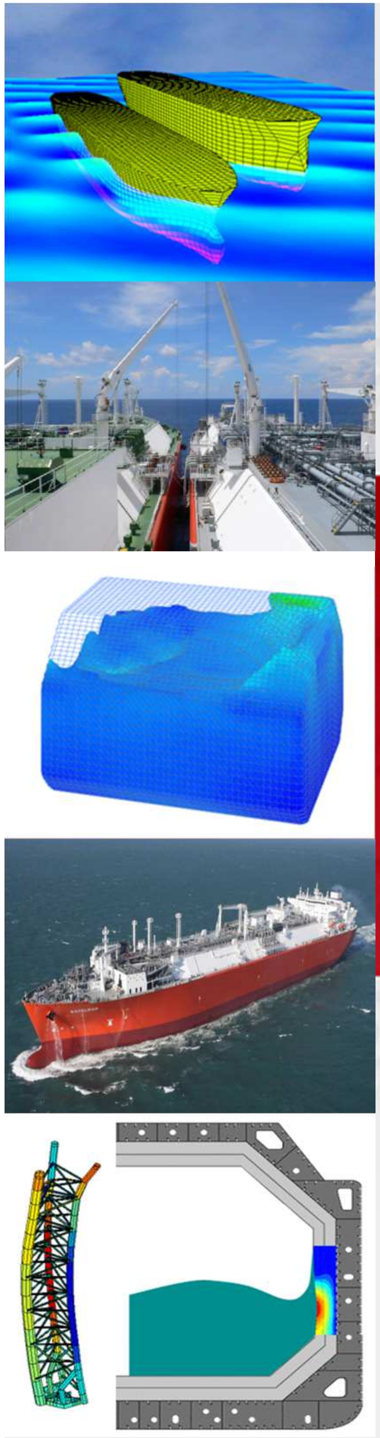

MULTIPHASE 2017

Numerical Study of Anti-Roll Tanks

PARIS, October 2017

Louis DIEBOLD

BUREAU
VERITAS

Move Forward with Confidence*

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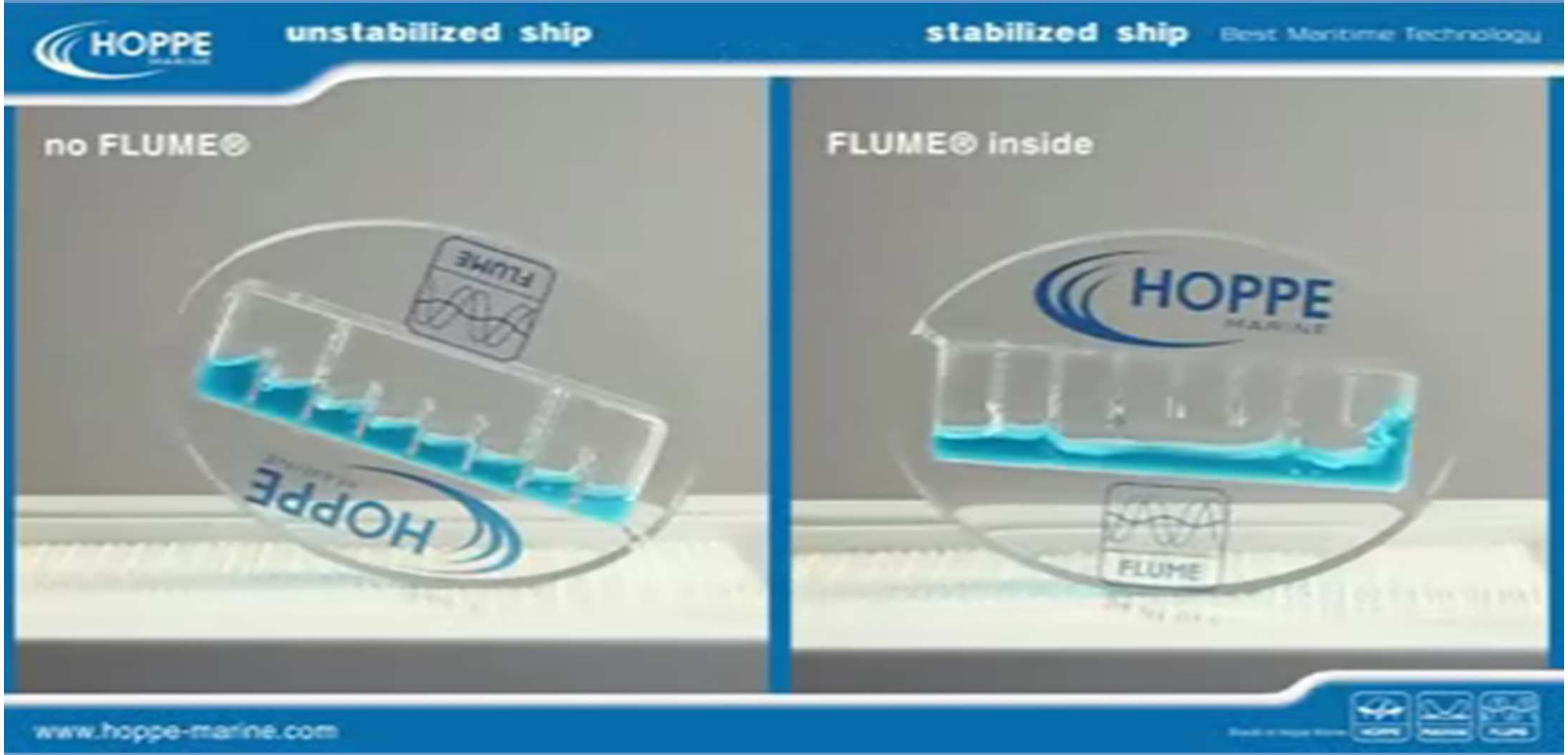
Bureau Veritas / Marine Division

Anti Rolling Tank = ART
Principle of Flume Tank



See Video on www.hoppe-marine.com

Influence of Flume Tanks on Rolling Behaviour?
Flume Tanks = Anti-Rolling Tanks = ART

- **Assumption => Flume tank (ART) has a small $\frac{\text{Length}}{\text{Breadth}}$ ratio**
- **How to take into account consistently the ARTs (and their non-linearities) in a linear seakeeping calculation?**

- **How to evaluate the reponse of the ARTs?**
  - CFD => to be validated through some comparisons with experiments
  - How to use model tests?

- **How to apply the ART response into a linear seakeeping calculation within the frequency domain (HydroSTAR)?**
  - Potential approach satisfactory?
  - Which amplitudes for forced motions are to be considered?

- **Application of Flume Tank(s) to an existing container ship**
  - Presentation of NR 625 regarding lashing forces
  - What is the obtained roll reduction factor for an existing container ship?

CONTENTS:

1. *Ship Motion Equation with Anti-Roll Tanks (ART)*
2. *Validation of CFD Calculations for Liquid Global Forces*
3. *Application to FPU Seakeeping*
4. *Effective Gravity Angle (EGA)*
5. *Coming Back to FPU Seakeeping for EGA Validation*
6. *Application to 9300 TEU Container Ship*
7. *Conclusion & Discussion*

1. *Ship Motion Equation with Anti-Roll Tanks (ART)*

Ship Motion Equation {Ship + Anti-Roll Tanks}
Linear Seakeeping in Frequency Domain

- ► **Galilean reference frame** $\{G_0, \vec{x}, \vec{y}, \vec{z}\}$
- ► **Within linear seakeeping in the frequency domain, ship's motion equation with anti-roll tanks {ship + tanks} can be written:**
  - $\left(-\omega^2\left(\left[\mathbf{M}_{\mathbf{G_0}}^{\mathbf{notk}}\right] + \left[\mathbf{A}_{\mathbf{G_0}}\right]\right) - i\omega\left[\mathbf{B}_{\mathbf{G_0}}\right] + \left[\mathbf{C}_{\mathbf{G_0}}\right]\right)\left\{\boldsymbol{\xi}_{\mathbf{G_0}}\right\} = \left\{\mathbf{F}_{\mathbf{G_0}}^{\mathbf{DI}}\right\} + \left\{\mathbf{F}_{\mathbf{G_0}}^{\mathbf{Liq}}\right\}$
  - $\left[\mathbf{M}_{\mathbf{G_0}}^{\mathbf{notk}}\right]$ inertia matrix without equivalent solid inertia of ART
  - $\left[\mathbf{A}_{\mathbf{G_0}}\right]$, $\left[\mathbf{B}_{\mathbf{G_0}}\right]$, $\left[\mathbf{C}_{\mathbf{G_0}}\right]$ => added mass, damping & hydrostatic stiffness
  - $\left\{\boldsymbol{\xi}_{\mathbf{G_0}}\right\}$ => 6 rigid body motions (6 dof)
  - $\left\{\mathbf{F}_{\mathbf{G_0}}^{\mathbf{DI}}\right\}$ => incident wave + diffraction forces
  - $\left\{\mathbf{F}_{\mathbf{G_0}}^{\mathbf{Liq}}\right\}$ => forces due to liquid internal motions within ART

Ship Motion Equation {Ship + Anti-Roll Tanks}
Linear Seakeeping in Frequency Domain

▶ ART forces can be decomposed as follows:

- $\left\{\mathbf{F}^{\mathbf{Liq}}_{\mathbf{G_0}}\right\} = \left(-\left[\mathbf{D}^{\mathbf{Re}}_{\mathbf{G_0}}\right] - \mathrm{i}\left[\mathbf{D}^{\mathbf{Im}}_{\mathbf{G_0}}\right]\right)\{\xi_{\mathrm{Q}}\}$
- $\left[\mathbf{D}^{\mathbf{Re}}_{\mathbf{G_0}}\right]$ => stiffness matrix for ART
- $\left[\mathbf{D}^{\mathbf{Im}}_{\mathbf{G_0}}\right]$ => damping matrix for ART

▶ These matrices $\left[\mathbf{D}^{\mathbf{Re}}_{\mathbf{G_0}}\right]$ & $\left[\mathbf{D}^{\mathbf{Im}}_{\mathbf{G_0}}\right]$ can be calculated by:

