Development of Unstructured Grid Free Surface Flow Solver

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Contents

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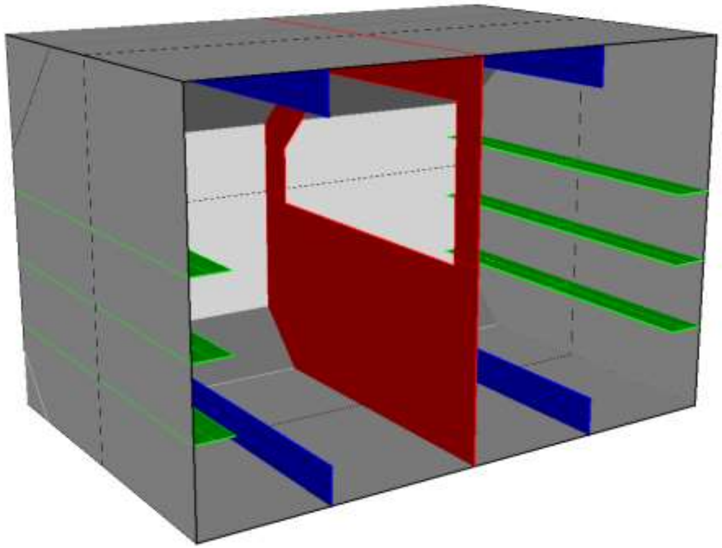
Tank sloshing with complicated inner structures

- Small-scale experiments
- Numerical simulations

  Lagrangian particle methods: SPH, MPS

  Eulerian Methods: FVM, FDM, and FEM



Tank model for a sloshing project in collaboration with ClassNK

Introduction

Challenges to long-time numerical simulation of sloshing

- **Difficulty to maintain free-surface interface sharpness**
- **Computation efficiency, parallelization**
- **Treat complicated physical phenomena**
  - Multi-scale physics (free-surface, turbulence, bubbles, ..)
  - Treatment of gas compressibility
  - Modeling inter-phase changes in some applications

Introduction

Aim of this work is to develop an incompressible unstructured free surface finite volume solver with the following aspects:

- Treat complicated solid boundaries **Unstructured code**
- Accurate and efficient interface capturing **UMTHINC**
- Accurate prediction of free surface impact
- Proper modeling of turbulence
- High parallel efficiency and suitable to GPUs

Governing Equations
and
Numerical Method

Governing Equations and Numerical Method

- Incompressible Reynolds-Averaged Navier-Stokes equations
- RANS Turbulence Modelling
  - Standard k-ε Model
  - Realizibale k-ε Model
  - Wilcox k-ω Model
  - Suitable wall functions are used to avoid excessive mesh refinement near the walls
- Volume of Fluid (VOF) method for interface capturing

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Numerical Method

- Finite Volume method
- Pressure – Velocity coupling using PISO algorithm
- Diffusion term approximated using 2nd order discretization
- Convection term discretized using various TVD schemes, i.e. Vanleer scheme
- Second order temporal discretization

Interface Capturing

- Popular methods include:
  - ✓ Level set method
  - ✓ Volume of Fluid (VOF) method

Level set method:

- ➢ Popular on Cartesian Grid codes
- ➢ Accurate curvature approx.
- ➢ Conservation Issues
- ➢ Applicability to unstructured grids ! (Still ongoing research)

Volume of Fluid (VOF) method:

- ➢ Conservative
- ➢ Applicable to unstructured grids
- ➢ Can be classified to :
  - Geometric: PLIC
  - Algebraic: CICSAM, HRIC, ….

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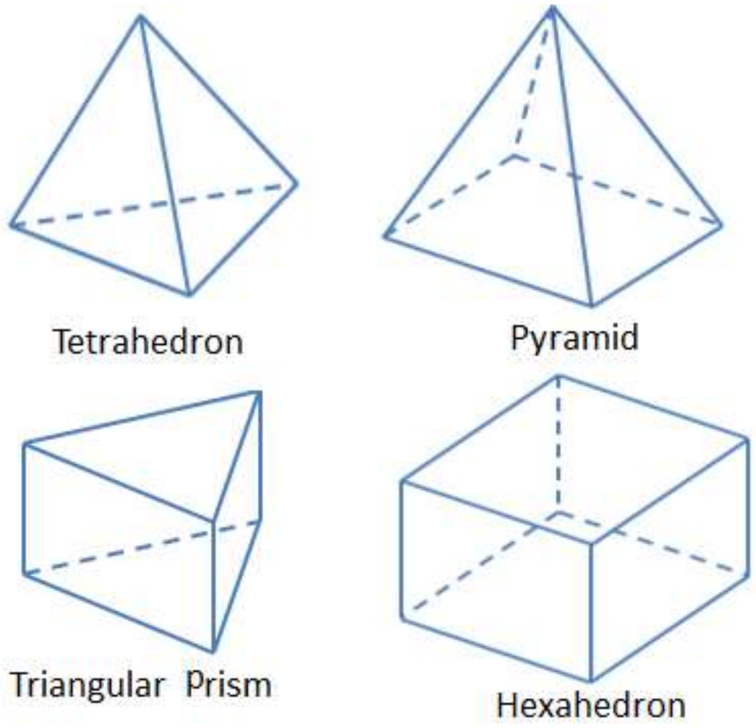
UMTHINC

- **THINC** method developed by Xiao et al. (2005)
- **UMTHINC** for unstructured grids developed by
  Satoshi Ii (2014)
  Bin Xie (2014, 2017)
- Applicable to all common unstructured grid cell shapes



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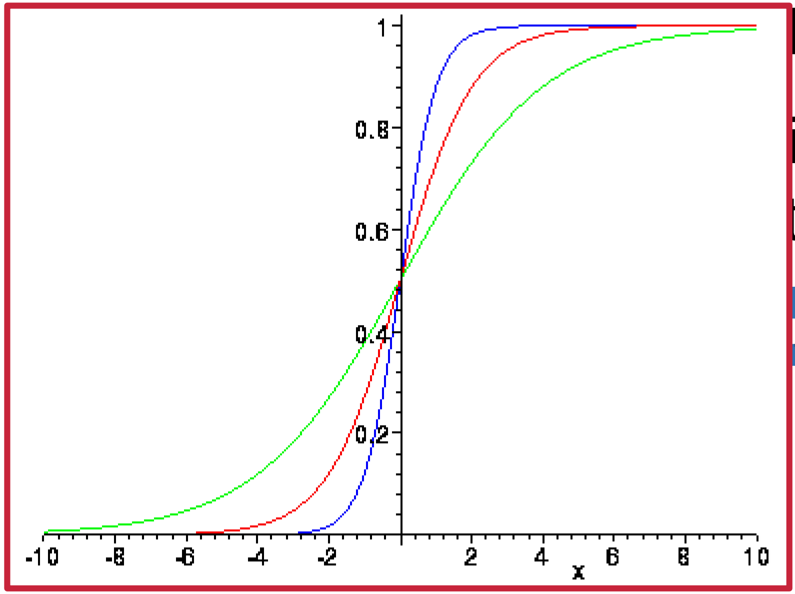
UMTHINC: Description

- UMTHINC: **U**nstructured **M**ulti-dimensional **T**angent **H**yperbolic



hod,

in the computational cell is approximated

the local cell coordinate (ξ, η, ζ)

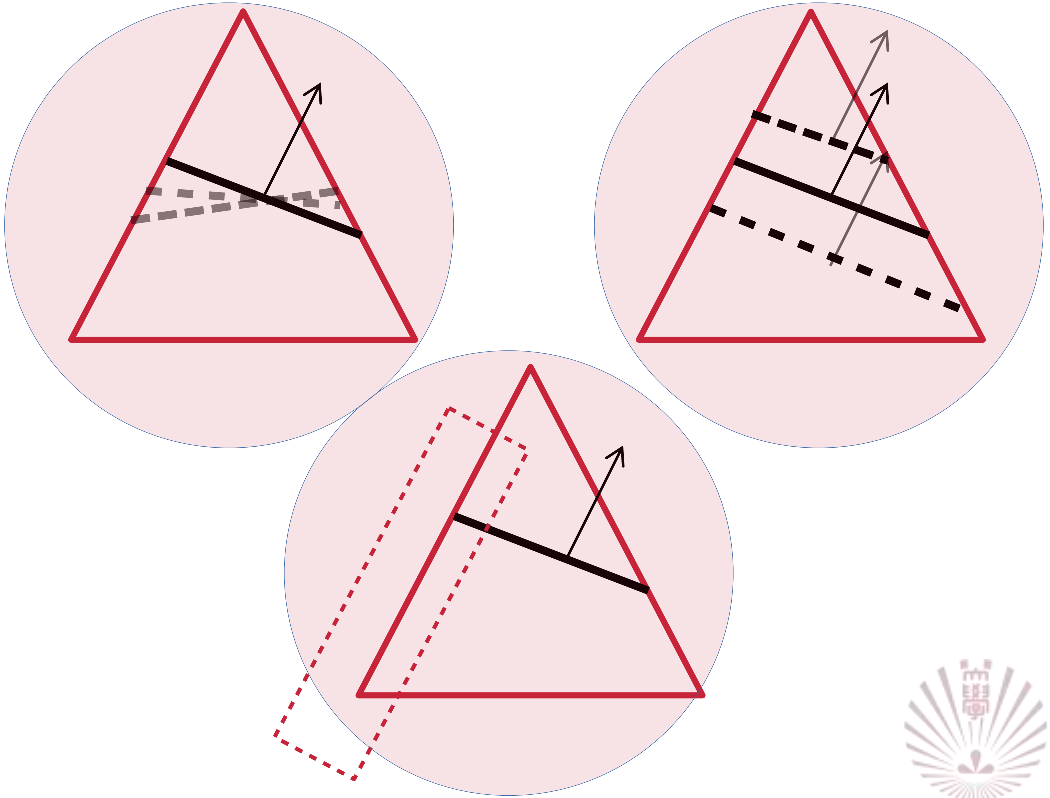
nterface sharpness control parameter

$$+ \tanh(\beta \mathcal{P}(\xi, \eta, \zeta)) \Big)$$

Interface surface approximation;
line/plane or any higher order surface

UMTHINC: Features

- Geometric reconstruction of the interface orientation based on the volume fraction field is necessary
- Since the interface transition is modeled as a tanh algebraic function, interface placement can be done using an analytic formula
- Similarly computation of the advected volume is done analytically



UMTHINC: Features

- Ability to model the interface as line/plane or quadratic surface with hardly any complication
- Implementation of the method (programming) is easy and straightforward
- Numerically stable until slightly higher than CFL = 0.5 which is suitable for practical transient flow applications
- Since it is technically a **geometric** method, the interface remain the same throughout the simulation (thickness is controlled by β)
- Computationally we can argue that its computation cost is somewhere in between PLIC Geom. VOF and Algebraic VOF

