# Comparative assessment of the speed and accuracy performances of numerical solvers for complex naval applications.

*CSI meeting*

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# Background

# Context

## Objectives

- ***Seakeeping response of ship with complex sea states***
  - ***Wave added resistance***
    - ***Hull form optimisation***

## Means

- ***Development of  a methodology with existing solutions***
- ***Improvement of these solutions***
  - *Improvement of accuracy*
  - *Improvement of computational time (Industrial context)*
  - *New developments*

# *Internal tools*

## foamStar

*Internally developed by Centrale Nantes and Bureau Veritas Marine & Offshore*

- *C++ code based on open-source library OpenFOAM*
- *Finite volume*
- *RANSE*

## HOS-Ocean / HOS-NWT

- *Complex irregular see states simulations using High Order Spectral (HOS) method*
- *Potential flow code =* ***fast***

## Grid2Grid

- *Reconstruct volumic field from HOS modal decomposition*

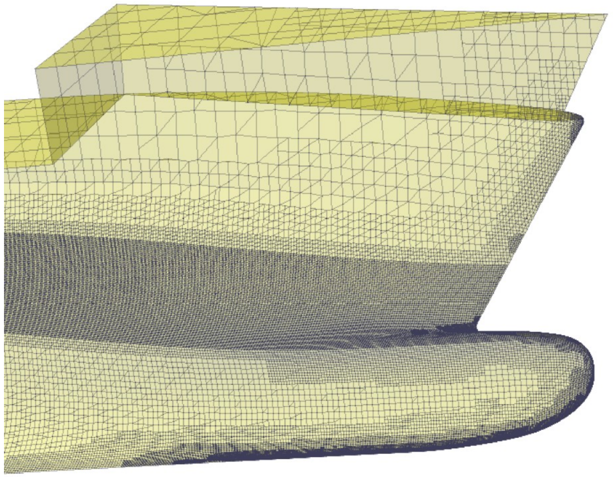
# External tools

## CAD

- *Rhinoceros 3D*

## Mesh generators

- *Hexpress*
- *STAR-CCM+ mesh generator*
- *OpenFOAM mesh tools: “blockMesh”, “snappyHexMesh”*

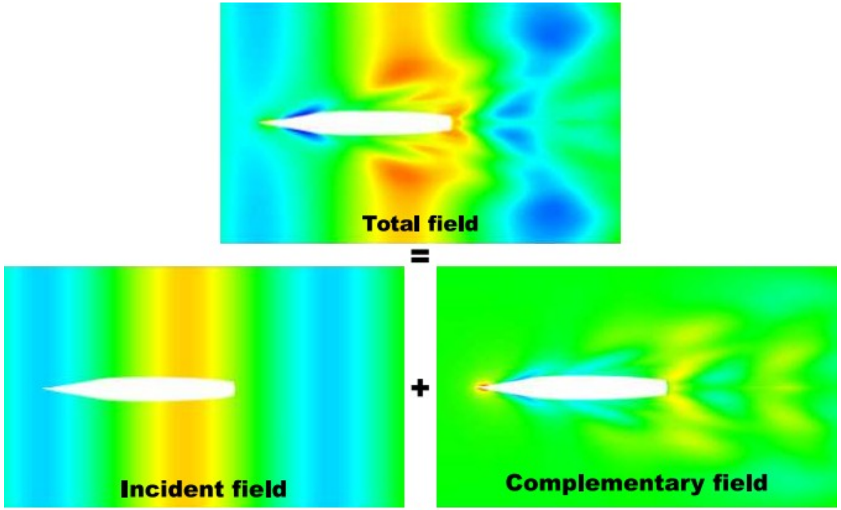


# Spectral Wave Explicit Navier Stokes (SWENSE)

## SWENSE model

⇒Decompose the fileds
⇒Incident field pre-solved
⇒Complementary filed (CFD computation)

$$\mathbf{u} = \mathbf{u}_I + \mathbf{u}_C$$
$$P = P_I + P_C$$




***Accurate simulation of sea states (HOS)***

***Better wave propagation with coarse meshes***

***Computational cost reduced***

# SWENSE backgroung

## ICARE: The first SWENSE CFD solver

- ***Single phase solver***

P. Ferrant et. al., A potential/RANSE approach for regular water wave diffraction about 2-D structures (2003)

## Two phase solver based on OpenFOAM

- ***First two phase solver implementation***

V. Vukcevic, Numerical Modelling of Coupled Potential and Viscous Flow for Marine Applications (2016)

## foamStar-SWENSE

- ***Internal development***
- ***Several studies on SWENSE already carried out***

Z. Li, Two-phase spectral wave explicit Navier-Stokes equations method for wave-structure interactions (2018)

Y.M. Choi, Two-way coupling between potential and viscous flows for a marine application (2019)

Y.J. Kim Influence of interface treatment in wave propagation in CFD (2018)

