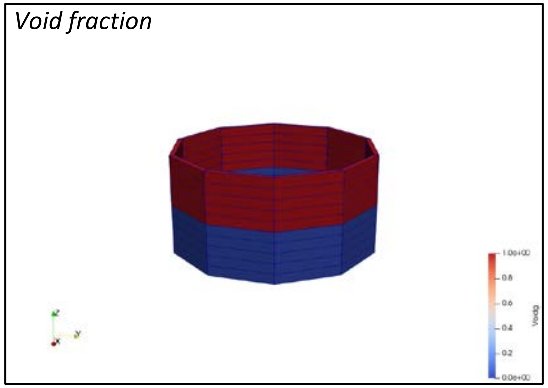
❖ Problem 2: 2-phase cylindrical MULTID under rolling motion



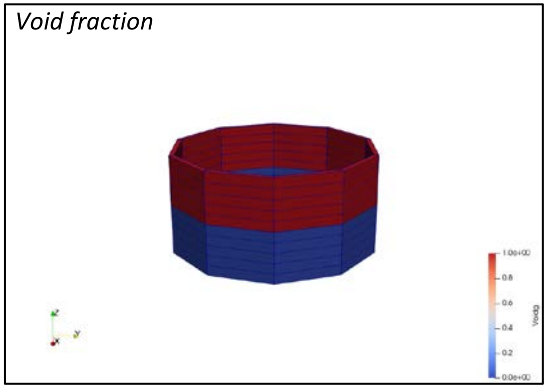
MARS-KS nodalization



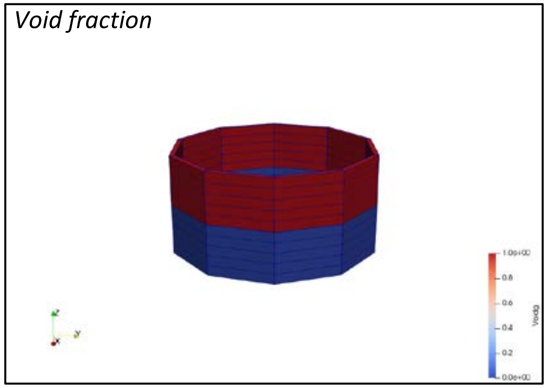
Simulation result



30° rolling motion



60° rolling motion



90° rolling motion

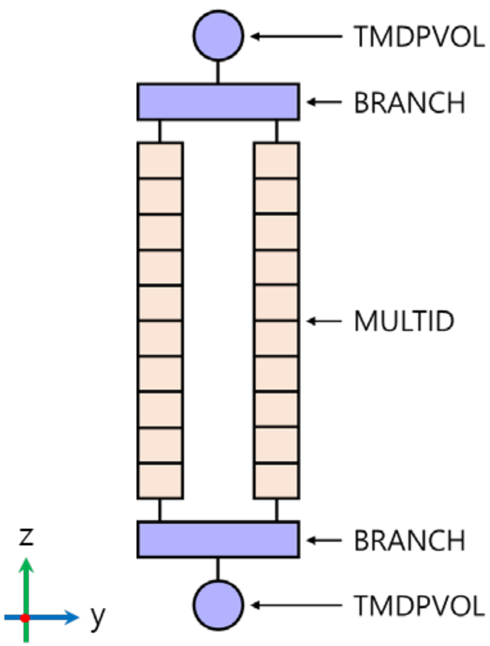
4 Application of MARS-KS motion model

- Prediction of flow instability
- Prediction of Critical Heat Flux

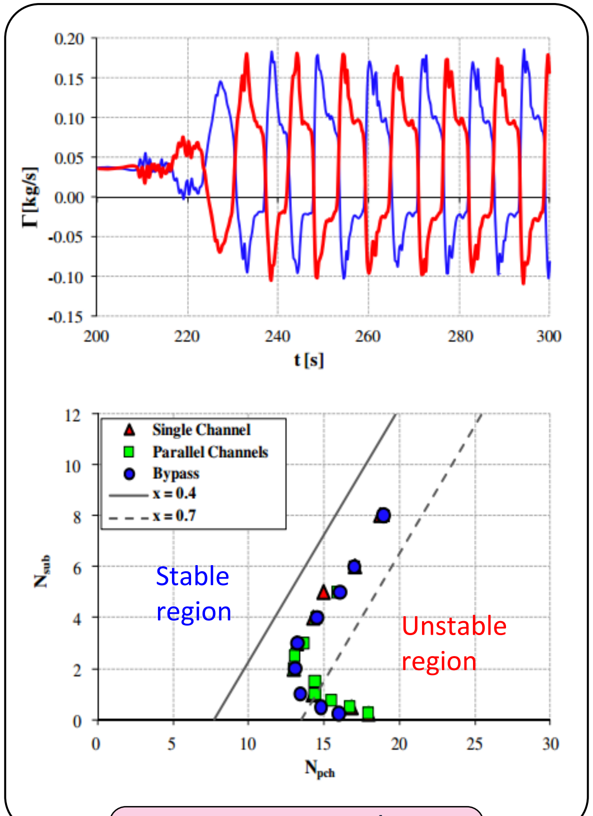
Application of MARS-KS motion model