On Our in-House Unstructured Mesh Code

- Original Code developed as part of Mohamed's PhD degree research*
- Implemented using C/C++ programming language
- Includes various turbulence models RANS and LES
- Interface capturing scheme is done using UMTHINC VOF
- Parallel programming model is OpenMP
- Another version has also been completed recently using pure MPI or MPI+OpenMP
- A CUDA GPU version is under development

※ Mohamed M. Kamra, "Development of an Unstructured Grid Solver for Complex Wave Impact Problems", PhD Thesis, Kyushu University 2018

Validation Case Studies

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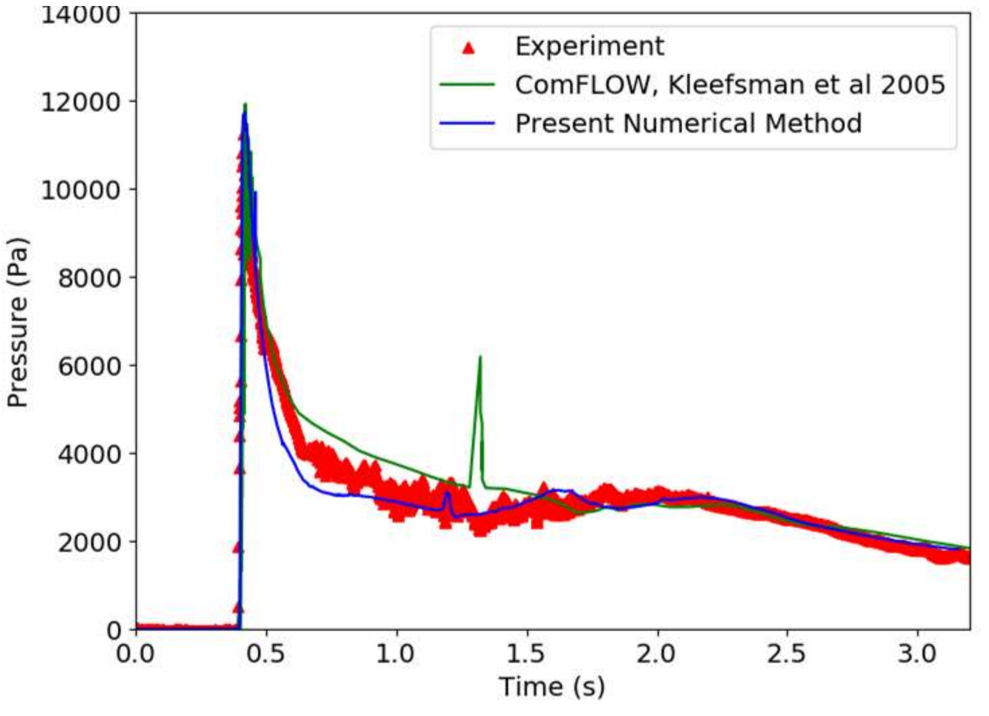
Validation Case I: Dam-Break with Obstacle



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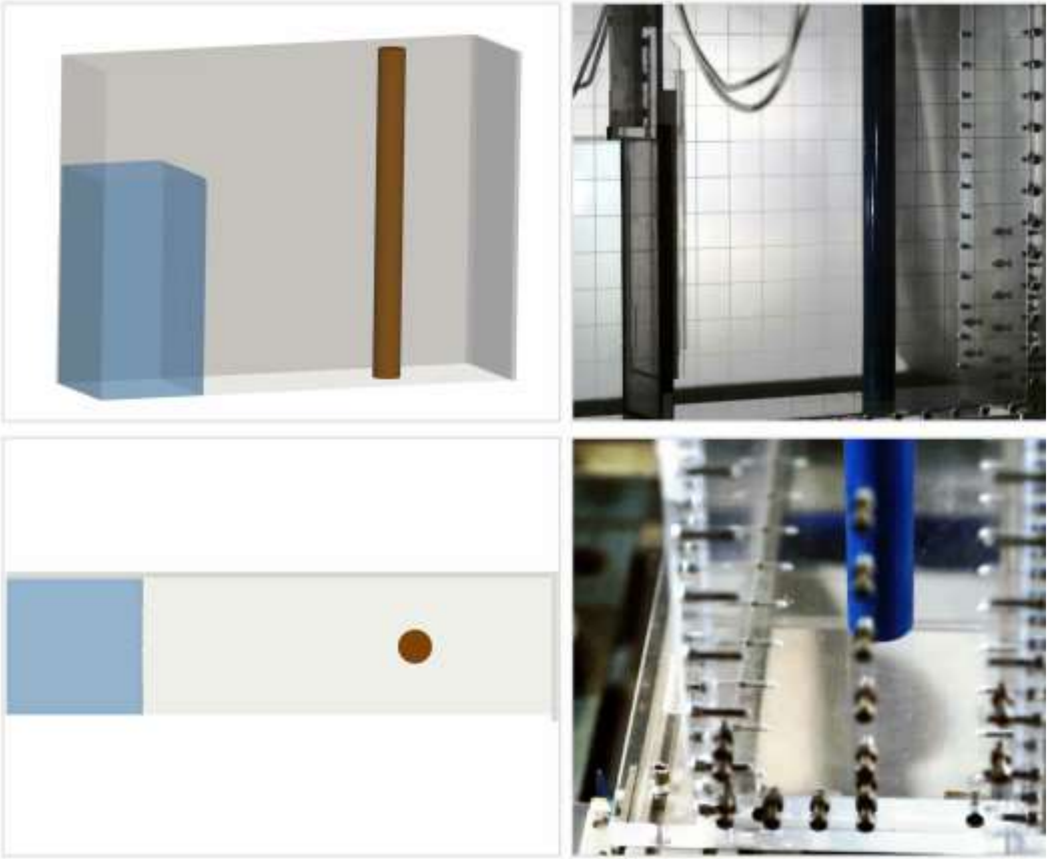
Validation Case II: Dam-Break with Circular Cylinder



※ Mohamed M. Kamra, Jabir Al Salami, Makoto Sueyoshi, Changhong Hu, Experimental study of the interaction of dambreak with a vertical cylinder, Journal of Fluids and Structures, V. 86, pp. 185-199 (2019)

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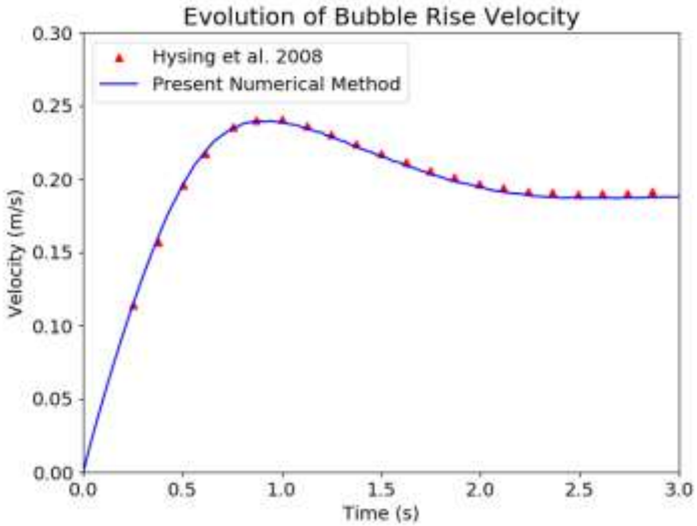
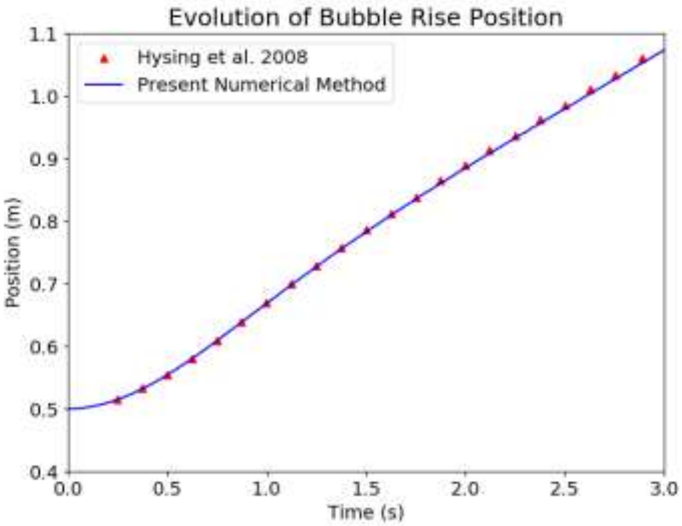
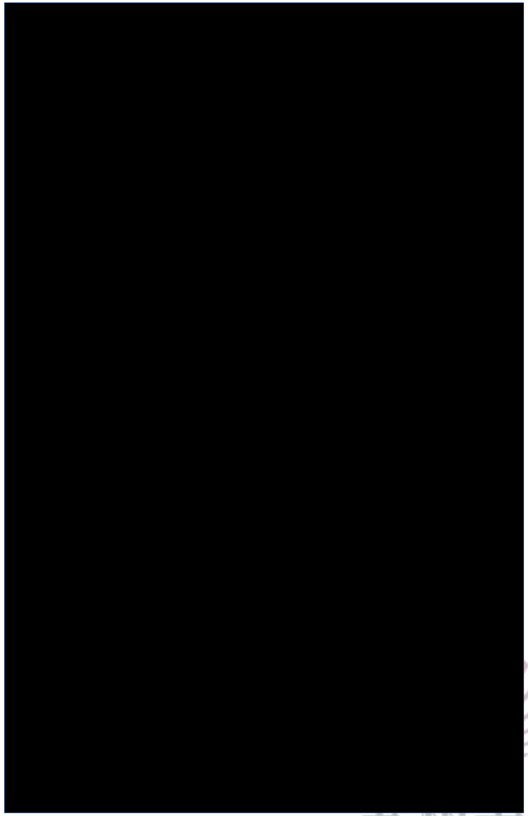
Validation Case III: Rising Bubble



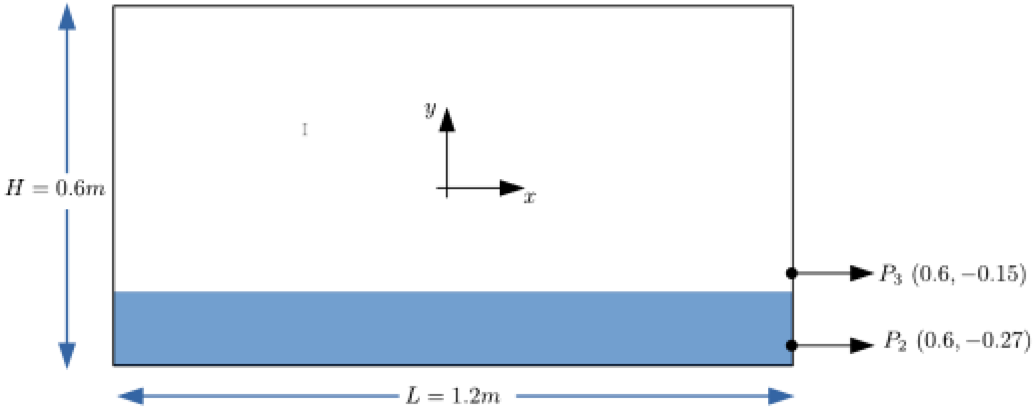




Validation Case IV: Tank Sloshing

-- Check Interface Smearing and Effect of Turbulence Model --

Motion Parameter	Value
Motion Direction	X direction
Motion Profile	Sinosoidal
Amplitude(mm)	60mm
Period Case A (seconds)	1.74
Period Case B (seconds)	1.94
Filing Level	20%