# foamStar-SWENSE

## Total field = RANS equations

$$\nabla\cdot\mathbf{u} = 0$$

$$\frac{\partial(\rho\mathbf{u})}{\partial t} + \nabla\cdot(\rho\mathbf{u}\mathbf{u}) - \nabla\cdot(\mu_{\mathrm{eff}}(\nabla\mathbf{u} + \nabla\mathbf{u}^{\mathrm{T}})) = -\nabla p_{\mathrm{d}} + gz\nabla\rho$$

## Incident field = Euler equations

$$\nabla\cdot\mathbf{u}_{\mathrm{I}} = 0$$

$$\frac{\partial(\rho_{\mathrm{water}}\mathbf{u}_{\mathrm{I}})}{\partial t} + \nabla\cdot(\rho_{\mathrm{water}}\mathbf{u}_{\mathrm{I}}\mathbf{u}_{\mathrm{I}}) = -\nabla p_{\mathrm{I}} + \rho_{\mathrm{water}}\,\mathbf{g}$$

## Complementary field

$$\mathbf{u}_C = \mathbf{u} - \mathbf{u}_I$$
$$P_C = P - P_I$$

$$\frac{\partial(\rho\mathbf{u}_{\mathrm{C}})}{\partial t} + \nabla\cdot(\rho\mathbf{u}\mathbf{u}_{\mathrm{C}}) + \rho\mathbf{u}_{\mathrm{C}}\cdot\nabla\mathbf{u}_{\mathrm{I}} = -\nabla p_{\mathrm{C}} - \frac{p_{\mathrm{I}}}{\rho_{\mathrm{I}}}\nabla\rho + \nabla\cdot(\mu_{\mathrm{eff}}(\nabla\mathbf{u}_{\mathrm{C}} + \nabla\mathbf{u}_{\mathrm{C}}^{\mathrm{T}}))$$

# Wave generation

*1st step*

# Regular wave propagation

## Background

- ***2D foamStar and foamStar SWENSE wave propagation already studied by Z. Li, YM. Choi and YJ. Kim***

## Objective

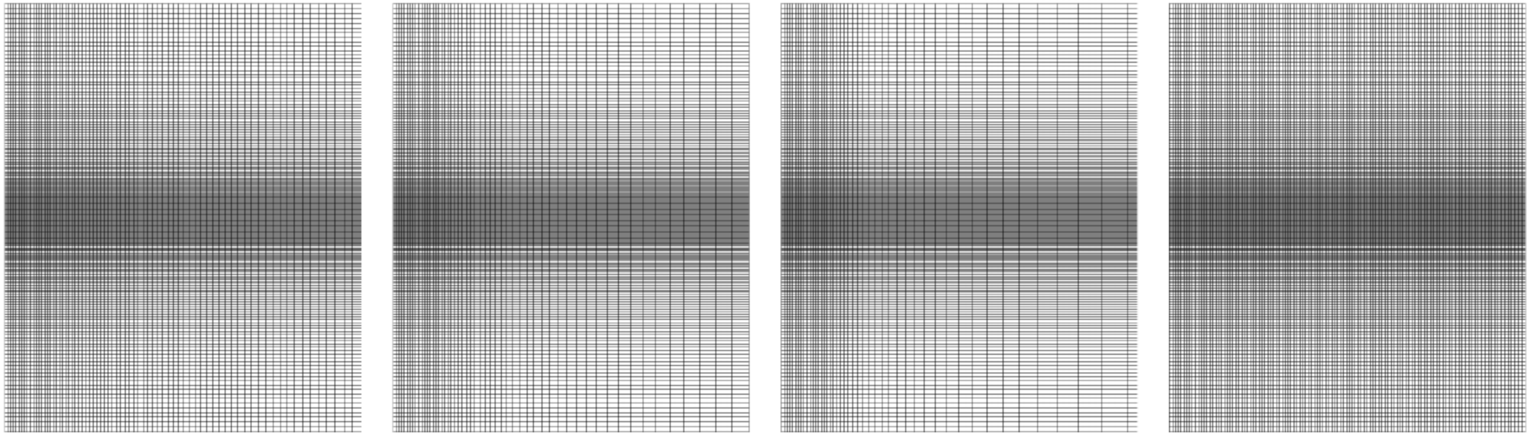
- ***To study it in the naval application context:***

→ *Take into account the forward speed*

→ *Use the naval mesh generator used by ECN and BVS M&O*

→ *Optimise the mesh generation: Accuracy + computation time*

# Regular wave propagation



4 examples extracted from the Young Myung Choi Ph.D.

