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Time domain simulation of coupled sloshing-seakeeping problems by coupling PFEM-2 and SeaFEM

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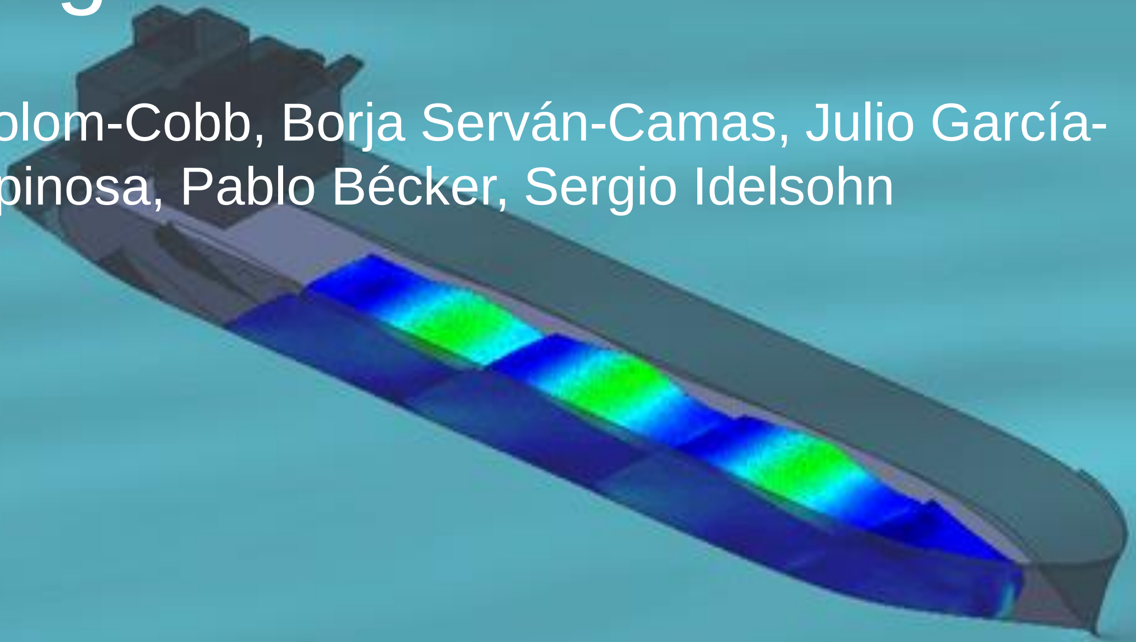

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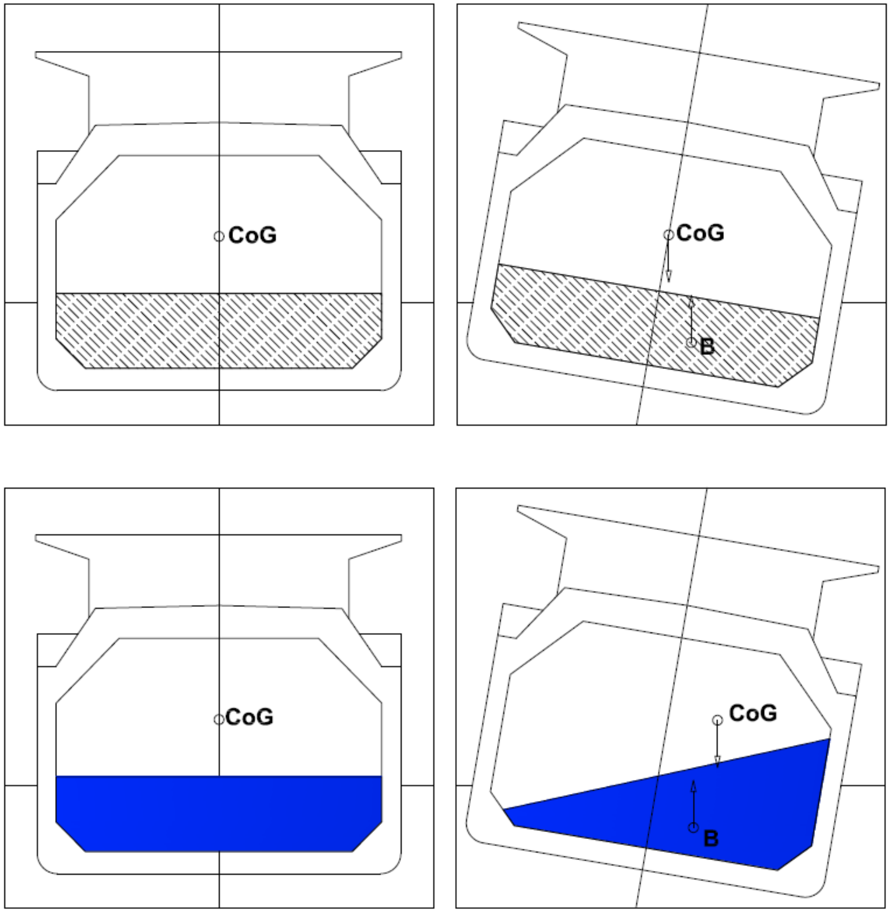
OUTLINE

- ✓ Introduction to the Internal flow in tanks problem
- ✓ Hydrodynamics solvers:
  - ✓ Seakeeping Solver: SeaFEM
  - ✓ Internal Flow Solver: PFEM – 2
- ✓ Coupling strategy
- ✓ Validations
  - ✓ Sloshing effect in barge
  - ✓ Anti Roll Tank

INTERNAL FLOWS IN TANKS

- ✓ Flows in tanks can be found in:
  - ✓ LNG carriers
  - ✓ Offshore extraction structures
- ✓ Free-surface effect is already a known problem
- ✓ Problematic when the movement of the fluid becomes harsh: Compromised stability and sloshing



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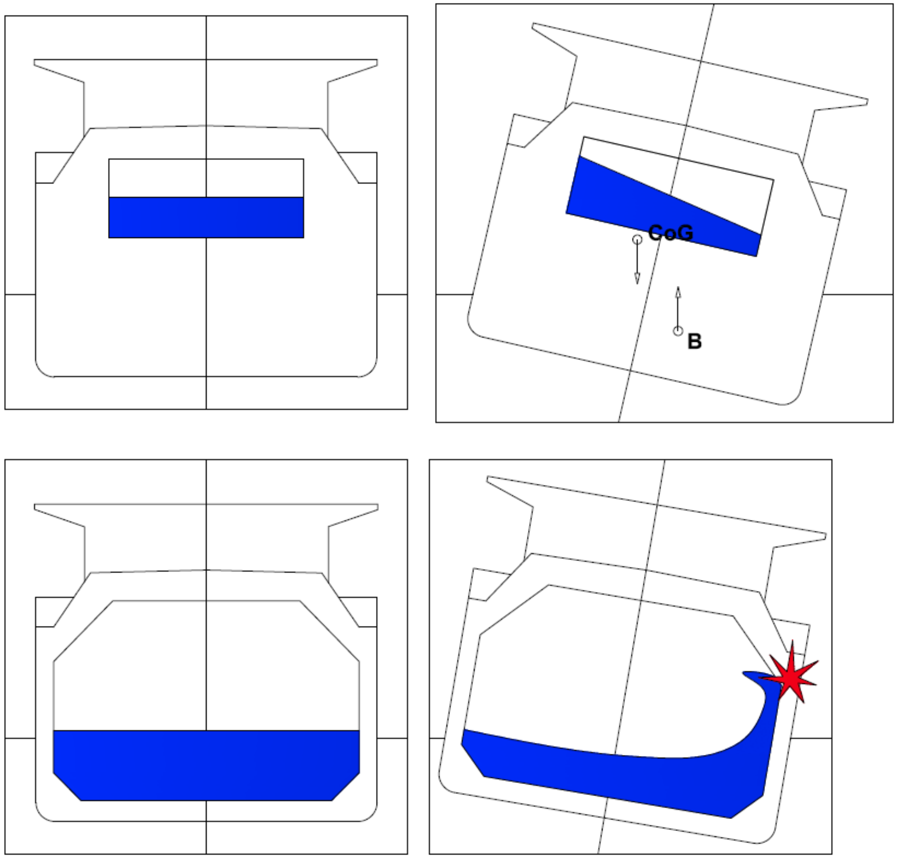
INTERNAL FLOW IN TANKS