Validation Case IV: Tank Sloshing

Numerical Simulation Parameters

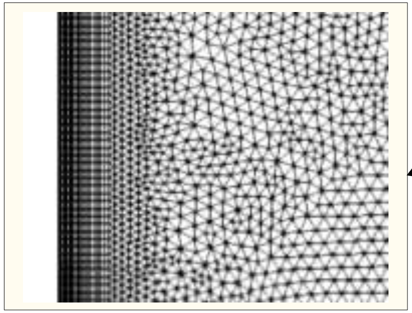
- Revised version of UMTHINC is used*
- Maximum CFL = 0.25
- UMTHINC Interface Sharpness Parameter β = 6
- Four PISO corrections per time step
- Surface tension effect is neglected

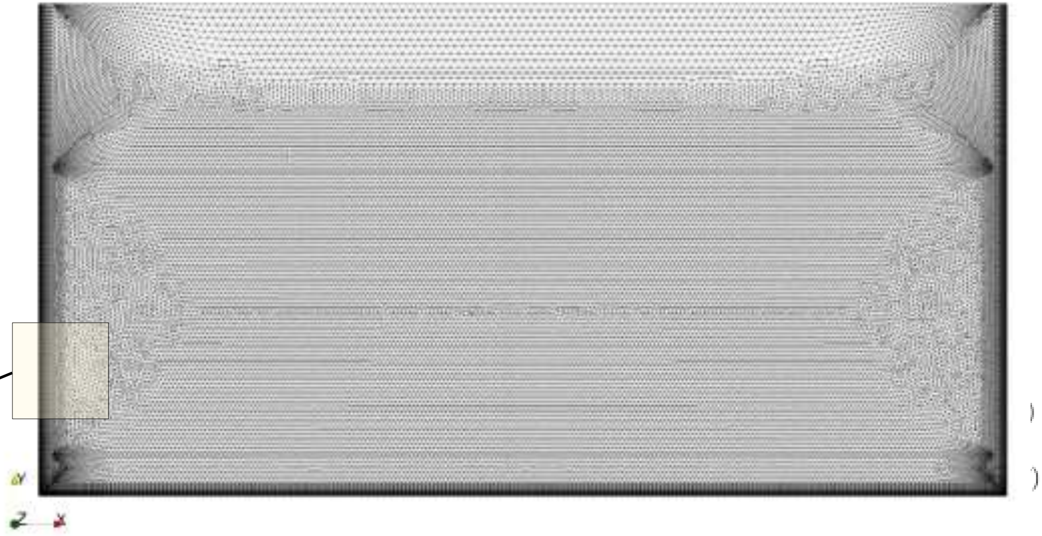
- Interface smearing over time
- Examine the effect of turbulence model choice
- UMTHINC Interface Sharpness Parameter

※ Mohamed M. Kamra, "Development of an Unstructured Grid Solver for Complex Wave Impact Problems", PhD Thesis, Kyushu University 2018

Validation Case IV: Tank Sloshing

- The model problem is based on the experiments conducted by the National Maritime Research Institute of Japan





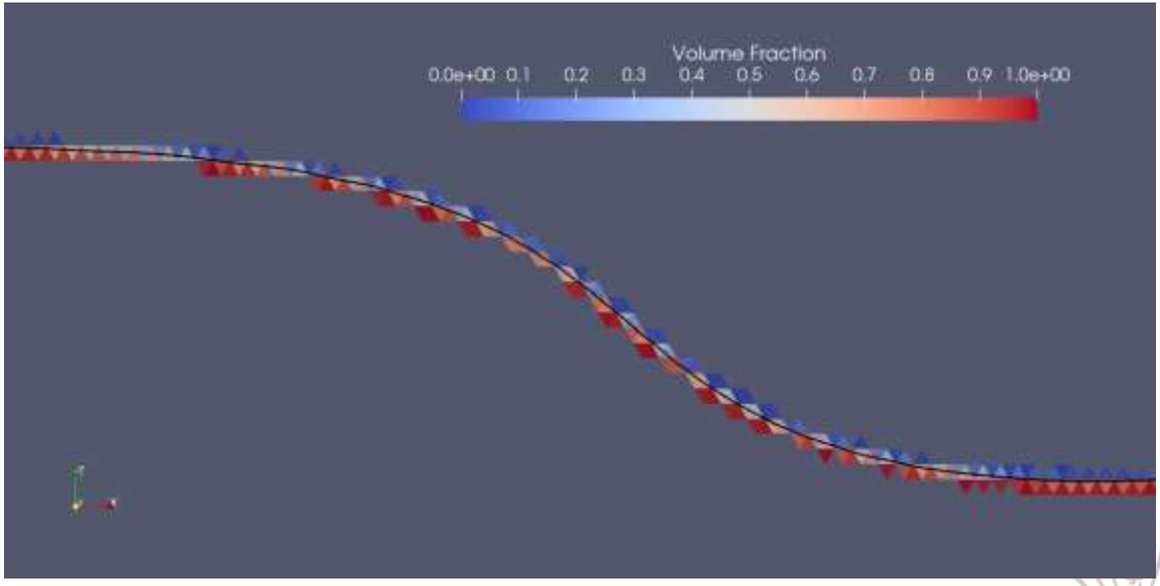
- Mixed unstructured mesh
- For accurate resolution of the boundary layer:
- 20 quadrilateral layers are attached to the walls of the tank
- First layer thickness of 0.5mm.
- Triangular cells have an avg effective length is 5mm

Validation Case IV: Tank Sloshing

-- Check Interface Smearing over Time --

- After 6 Periods
- After 16 Periods
- After 26 Periods

Case A: T = 1.74s



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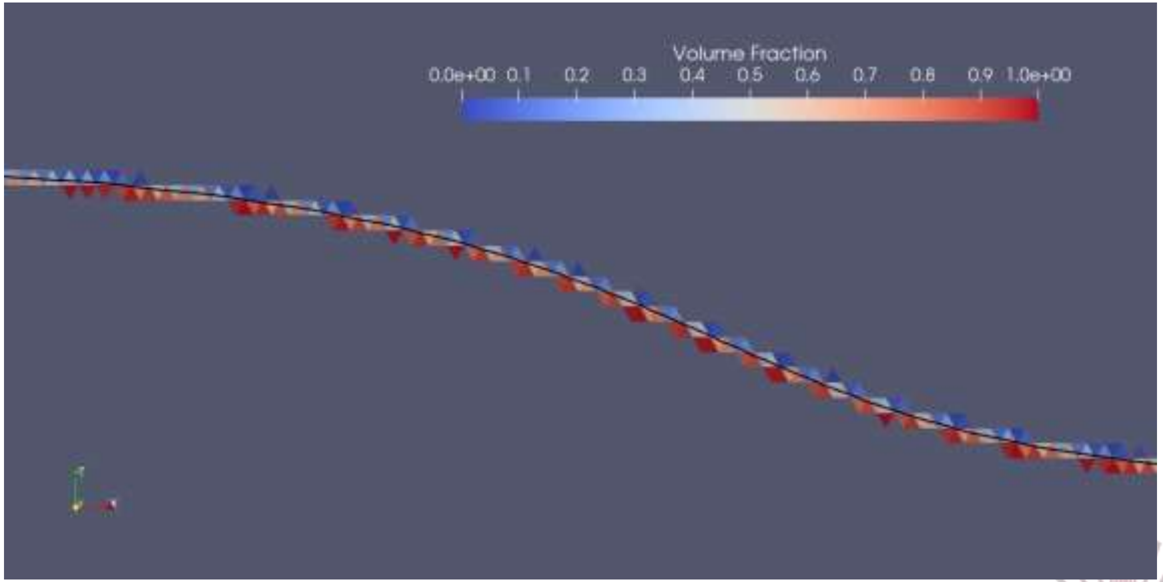

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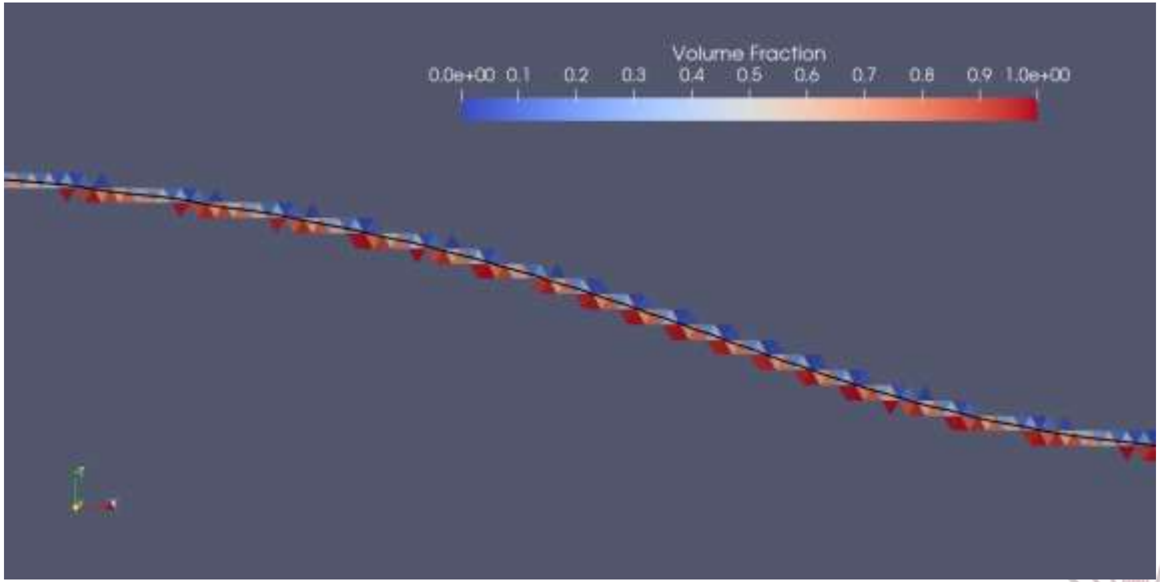