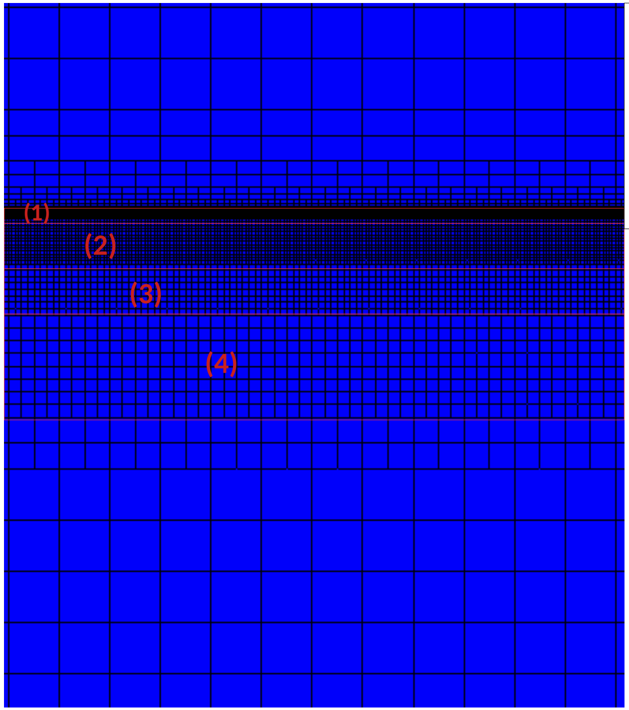
- ***Particularities:*** ⇒*Constant horizontal refinement.*
  ⇒*Using refinement gradient*

- ***To apply it to naval study implies:***

  ⇒*Large number of cells for 3D meshes*
  ⇒*refinement gradientnot available with used naval mesh generator*

# Regular wave propagation

## Naval mesh structure :




**ZONES:**

(1) ΔZ = 2H
(2) Zmin = λ/4
(3) Zmin = λ/2
(4) Zmin = λ

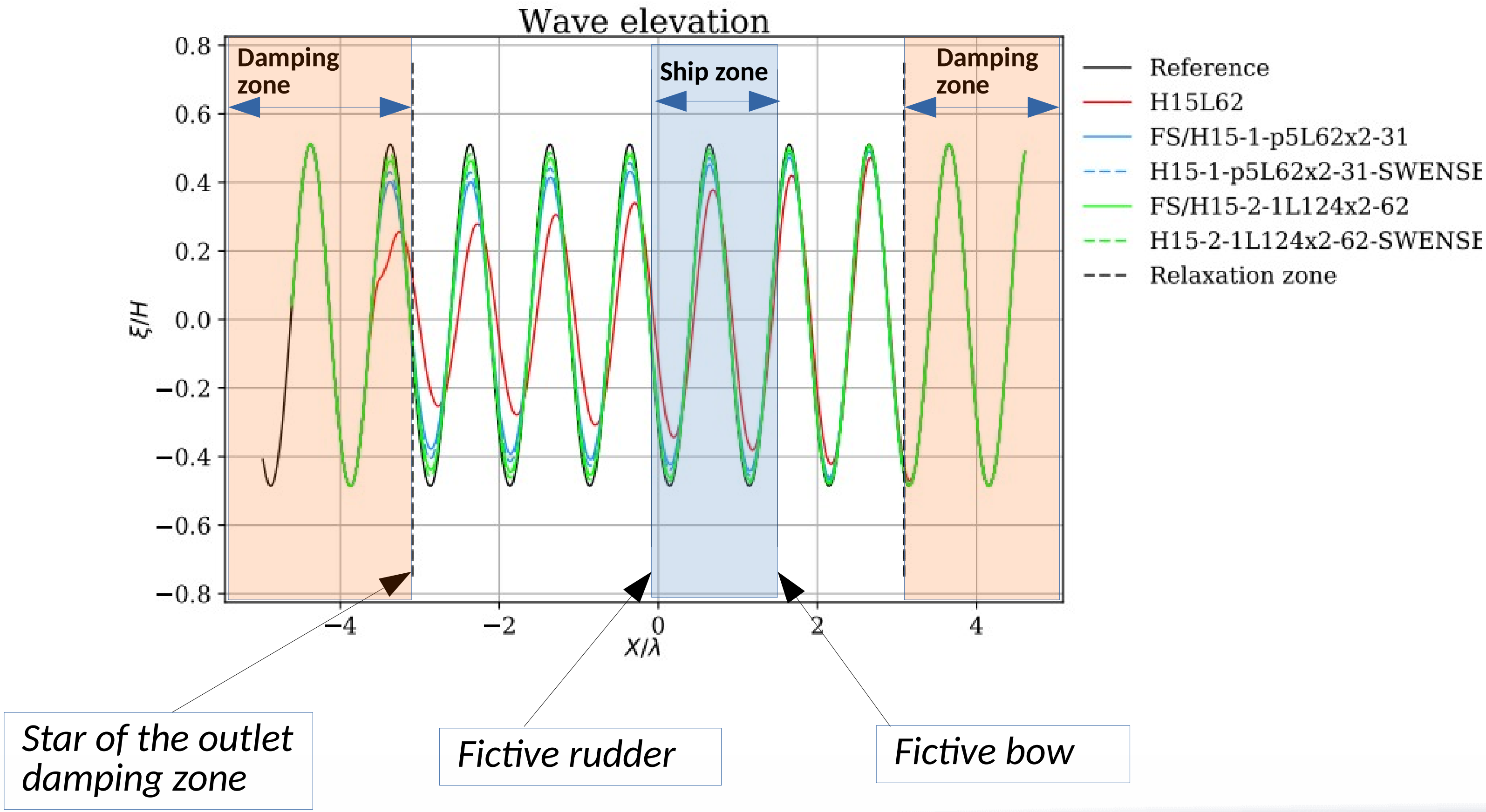
2D mesh dedicated to wave propagation analysis (λ = 3.9 m; H=0.062 m)