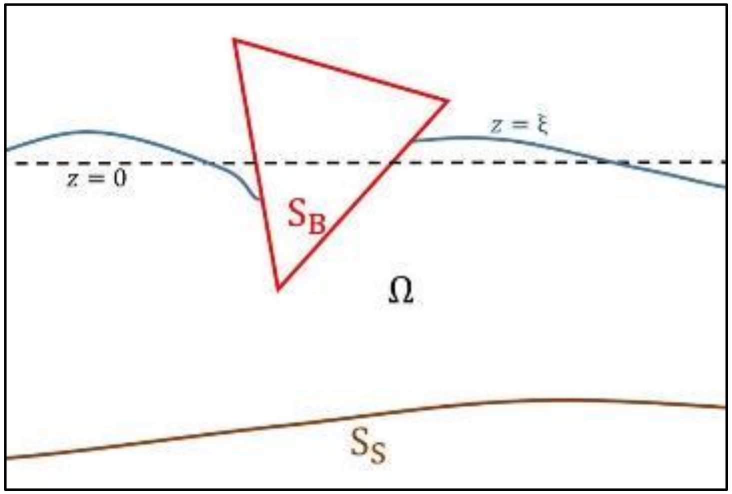
- Our work focuses on two different problems.
- First, if it negatively affects the seakeeping behavior of the floating object
- Second if it improves it: Anti Roll Tanks (ART)
  - ARTs used to improve seakeeping behavior at certain frequencies
- We have coupled Kratos – PFEM – 2 to SeaFEM using an effective coupling algorithm.



SEAKEEPING SOLVER

- ✓ Governing equations based on incompressible and irrotational flow

$\Delta\varphi = 0$	$in\ \Omega$	incompressible and irrotational flow
$\frac{\partial \xi}{\partial t} + \frac{\partial \varphi}{\partial \mathrm{x}}\frac{\partial \xi}{\partial x} + \frac{\partial \varphi}{\partial \mathrm{y}}\frac{\partial \xi}{\partial y} - \frac{\partial \varphi}{\partial \mathrm{z}} = 0$	$on\ z = \xi$	free surface kinematic boundary condition
$\frac{\partial \varphi}{\partial \mathrm{t}} + \frac{1}{2}\nabla\varphi \cdot \nabla\varphi + \frac{P_{fs}}{\rho} + g\xi = 0$	$on\ z = \xi$	free surface dynamic boundary condition
$\boldsymbol{v}_p \cdot \boldsymbol{n}_p + \boldsymbol{v}_\varphi \cdot \boldsymbol{n}_p = 0$	$on\ \mathrm{P} \in \mathrm{S}_B$	body boundary condition
$\boldsymbol{v}_\varphi \cdot \boldsymbol{n}_p = 0$	$on\ \mathrm{P} \in \mathrm{S}_S$	seabed boundary condition
$P_p = -\rho\frac{\partial \varphi}{\partial t} - \frac{1}{2}\rho\nabla\varphi \cdot \nabla\varphi - \rho g z_p$		pressure at a point P.



SEAKEEPING SOLVER

- Use a Taylor expansion and a perturbed solution to simplify free-surface boundary conditions

$\Delta\varphi^1 = 0$	$in\ \Omega$	Incompressible and irrotational flow
$\frac{\partial \xi^1}{\partial t} - \frac{\partial \varphi^1}{\partial z} = 0$	$on\ z = 0$	Free Surface kinematic boundary condition
$\frac{\partial \varphi^1}{\partial t} + \frac{P_{fs}}{\rho} + g\xi^1 = 0$	$on\ z = 0$	Free Surface dynamic boundary condition
$\boldsymbol{v}_p^1 \cdot \boldsymbol{n}_p^0 + \boldsymbol{v}_\varphi^1 \cdot \boldsymbol{n}_p^0 = 0$	$on\ P \in S_B^0$	Body boundary condition
$\boldsymbol{v}_\varphi^1 \cdot \boldsymbol{n}_\mathrm{p} = 0$	$on\ P \in S_S$	Seabed boundary condition

- Limitations:
  - Limited slope and non-breaking free-surface
  - Small body movements

SEAKEEPING SOLVER

- ✓ Solution is split into two components:

$$\varphi^1 = \psi^1 + \phi^1$$

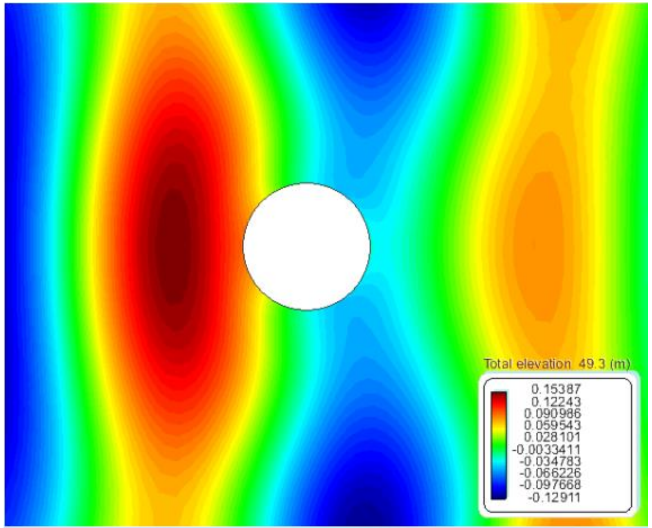
$$\xi^1 = \zeta^1 + \eta^1$$

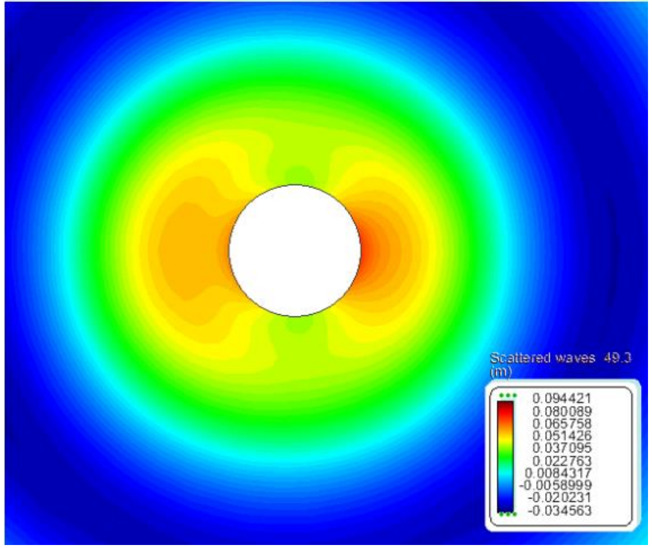
ψ^1: Incident waves velocity potential.
ζ^1: Incident waves free surface elevation.
ϕ^1: Diffracted-radiated waves velocity potential.
η^1: Diffracted-radiated waves free surface elevation

  - ✓ Incident waves (modelled analytically)