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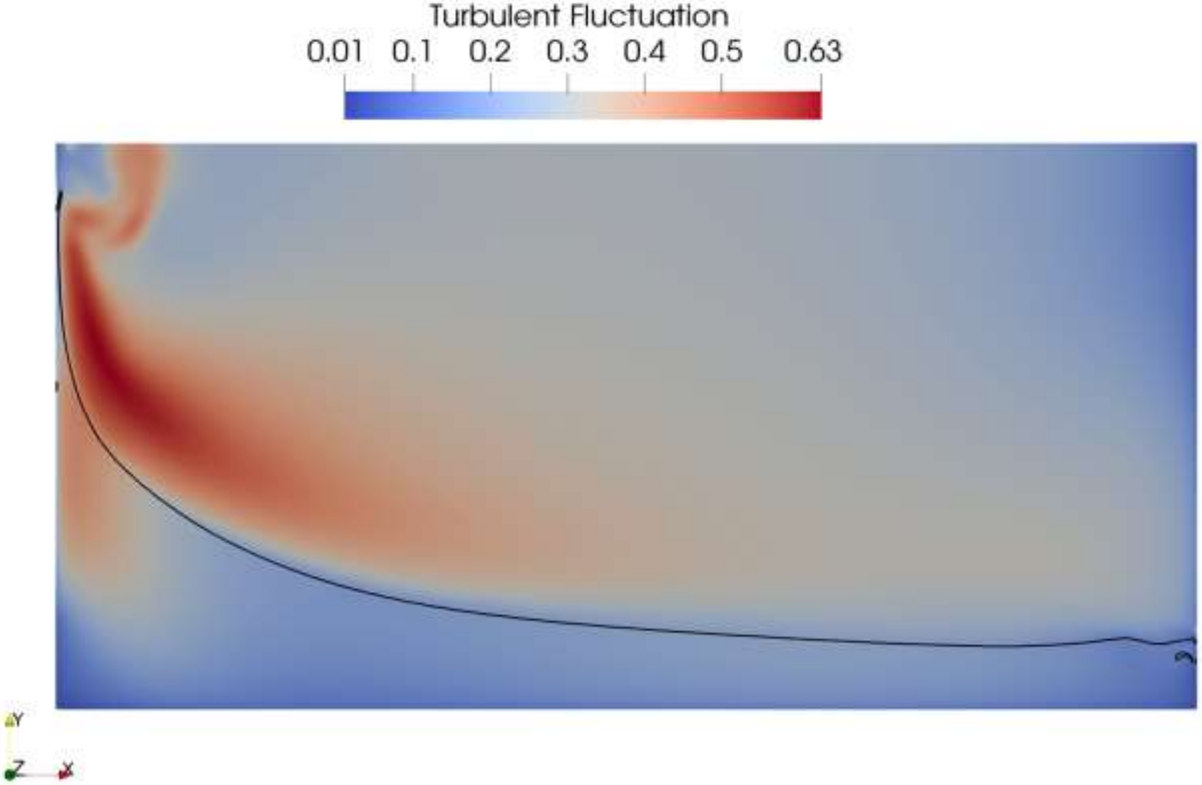
Validation Case IV: Tank Sloshing

-- Check Effect of Turbulence Model --

- Standard k-ε Model
- Realizibale k-ε Model
- Wilcox k-ω Model



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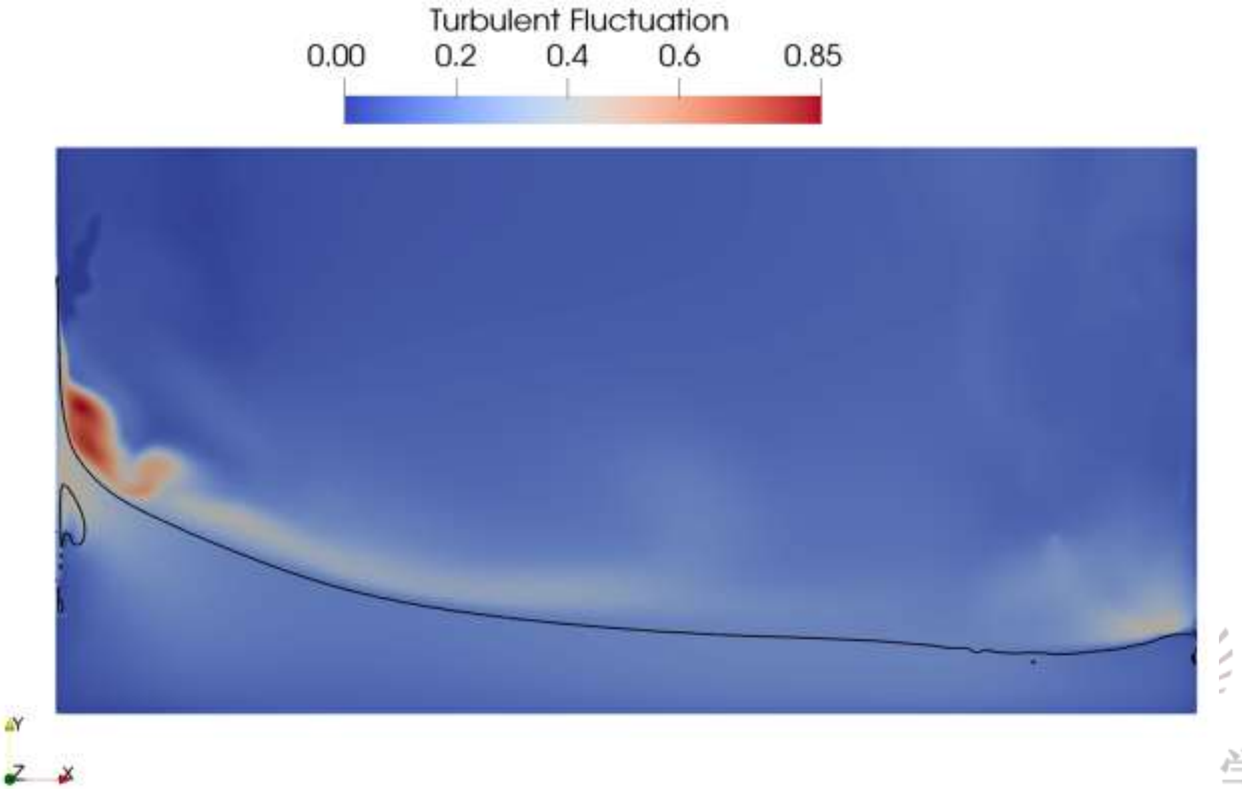

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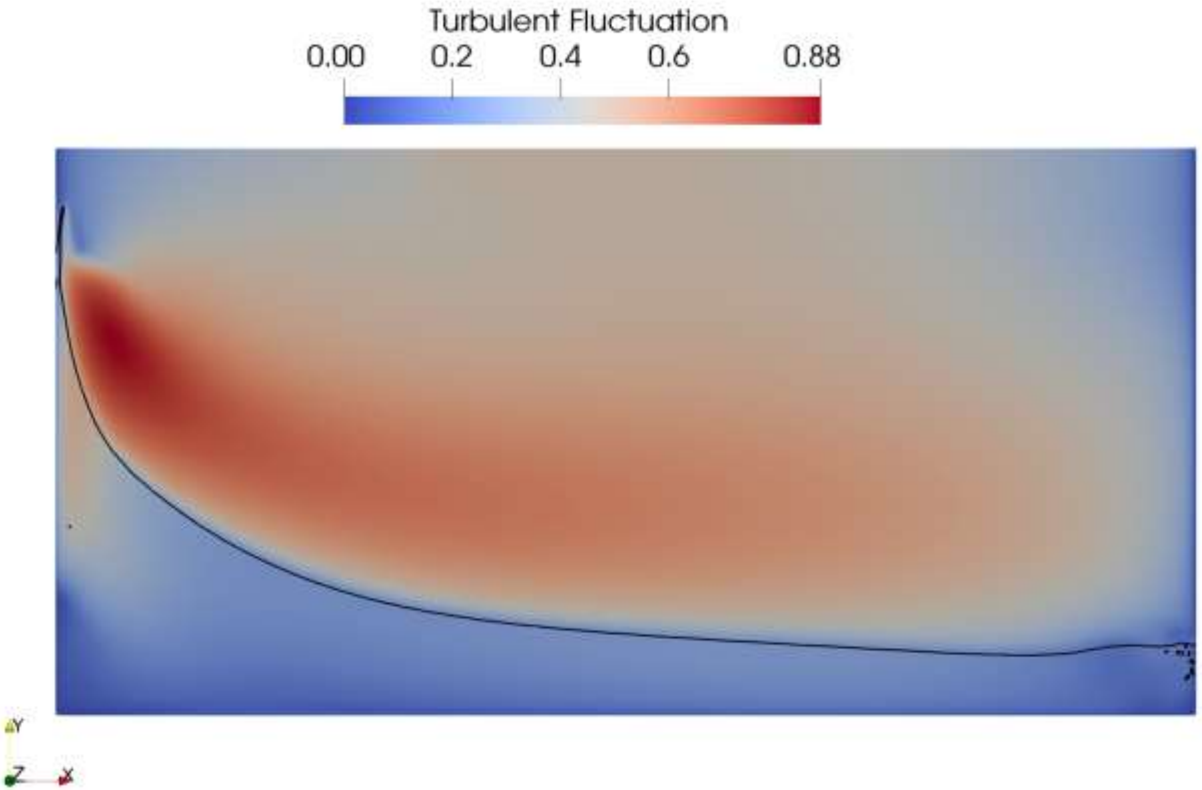