❖ Prediction of flow instability

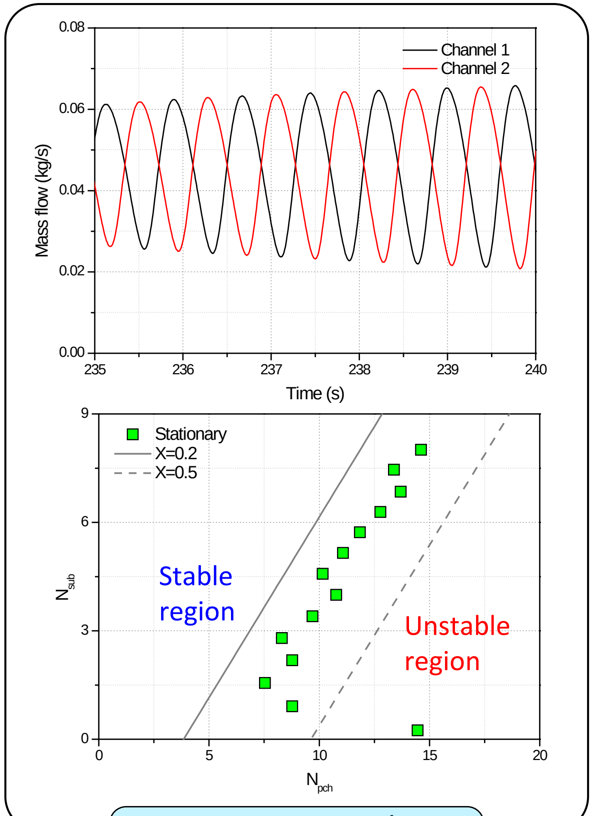
- Analysis model: Parallel channels with MULTID component ($\dot{m} = 0.2369\,kg/s$)
- Comparison of RELAP5 and MARS-KS analysis results
  - Counter-phase oscillations of the flow rate in the two channels
  - "L shape" in the dimensionless stability map



MARS-KS nodalization



RELAP5 result



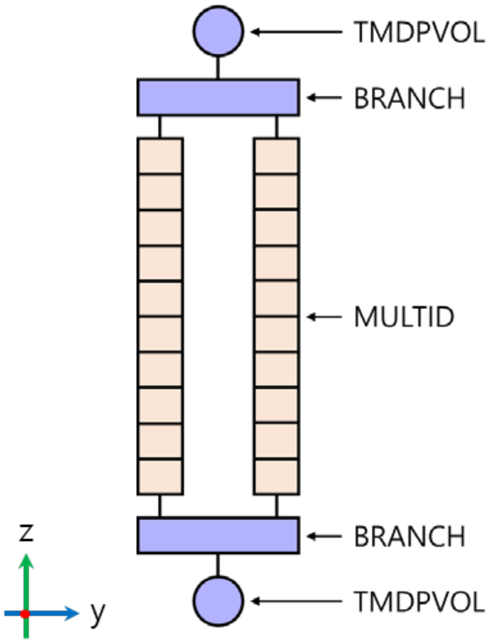
MARS-KS result

Marco Colombo et al., RELAP5/MOD3.3 study on density wave instabilities in single channel and two parallel channels, 2012