$\Delta\psi^1 = 0 \qquad in\ \Omega$ $\frac{\partial\zeta^1}{\partial t} - \frac{\partial\psi^1}{\partial z} = 0 \quad on\ z = 0$ $\frac{\partial\psi^1}{\partial t} + g\zeta^1 = 0 \quad on\ z = 0$ $\boldsymbol{v}_\psi^1 \cdot \boldsymbol{n}_\mathrm{p} = 0 \qquad on\ \mathrm{z} = -\mathrm{H}$	Analytical solution: $\psi^1 = \sum_i \frac{A_i g}{\omega_i} \frac{\cosh\left(\lvert\boldsymbol{k}_i\rvert(H+z)\right)}{\cosh(\lvert\boldsymbol{k}_i\rvert H)} \sin(\boldsymbol{k}_i\boldsymbol{x} - \omega_i t + \delta_i)$ $\zeta^1 = \sum_i A_i \cos(\boldsymbol{k}_i\boldsymbol{x} - \omega_i t + \delta_i)$

  - ✓ Diffracted-radiated waves

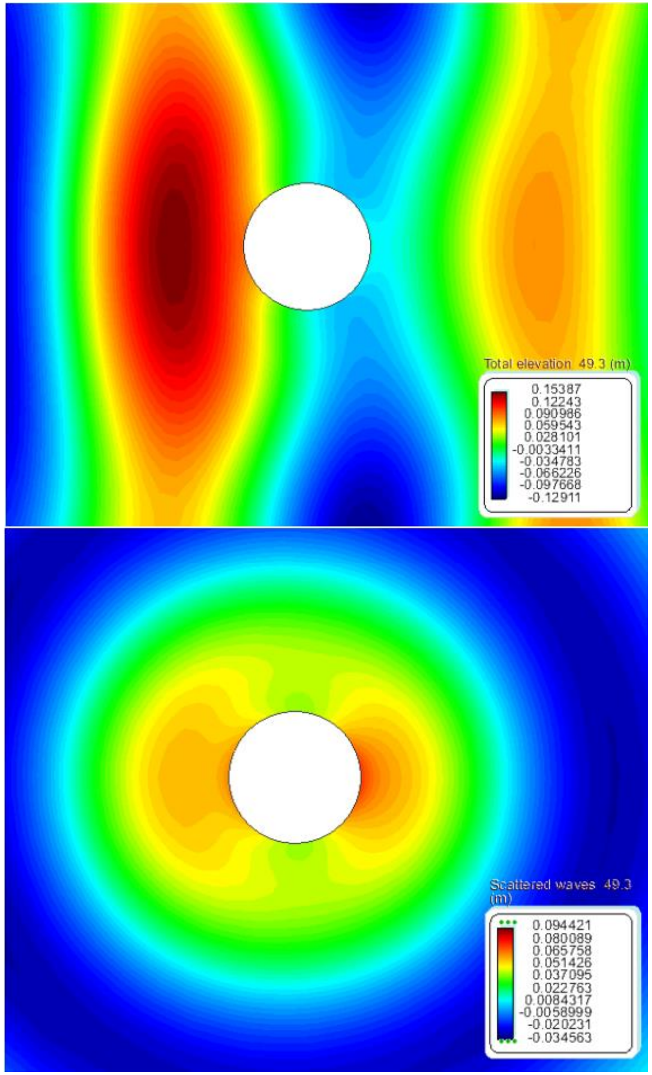




SEAKEEPING SOLVER

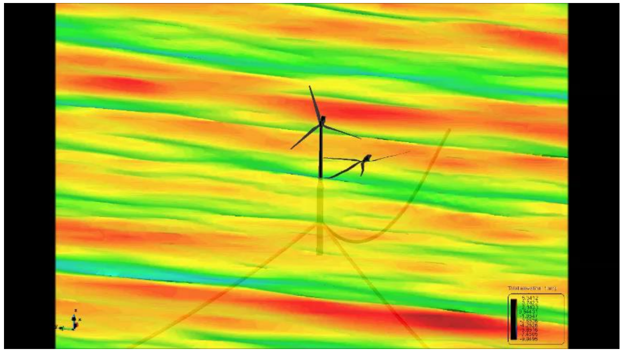
- ✓ Solution is split into two components:
  - ✓ Incident waves (modelled analytically)
  - ✓ Diffracted-radiated waves

$$
\boxed{
\begin{array}{ll}
\Delta\phi^1 = 0 & in\ \Omega \\[2ex]
\dfrac{\partial\eta^1}{\partial t} - \dfrac{\partial\phi^1}{\partial z} = 0 & in\ z = 0 \\[3ex]
\dfrac{\partial\phi^1}{\partial t} + \dfrac{P_{fs}}{\rho} + g\eta^1 = 0 & in\ z = 0 \\[3ex]
\boldsymbol{v}_\phi^1 \cdot \boldsymbol{n}_p^0 = -\left(\boldsymbol{v}_p^1 + \boldsymbol{v}_\psi^1\right) \cdot \boldsymbol{n}_p^0 & on\ P \in S_B^0 \\[1ex]
\boldsymbol{v}_\phi^1 \cdot \boldsymbol{n}_p = -\boldsymbol{v}_\psi^1 \cdot \boldsymbol{n}_p & on\ P \in S_S
\end{array}
}
$$



SEAKEEPING SOLVER

- Solver is called SeaFEM
- **Numerical model**
  - FEM used for the spatial integration
  - Time integration uses a fourth order compact Padé scheme
  - Wave absorption and radiation condition for the diffracted-radiated waves
- **Capabilities**
  - 3D time-domain 1st and 2nd order wave diffraction-radiation solver
  - Multi-body dynamics solver including body-links
  - Non-linear hydrodynamics, drift and current effects
  - Mooring solver
  - Coupled with FAST for the analysis of floating wind turbines
  - Other (non-linear hydrostatics, non-linear user defined forces, slender elements, fluid-structure interaction, …)
  - Coupling with external solvers: Internal flow solvers, power take off systems …
- See **http://www.compassis.com/seafem**



INTERNAL FLOW SOLVER

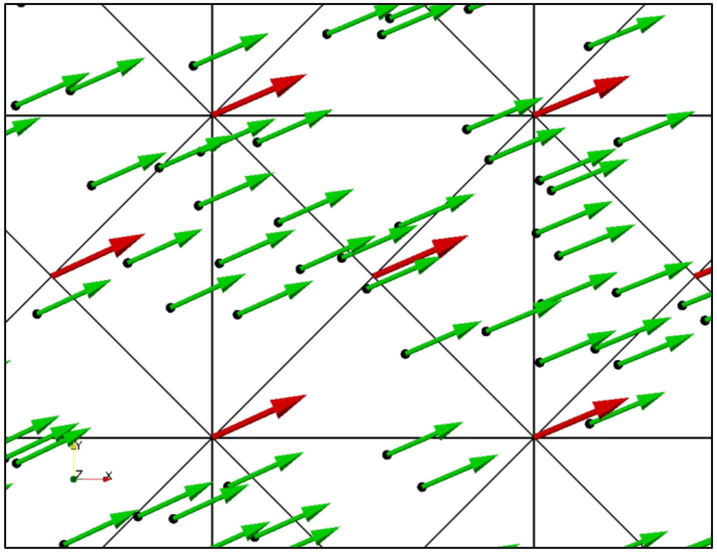
- ✓ Governing equations are the incompressible Navier-Stokes equations
- ✓ Solved using a semi-lagrangian method
- ✓ Convective part of the equation is solved using particles

Lagrangian governing equations: $d_t U_\lambda = A_\lambda \qquad d_t X_\lambda = U_\lambda$

Integration along trajectory: $$\frac{U_\lambda\left(X_\lambda^{n+1}\right) - U_\lambda(X_\lambda^n)}{\Delta t} = A_\lambda\left(X_\lambda^{n+1}\right)$$

Lagrangian splitting: $$\begin{cases} \dfrac{U_\lambda^*\left(X_\lambda^{n+1}\right) - U_\lambda(X_\lambda^n)}{\Delta t} = 0 \rightarrow U_\lambda^*\left(X_\lambda^{n+1}\right) = U_\lambda(X_\lambda^n) \\ \dfrac{U_\lambda\left(X_\lambda^{n+1}\right) - U_\lambda^*\left(X_\lambda^{n+1}\right)}{\Delta t} = A_\lambda\left(X_\lambda^{n+1}\right) \end{cases}$$