| Zones | 1 | | 2 | | 3 | | 4 | |
|---|---|---|---|---|---|---|---|---|
| | Δz | Δx | Δz | Δx | Δz | Δx | Δz | Δx |
| **H15L62** | H/15 | L/62 | | | | | | |
| **H15-4x3L62x4** | H/15 | L/62 | H/4 | L/62 | H/4 | L/62 | H/4 | L/62 |
| **H15-1x3L62x4** | H/15 | L/62 | H/1 | L/62 | H/1 | L/62 | H/1 | L/62 |
| **H15-1-p5L62x2-31** | H/15 | L/62 | H/1 | L/62 | H/0.5 | L/31 | | |
| **H15-2-1L124x2-62** | H/15 | L/124 | H/2 | L/124 | H/1 | L/62 | | |

Mesh refinement by zone

# Regular wave propagation

## Results



# Regular wave propagation

## Results

| | foamStar | | | FoamStar-SWENSE | | |
|---|---|---|---|---|---|---|
| | $D_{bow}$ | $D_{rudder}$ | $D_{domain}$ | $D_{bow}$ | $D_{rudder}$ | $D_{domain}$ |
| **H15L62** | 18.20% | 28.50% | 46.70% | | | |
| **H15-4x3L62x4** | 7.70% | 12.60% | 21.80% | 5.35% | 9.33% | 16.20% |
| **H15-1x3L62x4** | 7.68% | 12.60% | 21.70% | 5.35% | 9.32% | 16.20% |
| **H15-1-p5L62x2-31** | 7.70% | 12.60% | 21.80% | 5.36% | 9.34% | 16.20% |
| **H15-2-1L124x2-62** | 3.40% | 0.50% | 9.57% | 1.65% | 2.91% | 5.50% |