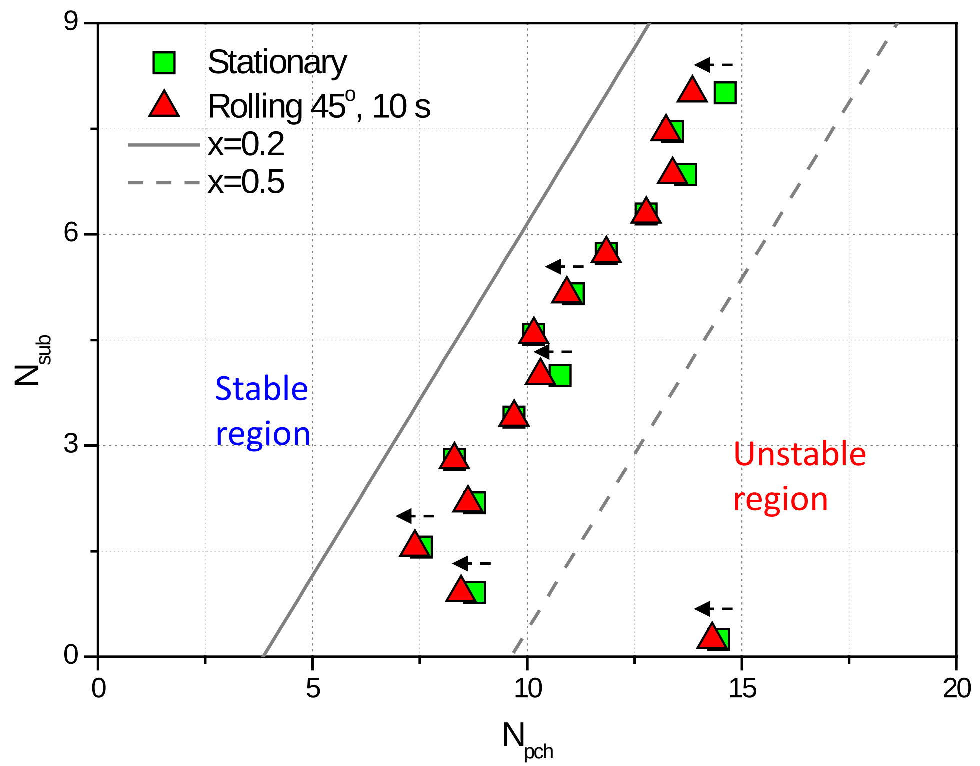
Application of MARS-KS motion model

❖ Prediction of flow instability

- Analysis model: Parallel channels with MULTID component ($\dot{m} = 0.2369\,kg/s$)
- Comparison of analysis results under stationary and rolling conditions
  - Motion condition: Rotational motion along the x-axis (45°, 10s)
  - A slight increase of unstable region under rolling condition



MARS-KS nodalization



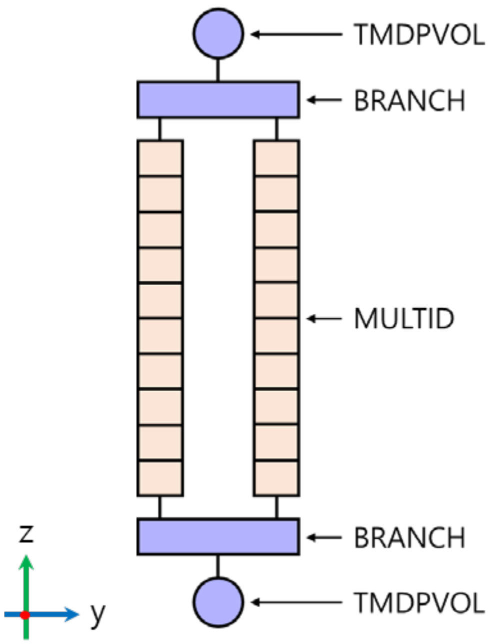
MARS-KS result

Marco Colombo et al., RELAP5/MOD3.3 study on density wave instabilities in single channel and two parallel channels, 2012