INTERNAL FLOW SOLVER



- Velocities are projected onto the FE mesh
- Mesh computes the rest of the NS equations using a monolithic approach

$$\frac{u^{n+1}-\mathrm{u}^{*}}{\Delta t} = a^{n+1} = -\frac{1}{\rho}\nabla P^{n+1} + \nu\Delta u^{n+1}$$

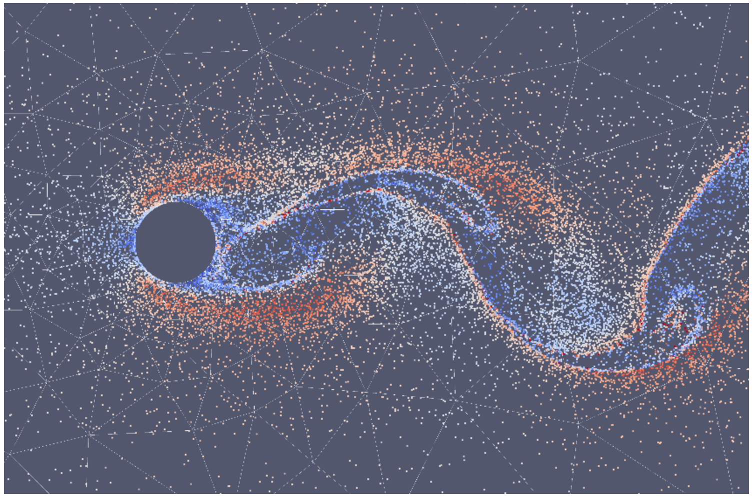
- Interpolate acceleration to the particle location using FE interpolants

$$A_{\lambda}\left(X_{\lambda}^{n+1}\right) = a_{i}^{n+1} N_{i}\left(X_{\lambda}^{n+1}\right) = \frac{u^{n+1}-\mathrm{u}^{*}}{\Delta t} N_{i}\left(X_{\lambda}^{n+1}\right)$$

- Update particle velocities at t^{n+1}: $U_{\lambda}\left(X_{\lambda}^{n+1}\right) = U_{\lambda}\left(X_{\lambda}^{n}\right) + \Delta t A_{\lambda}\left(X_{\lambda}^{n+1}\right)$

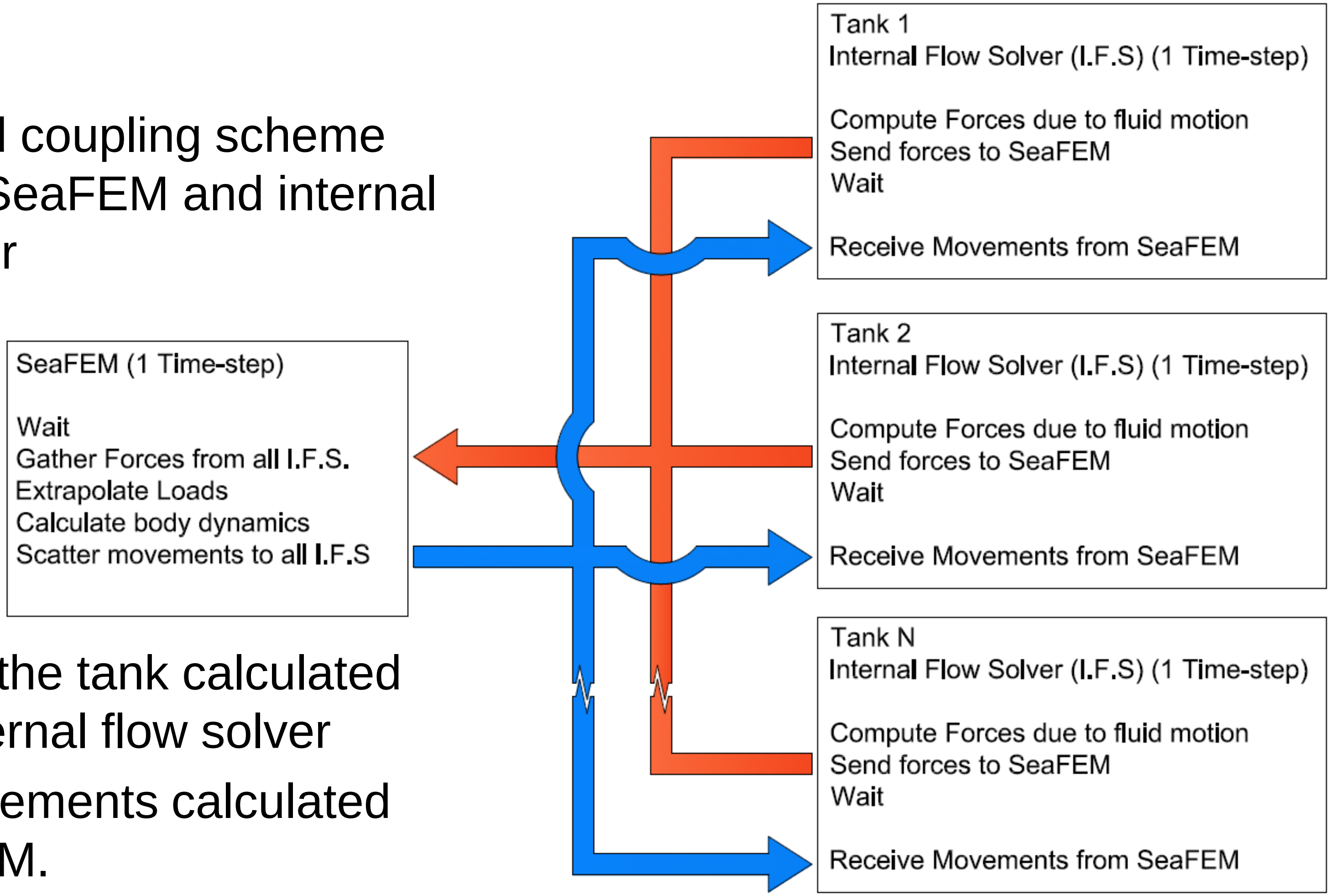
INTERNAL FLOW SOLVER

- ✓ Solver is called: PFEM – 2
- ✓ **Capabilities**
  - ✓ 3D Navier-Stokes solver
  - ✓ Integrated into the Kratos environment
  - ✓ Incompressible approach used
  - ✓ Open Source
  - ✓ Python extensible
- ✓ See **http://www.cimne.com/kratos/**



COUPLING SCHEME

- ✓ Main idea:
  - ✓ Staggered coupling scheme between SeaFEM and internal tank solver
  - ✓ Forces in the tank calculated by the internal flow solver
  - ✓ Body movements calculated by SeaFEM.