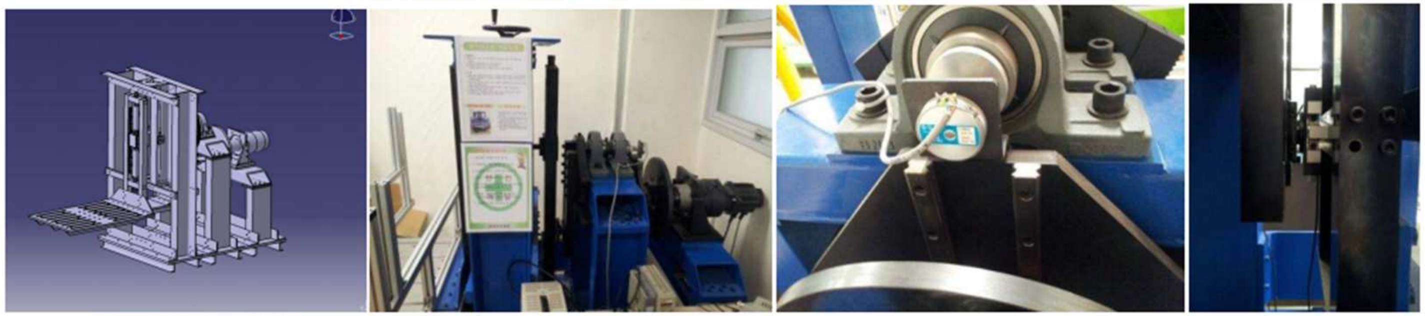
- Potential approach
- Hybrid approach => potential + CFD
  - » Some coeff. Associated to given motions are calculated by potential approach
  - » The others by **CFD (sway + roll)**
  - » $\begin{bmatrix} \mathrm{D}^{\mathrm{Re,Im}}_{\mathrm{G_0}{}_{11}}(\mathrm{pot}) & \mathbf{D}^{\mathbf{Re,Im}}_{\mathbf{G_0}{}_{\mathbf{12}}}(\mathbf{cfd}) & \mathrm{D}^{\mathrm{Re,Im}}_{\mathrm{G_0}{}_{13}}(\mathrm{pot}) & \mathbf{D}^{\mathbf{Re,Im}}_{\mathbf{G_0}{}_{\mathbf{14}}}(\mathbf{cfd}) & \mathrm{D}^{\mathrm{Re,Im}}_{\mathrm{G_0}{}_{15}}(\mathrm{pot}) & \dots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \mathrm{D}^{\mathrm{Re,Im}}_{\mathrm{G_0}{}_{61}}(\mathrm{pot}) & \mathbf{D}^{\mathbf{Re,Im}}_{\mathbf{G_0}{}_{\mathbf{62}}}(\mathbf{cfd}) & \mathrm{D}^{\mathrm{Re,Im}}_{\mathrm{G_0}{}_{63}}(\mathrm{pot}) & \mathbf{D}^{\mathbf{Re,Im}}_{\mathbf{G_0}{}_{\mathbf{64}}}(\mathbf{cfd}) & \mathrm{D}^{\mathrm{Re,Im}}_{\mathrm{G_0}{}_{65}}(\mathrm{pot}) & \vdots \end{bmatrix} = \left[\mathbf{D}^{\mathbf{Re,Im}}_{\mathbf{G_0}}\right]$
- CFD approach => All coeff. are evaluated by CFD

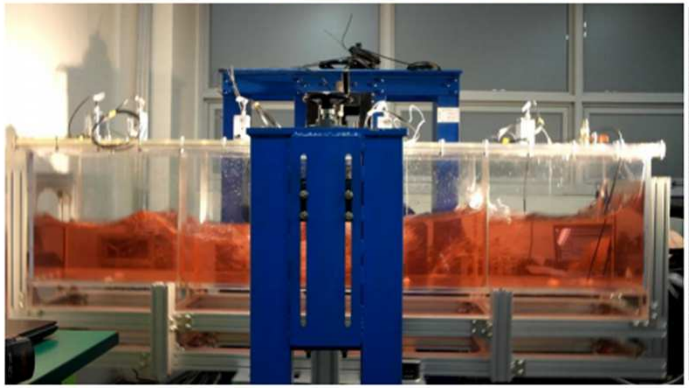
2. Validation of CFD Calculations for Liquid Global Forces

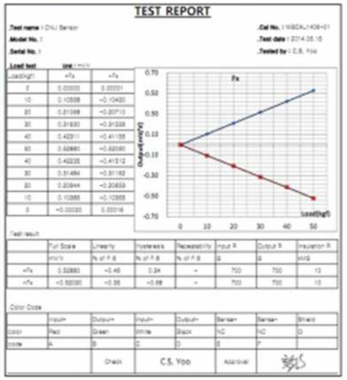
Model Tests HHI

HHI Bench Tests & ART (see S. Lee, ISOPE 2015)

- ► **Model bench tester**





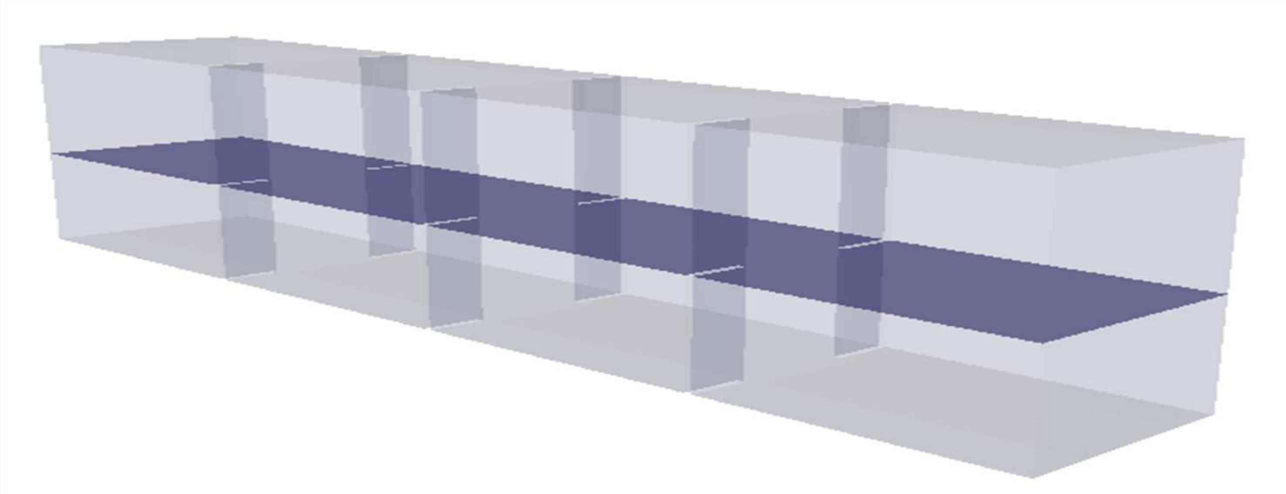


TEST REPORT

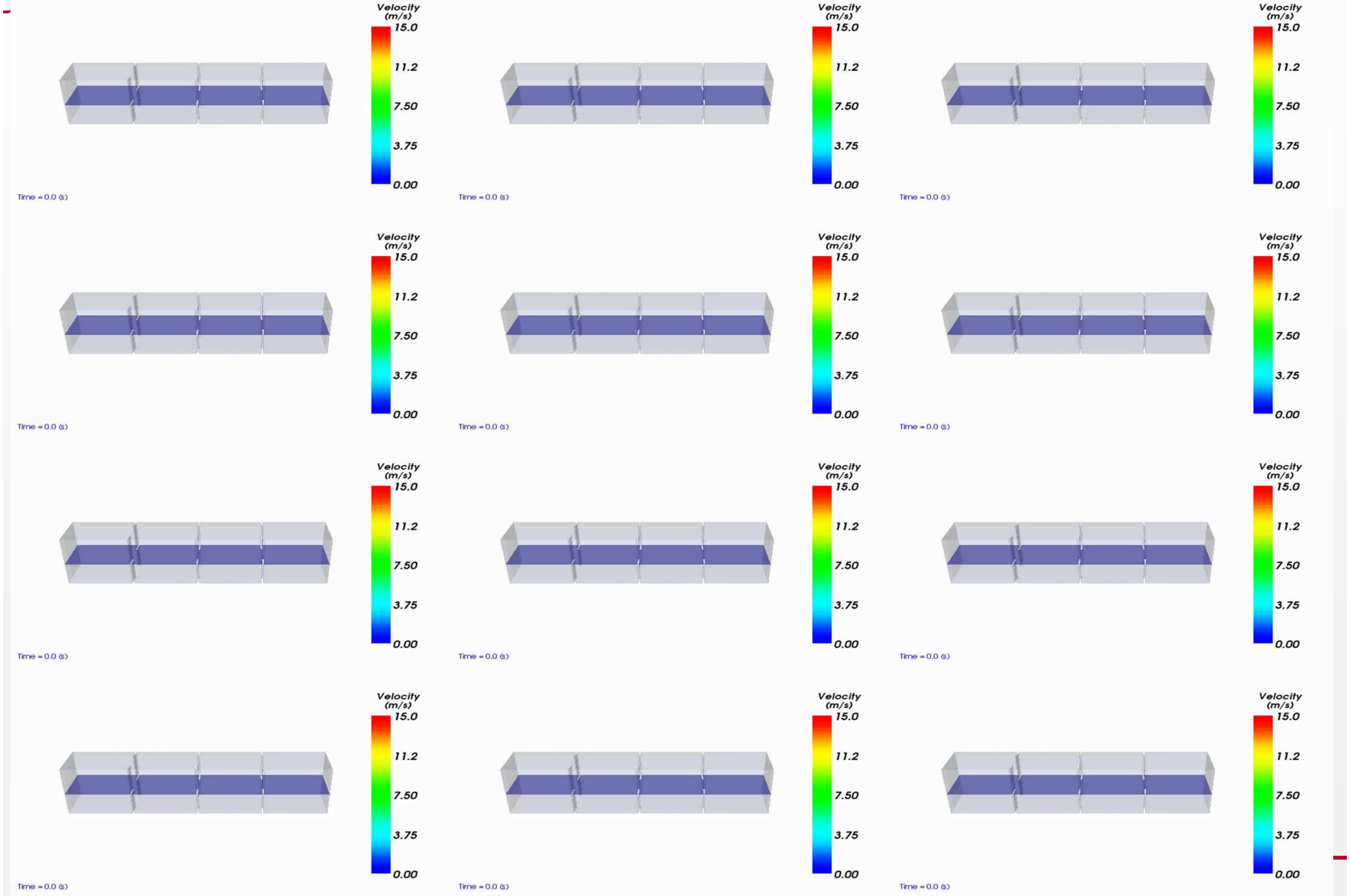
- ► **Tested ART**

CFD Mesh for the ART (3 baffles)