***Conclusions***

*⇒Fast vertical mesh expansion is possible*

*⇒Horizontal unrefinement far from the free surface is possible*

*⇒foamStar SWENSE provides better results than foamSTAR*

***Deepen analysis to be done***

*⇒Wave damping remain significant anlong the domain even with SWENSE*

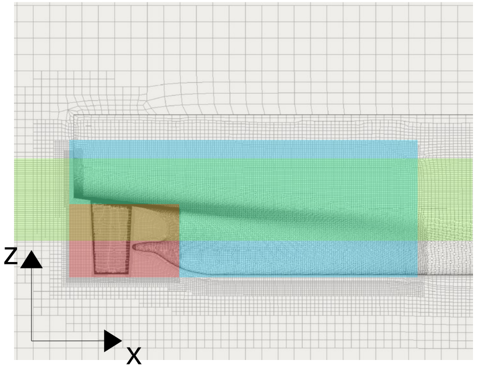
*⇒Forward speed influence ?*

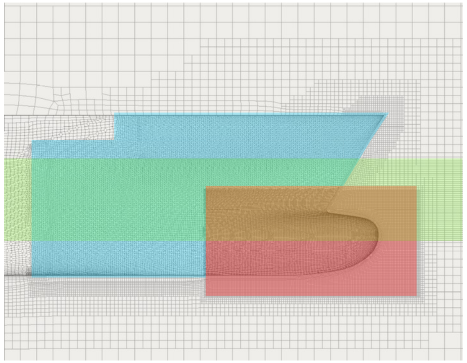
*⇒Impact on naval application ?*

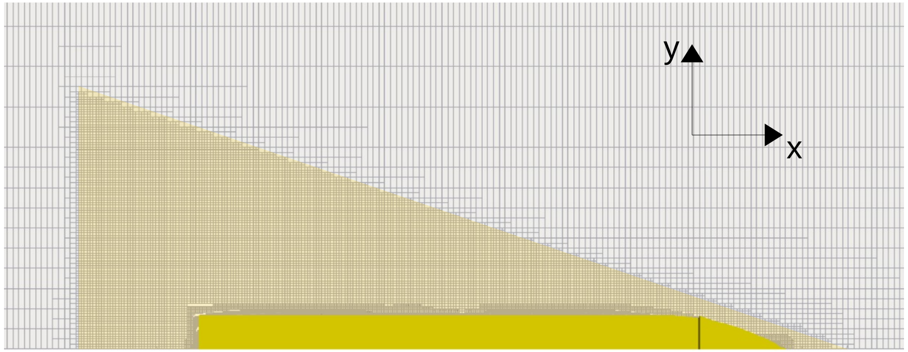
# Naval mesh generation

# Mesh generation

## Mesh refinement zones






Surface specific refinement

Free surface 3D box refinement

Specific 3D box refinement

Wake 3D box refinement

***Objective:*** *Adapt the mesh refinement to the phenomena scale in specific region.*

*Meshing method generally provided by guidelines (Hexpress and STAR-CCM+)*

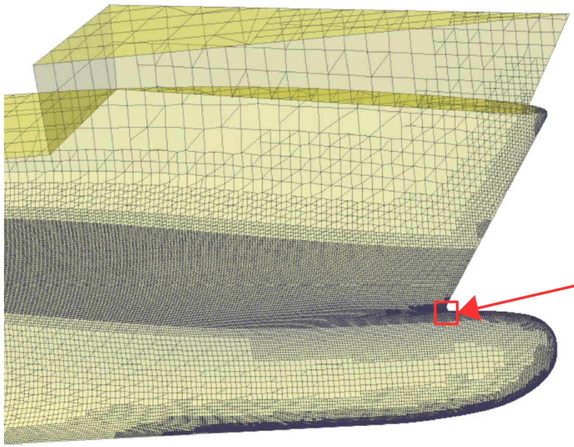
# Mesh quality

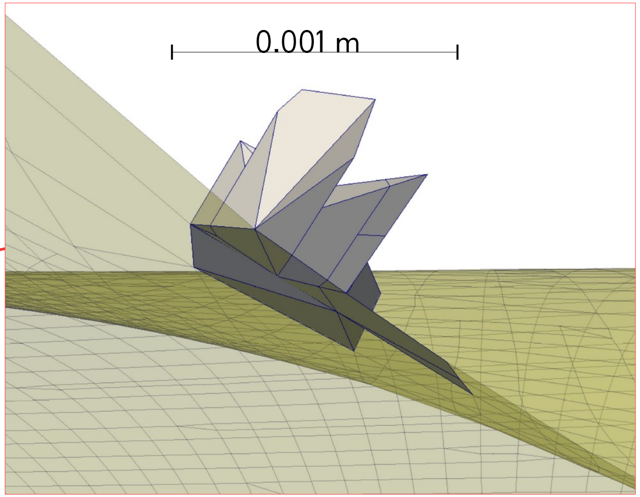
## Skewness and Orthogonality

***Cells aspect impact the numerical model accuracy***

⇒*Increase of the errors*
⇒*Instabilities*

***Keep a "good" mesh quality remains difficult***






*KCS; attempt of very fine mesh (11M cells)*

# Mesh quality

## Mesh verification

***Tools provided by OpenFOAM libraries:*** *"checkMesh"*

**Boundary openness** (-7.8372767e-17 2.3320955e-14 6.4269804e-17) **OK.**
**Max cell openness** = 3.3379624e-16 **OK.**
**Max aspect ratio** = 128.00029 **OK.**
**Minimum face area** = 1.721246e-08. Maximum face area = 1.0235389. Face area magnitudes **OK.**
Min volume = 6.9813407e-12. Max volume = 1.0355145. Total volume = 12055.8. Cell volumes **OK.**
Mesh non-orthogonality Max: 88.210091 average: 6.9040656
***Number of severely non-orthogonal (> 70 degrees) faces**: 1108
**Non-orthogonality check OK.**
**Face pyramids OK.**
*****Max skewness** = 4.240074, **3 highly skew faces detected which may impair the quality of the results**
<<Writing 3 skew faces to set skewFaces

Example of mesh verification done using checkMesh tool

⇒ *Large amount of time spent on mesh generation*

⇒ *To improve foamStar stability risking to reduce the accuracy ?*

# foamStar vs foamStar-SWENSE

*naval application*

# Study case

## Tokyo 2015 workshop: KRISO Container Ship (KCS)

| Main particulars | Full | Model |
|---|---|---|
| Length ($L_{PP}$) [m] | 230 | 6.0702 |
| Breadth ($B_{WL}$) [m] | 32.2 | 0.8498 |
| Depth ($D$) [m] | 19.0 | 0.5015 |
| Draft ($T$) [m] | 10.8 | 0.2850 |
| Volume ($\Delta$) [$m^3$] | 52030 | 0.9571 |
| Wetted surface ($S_W$) [$m^2$] | 9539 | 6.6978 |
| Horizontal buoyancy center ($L_{CB}$) [m] | 111.5 | 2.944 |
| Vertical Center of Gravity ($K_G$) [m] | 14.32 | 0.378 |
| Moment of Inertia ($\frac{K_{xx}}{B}$) | 0.40 | 0.40 |
| ($\frac{K_{yy}}{L_{PP}}$, $\frac{K_{yy}}{L_{PP}}$) | 0.250 | 0.252 |

| Surge | Sway | Heave | Roll | Pitch | Yaw |
|---|---|---|---|---|---|
| *Towing* | *Fixed* | *Free* | *Fixed* | *Free* | *Fixed* |

| Ship speed ($U_0$) [$m.s^{-1}$] | Fr | Re |
|---|---|---|
| 2.017 | 0.261 | $1.074 \cdot 10^7$ |