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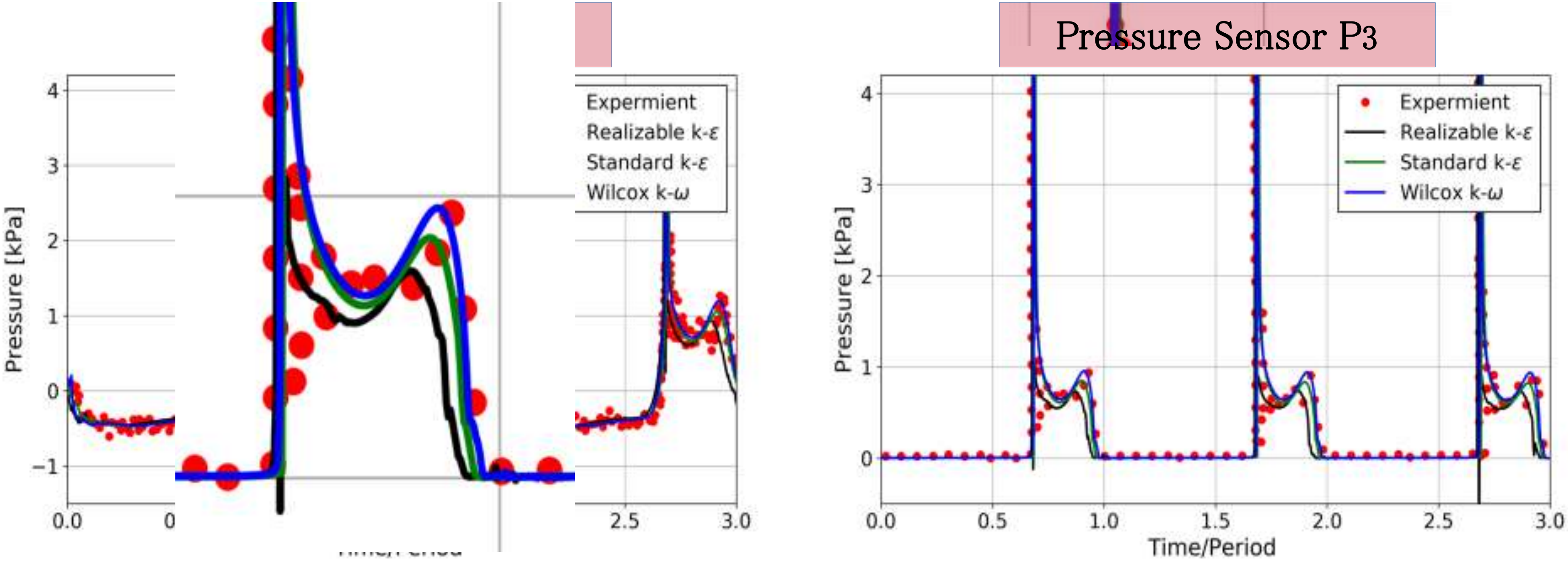
Validation Case IV: Tank Sloshing

-- Check Effect of Turbulence Model --

Case A

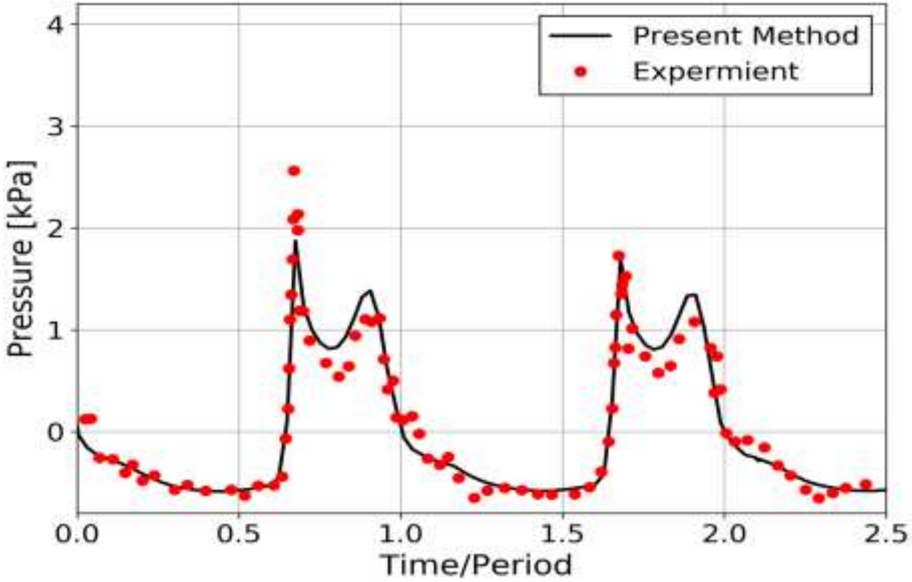


Validation Case IV: Tank Sloshing

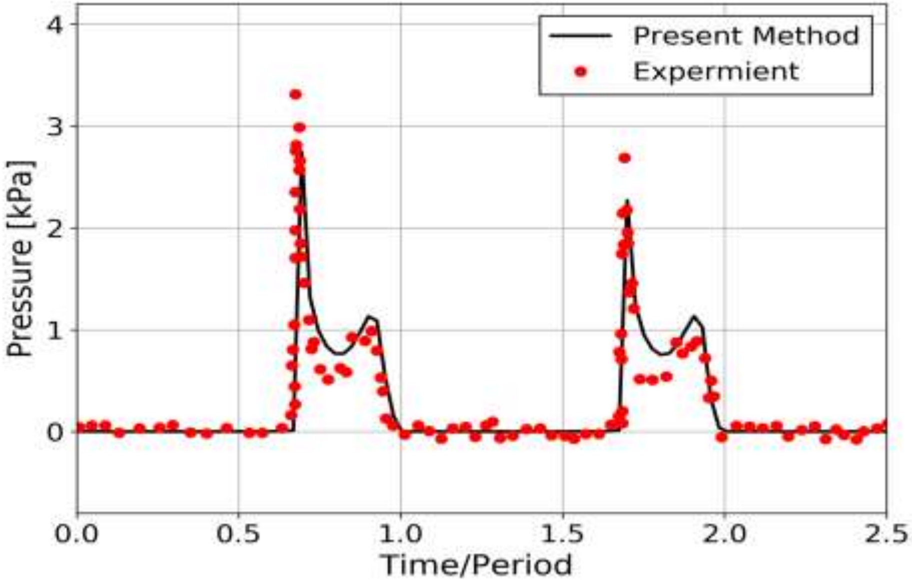
-- Check Effect of Turbulence Model --

Case B

Pressure Sensor P2



Pressure Sensor P3



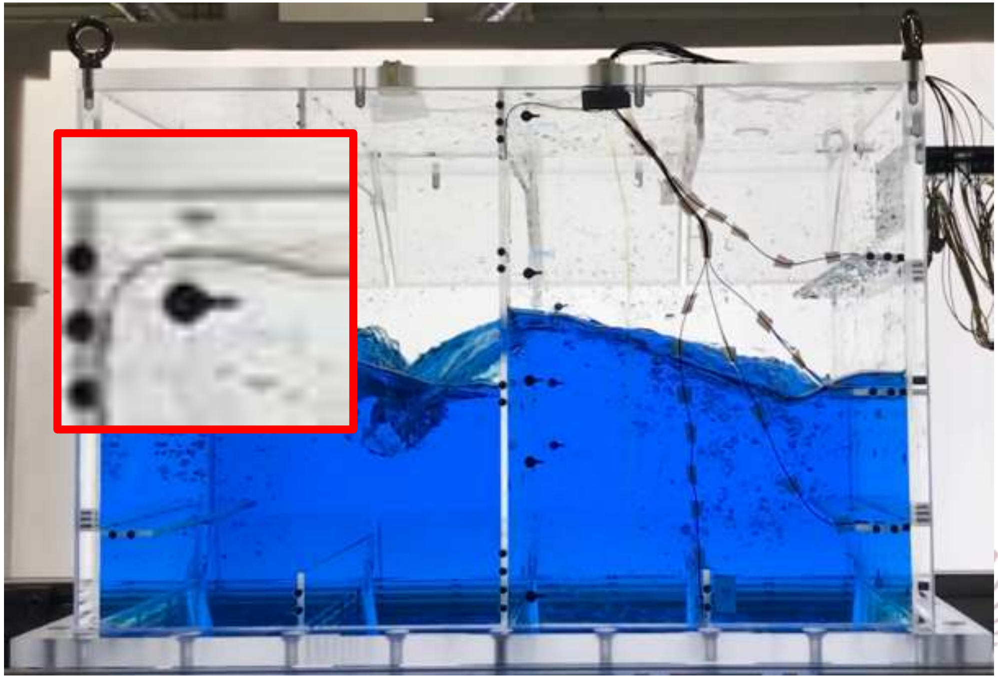
Validation Using Recent Experiment

Validation Using Recent Experiment

Sloshing Experiment Project
in collaboration with ClassNK

Project Highlights:

- Small-Scale Chamfered tank
- Large number of pressure sensors
- Two Pressure Sensor Types:
  - ✓ FBG Sensors
  - ✓ Strain-Gauge Sensors
- Five internal structure configurations



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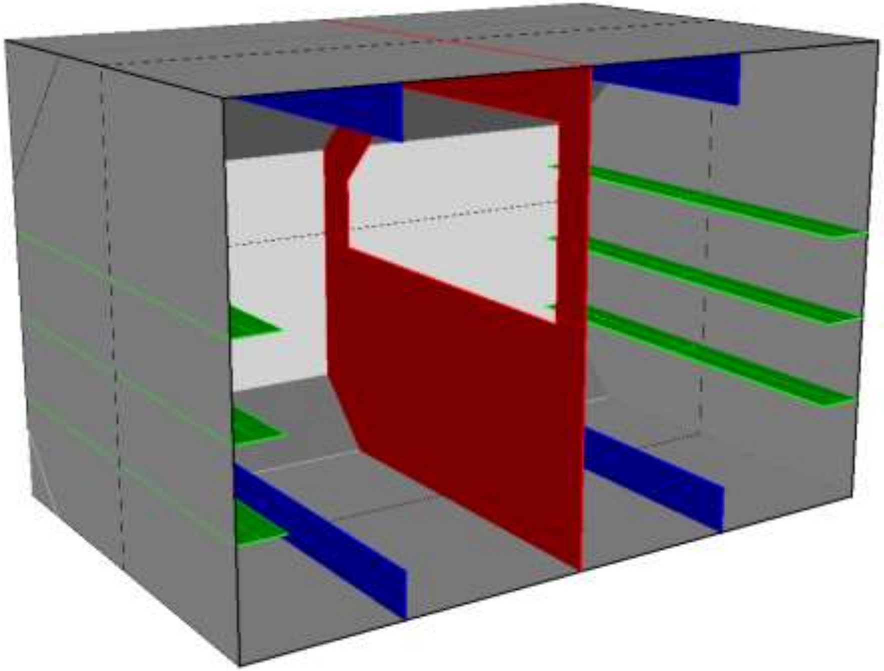

Validation Using Recent Experiment

- For every Configuration:
  - Motion Amplitude: 20mm, 40mm
  - Filling Level: 20%, 50%, 80%
  - Motion Frequency: 0.667Hz, 1Hz, 2Hz