- ▶ **OpenFOAM**
  - Solver interDyMFoam
  - Finite Volume
  - VOF for free surface capturing
  - Laminar model
  - Euler implicit for time scheme
- ▶ **CFD Mesh ⇨ 130 000 cells (convergence study => 250kc & 500kc)**



Vidéos for h=0.2039m ⇨ Acceleration (pptx) = 10 times
Rx=±9dg, T=1.888s (top left) to T=4.585s (bottom right)

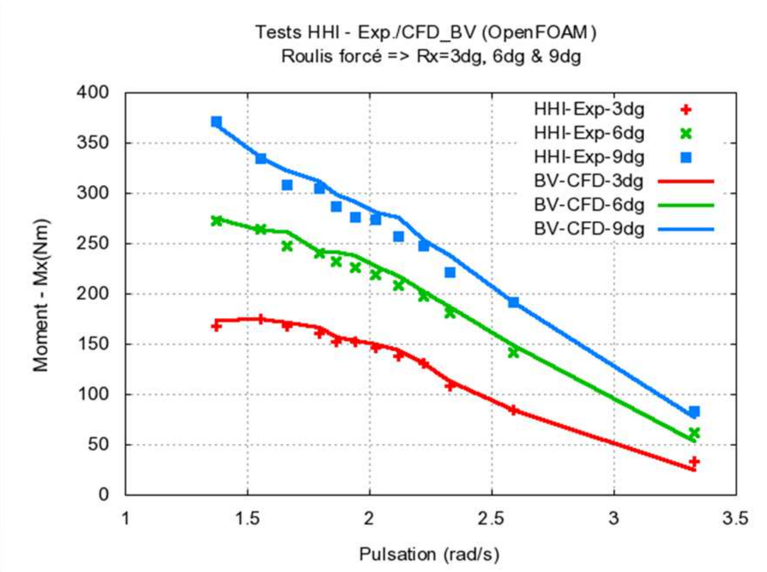


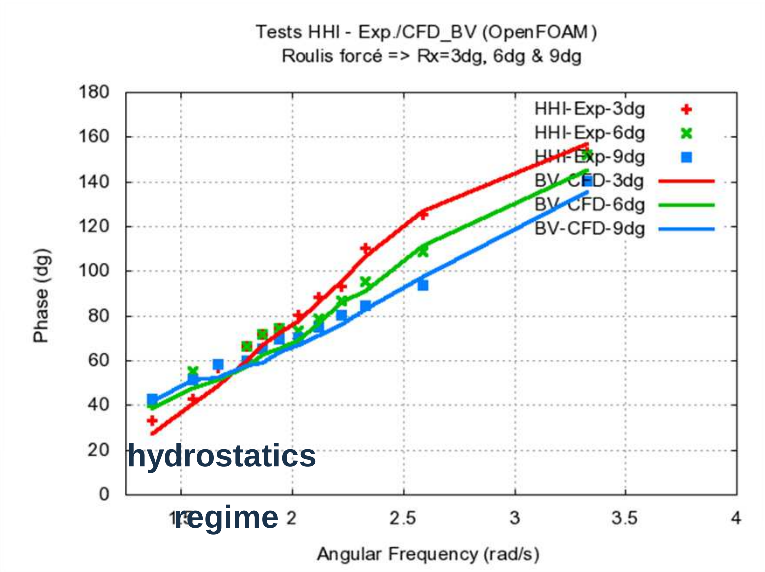
Results for h=0.2039m ⇨ Fourier Decomposition
Comparison Exp.(HHI) / CFD (BV) & Exp.(HHI) / CFD (HHI)

Moment Amplitude

Phase =>

Non-linear behavior of ART





hydrostatics regime

- ► **The liquid global forces due to liquid motions inside ART are well predicted by CFD**
- ► **For forced harmonic roll motions => very good agreement between CFD (BV-OpenFOAM & HHI-Star-CCM+) & Exp. (HHI) for Mx**
  - For all amplitudes
  - For all periods

3. Application to FPU Seakeeping

FPU + 3 ART
Filling Levels => h=2.2m in eaach ART

► **The considered FPU is equipped with 3 ARTs:**

- FPU hydrodynamic mesh

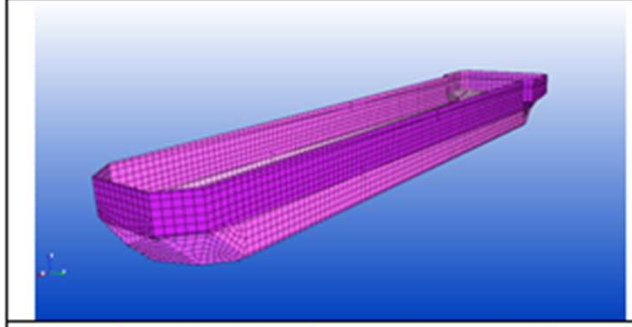


Fig.6a: Hydrodynamic mesh of the considered.

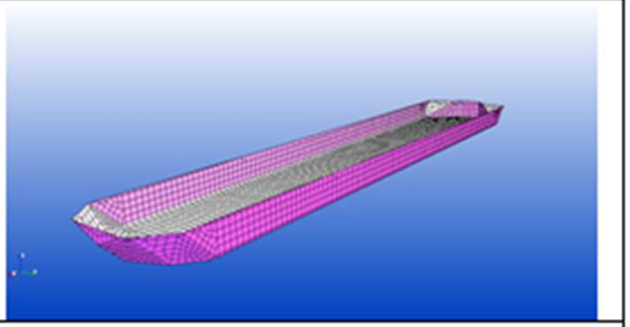


Fig.6b: Hydrodynamic mesh of the wetted part of the ship.

- Each ART has 3 baffles (at1/4, half & 3/4 of the width)

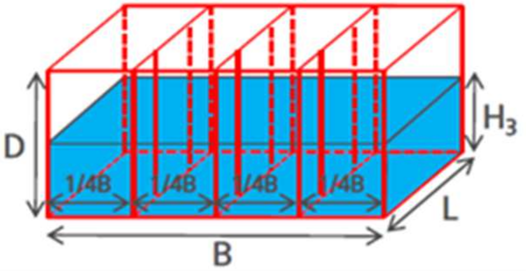
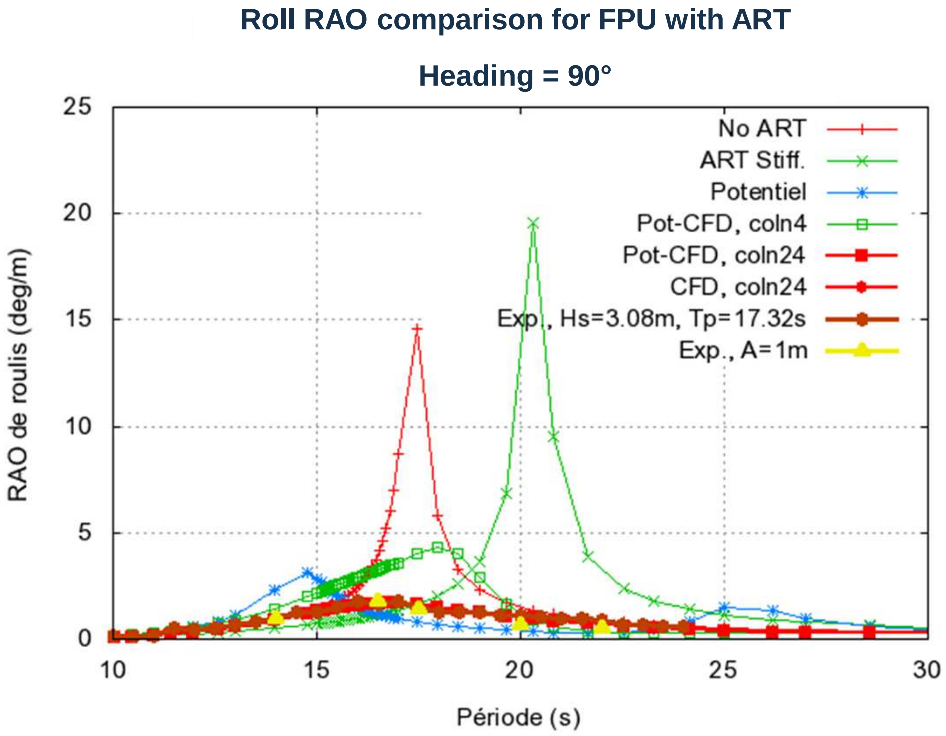


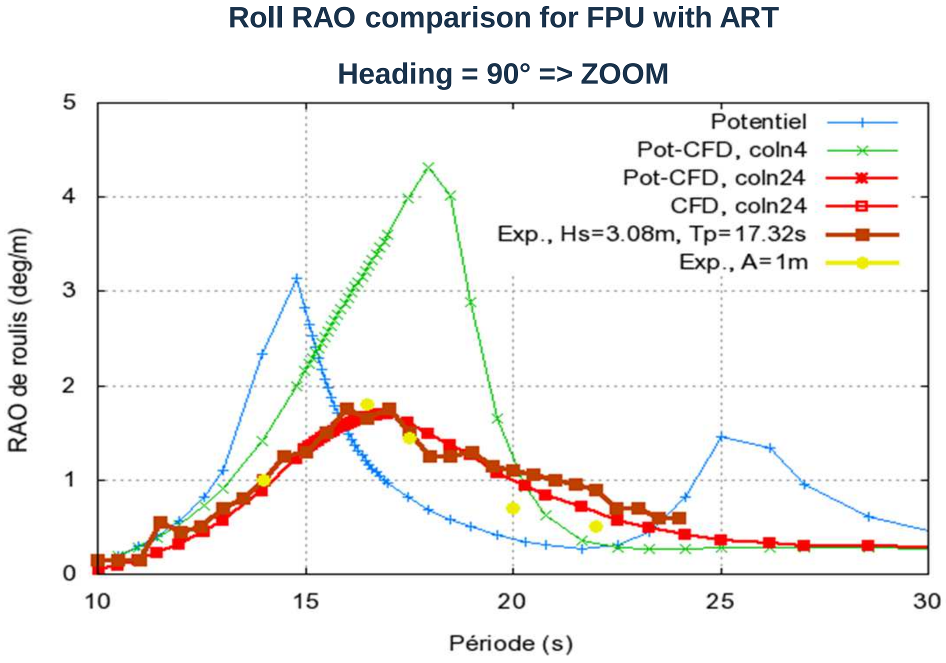
Fig.6c: ART configuration with 3 baffles located at one ¼, ½ and ¾ of tank's breadth.