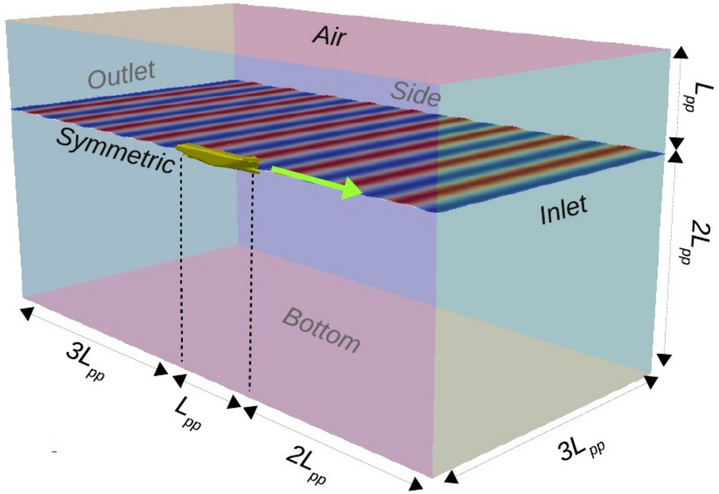
| Case | $\lambda$ [m] | $\frac{\lambda}{L_{PP}}$ | H [m] | T [s] | $\varepsilon$ |
|---|---|---|---|---|---|
| *C1* | 3.949 | 0.651 | 0.062 | 1.591 | 0.016 |
| *C2* | 5.164 | 0.851 | 0.078 | 1.819 | 0.015 |
| *C3* | 6.979 | 1.150 | 0.123 | 2.115 | 0.018 |
| *C4* | 8.321 | 1.371 | 0.149 | 2.309 | 0.018 |
| *C5* | 11.840 | 1.951 | 0.196 | 2.754 | 0.017 |

Regula wave conditions

- *Model scale*
- *Head regular wave with small steepness*

# Study case

## Numerical domain




## Numerical schemes

- ***Spatial discretisation:***

  *Second order schemes*

- ***Temporal discretisation:***

  *First order schemes*

***⇒ Second order shemes and Crank Nicolson schemes was tried.***

*⇒ Strong instability for both foamStar and foamStar SWENSE*

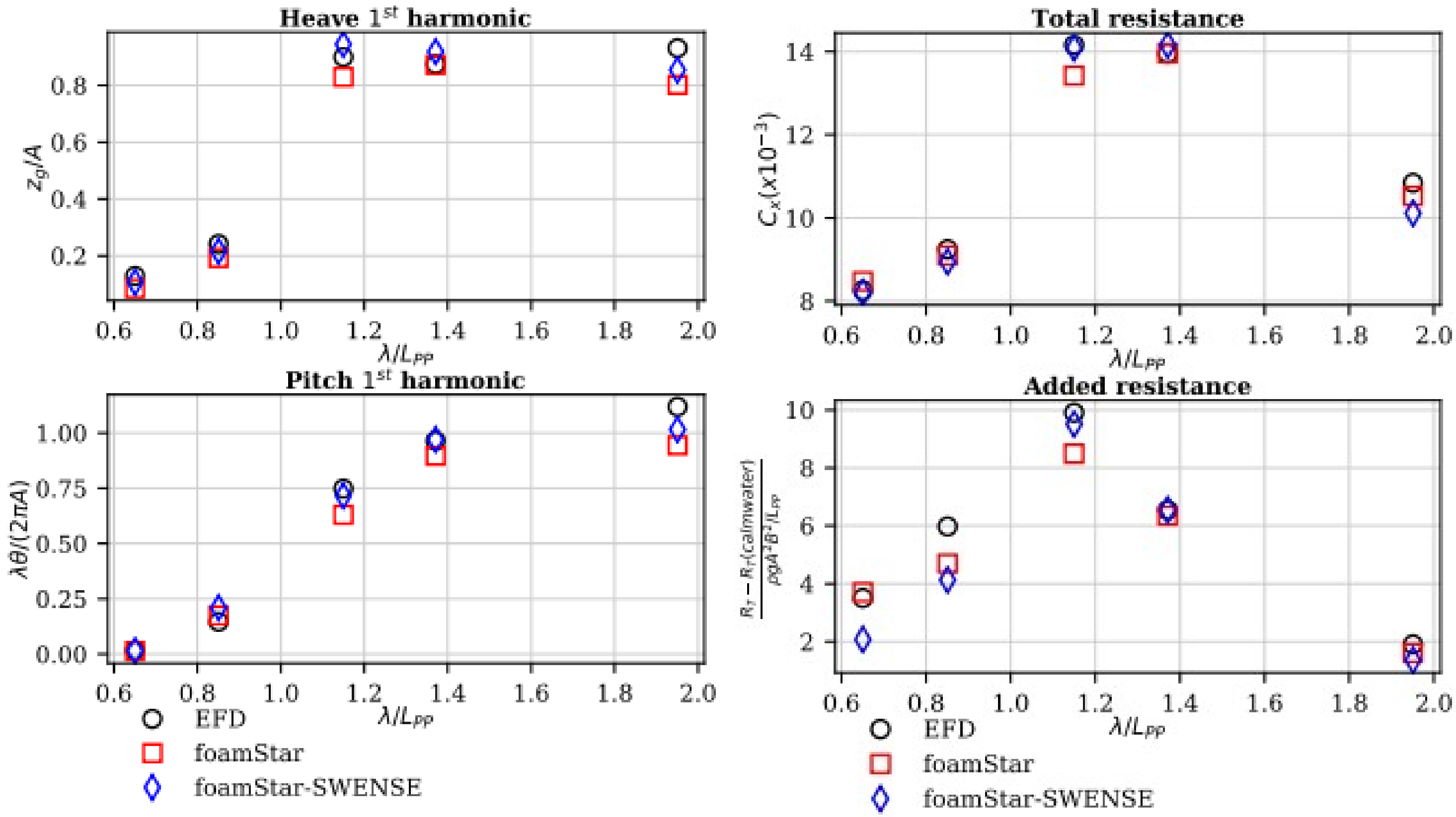
*⇒ A key point to improve for future work*