- High Speed Camera recording at 250fps

  Resolution: 1920 x 1080 pixels

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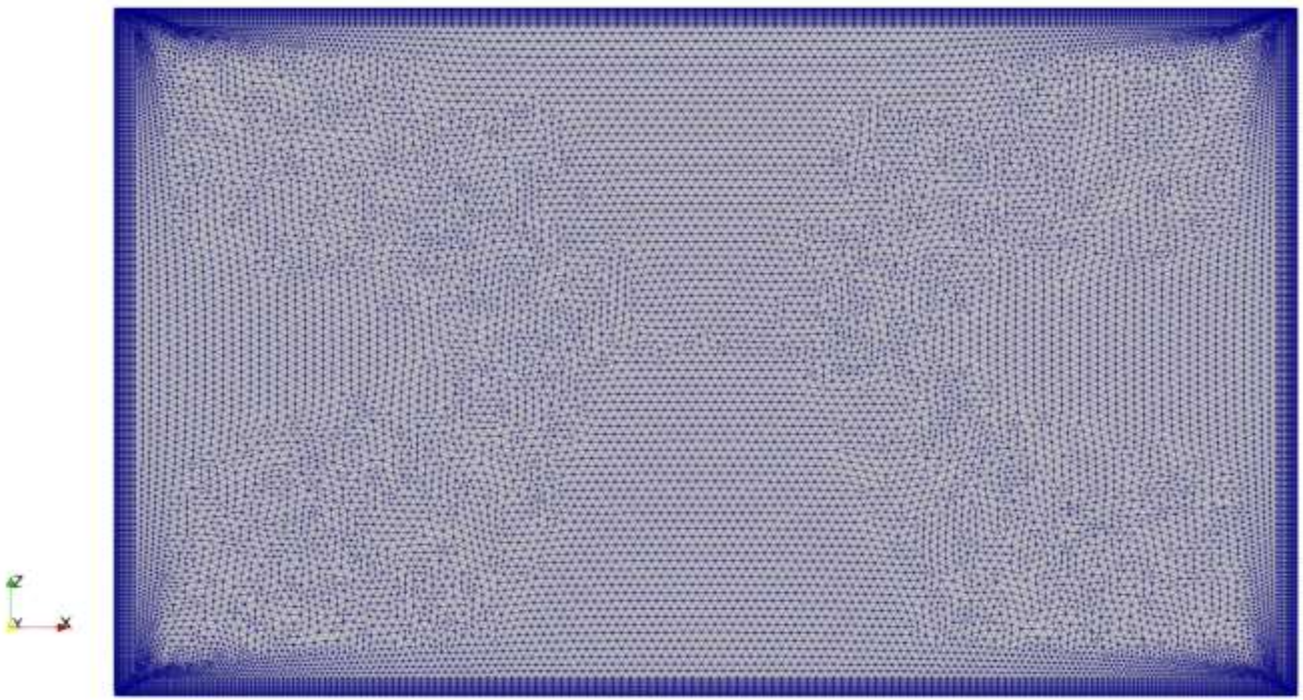
Validation Using Recent Experiment