FPU + 3 ART
RAO Comparisons

- **No_ART** => liquid in ART considered as solid
- **ART_Stiff** => only the ART hydrostatic stifness is considered
- **Potentiel** => ART dynamic effects are evaluated by potential approach
- **Pot-CFD, coln4** => column 4 (forced roll motion ±2°) is evaluated by CFD, the other coeff. are evaluated by potential approach
- **Pot-CFD, coln24** => columns 2, 4 (forced sway ±1m & roll ±2°) are evaluated by CFD, the other coeff. are evaluated by potential approach
- **CFD, coln24** => columns 2, 4 (forced sway & roll) are evaluated by CFD, the other coeff. = 0
- **Exp., Hs=3.08m, Tp=17.32s**: JONSWAP spectrum is considered & Hs=3.08m, Tp=17.32s & γ=3.3
- **Exp., A=1m**, regular wave i.e. ±1m for free surface elevation


Roll RAO comparison for FPU with ART

Heading = 90°


Roll RAO comparison for FPU with ART

Heading = 90° => ZOOM

Intermediate Conclusion

- **ART dynamic effects are to be taken into account**
- **The potential approach for the considered kind of ART is not completely satisfactory:**
  - CFD calculations are to be perfomed
- **The only forced roll motion (column 4) is not sufficient:**
  - Sway forced motion is to be calculated by CFD
- **The coeff. associated with forced sway and roll motions (columns 2 & 4) are sufficient and should calculated by CFD**

- **Here the sway and roll amplitudes were chosen knowing the final results (basin tests).**

- **In practice (without basin tests), which amplitudes are to be considered for**
  - Forced sway motions???
  - Forced roll motions???
  - Iteration procedure for sway and roll amplitudes => complex and time consumming
- **Introduction of Effective Gravity Angle**

4. Effective Gravity Angle (EGA)

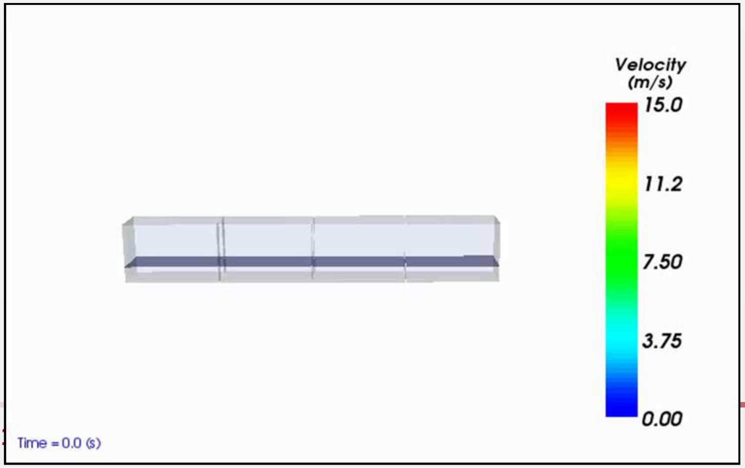
”Effective Gravity Angle” Definition (EGA) In the ART Reference Frame (Non Galilean)

- **EGA quantity, which was first developed to evaluate a mobility criteria (for crew) aboard ships, is used by Carette (MARIN) to study the ART**
- **In the ART reference frame (R’)**
- **EGA definition =>** $\mathrm{EGA(t)} = \mathrm{arctan}\left(\frac{\ddot{\mathrm{y}}(\mathrm{t})}{\ddot{\mathrm{z}}(\mathrm{t})}\right)$
  - $\ddot{\mathrm{y}}(\mathrm{t})$ denotes the transverse acceleration in (R’)
  - $\ddot{\mathrm{z}}(\mathrm{t})$ denotes the vertical acceleration in (R’) including the **gravity (upwards)**

- **EGA => relevant quantity for ART?**
- **For a same EGA at ART’s center volume at rest, do different motions (for instance pure sway or pure roll) give:**
  - Equivalent flows?
  - Identical liquid global forces in (R’)?

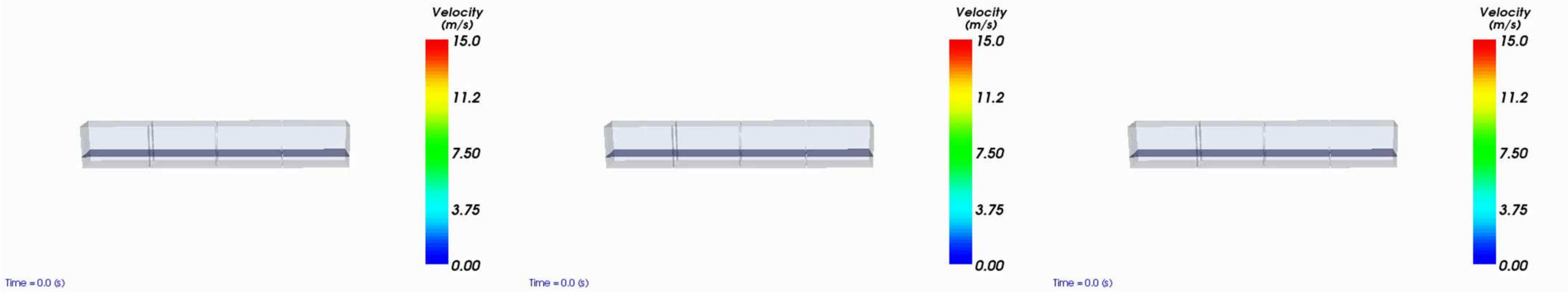
Effective Gravity Angle (EGA)
Particular Cases

- **If pure roll** $\phi(t) = \phi_0 \sin(\omega t)$ **then**
  - $\mathrm{EGA}(t) = \arctan\left(\frac{g \sin(\phi(t))}{g \cos(\phi(t))}\right) = \phi(t)$
  - For pure roll motion, EGA is equal to roll angle
- **If pure sway** $y(t) = y0 \sin(\omega t)$ **then**
  - $\mathrm{EGA}(t) \underbrace{=}_{\mathrm{lin}} \frac{-\omega^2 y_0}{g} \sin(\omega t)$
- **Particular case (sway + roll) / EGA(t)=0 at center volume at rest**
  - => $-\omega^2 y0 + g\phi_0 = 0$ =>



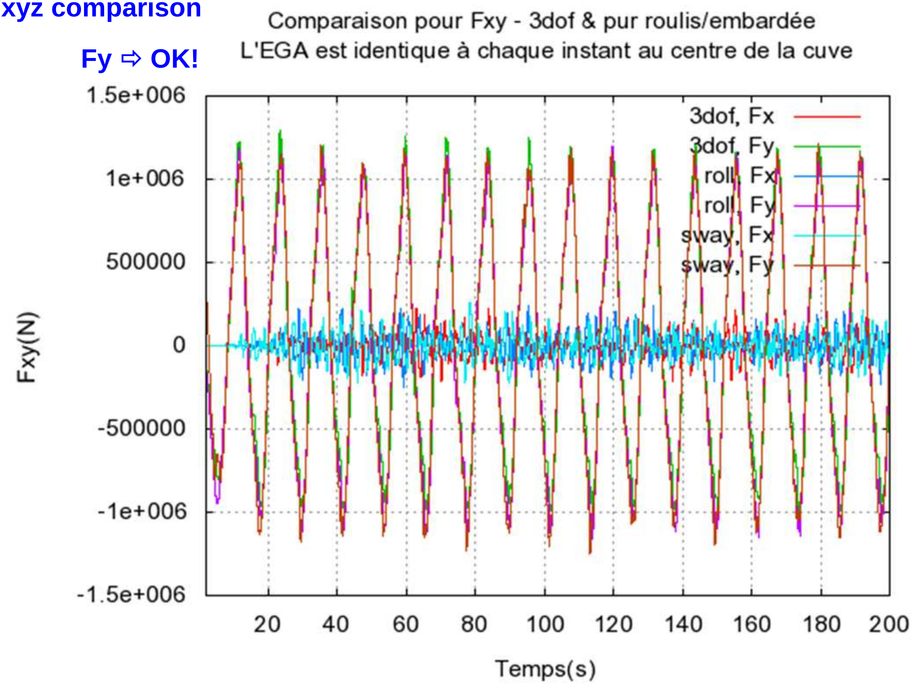
Equivalence 3 d.o.f. / Pure Roll / Pure Sway???
∀ t, EGA=12° at ART's center for all 3 motions