SeaFEM (1 Time-step)

Wait
Gather Forces from all I.F.S.
Extrapolate Loads
Calculate body dynamics
Scatter movements to all I.F.S

Tank 1
Internal Flow Solver (I.F.S) (1 Time-step)

Compute Forces due to fluid motion
Send forces to SeaFEM
Wait

Receive Movements from SeaFEM

Tank 2
Internal Flow Solver (I.F.S) (1 Time-step)

Compute Forces due to fluid motion
Send forces to SeaFEM
Wait

Receive Movements from SeaFEM

Tank N
Internal Flow Solver (I.F.S) (1 Time-step)

Compute Forces due to fluid motion
Send forces to SeaFEM
Wait

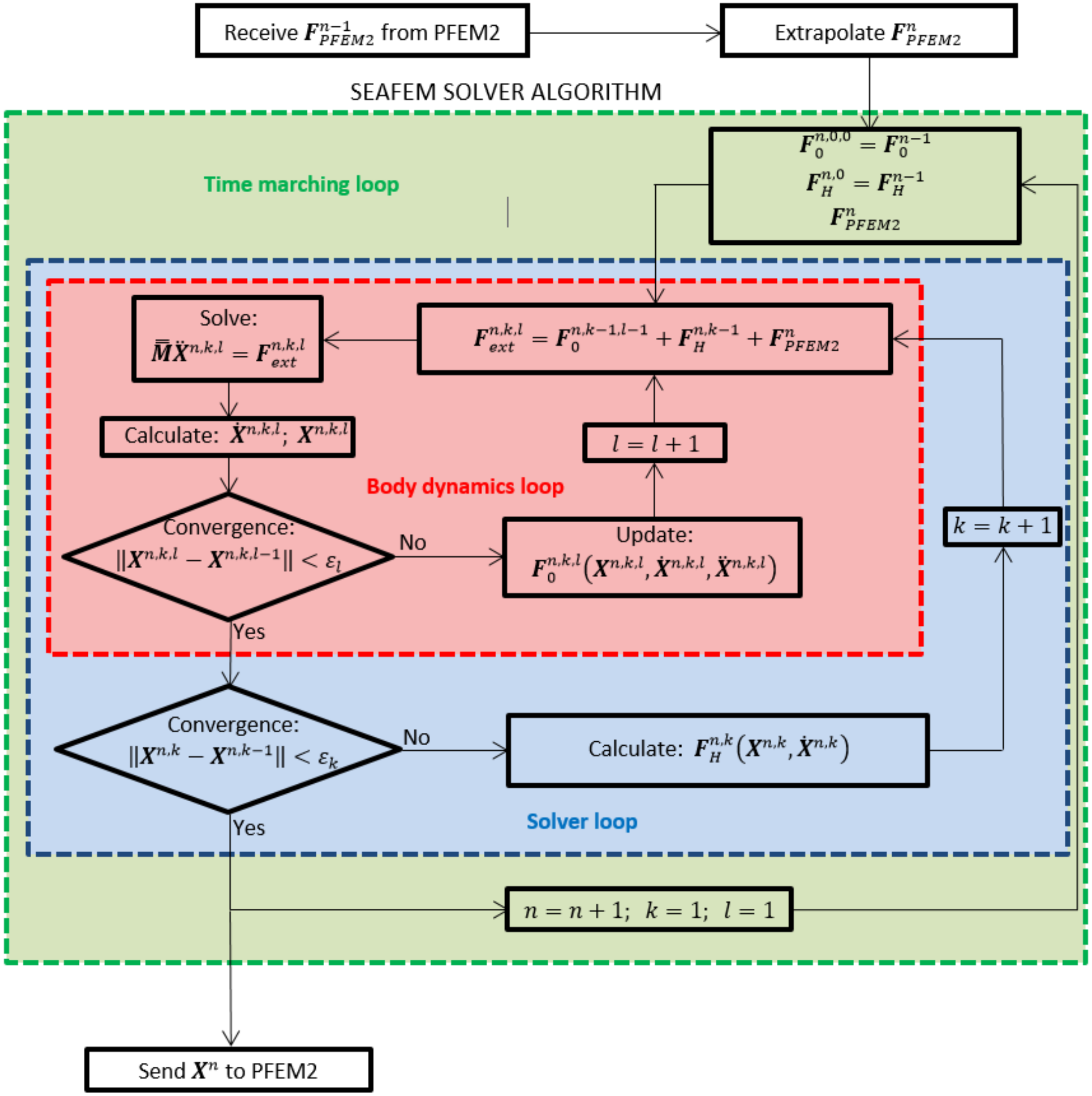
Receive Movements from SeaFEM

COUPLING SCHEME

- ✓ Use TCP/IP
  - ✓ Solve Multiple tanks
  - ✓ Use different machines for internal flow solver.
  - ✓ No overhead as forces and movements are vectors of six components
- ✓ Internal Flow Solver has lower time-steps (linear interpolation of movements
- ✓ Seakeeping solver extrapolates loads from the internal flow solver using a five point Lagrange polynomial

BODY DYNAMICS

- ✓ SeaFEM solves the body dynamics
- ✓ Implicit solver using two nested loops
  - ✓ Laplace equation solver
  - ✓ Body dynamics solver
- ✓ Includes Internal flow solver forces are inserted into the body dynamics loop



Receive $\boldsymbol{F}^{n-1}_{PFEM2}$ from PFEM2

Extrapolate $\boldsymbol{F}^{n}_{PFEM2}$

SEAFEM SOLVER ALGORITHM

Time marching loop

$\boldsymbol{F}^{n,0,0}_{0} = \boldsymbol{F}^{n-1}_{0}$

$\boldsymbol{F}^{n,0}_{H} = \boldsymbol{F}^{n-1}_{H}$

$\boldsymbol{F}^{n}_{PFEM2}$

$\boldsymbol{F}^{n,k,l}_{ext} = \boldsymbol{F}^{n,k-1,l-1}_{0} + \boldsymbol{F}^{n,k-1}_{H} + \boldsymbol{F}^{n}_{PFEM2}$

Solve: $\bar{\bar{\boldsymbol{M}}}\ddot{\boldsymbol{X}}^{n,k,l} = \boldsymbol{F}^{n,k,l}_{ext}$

Calculate: $\dot{\boldsymbol{X}}^{n,k,l};\ \boldsymbol{X}^{n,k,l}$

$l = l + 1$

Body dynamics loop

Convergence: $\|\boldsymbol{X}^{n,k,l} - \boldsymbol{X}^{n,k,l-1}\| < \varepsilon_l$

No

Update: $\boldsymbol{F}^{n,k,l}_{0}(\boldsymbol{X}^{n,k,l}, \dot{\boldsymbol{X}}^{n,k,l}, \ddot{\boldsymbol{X}}^{n,k,l})$

Yes

$k = k + 1$

Convergence: $\|\boldsymbol{X}^{n,k} - \boldsymbol{X}^{n,k-1}\| < \varepsilon_k$

No

Calculate: $\boldsymbol{F}^{n,k}_{H}(\boldsymbol{X}^{n,k}, \dot{\boldsymbol{X}}^{n,k})$

Solver loop

Yes

$n = n + 1;\ k = 1;\ l = 1$

Send $\boldsymbol{X}^{n}$ to PFEM2

VALIDATIONS OF THE COUPLED PROBLEM

PREVIOUS WORK

- ✓ Coupling done using an SPH algorithm: AquaGPUSPH
- ✓ Results where given using around 100K to 200K particles per tank

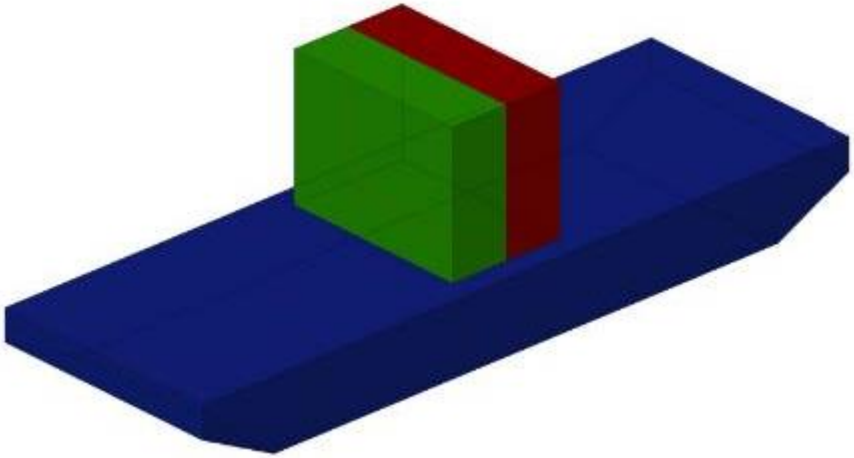
- ✓ See paper at:

  B. Servan Camas, J. Cercós-Pita, J. Colom Cobb, J. García- Espinosa and A. Souto-Iglesias, "Time domain simulation of coupled sloshing–seakeeping problems by SPH–FEM coupling", Ocean Engineering, 123, (2016), 383–396

https://www.scipedia.com/public/Servan_Camas_et_al__2016a

BARGE WITH WATER IN TANKS

- ✓ The first validation case is based on the experiments presented in Molin et al., 2002.
- ✓ They consist on the study of the seakeeping response of a barge-like ship.
- ✓ There are two tanks next to each other at the mid-ship whose transverse dimension is close to the model breadth.