Clean Case

Motion Amplitude:
40mm

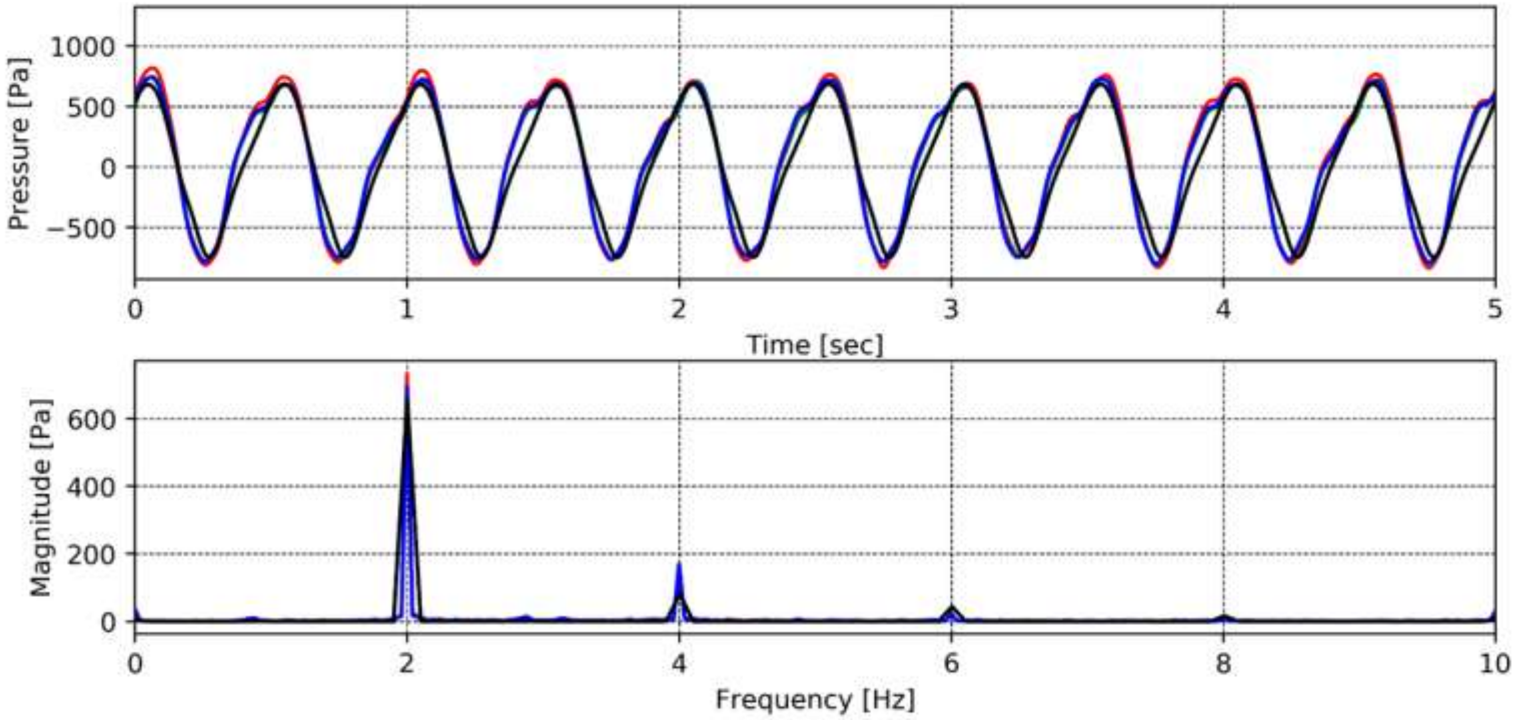
Filling Level:
50%

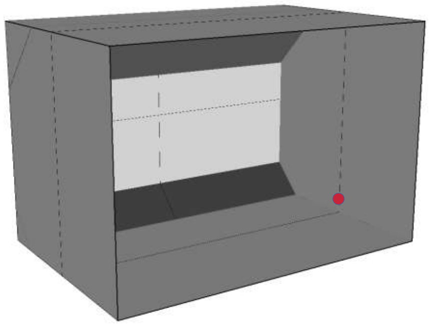
Motion Frequency:
2Hz



Validation Using Recent Experiment

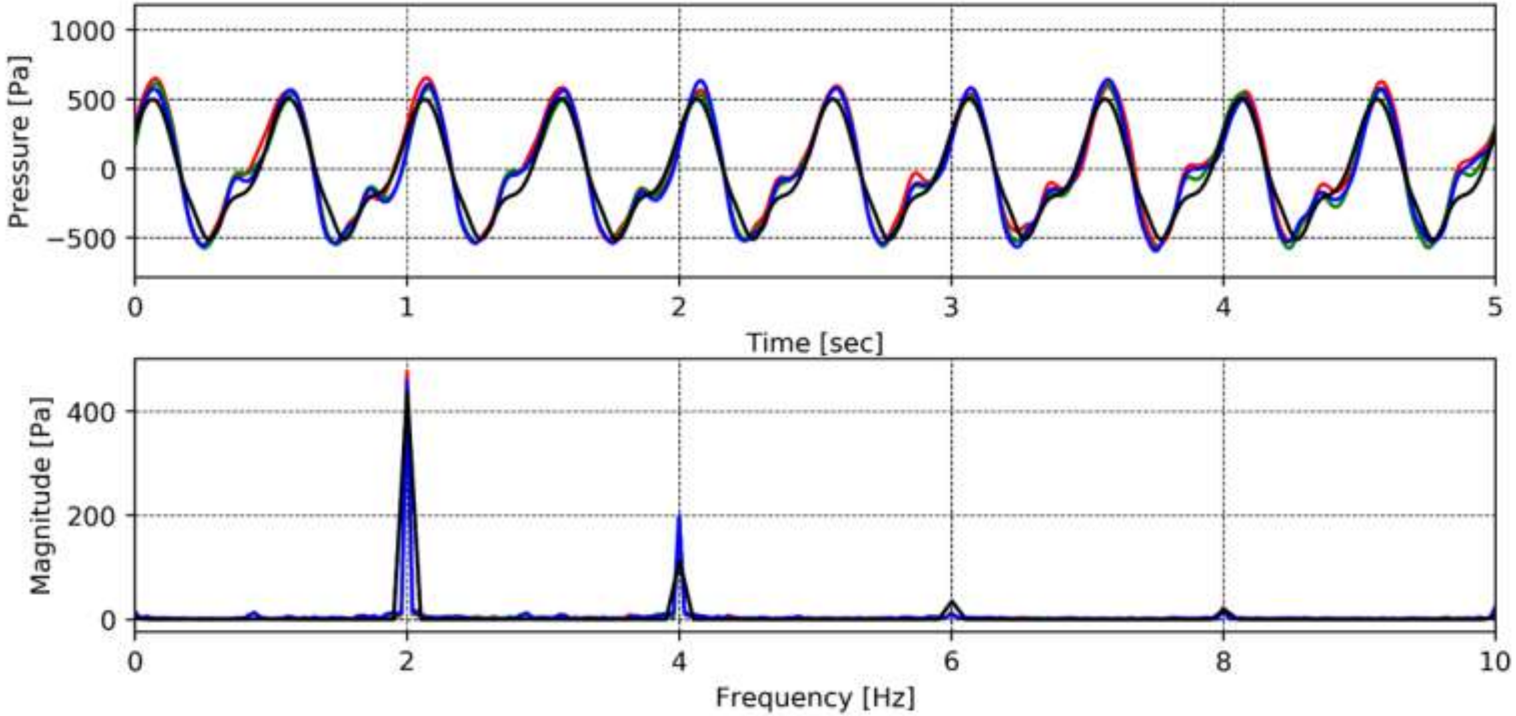
Clean Case

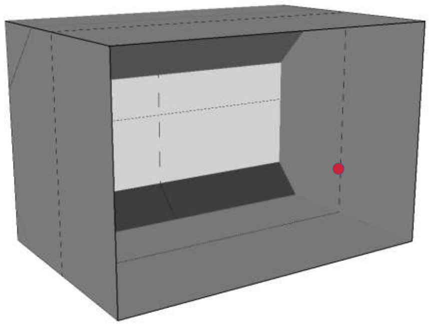




Validation Using Recent Experiment

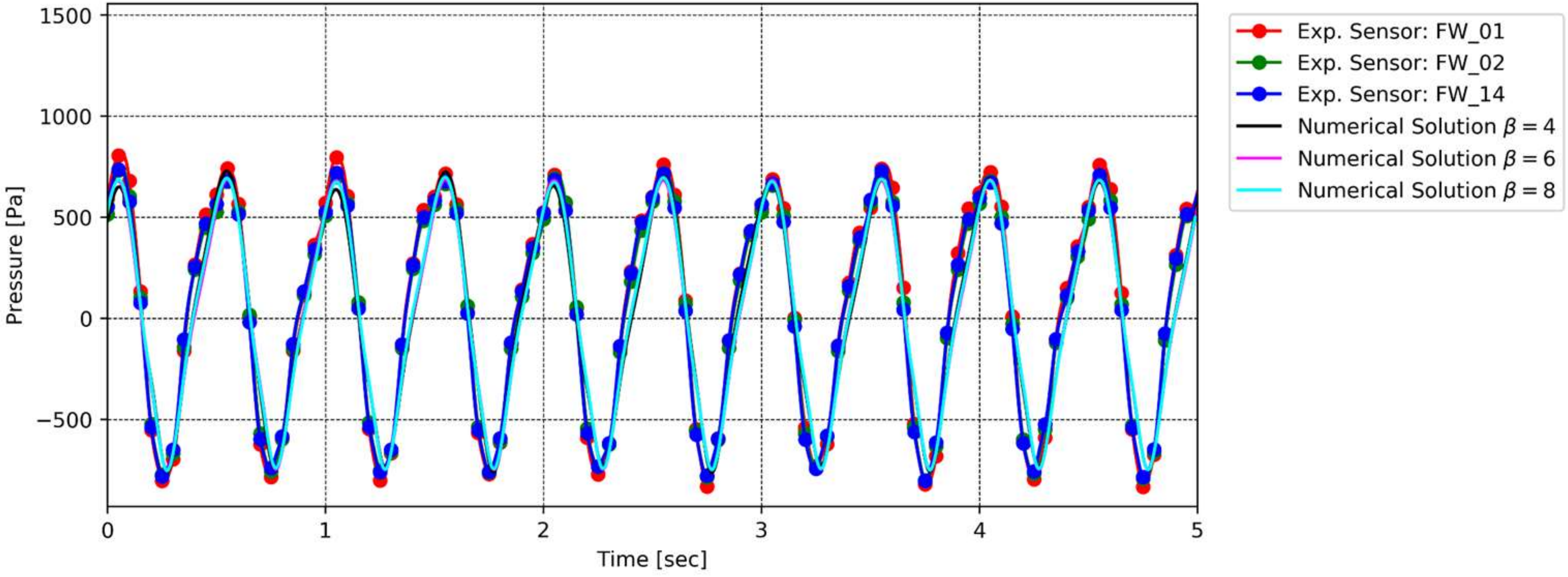
Clean Case





Validation Using Recent Experiment

Clean Case



Validation Using Recent Experiment

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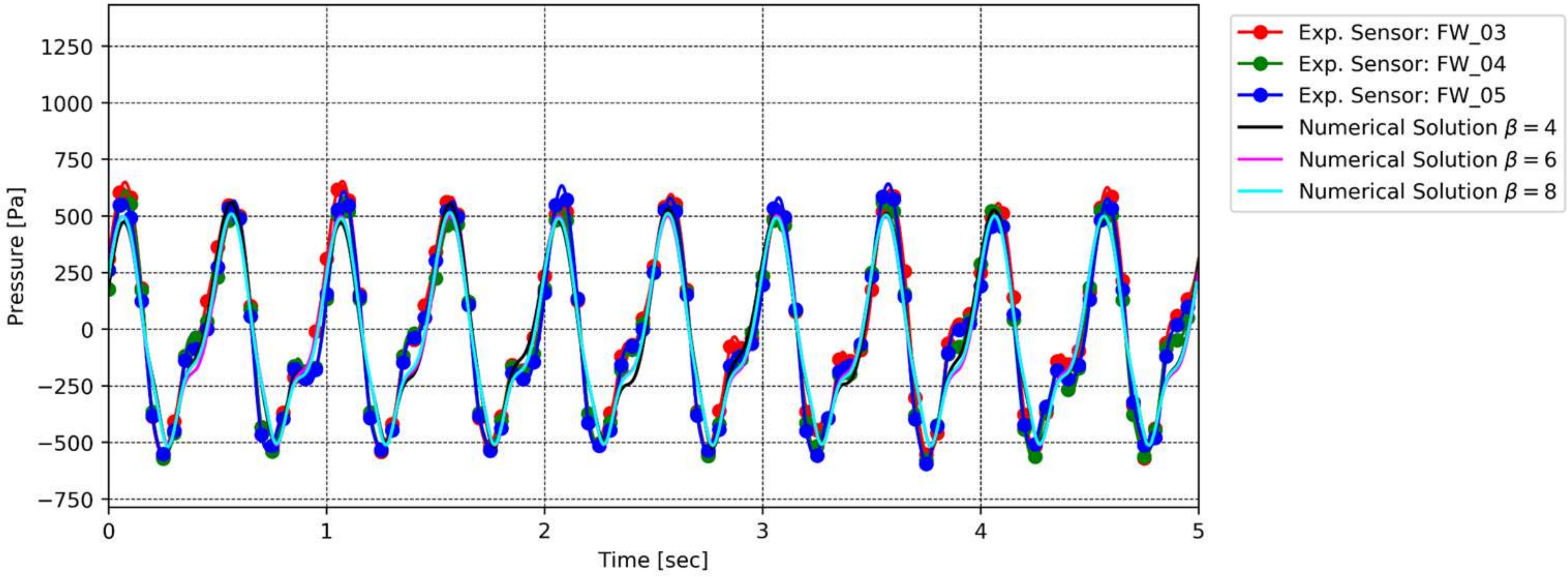


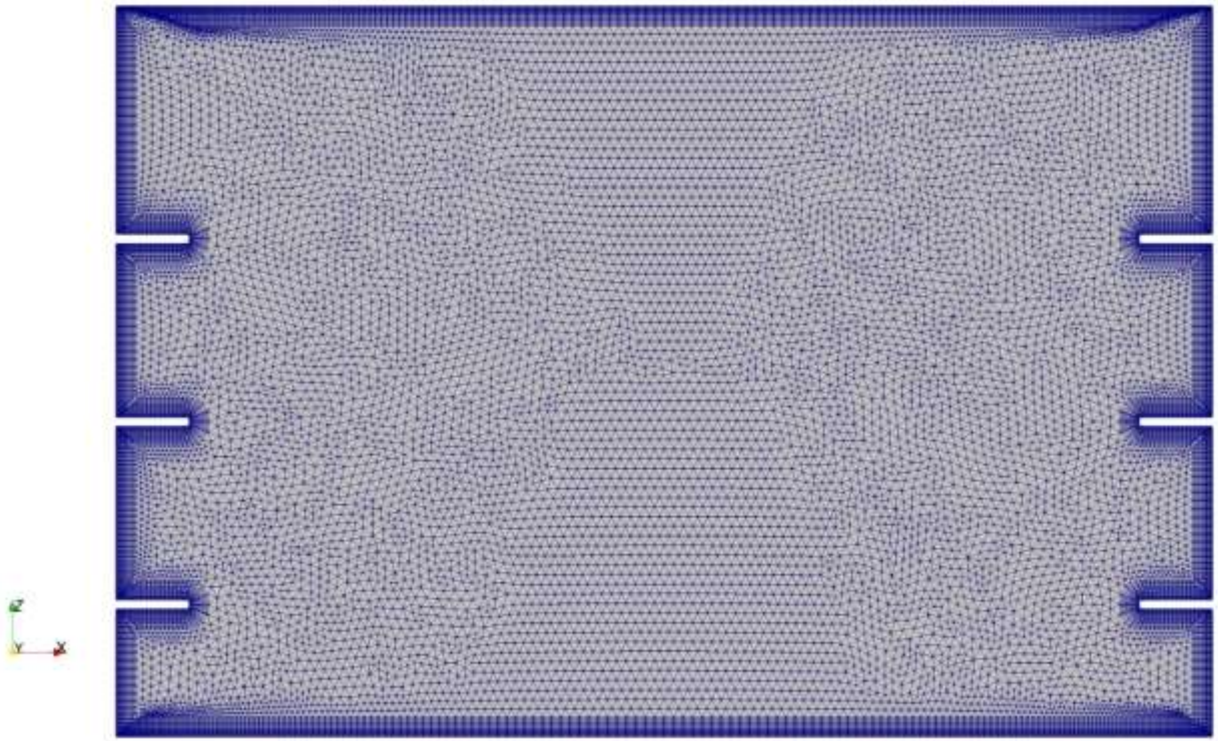
Validation Using Recent Experiment

Side Horizontal Baffle Case

Motion Amplitude:
40mm

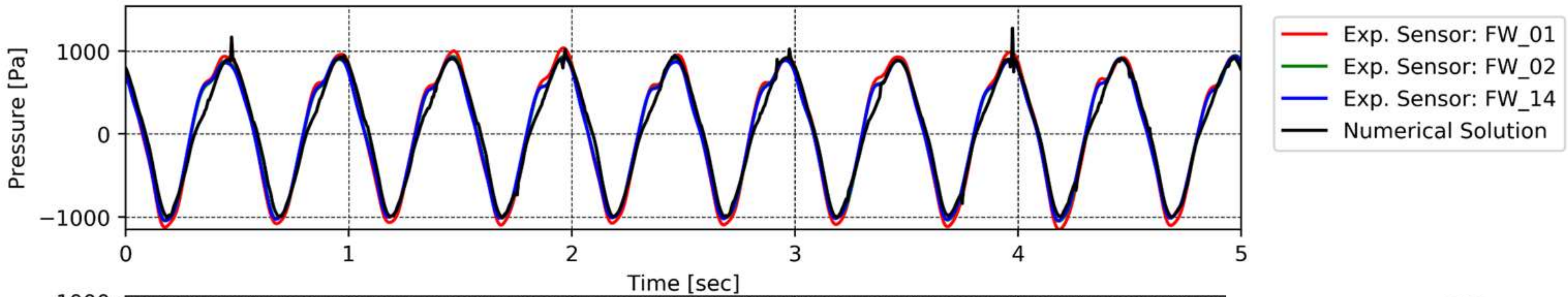
Filling Level:
50%

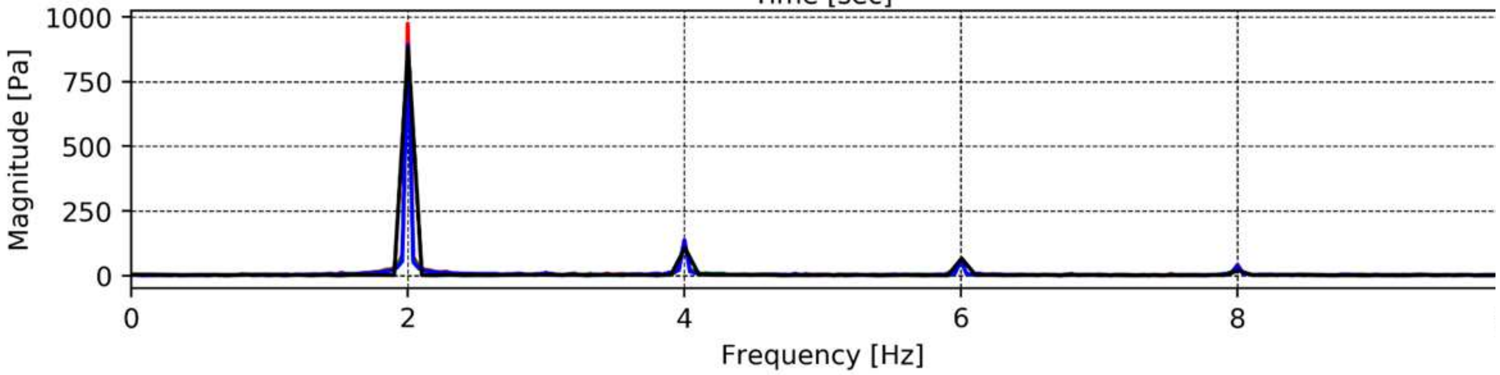
Motion Frequency:
2Hz

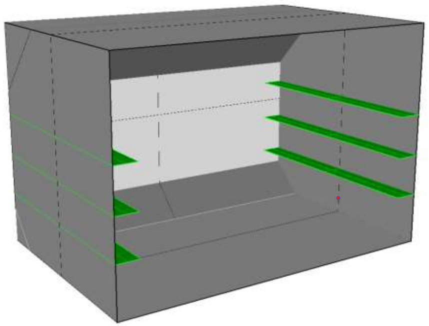


Validation Using Recent Experiment

Side Horizontal Baffle Case







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Validation Using Recent Experiment