- **Comparaison entre 3 dof / Roulis / Embardée**



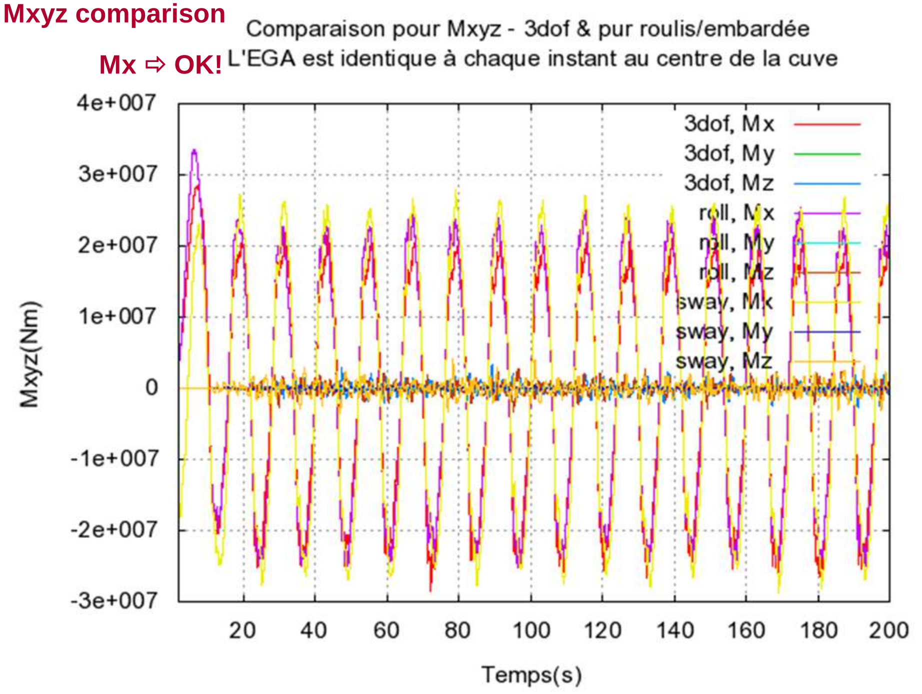
Fxyz comparison

Fy ⇨ OK!



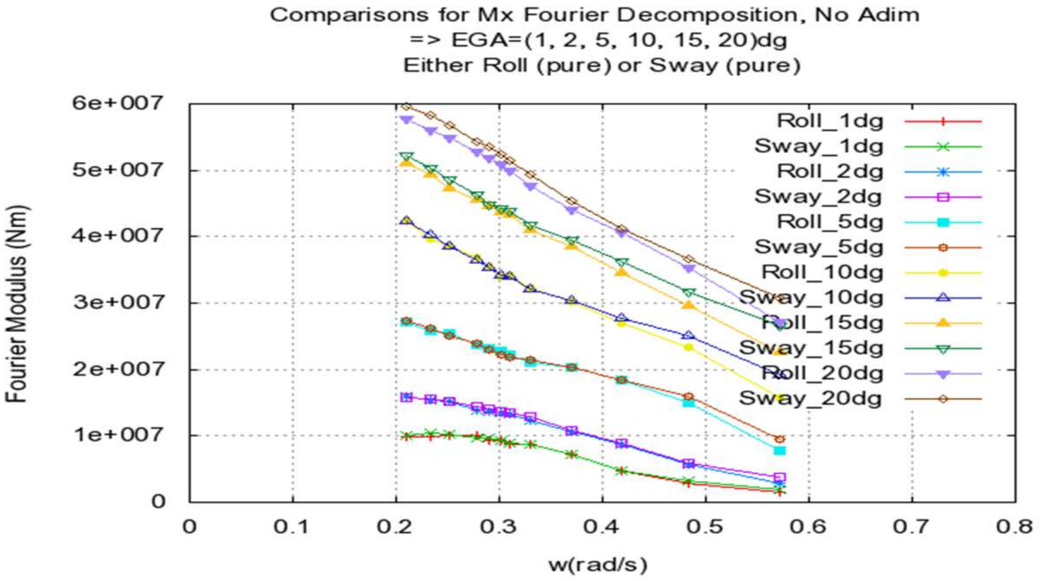
Mxyz comparison

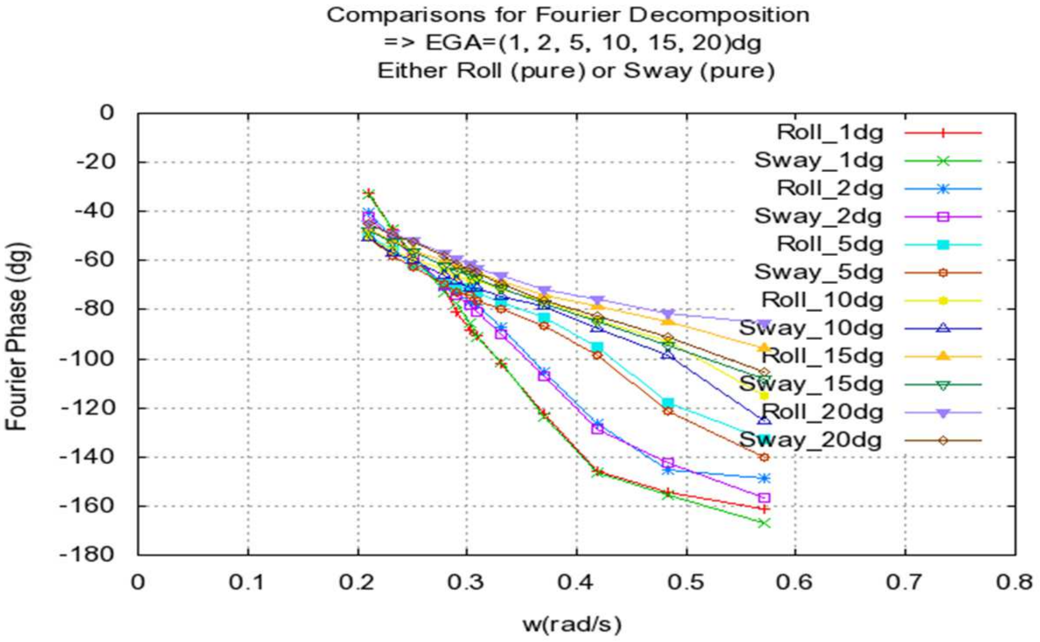
Mx ⇨ OK!



Comparison between Pure Sway & Pure Roll
Same EGA{1°, 2°, 5°, 10, 15°, 20°} ⇨ Mx equivalent? => YES

- ► **Mx comp. for all EGA**
  - Module →
  - Phase →





► **Finally, we can reduce CFD calculations from 6 d.o.f. to 1 d.o.f.**

Coupling with Seakeeping Software

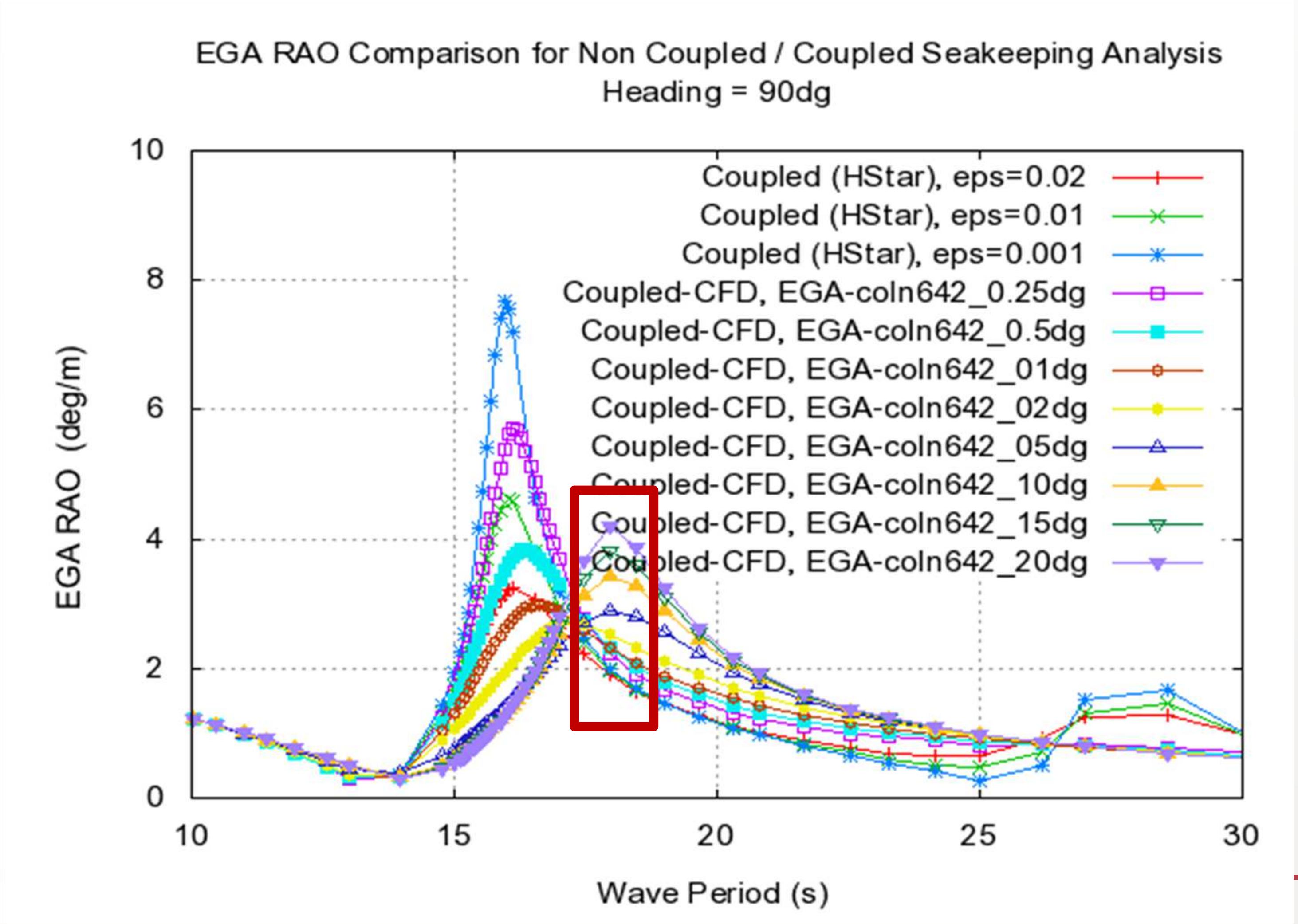
- **ART forces can be written as follows**
  - $\left\{\mathbf{F}_{\mathrm{C}}^{\mathbf{Liq}}\right\}_{|\mathrm{R}'} = \left\{\mathbf{F}_{\mathrm{C}}^{\mathbf{ega}}\right\}_{|\mathrm{R}'} . \mathrm{EGA}_{\mathrm{C}}$ where $\mathrm{EGA}_{\mathrm{C}}$ denotes EGA at the tank's centre of volume
- **EGA is linerised and can be expressed as a function of ship' motions @ centre of gravity (G)**
  - Remind => $\mathrm{EGA}(\mathrm{t}) \stackrel{\mathrm{def}}{=} \arctan\left(\frac{\ddot{\mathrm{y}}(\mathrm{t})}{\ddot{\mathrm{z}}(\mathrm{t})}\right)$
  - $\mathrm{EGA}_{\mathrm{C}} \underbrace{=}_{\mathrm{lin}} [\mathrm{B}]\left\{\boldsymbol{\xi}_{\mathbf{G_0}}\right\}$ with $[\mathrm{B}] = \begin{bmatrix} 0 & \frac{-\omega^2}{\mathrm{g}} & 0 & 1+\frac{\omega^2 \mathrm{Z}_{\mathrm{C}}}{\mathrm{g}} & 0 & \frac{-\omega^2 \mathrm{X}_C}{\mathrm{g}} \end{bmatrix}$
  - where (X_C , Y_C , Z_C) = tank's relative position to CoG
- **Projecting forces from (R') to (R)**
  - $\left\{\mathbf{F}_{G_0}^{\mathbf{Liq}}\right\}_{|R} = \left([\mathrm{F}]^{\mathrm{T}} . [\mathrm{B}]\right)\left\{\boldsymbol{\xi}_{\mathbf{G_0}}\right\}$ => to be transferred in the Left Hand Side of ship's motion equation
- **For each EGA, ship's motion equation is solved**
  - 6 motions RAO are obtained for each EGA
  - EGA RAO is obtained for each EGA
- **Iteration Procedure**
  - EGA(final) = EGA(initial)