- ✓ Molin, B., Remy, F., Rigaud, S., de Jouette Ch., 2002. “LNG-FPSO’s: frequency domain coupled analysis of support and liquid cargo motions”. In: Proceedings of INAM Conference, Rethymnon, Greece

VALIDATION I: CASES

- ✓ Two cases were analysed:
    - ✓ Case 1: same water level in both tanks (19cm) plus an additional mass of 40kg added on the deck of the barge to achieve the target draft of 10.8cm.
    - ✓ Case 2: different water level in tanks (19cm and 39cm).
- ✓ Numerical simulations carried out with free sway, heave and roll
- ✓ Linear roll damping of 11% of critical value was used in both cases

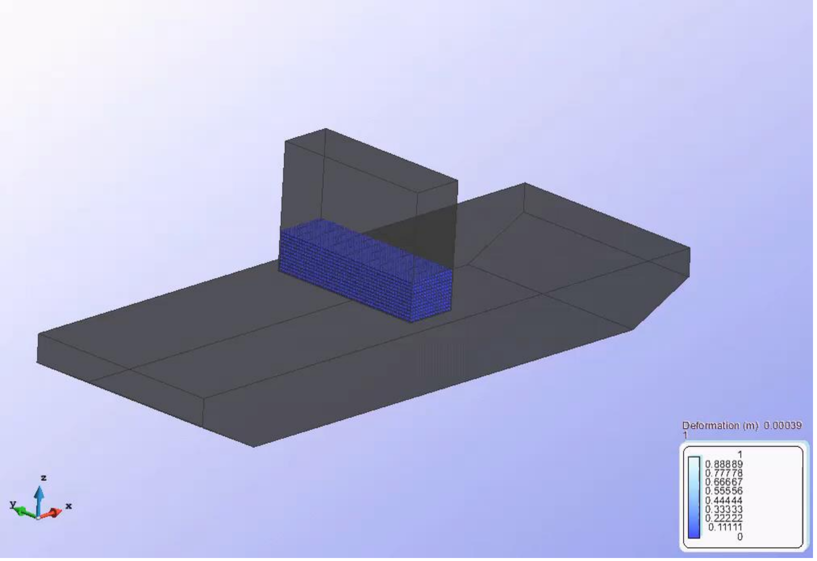
VALIDATION I: NUMERICAL DATA

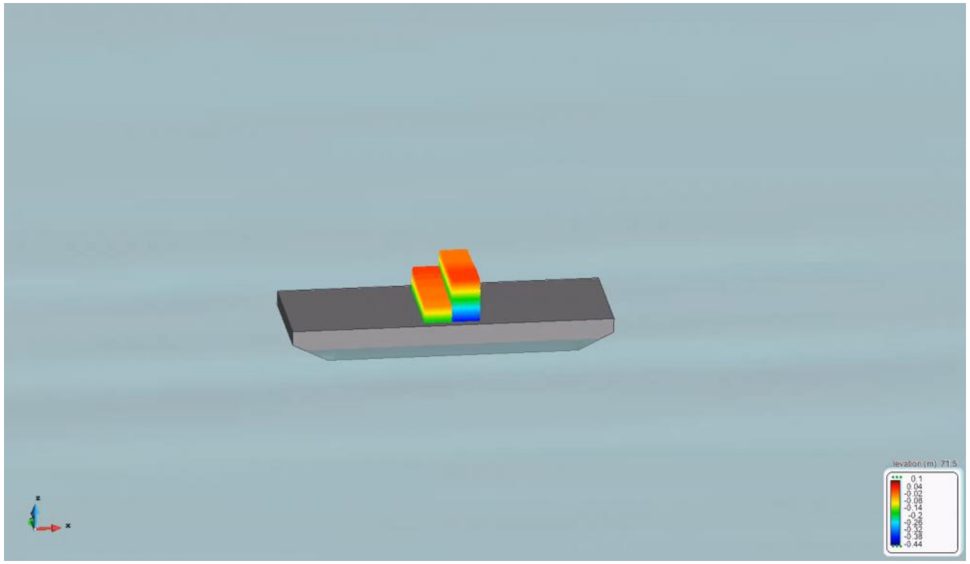
- ✓ Jonswap spectrum used to reproduce experimental conditions

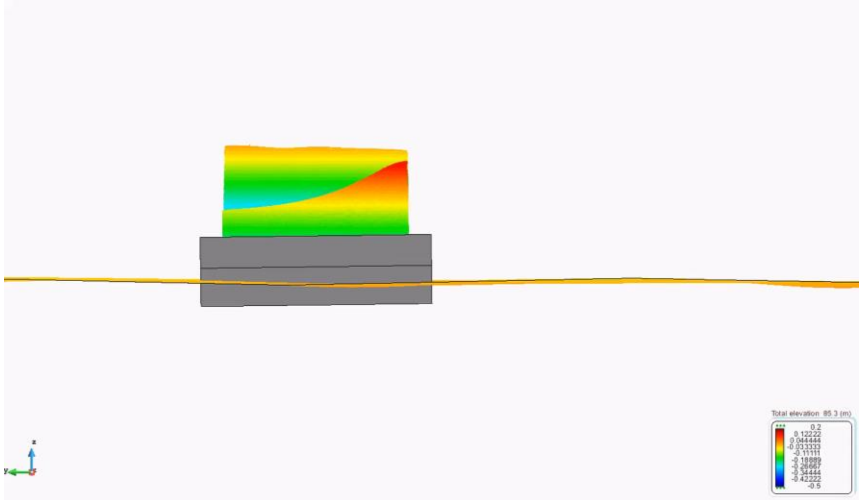
Peak enhancement factor	2
Significant wave height	6.6 cm
Peak period	1.6 s

- ✓ Kratos – PFEM2 data:
  - ✓ Convergence analysis performed using different mesh sizes
  - ✓ Results are given for a case that has 15346 elements and 300K particles
- ✓ SeaFEM data:
  - ✓ Model calibrated to have the most approximate roll RAO of experimental results
  - ✓ Results are given for the case using 236K tetrahedras

VALIDATION I: VIDEOS







VALIDATION I: CONVERGENCE

- ✓ Monochromatic wave test:
  - ✓ Simulation time: 30s
  - ✓ SeaFEM time-step: 0.01s
  - ✓ Same fill in the two tanks
- ✓ Coupling with SPH shows convergence to a lower value
- ✓ Faster convergence and faster compute times using Kratos – PFEM2

SPH Roll amplitude convergence test

Number of particles	RAO Roll [rad/m]
10,000	2.29
35,000	2.45
100,000	2.55
250,000	2.60
500,000	2.64

Kratos – PFEM2 amplitude convergence

Number of elements	Number of particles	RAO Roll [rad/m]
7901	39505	2.74
11371	56855	2. 80
15346	76730	2.84
22584	112920	2.83
31460	157300	2.83