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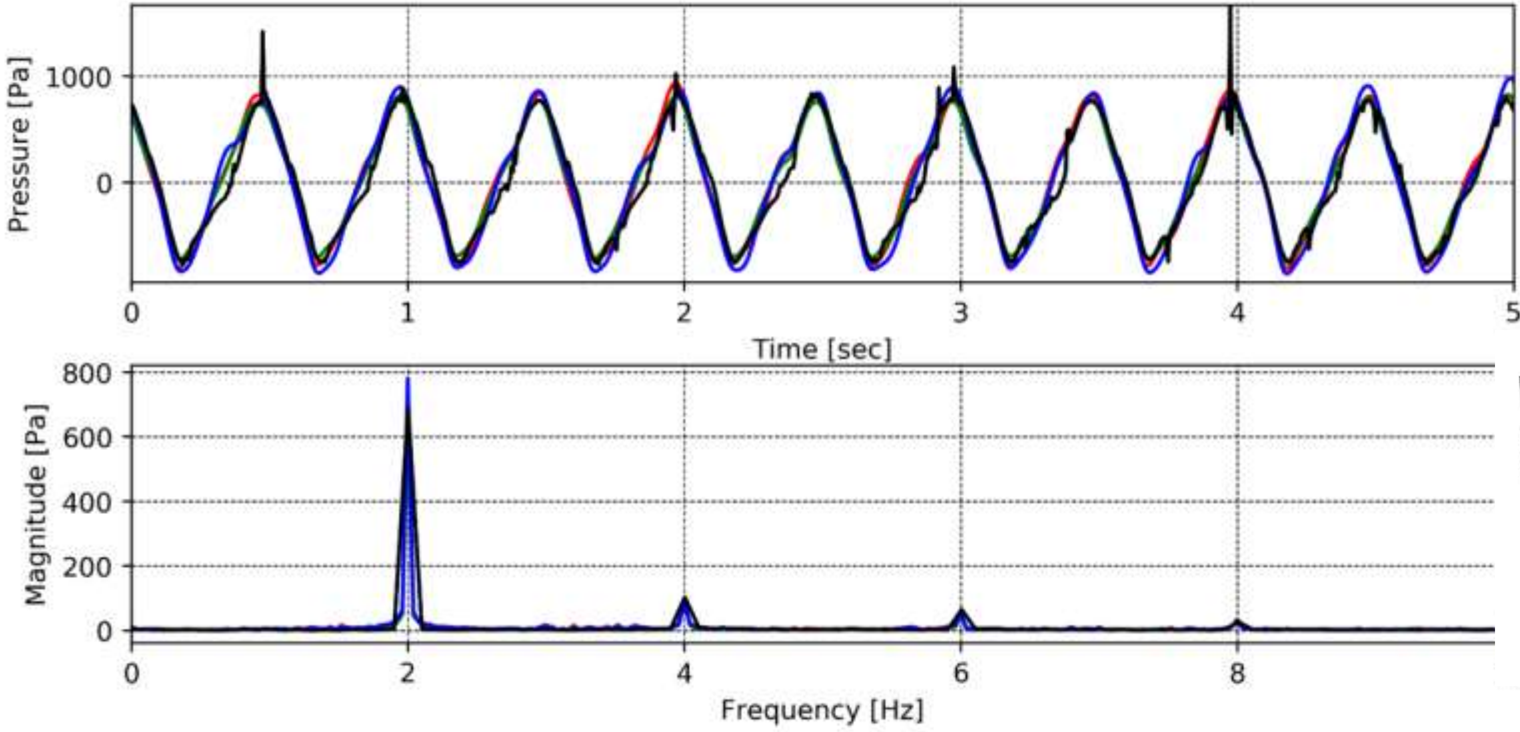

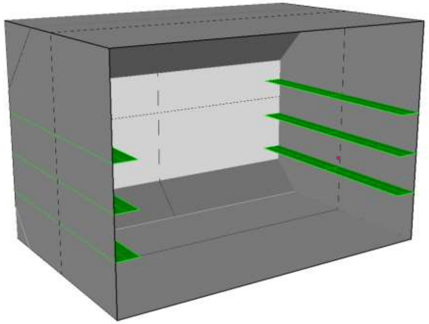

Validation Using Recent Experiment

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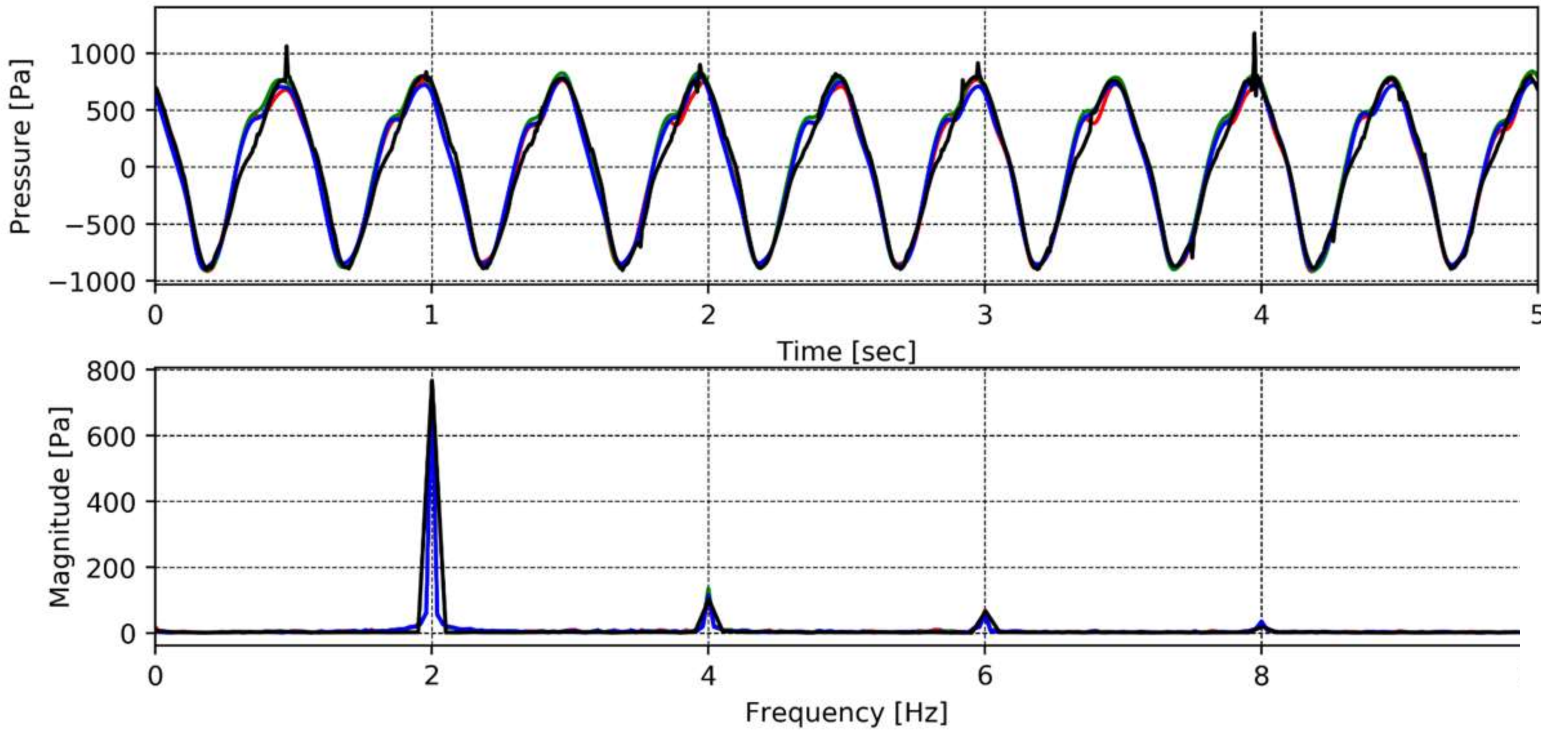

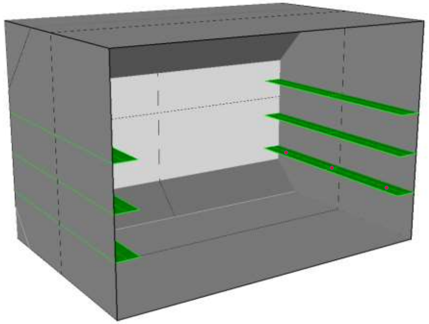

Validation Using Recent Experiment

Side Horizontal Baffle Case

Conclusion and Future Work

Conclusion and Future Work

- The developed numerical solver has demmonstrated its ability to accurately predict the pressure loading in sloshing problems with complex internal structures
- UMTHINC is a very good candidate for efficient and accurate interface capturing
- The method is able to maintain the interface thickness without additional smearing through long time integration

Conclusion and Future Work

- Turbulence modelling can have significant effect on the accuracy of numerical solution of the sloshing problem
- K-omega model has showed that it can be a slightly better choice for turbulence modeling than other turbulence model candidates
- More work is required to highlight the effect of baffle thickness on pressure loading

Conclusion and Future Work

- Further testing of cases that has significant three-dimentional behavior is required and LES can be added to turbulence models candidates
- The computational efficiency is a major concern for simulating sloshing problems so emphasis on the importance of parallel performance

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