5. *Coming Back to FPU Seakeeping for EGA Validation*

Application to Seakeeping Problem for a Regular Wave (T=18.0s)
For each EGA(initail) Value => EGA RAO is obtained

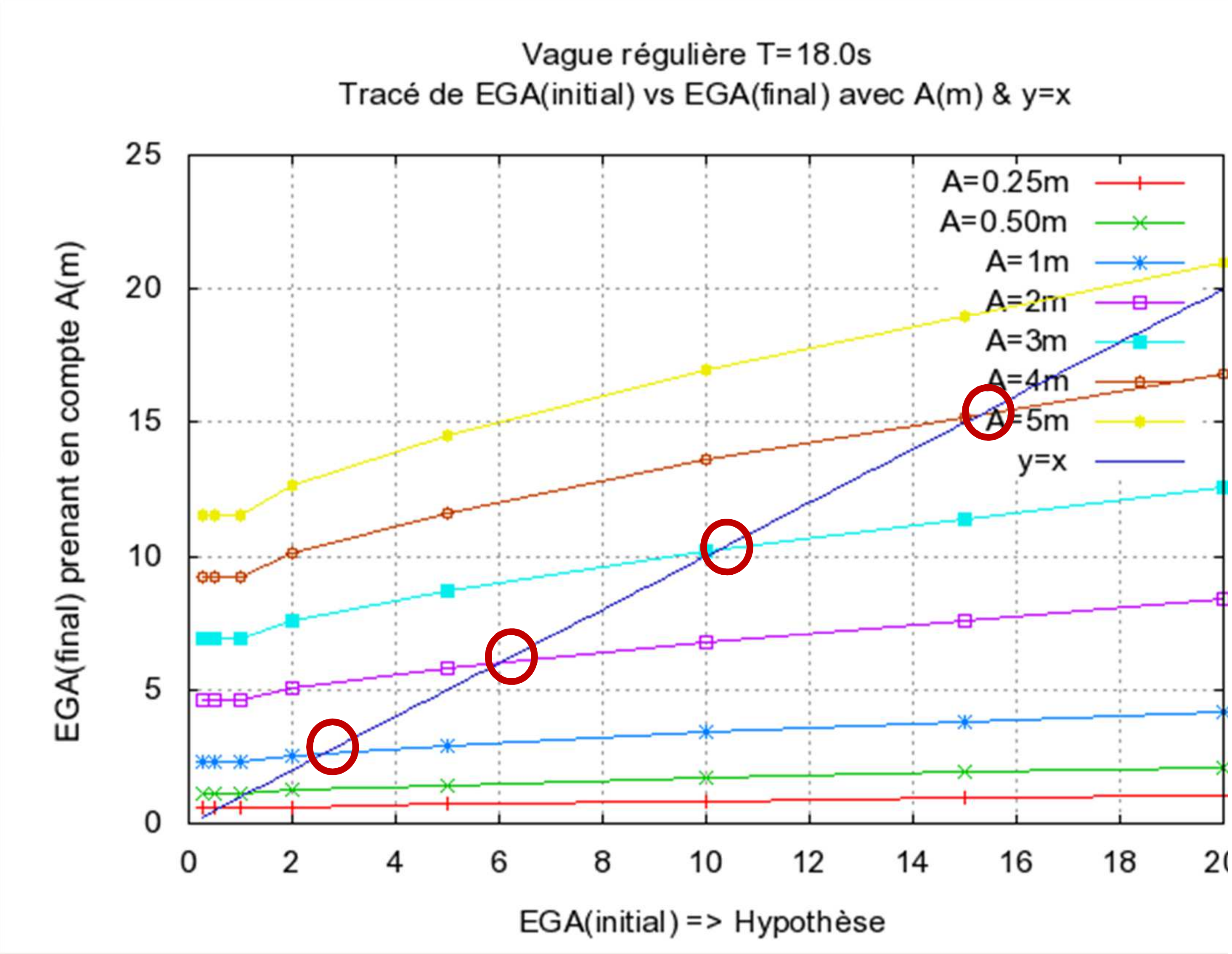
► Application to seakeeping problem

- For each EGA(initial) value {0.25dg,…, 20dg} => EGA RAO is obtained



To be Consistent => Iteration Procedure => EGA(final) = EGA(initial)
For a Regular Wave T=18.0s

- ► The right EGA must satisfy EGA(final)=EGA(initial)



A=Wave amplitude

Si

A=1m => EGA=2.5°

A=2m => EGA=6.0°

A=3m => EGA=10.5°

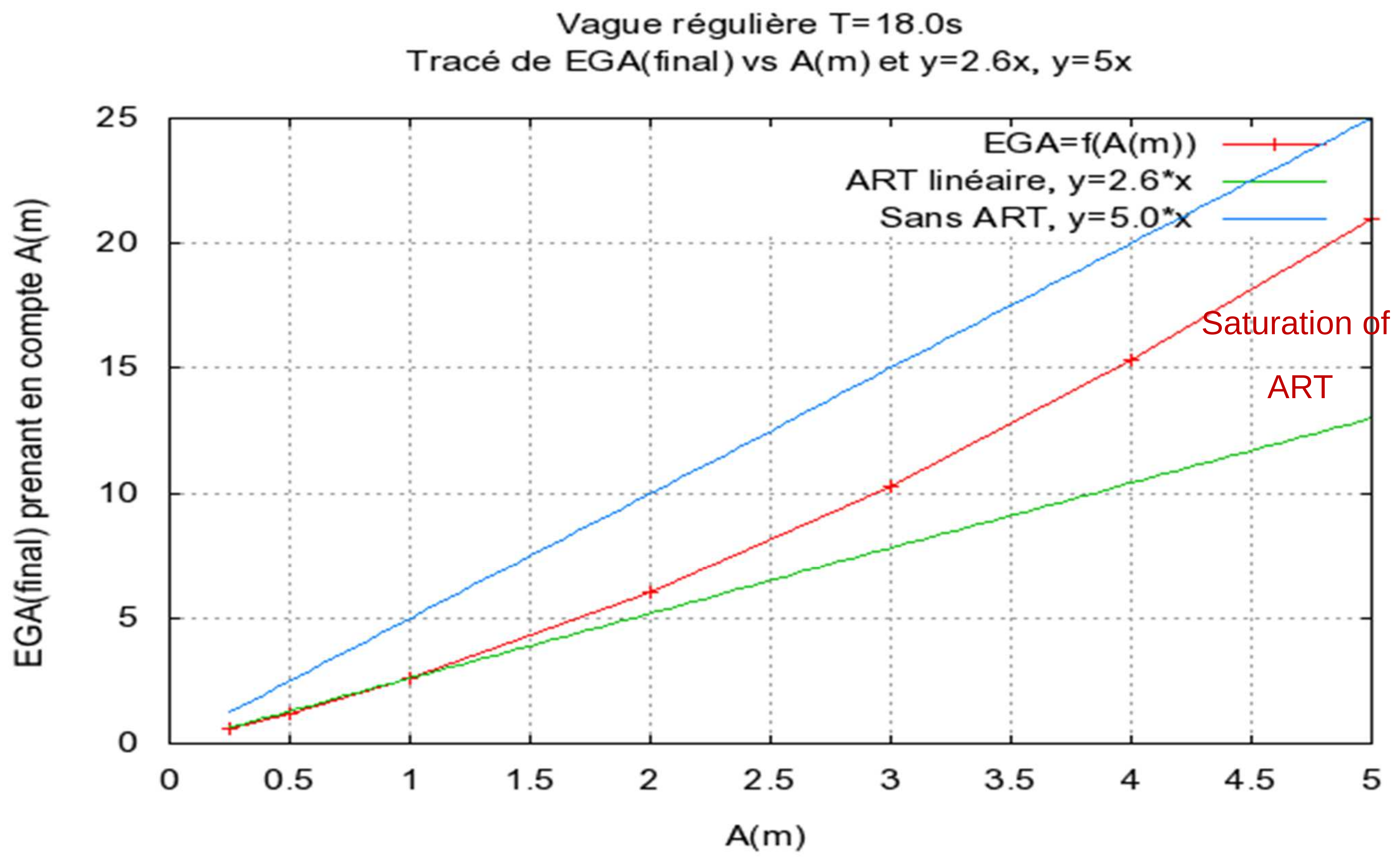
A=4m => EGA=15.0°

…

The non-linearities are taken into account consistently

For a Regular Wave (T=18.0s)
EGA=fct(A)?