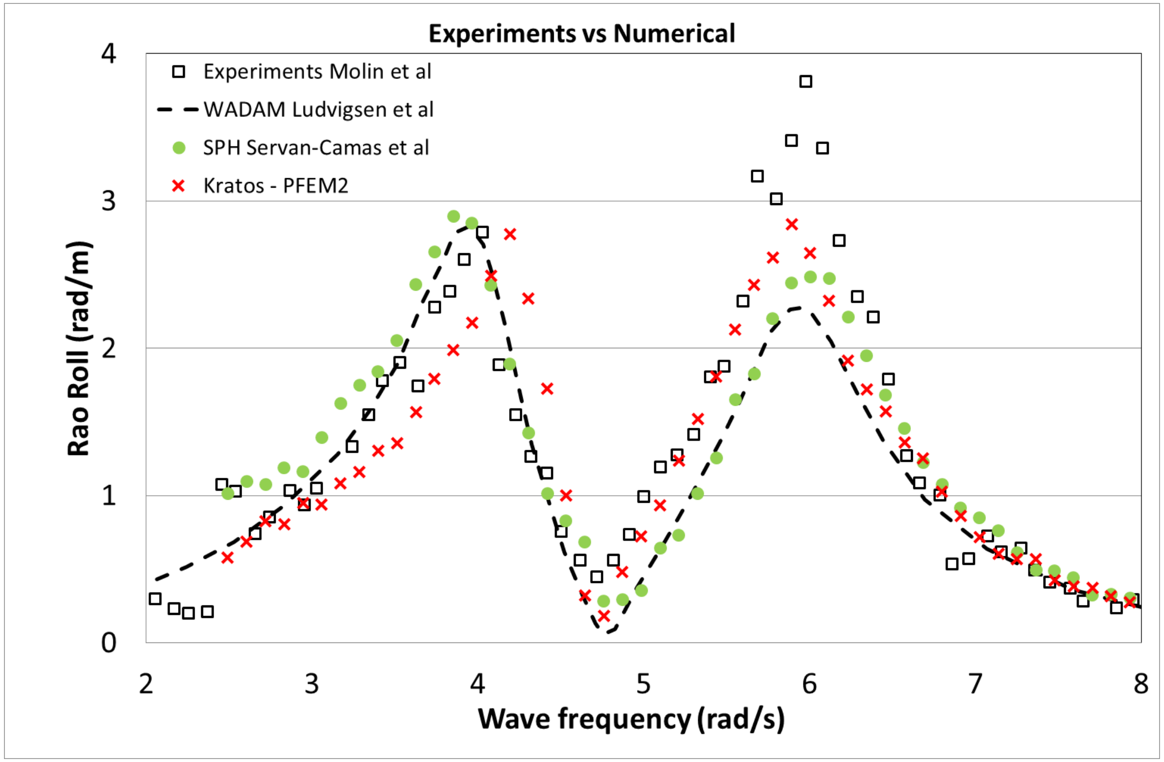
SPH Computational time

Number of particles	Computational time (s)	SPH (%)	FEM (%)
10,000	1938	33.5	66.5
35,000	4109	68.4	31.6
100,000	13110	88.5	11.5
250,000	41577	95.5	4.5
500,000	98616	98.2	1.8

Kratos – PFEM2 Computational time

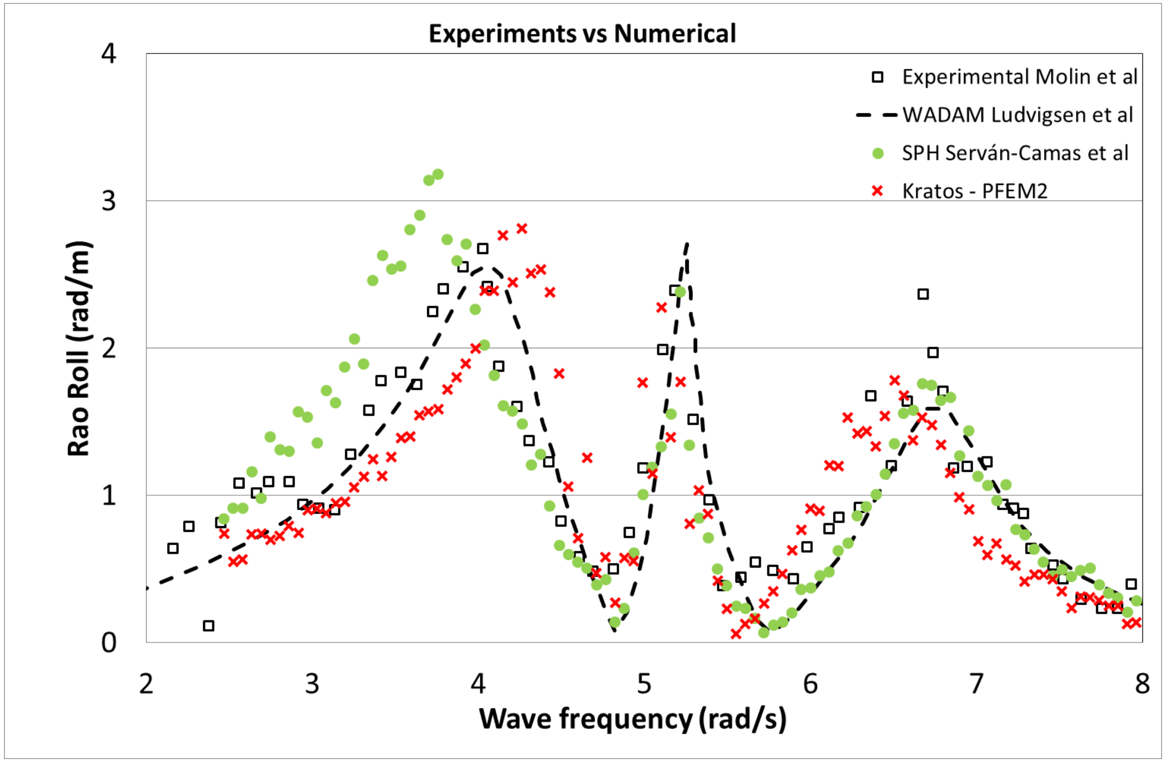
Number of elements	Number of particles	Computational time (s)	PFEM2 (%)	FEM (%)
7901	39505	3695	34.59	65.41
11371	56855	4583	45.86	54.14
15346	76730	5472	54.41	45.59
22584	112920	7545	67.33	32.67
31460	157300	11075	78.12	21.88

VALIDATION I: CASE 1 RESULTS



- ✓ This case was calculated using only one tank and then the obtained forces were duplicated
- ✓ PFEM – 2 obtains the most approximate results

VALIDATION I: CASE 2 RESULTS



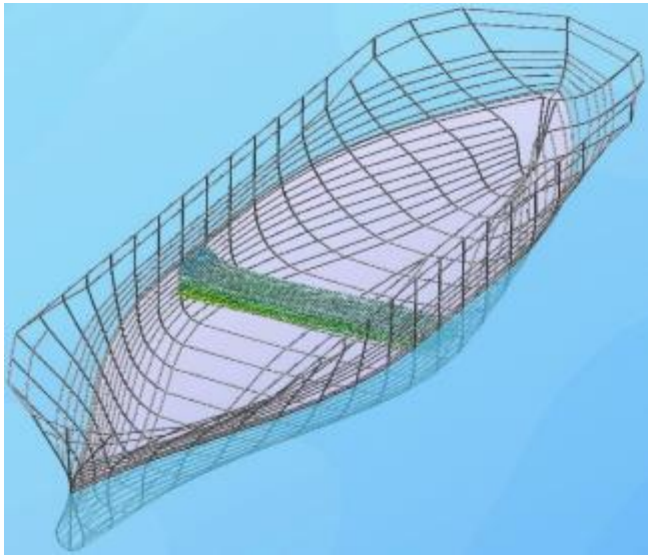
Ludvigsen, A., Pan, Z.Y., Gou, P., Vada, T., 2013. “Adapting a linear potential theory solver for the outer hull to account for fluid dynamics in tanks”. In: Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering OMAE2013 June 9–14, Nantes, France

