Physical and numerical modeling of mooring systems of floating Wave Energy Converters

SDWED 2nd Symposium - Copenhagen, April 26th, 2012
Motivation

Moorings

Power production

Project feasibility

Wave farm layout

Devices stability
Outline

• Extreme waves: survivability
• Operational wave climate: power production
• Procedure for preliminary mooring design and optimization
Physical model tests

Extreme climate – WAVE DRAGON

Typical climate - DEXA
Physical model tests

Extreme climate – WAVE DRAGON

Typical climate - DEXA
Experience with Wave Dragon

• **Aims:**
  – Measure the loads on WD and on the mooring lines in extreme conditions;
  – Evaluate the WD hydrodynamic behavior;
  – Determine the relevance of some selected parameters (freeboard level $R_c$, mooring stiffness, wave condition, device stability).
  – Check the efficacy of the survivability mode.

• **Where:** Aalborg deep water wave basin

• **When:** September-December 2010

• **Model:** 1 : 51.8 scale model of Wave Dragon
## Wave conditions

<table>
<thead>
<tr>
<th>WS</th>
<th>Sop</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tr10</td>
<td>-1</td>
<td>0.154</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.154</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>+1</td>
<td>0.165</td>
<td>1.82</td>
</tr>
<tr>
<td>Tr50</td>
<td>-1</td>
<td>0.174</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0.174</td>
<td>1.917</td>
</tr>
<tr>
<td></td>
<td>+1</td>
<td>0.187</td>
<td>1.917</td>
</tr>
<tr>
<td>Tr100</td>
<td>0</td>
<td>0.193</td>
<td>2.015</td>
</tr>
</tbody>
</table>

Water depth: $h=0.65$ m
**Mooring scheme**

- **Main line**
  - Rubber band
  - Stiffness: 460 [N/m]
  - Pretension: 11.5 [N]

- **Rear lines**
  - Rubber band
  - Stiffness: 300 [N/m]
  - Pretension: 13.3 [N]

- **Arms cable**
  - Synthetic rope
  - Stiffness: 21 [N/m]
  - Pretension: 8.4 [N]
Extreme forces

\[ F_{nd} = F_{1,250} / (\rho \, g \, Hm0 \, Ac) \]

- High Rc
- Mid Rc, low stability
- Mid Rc, high stability
- Low Rc
Extreme movements

\[ \text{Snd} = \text{Surge}_{1.250}/\text{Hm0} \]

- High Rc
- Mid Rc, low stability
- Mid Rc, high stability
- Low Rc
**Effect of the mooring stiffness**

\[ F_{nd} = \frac{F_{1/250}}{(p \cdot g \cdot H_{0} \cdot A_{c})} \cdot [-] \]

\[ S_{nd} = \frac{S_{1/250}}{H_{0}} \cdot [-] \]

- MMst0 - high Rc
- MMst0 - low Rc
- MMst1 - high Rc
- MMst1 - low Rc

Graph showing the relationship between \( F_{nd} \) and \( H_{0}/Rc \), and \( S_{nd} \) and \( H_{0}/Rc \).
Physical model tests

Extreme climate – WAVE DRAGON

Typical climate - DEXA
Experience with DEXA

• **Aims:**
  – Evaluate power production and wave transmission in operational conditions;
  – Underline the effects of moorings on DEXA’s performances;
  – Assess the effects on mooring systems induced by the placement in wave farms,
  – Check the scale effects and the consequences of tide and climate change.

• **Where:** Aalborg deep water wave basin
• **When:** January-March 2011
• **Model:** 1:30 and 1:60 scale model of DEXA
# Wave conditions

<table>
<thead>
<tr>
<th>WS</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
<th>WS</th>
<th>$H_s$ [m]</th>
<th>$T_p$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
<td>0.74</td>
<td>5</td>
<td>0.067</td>
<td>1.01</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>0.84</td>
<td>6</td>
<td>0.067</td>
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<tr>
<td>3</td>
<td>0.05</td>
<td>1.01</td>
<td>7</td>
<td>0.083</td>
<td>1.01</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
<td>1.37</td>
<td>8</td>
<td>0.083</td>
<td>1.37</td>
</tr>
</tbody>
</table>

- **Water depth:** $h=0.6$ m
- **Wave obliquities:** $0^\circ$, $15^\circ$ and $30^\circ$
Mooring schemes