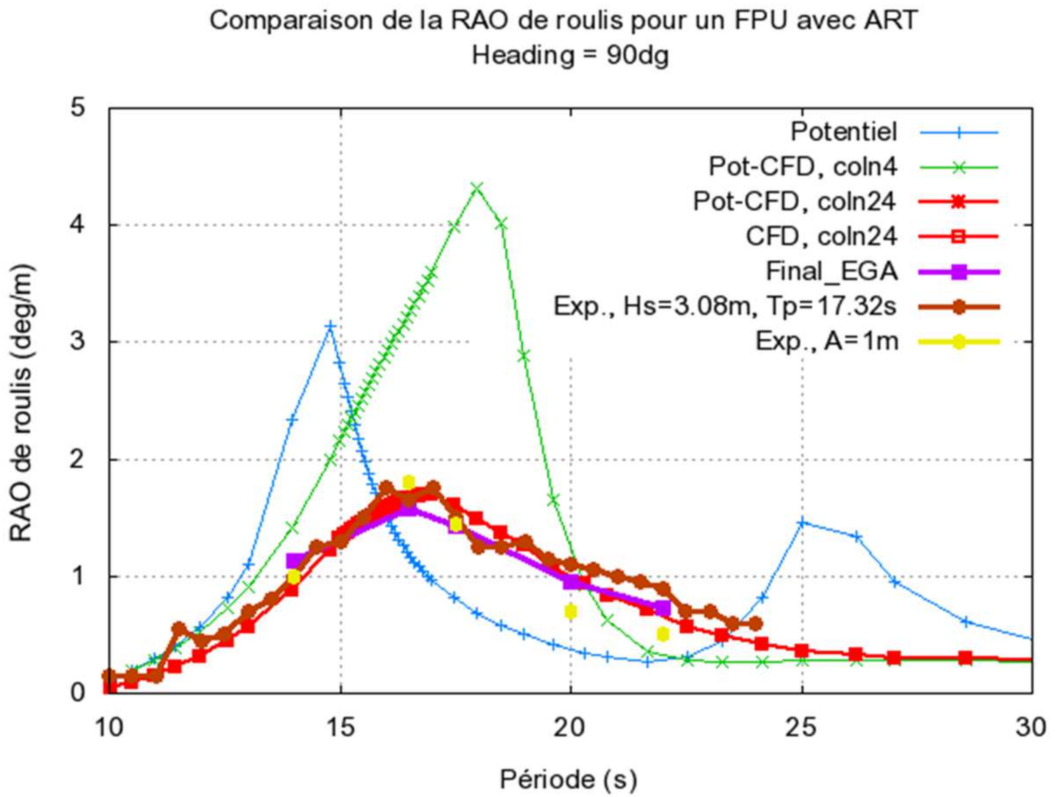
► ART saturation for large EGA



Saturation of ART

Final Application to FPU Seakeeping

- **Very good agreement between the experiments and the final_EGA value**
  - Without any assumption on the amplitude forced motion
- **The method using EGA is relevant and validated for this particular case**
- **Further and systematic validations with higher Hs ({3m, 6m, 9m, 12m, 15m}) like those encountered in North Atlantic are to be carried out**



6. Application to (Small) Container Ship

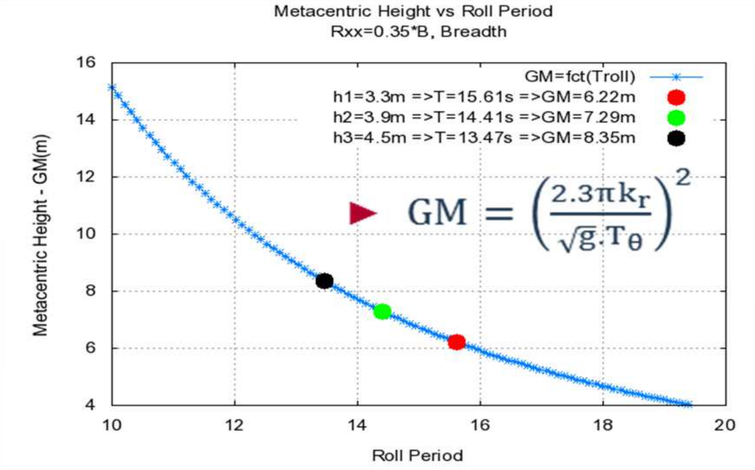
Methodology NR625
Roll Reduction Factor

- **This roll reduction factor depends on GM**
- **Application of NR625 for the evaluation of roll reduction factor for each GM**
  - For each (GM, draft) combination, seakeeping and long-term analyses are performed to compute the extreme roll angle
    - with ART
    - without ART
- **BV NR625 => The roll reduction factor is determined by dividing the extreme long term roll angle including ART with the extreme roll angle θ (without ART) as defined in BV NR 625 Ch 4, Sec 3, [2.1.1]**
- **For each GM, the roll reduction factor is applied to correct the lashing accelerations**

GM vs Draft Operational Data
GM from 1m to 10m are investigated
ART considers 3 operating filling levels

- ► **Operational GM-Draft data are considered**
- ► **For each GM corresponds a roll period**

► $T_\theta = \frac{2.3\pi k_r}{\sqrt{gGM}}$

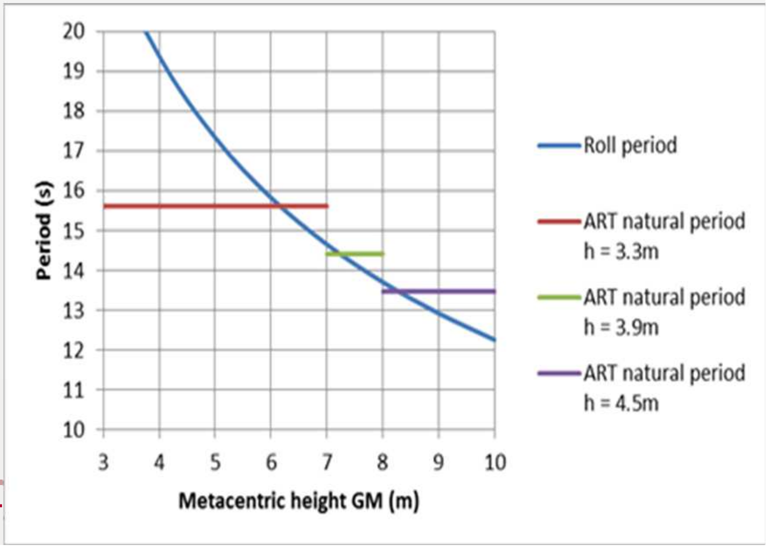


► $$GM = \left(\frac{2.3\pi k_r}{\sqrt{g}.T_\theta}\right)^2$$

- ► **To cover these roll periods, one considers 3 filling levels for their ART**
  - $h = \{3.3, 3.9, 4.5\}m$, Treso=

