MULTIPHASE 2017
Numerical Study of Anti-Roll Tanks
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Move Forward with Confidence*
*Avançons en confiance
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 response 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?
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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)
Galilean reference frame \( \{G_0, \bar{x}, \bar{y}, \bar{z}\} \)

Within linear seakeeping in the frequency domain, ship’s motion equation with anti-roll tanks \{ship + tanks\} can be written:

\[
\begin{align*}
( -\omega^2 ( [M_{G_0}^{notk}] + [A_{G_0}] ) - i\omega [B_{G_0}] + [C_{G_0}] ) \{\xi_{G_0}\} &= \{F_{G_0}^{DI}\} + \{F_{G_0}^{Liq}\} \\
[M_{G_0}^{notk}] &= \text{inertia matrix without equivalent solid inertia of ART} \\
[A_{G_0}], [B_{G_0}], [C_{G_0}] &= \Rightarrow \text{added mass, damping & hydrostatic stiffness} \\
\{\xi_{G_0}\} &= \Rightarrow 6 \text{ rigid body motions (6 dof)} \\
\{F_{G_0}^{DI}\} &= \Rightarrow \text{incident wave + diffraction forces} \\
\{F_{G_0}^{Liq}\} &= \Rightarrow \text{forces due to liquid internal motions within ART}
\end{align*}
\]
**Ship Motion Equation \{Ship + Anti-Roll Tanks\}**

**Linear Seakeeping in Frequency Domain**

- **ART forces can be decomposed as follows:**

  - \( \{F_{G0}^{Liq}\} = (-[D_{G0}^{Re}] - i[D_{G0}^{Im}])\{\xi_Q\} \)
  - \( [D_{G0}^{Re}] \) => stiffness matrix for ART
  - \( [D_{G0}^{Im}] \) => damping matrix for ART

- **These matrices \([D_{G0}^{Re}]\) & \([D_{G0}^{Im}]\) 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)**

\[
\begin{bmatrix}
D_{G0_{11}}^{Re,Im} \text{(pot)} & D_{G0_{12}}^{Re,Im} \text{(cfd)} & D_{G0_{13}}^{Re,Im} \text{(pot)} & D_{G0_{14}}^{Re,Im} \text{(cfd)} & D_{G0_{15}}^{Re,Im} \text{(pot)} & \ldots \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
D_{G0_{61}}^{Re,Im} \text{(pot)} & D_{G0_{62}}^{Re,Im} \text{(cfd)} & D_{G0_{63}}^{Re,Im} \text{(pot)} & D_{G0_{64}}^{Re,Im} \text{(cfd)} & D_{G0_{65}}^{Re,Im} \text{(pot)} & \vdots
\end{bmatrix} = [D_{G0}^{Re,Im}]
\]

- 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

► 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 $h=0.2039\text{m}$ ⇒ Acceleration (pptx) = 10 times $R_x=\pm9\text{dg}$, $T=1.888\text{s}$ (top left) to $T=4.585\text{s}$ (bottom right)
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
The considered FPU is equipped with 3 ARTs:

- FPU hydrodynamic mesh

- Each ART has 3 baffles (at 1/4, half & 3/4 of the width)

Fig. 6a: Hydrodynamic mesh of the considered.

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

Fig. 6c: ART configuration with 3 baffles located at one 1/4, 1/2 and 3/4 of tank’s breadth.
FPU + 3 ART
RAO Comparisons

- **No_ART** => liquid in ART considered as solid
- **ART Stiff** => only the ART hydrostatic stiffness 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
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 performed
- 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 be 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 consuming
- 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 \(\Rightarrow EGA(t) = \arctan\left(\frac{\ddot{y}(t)}{\ddot{z}(t)}\right)\)
  - \(\ddot{y}(t)\) denotes the transverse acceleration in (R’)
  - \(\ddot{z}(t)\) denotes the vertical acceleration in (R’) including the gravity (upwards)

- EGA \(\Rightarrow\) 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

- $EGA(t) = \arctan\left(\frac{\sin(\phi(t))}{\cos(\phi(t))}\right) = \phi(t)$
- For pure roll motion, EGA is equal to roll angle

► If pure sway $y(t) = y_0 \sin(\omega t)$ then

- $EGA(t) = -\frac{\omega^2 y_0}{g} \sin(\omega t)$

► Particular case (sway + roll) / $EGA(t)=0$ at center volume at rest

- $\Rightarrow -\omega^2 y_0 + g\phi_0 = 0 \Rightarrow$
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

**F_xyz comparison**

Fy ⇒ OK!

**M_xyz 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
  \[ \left\{ F_{\text{Liq}}^C \right\}_{R'} = \left\{ F_{\text{ega}}^C \right\}_{R'} \cdot \text{EGA}_C \]
  where EGA\(_C\) 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 \(\Rightarrow\) EGA(t) \(\triangleq\) arctan\(\left( \frac{y(t)}{z(t)} \right)\)
  - EGA\(_C\) \(\triangleq\) lim \(\left[ B \right] \{ \xi_{G_0} \}\) with \(\left[ B \right] = \begin{bmatrix} 0 & -\omega^2 & 0 & 1 + \frac{\omega^2 Z_0}{g} & 0 & -\omega^2 X_0 \end{bmatrix} \)
  - where \((X_C, Y_C, Z_C) =\) tank’s relative position to CoG

- Projecting forces from (R’) to (R)
  \[ \left\{ F_{G_0}^\text{Liq} \right\}_R = \left( [F]^T \cdot [B] \right) \{ \xi_{G_0} \} \Rightarrow \text{to be transferred in the Left Hand Side of ship’s motion equation} \]

- 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(initial) Value => EGA RAO is obtained

► Application to seakeeping problem

- For each EGA(initial) value \{0.25\text{dg}, \ldots, 20\text{dg}\} => 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

Vague régulière T=18.0s
Tracé de EGA(final) vs A(m) et y=2.6x, y=5x

EGA=f(A(m))
ART linéaire, y=2.6*x
Sans ART, y=5.0*x

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
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 $\theta$ (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

\[ T_0 = \frac{2.3\pi k_r}{\sqrt{gGM}} \]

- To cover these roll periods, one considers 3 filling levels for their ART

<table>
<thead>
<tr>
<th>h(m)</th>
<th>Troll</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>15.61</td>
</tr>
<tr>
<td>3.9</td>
<td>14.41</td>
</tr>
<tr>
<td>4.5</td>
<td>13.47</td>
</tr>
</tbody>
</table>

- 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
The following roll reduction factors depending on GM are derived:

<table>
<thead>
<tr>
<th>9300 TEU, V=5 knots, GM=</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>cf1 - 20TEU Above Engine Room</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>22</td>
<td>17</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>cf2 - 40TEU Above Engine Room</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>24</td>
<td>18</td>
<td>16</td>
<td>15</td>
</tr>
</tbody>
</table>

![Roll Reduction factors (%) depending on GM](image)
Conclusion

► For a 10kTEU (approx.), the roll reduction factor was obtained considering long term approach

\[
Roll_{\text{reduction\_factor}} = \frac{\text{Roll(25 year, with ART)}}{\text{Roll(25 year, without ART)}}
\]

► According NR625, this roll reduction 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
- According NR625, roll reduction factor can be applied for the evaluation of lashing forces
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