# Results



⇒ *foamStar and foamStar SWENSE =* ***good agreement*** *with experiment*

⇒ *Motions amplitude slightly underestimated by foamStar*




***Future work:***

⇒ *Error an uncertainties*

⇒ *Mesh convergence in order to evaluate the computation time gain using SWENSE*

# Irregular waves with foamStar-SWENSE

*Naval application*

# Study case

## Ship: Same KCS model scale

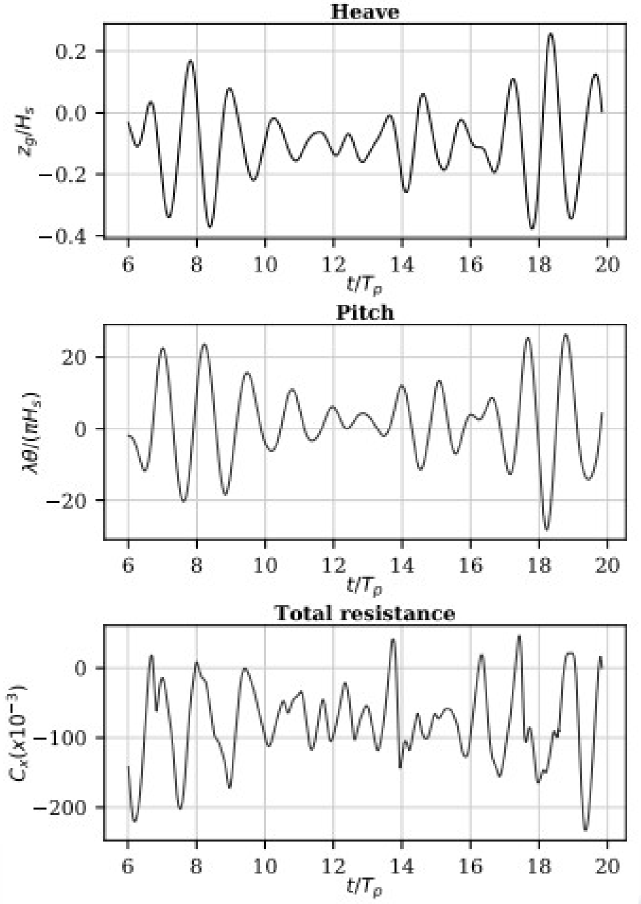
## Sea sate:

| Scale | $H_s$ [m] | $T_p$ [s] | $H_s/\lambda_p$ |
|---|---|---|---|
| Full | 5.0 | 12.4 | 0.021 |
| Model | 0.132 | 2.0145 | |

- ***First trial of ship seakeeping with irregular waves***
- ***Stability issue***

  ⇒ *Impossibility to compute long time simulations*

  ⇒ *Impossibility to do a rigorous spectral analysis of the ship response*




Thank you

# *Irregular wave generation*

## Work objective:

- ***To generate complex sea states with HOS-Ocean usable with foamStar and foamStar-SWENSE***