	h(m)	Troll
h1=	3.3	15.61
h2=	3.9	14.41
h3=	4.5	13.47

  - Operational filling as a function of GM →

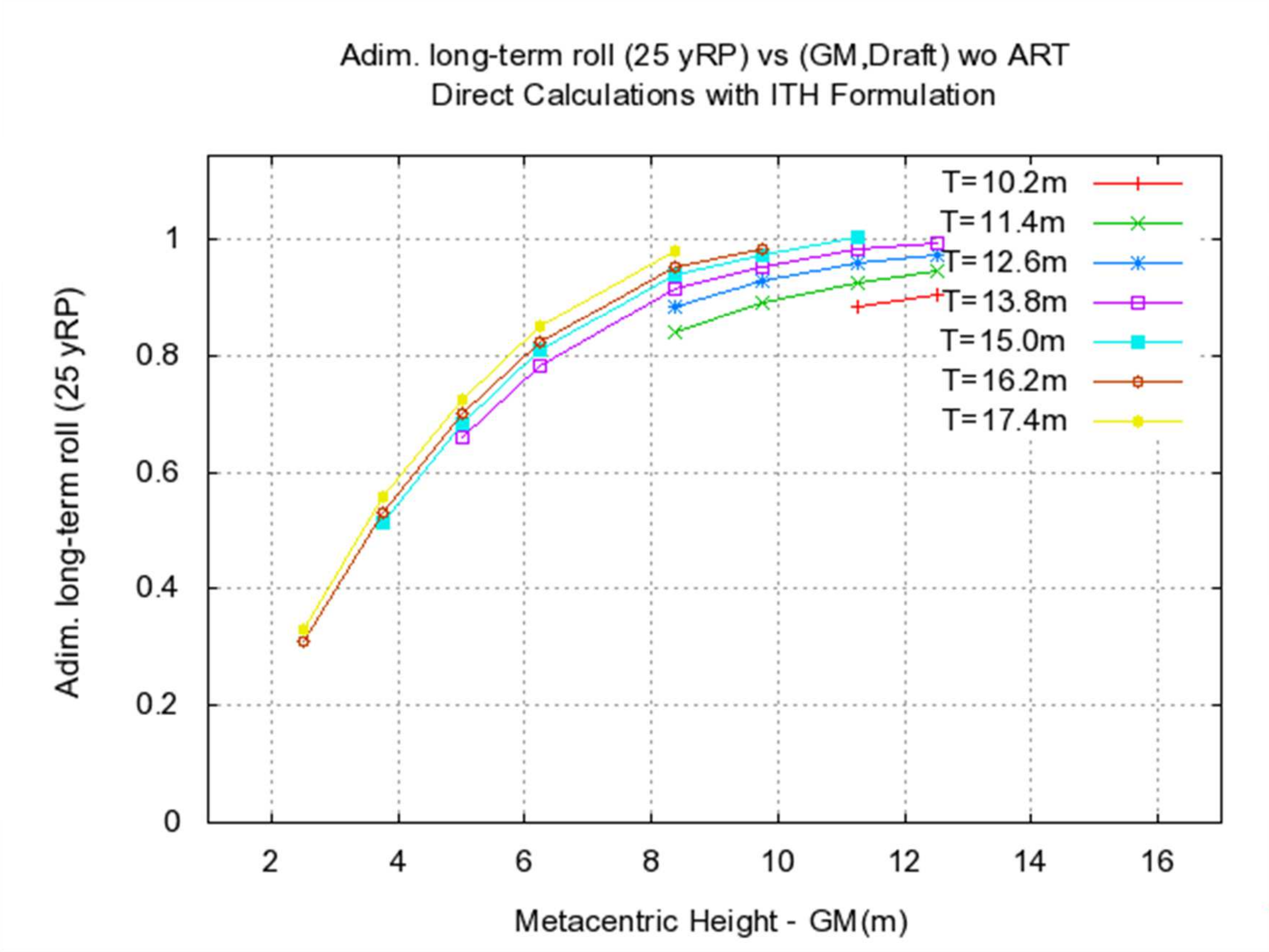


Assumptions for Seakeeping Analysis

- **Approx. 10kTEU container ship is considered**
- **For long term calculations, a 25 year return period is considered**
- **V=5 knots**
- **Infinite water depth**
- **North Atlantic scatter diagram (BV NI611)**
- **ITH formulation is used to take into account bilge keels**
  - (BLIN, BQUAD) are evaluated with ITH formulation
- **Seakeeping calculations & long term analysis**
  - Without ART
  - With ART
- **ART response is calculated using CFD calculations**
  - 3 filling levels, 9 amplitudes, 24 periods
  - => 648 CFD calculations (forced roll motions) were carried out
- **Using Effective Gravity Angle, ART sway response is evaluated**

Adimensionalized Extreme Roll Response for 25 year Return Period

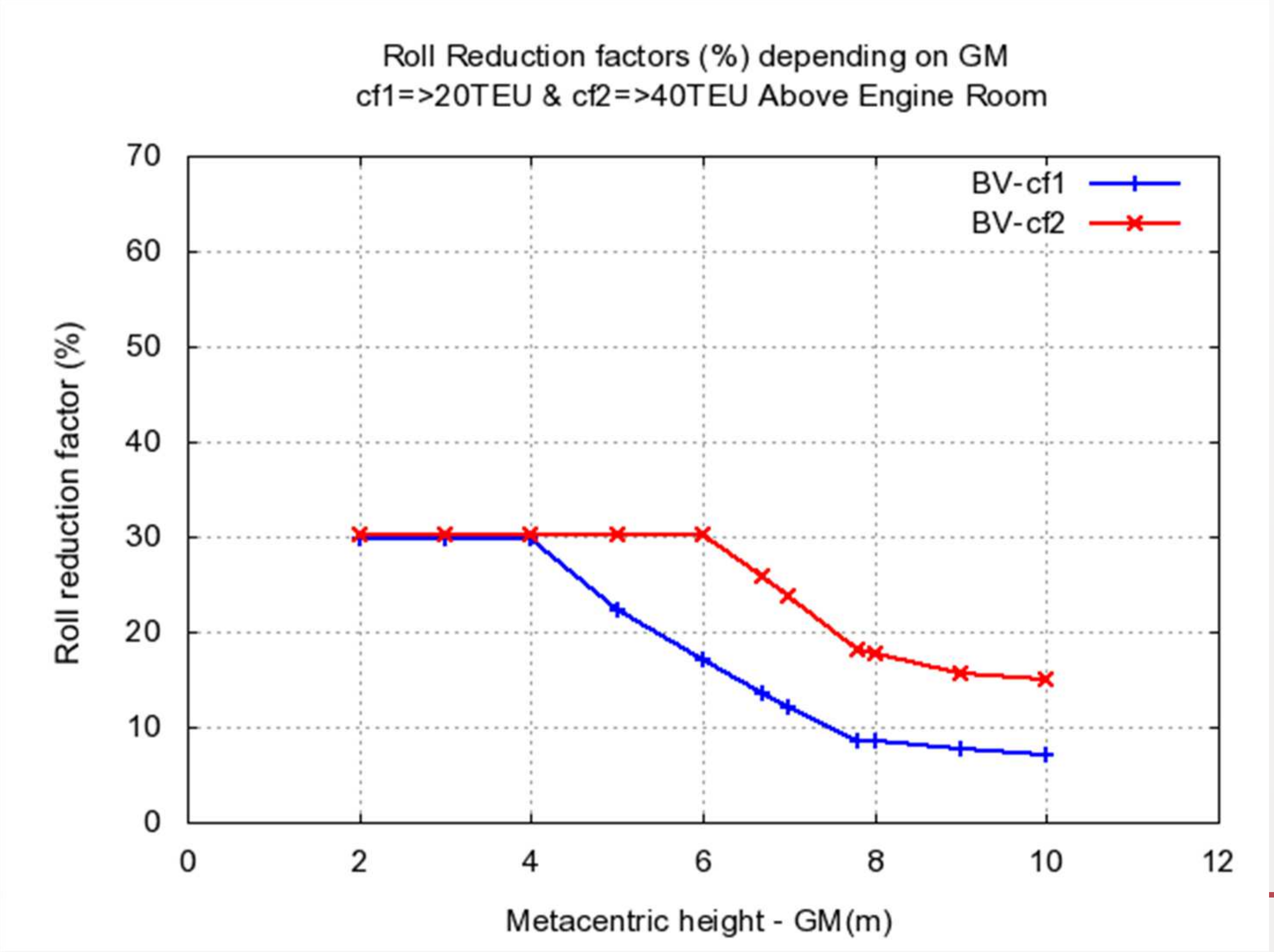
- ► **All operational (GM, T) are considered**



Roll Reduction Factors for the Container Ship

► **The following roll reduction factors depending on GM are derived**

9300 TEU, V=5 knots, GM=	2	3	4	5	6	7	8	9	10
cf1 - 20TEU Above Engine Room	30	30	30	22	17	12	8	8	7
cf2 - 40TEU Above Engine Room	30	30	30	30	30	24	18	16	15



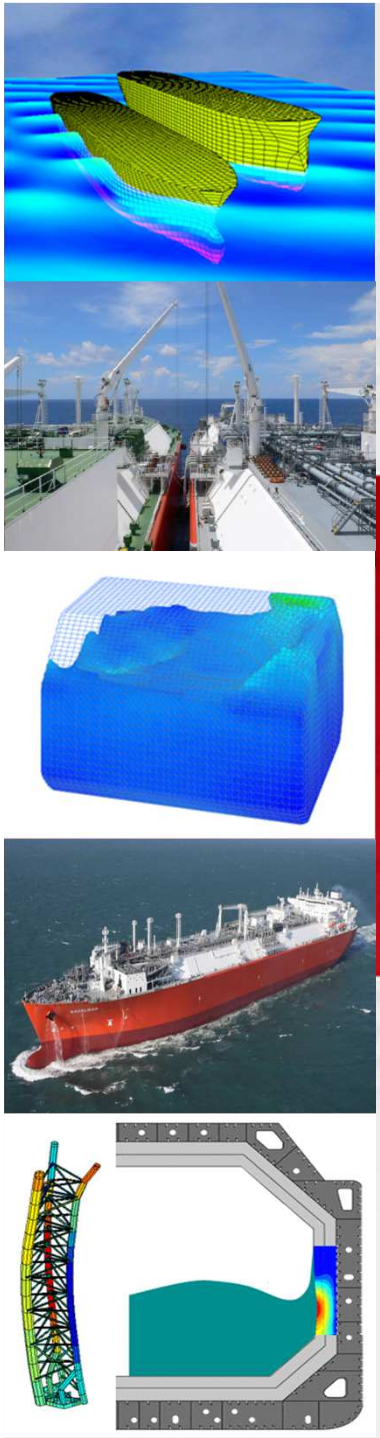
Conclusion

- For a 10kTEU (approx.), the roll reduction factor was obtained considering long term approach
  - $Roll\_reduction\_factor = \frac{Roll(25year, with\ ART)}{Roll(25\ year, without\ ART)}$
- Accroding NR625, this roll reuction factor can be taken into account for the evaluation of lashing forces
- The roll reduction factor here obtained for a 10kTEU container ship will be even larger on a bigger container ship
- Installation of ART is also a way how to mitigate parametric roll
- ART optimization can be carried out
  - Number of nozzle plates
  - Nozzle plate area

7. *Conclusion & Discussion*

Conclusion

- **CFD is validated for the calculations of liquid global forces for ART**
- **Forced sway & roll motions (model tests / CFD) are sufficient for seakeeping**
- **Effective Gravity Angle (EGA) quantity is used**
  - If same EGA (∀ t) at ART center then
    - ∀ motion => Forces (Fy, Mx) identical in the ART reference frame
- **EGA is linearized and expressed in terms of ship motions**
- **For each EGA, ship motion equation is solved:**
  - For each EGA => Motions RAO => EGA RAO
  - The final EGA must satisfy EGA(final) = EGA(initial)
- **EGA is validated through CFD/Exp. comparisons for a FPU (HHI experiments)**
- **Application to existing container ship (approx. 10kTEU) is presented**
  - NR625 regarding ART is presented
  - Roll reduction factor is obtained
- **Accroding NR625, roll reduction factor can be applied for the evaluation of lashing forces**



MULTIPHASE 2017

Numerical Study of Anti-Roll Tanks

PARIS, October 2017

Louis DIEBOLD

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