<table>
<thead>
<tr>
<th>SPREAD mooring</th>
<th>CALM mooring</th>
</tr>
</thead>
<tbody>
<tr>
<td>N° of lines</td>
<td>4</td>
</tr>
<tr>
<td>Line type</td>
<td>Steel chains</td>
</tr>
<tr>
<td>Length</td>
<td>3 m</td>
</tr>
<tr>
<td>Weight</td>
<td>1 kg/m</td>
</tr>
<tr>
<td>Angle</td>
<td>45°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N° of lines</th>
<th>4 + 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line type</td>
<td>chains/rubber band</td>
</tr>
<tr>
<td>Length</td>
<td>3 m /1.3 m</td>
</tr>
<tr>
<td>Weight</td>
<td>1 kg/m</td>
</tr>
<tr>
<td>Angle</td>
<td>45°/0°</td>
</tr>
</tbody>
</table>
Power production

$P_m$ [W] vs $l/L_P$ [-]

- Spread 0°
- Spread 15°
- Spread 30°
- CALM 0°
- CALM 15°
- CALM 30°
Device efficiency

\( \eta [\text{-}] \)

\( \frac{l}{L_p} [\text{-}] \)

- Spread 0°
- Spread 15°
- Spread 30°
- CALM 0°
- CALM 15°
- CALM 30°
Observations and conclusions

• The efficiency of the device is highest when DEXA length is around peak wave length (l/Lp≈1);
• A CALM mooring configuration allows larger movements and improves the power production (0° direction);
• In case of oblique placement of the device, the difference between the efficiency curve for CALM and spread mooring decreases.
What is missing?

• Tests with operational wave conditions did not provide simultaneous information on mooring forces and device motions.
• Tests with extreme wave conditions did not represent a real mooring system.
• Since combined motion-forces measurements are not available
  – Plan for new tests in Aalborg
  – There are insufficient data for model validation and calibration
Numerical model tests

• Step 1: preliminary chain design in static conditions (catenary equation)

• Step 2: parametric modelling of the mooring resistance and device stability (maximum loads)

• Step 3: optimization of the mooring scheme (maximum movements)

• Step 4: response of the optimized scheme to wave direction
The Ansys AQWA code

- AQWA-LINE
- AQWA-LIBRIUM
- AQWA-FER
- AQWA-DRIFT
- AQWA-NAUT

WorkBench

Hydrodynamic Diffraction

Hydrodynamic Time Response
Modelling with AQWA

INPUT

• Definition of the geometry;
• Mass distribution and inertia;
• Wave, wind and current;
• Water depth.

OUTPUT

• Radiated/diffracted field around the device;
• Motion time series in the 6 dof;
• Non linear mooring forces time series.
Numerical setup

- Dimension and weight may represent a DEXA in 1:3 scale with respect to the North Sea prototype.
- Extreme sea states correspond to the Northern Adriatic Sea.
Numerical model tests

• Step 1: preliminary chain design in static conditions (catenary equation)
  • Step 2: parametric modelling of the mooring resistance and device stability (maximum loads)
  • Step 3: optimization of the mooring scheme (maximum movements)
  • Step 4: response of the optimized scheme to wave direction
Preliminary design

Catenary equation

Input

Output
Preliminary design

<table>
<thead>
<tr>
<th></th>
<th>L [m]</th>
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<th></th>
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<tbody>
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<td>100</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>120</td>
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<td>X</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>140</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
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<td>0.054</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
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<td>X</td>
<td>X</td>
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<td>X</td>
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<tr>
<td></td>
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<td>X</td>
<td>X</td>
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<tr>
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<td>X</td>
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<td>X</td>
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<tr>
<td></td>
<td>125</td>
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<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>D [m]</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.06</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>0.064</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>0.07</td>
<td>X</td>
<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Δx [m]</th>
<th></th>
<th></th>
<th></th>
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<tr>
<td></td>
<td>85</td>
<td>X</td>
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<td></td>
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<td></td>
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<td>X</td>
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<td></td>
<td>125</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Characteristics of the chains

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>D [mm]</td>
<td>54</td>
<td>60</td>
<td>64</td>
</tr>
<tr>
<td>w [kg/m]</td>
<td>62.6</td>
<td>78</td>
<td>87</td>
</tr>
<tr>
<td>A [m²]</td>
<td>0.00458</td>
<td>0.00565</td>
<td>0.0064</td>
</tr>
<tr>
<td>EA [kN]</td>
<td>920000</td>
<td>1140000</td>
<td>1280000</td>
</tr>
<tr>
<td>Tmax [kN]</td>
<td>1580</td>
<td>1950</td>
<td>2150</td>
</tr>
<tr>
<td>Tmax [kN]</td>
<td>2269</td>
<td>2794</td>
<td>3079</td>
</tr>
<tr>
<td>Tmax [kN]</td>
<td>2438</td>
<td>3000</td>
<td>3310</td>
</tr>
</tbody>
</table>
Numerical model tests

- **Step 1:** preliminary chain design in static conditions (catenary equation)

- **Step 2:** parametric modelling of the mooring resistance and device stability (maximum loads)

- **Step 3:** optimization of the mooring scheme (maximum movements)