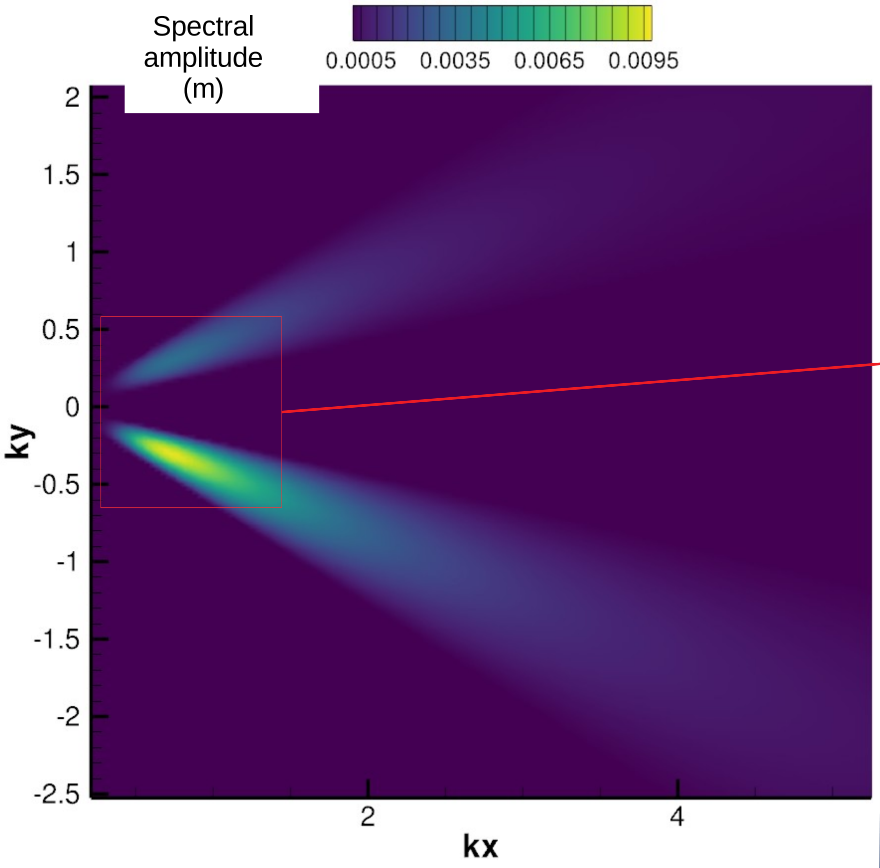
⇒*Try to generate a crossed sea state with spreading*

Cross Sea state characteristics.

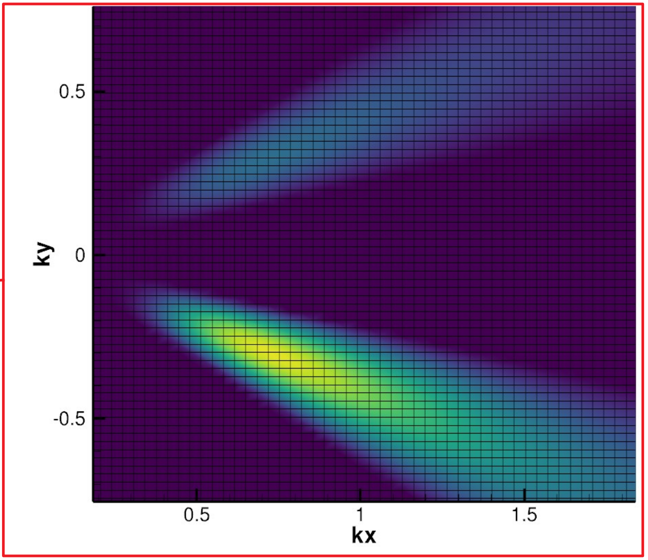
| Sea State | Scale factor | Spectrum | Hs (m) | Tp (s) | 3D spreading |
|---|---|---|---|---|---|
| ***SS4*** | 37,89 | Jonswap $\gamma = 1$ | 0,0496 | 1,4296 | 10° |
| ***SS6*** | | | 0,132 | 2,0145 | |
| ***Crossed SS6 and SS4*** | | | $Hs_{SS4}$=0,0496<br>$Hs_{SS6}$= 0,132 | $Tp_{SS4}$=0,0496<br>$Tp_{SS6}$=2,0145 | |

# Irregular wave generation

## HOS-Ocean crossed wave implementation




***The grid represent the modal discretization.***




*Crossed SS6 and SS4 (-22.5°; +22.5°);*
*Spectral amplitude HOS-Ocean output*

# Irregular wave generation

**_More development needed before naval application with foamStar_**

*⇒ In spite of the “light” parameters chosen in terms of modal discretization, the mono-processor HOS wave generation is quite “slow” for 3D seastates generation.*

*⇒ A parallelised process have to be implemented.*

| | 2D SS6 | 3D SS6 (10° of spreading) | Crossed SS6 and SS4 |
|---|---|---|---|
| *Duration (h)* | 0.5 | 15.5 | 5.25 |
| *Number of simulate peak periods (Tp)* | 200 | 20 | 1 |
| *Output frequency (per Tp)* | 20 | | |
| *SWENSE Output file size (GB)* | 0.37 | 7.0 | 1.8 |