B. Servan Camas, J. Cercós-Pita, J. Colom Cobb, J. García-Espinosa and A. Souto-Iglesias, "Time domain simulation of coupled sloshing–seakeeping problems by SPH–FEM coupling", Ocean Engineering, 123, (2016), 383–396

ANTIROLL TANK ANALYSIS

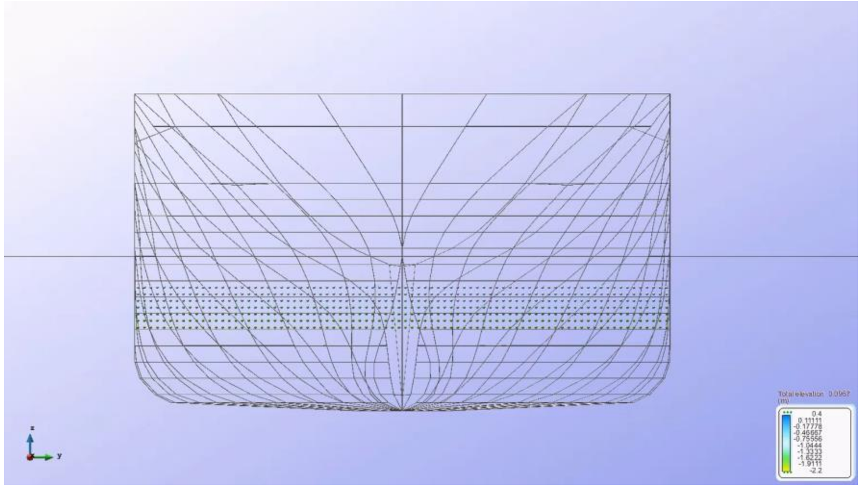
- ✓ The second validation case is based on the experimental work by Bai and Rhee, 1987. They provided experimental RAOs, obtained in a model basin, for a supply vessel equipped with an anti-roll tank (ART).
- ✓ Used a modified S175 type of hull
- ✓ Particulars of the ART:

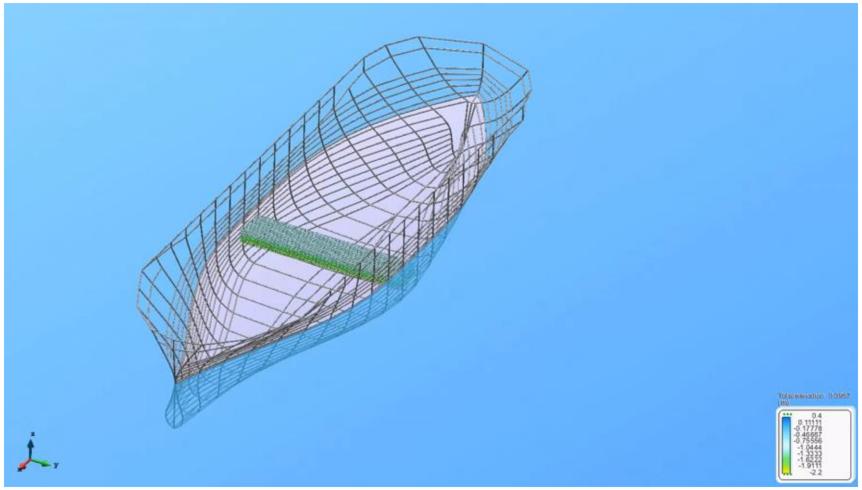
Length	2. 8 m
Breadth	13.699 m
Draft	2.4 m
XR (mid tank)	-0.73 m
YR (mid tank)	0 m
ZR (base tank)	-1.8564 m



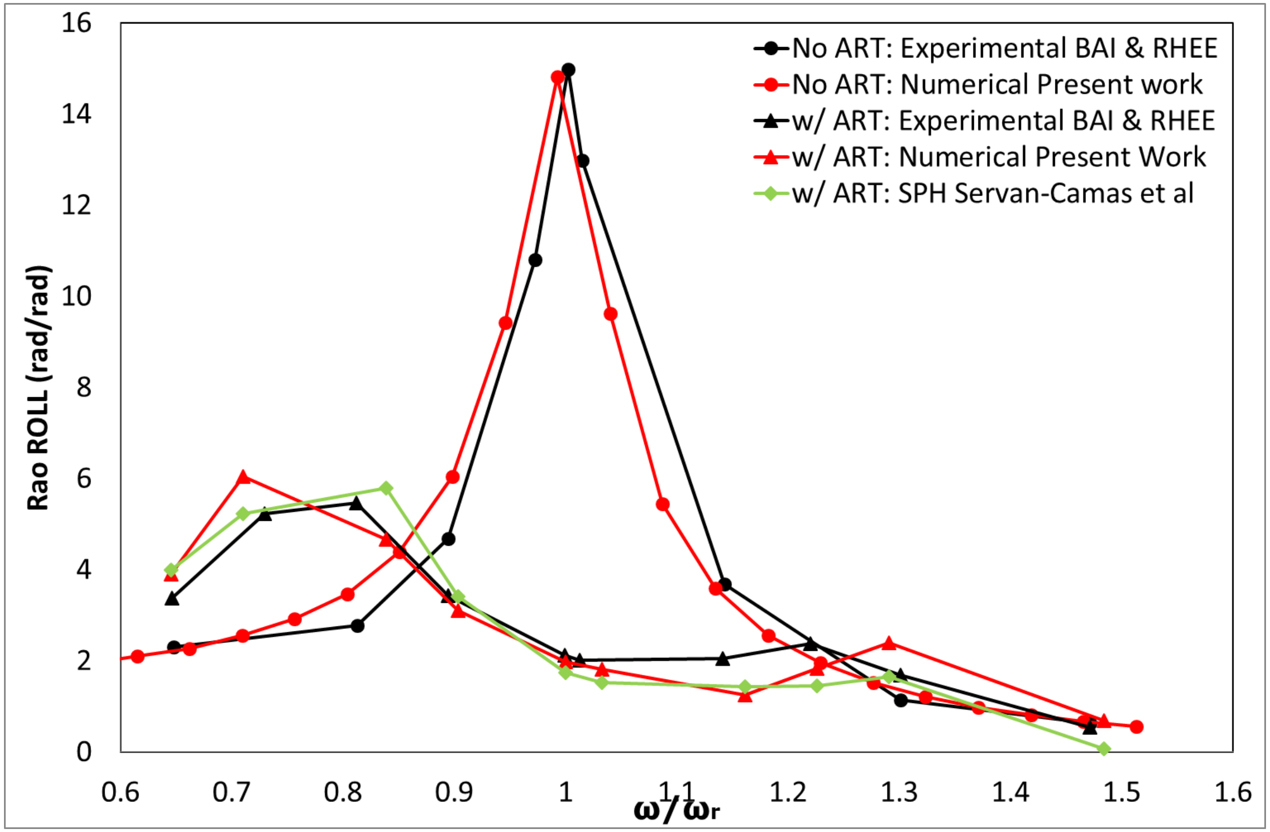
Bai K.J. and Rhee K.P., “Roll-Damping Tank Test”. Project report, 1987, Seoul National University

VALIDATION II: VIDEOS





VALIDATION II: RESULTS



- ✓ RAO reduction due to the ART effect
- ✓ When inserting the ART effect in the calculations, the results are quite similar to those obtained by Bai and Rhee with a very similar reduction of roll movements.

THE END

- ✓ Conclusions:
  - ✓ The coupled solver showed to be effective for solving seakeeping dynamics coupled with internal flows including sloshing. It was validated for three cases against available experimental data, providing good agreement.
  - ✓ Proves the capability of handling highly non-linear phenomena
  - ✓ The resulting solver could be used to solve real problems including complex sloshing phenomena under different sea conditions

- ✓ Thank you for your attention
- ✓ Questions?

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