- **Step 4:** response of the optimized scheme to wave direction
Effect of the chain length

\[ F_{nd} = \frac{F_{1/250}}{\rho g H_d} \]

![Graph showing the effect of chain length on Fnd](image-url)
Effect of the chain diameter

\[ F_{nd} = \frac{F_{1/250}}{pgHd} \]

- Diameter [m] on the x-axis
- \( F_{nd} \) on the y-axis
Effect of the chain diameter

![Graphs showing the effect of chain diameter on various parameters like Surge, Sway, Heave, Roll, Pitch, and Yaw. The graphs illustrate the relationship between the diameter of the chain and these parameters, with specific dimensions mentioned: Dim: 26 m, 10 m, and 2.5 m.]
...summarizing

<table>
<thead>
<tr>
<th>Test</th>
<th>$L_F$</th>
<th>$D_F$</th>
<th>Device stability</th>
<th>Chain resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>140</td>
<td>54</td>
<td>Instability in sway</td>
<td>Poor resistance</td>
</tr>
<tr>
<td>Test 2</td>
<td>140</td>
<td>60</td>
<td>Instability in sway</td>
<td>Resistant</td>
</tr>
<tr>
<td>Test 3</td>
<td>140</td>
<td>64</td>
<td>Instability in sway</td>
<td>Resistant</td>
</tr>
<tr>
<td>Test 4</td>
<td>120</td>
<td>60</td>
<td>Instability in sway</td>
<td>Poor resistance</td>
</tr>
<tr>
<td>Test 5</td>
<td>120</td>
<td>64</td>
<td>Instability in sway</td>
<td>Poor resistance</td>
</tr>
<tr>
<td>Test 6</td>
<td>100</td>
<td>60</td>
<td>Instability in sway</td>
<td>Broken</td>
</tr>
<tr>
<td>Test 7</td>
<td>100</td>
<td>64</td>
<td>Instability in sway</td>
<td>Broken</td>
</tr>
</tbody>
</table>

The rear lines are **oversized** and do not contribute to the stability in sway.
...summarizing

The rear lines are **oversized** and do not contribute to the stability in sway.
Numerical model tests

• Step 1: preliminary chain design in static conditions (catenary equation)

• Step 2: parametric modelling of the mooring resistance and device stability (maximum loads)

• **Step 3: optimization of the mooring scheme** (maximum movements)

• Step 4: response of the optimized scheme to wave direction
Effect of layout and n° of lines

Test 0

Test 1

Test 2

Test 3

Test 4

Test 5

\[ \text{Fnd} = \frac{F_{1}/250}{\rho g H_d} \]

\[ \text{Test 0: } D_B = 54 \text{mm} \]

\[ \text{Test 1: } L_B = 100 \text{m} \]

\[ \text{Test 2: } L_B = 90 \text{m}, D_B = 60 \text{mm} \]

\[ \text{Test 3: } L_B = 90 \text{m}, D_B = 60 \text{mm}, L_{L_2} = 100 \text{mm}, D_{L_2} = 60 \text{mm} \]

\[ \text{Test 4: } D_B = 54 \text{mm} \]

\[ \text{Test 5: } L_F = 140 \text{m}, D_F = 60 \text{mm} \]
Effect of layout and n° of lines

- Test 0
  - $D_B=54\text{mm}$
- Test 1
  - $L_B=100\text{m}$
- Test 2
  - $L_B=90\text{mm}$
  - $D_B=60\text{mm}$
- Test 3
  - $L_{L2}=100\text{mm}$
  - $D_{L2}=60\text{mm}$
- Test 4
  - $D_B=54\text{mm}$
- Test 5
  - $L_F=140\text{m}$
  - $D_F=60\text{mm}$

Graph:

- $X_{nd}=X_{i,250}/\text{Dim} [-]$

- Surge: 26 m
- Sway: 10 m
- Heave: 2.5 m

Dimensions:

- $L_B=100\text{m}$
- $D_B=54\text{mm}$
- $L_F=140\text{m}$
- $D_F=60\text{mm}$
Effect of layout and n° of lines