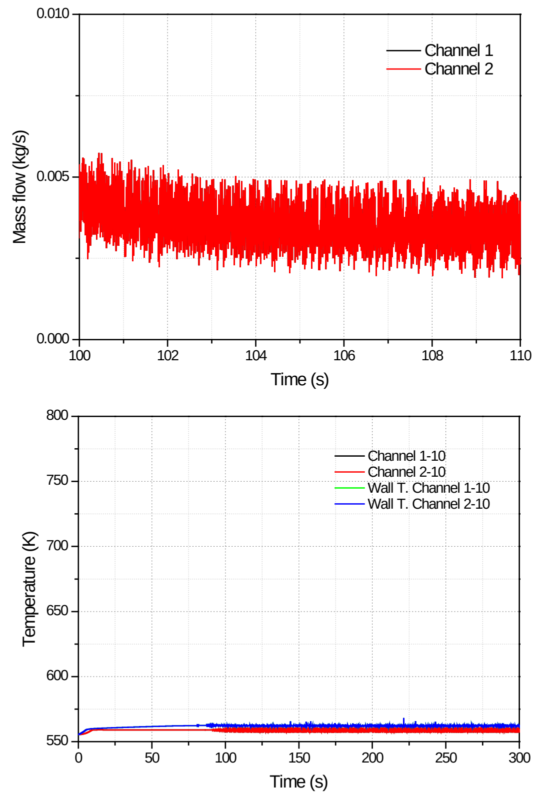
Application of MARS-KS motion model

Prediction of Critical Heat Flux

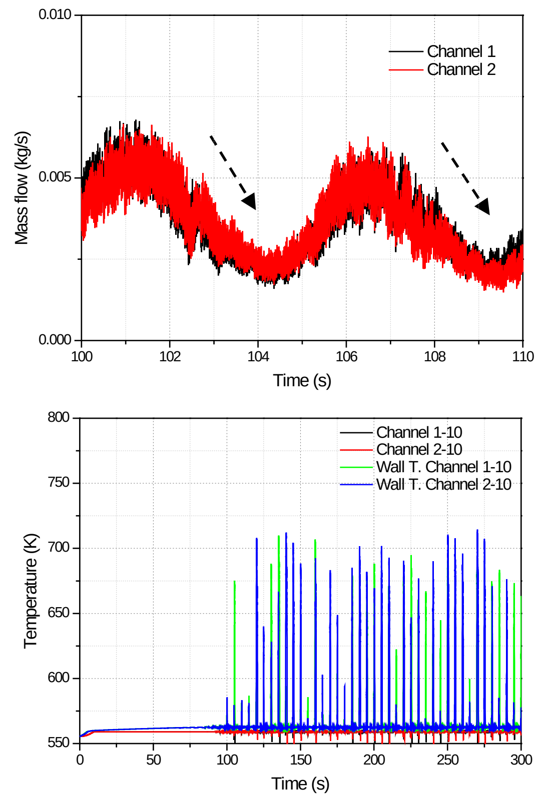
- Analysis model: Parallel channels ($\dot{m} = 0.02369\, kg/s$)
- Comparison of analysis results under stationary and rolling conditions (45°, 10 s)
  - CHF occurs earlier under rolling condition than stationary condition.



MARS-KS nodalization



Stationary



Rolling (45°, 10 s)

Marco Colombo et al., RELAP5/MOD3.3 study on density wave instabilities in single channel and two parallel channels, 2012

Conclusion

- **Implementation of multi-dimensional analysis capability in MARS-KS motion model**
  - User-friendly code adopting by auto-generated volume direction unit vector
  - Implementation of cross-flow model in MARS-KS motion model
  - Extension of MARS-KS motion model to MULTID component simulation

- **Contribution of the research**
  - Verification of modified MARS-KS motion model
    - The mathematical model of dynamic motion was confirmed.
    - MARS-KS can predict the fluid behaviors of cross-flow model and MULTID component.
  - Application of modified MARS-KS motion model
    - It was applied to predict the flow instability and Critical Heat Flux.

- **Limitation in the code and remaining research**
  - Modification of the energy equation
  - Heat transfer characteristic of 2-phase flow under the motion condition
  - Modification of MARS-KS motion model (Coriolis force and cylindrical MULTID)