Test 0

Test 1

Test 2

Test 3

Test 4

Test 5

Test 0

Test 1

Test 2

Test 3

Test 4

Test 5


## Table: Device stability

<table>
<thead>
<tr>
<th>Test</th>
<th>$N^\circ$ of lines</th>
<th>$L_F$ [m]</th>
<th>$D_F$ [mm]</th>
<th>$L_B$ [m]</th>
<th>$D_B$ [mm]</th>
<th>$L_{L1}$ [m]</th>
<th>$D_{L1}$ [mm]</th>
<th>$L_{L2}$ [m]</th>
<th>$D_{L2}$ [mm]</th>
<th>Device stability</th>
<th>Chain strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>140 (45°)</td>
<td>60</td>
<td>140 (45°)</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Instability in sway</td>
<td>Resistant</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>140 (45°)</td>
<td>60</td>
<td>140 (45°)</td>
<td>54</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Instability in sway</td>
<td>Resistant</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>140 (45°)</td>
<td>60</td>
<td>100 (45°)</td>
<td>54</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Instability in sway</td>
<td>Resistant</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>140 (45°)</td>
<td>60</td>
<td>90 (30°)</td>
<td>60</td>
<td>-</td>
<td>-</td>
<td>100 (60°)</td>
<td>60</td>
<td>Stable</td>
<td>Poor resistance</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>140 (45°)</td>
<td>64</td>
<td>90 (30°)</td>
<td>54</td>
<td>-</td>
<td>-</td>
<td>100 (60°)</td>
<td>54</td>
<td>Stable</td>
<td>Resistant</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>140 (30°)</td>
<td>60</td>
<td>90 (30°)</td>
<td>54</td>
<td>140 (60°)</td>
<td>60</td>
<td>100 (60°)</td>
<td>54</td>
<td>Stable</td>
<td>Resistant</td>
</tr>
</tbody>
</table>

The lateral lines (60°) are always slack.
...summarizing

The lateral lines (60°) are always slack
Numerical model tests

- Step 1: preliminary chain design in static conditions (catenary equation)
- Step 2: parametric modelling of the mooring resistance and device stability (maximum loads)
- Step 3: optimization of the mooring scheme (maximum movements)
- Step 4: response of the optimized scheme to wave direction
Effect of the wave direction

Test 0

Test 1

Test 2

Test 3

Test 4

D=64mm

D=64mm

Grd 3

L_B=100m

L_B=90m

Fnd=F1/250/ρgHd

Test 0

Test 1

Test 2

Test 3

Test 4

Fnd=F1/250/ρgHd

front

back

lat1

lat2
Effect of the wave direction

Test 0  Test 1  Test 2  Test 3  Test 4

D=64mm  D=64mm Grade 3  L_B=100m  L_B=90mm

\[ X_{nd} = X_{1/250}/\text{Dim} \]

Dim
- surge: 26 m
- sway: 10 m
- heave: 2.5 m

Test 0  Test 1  Test 2  Test 3  Test 4
Effect of the wave direction

Test 0  
Test 1  
Test 2  
Test 3  
Test 4  

D=64mm  

L_B=100m  
Grade 3  

L_B=90mm  

Rot $1/250$ [°]

Test 0  
Test 1  
Test 2  
Test 3  
Test 4  

roll  
pitch  
yaw

D=64mm

Test 0  
Test 1  
Test 2  
Test 3  
Test 4  

L_B=100m  
Grade 3  

L_B=90mm  

Rot $1/250$ [°]

Test 0  
Test 1  
Test 2  
Test 3  
Test 4  

roll  
pitch  
yaw

D=64mm
**...summarizing...**

<table>
<thead>
<tr>
<th>Test</th>
<th>Wave direction</th>
<th>$L_F$ [m]</th>
<th>$D_F$ [mm]</th>
<th>$L_B$ [m]</th>
<th>$D_B$ [mm]</th>
<th>$L_{L1}$ [m]</th>
<th>$D_{L1}$ [mm]</th>
<th>$L_{L2}$ [m]</th>
<th>$D_{L2}$ [mm]</th>
<th>Device stability</th>
<th>Chain strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30°</td>
<td>140 (30°)</td>
<td>60</td>
<td>90 (30°)</td>
<td>54</td>
<td>140 (60°)</td>
<td>60</td>
<td>100 (60°)</td>
<td>54</td>
<td>Stable</td>
<td>Broken</td>
</tr>
<tr>
<td>1</td>
<td>30°</td>
<td>140 (30°)</td>
<td>64</td>
<td>90 (30°)</td>
<td>64</td>
<td>140 (60°)</td>
<td>64</td>
<td>100 (60°)</td>
<td>64</td>
<td>Stable</td>
<td>Resistant</td>
</tr>
<tr>
<td>2</td>
<td>60°</td>
<td>140 (30°)</td>
<td>64</td>
<td>90 (30°)</td>
<td>64</td>
<td>140 (60°)</td>
<td>64</td>
<td>100 (60°)</td>
<td>64</td>
<td>Stable</td>
<td>Broken</td>
</tr>
<tr>
<td>3</td>
<td>60°</td>
<td>140 (60°)</td>
<td>grade 3</td>
<td>100 (60°)</td>
<td>grade 3</td>
<td>140 (60°)</td>
<td>grade 3</td>
<td>100 (60°)</td>
<td>grade 3</td>
<td>Instability</td>
<td>Poor resistance</td>
</tr>
<tr>
<td>4</td>
<td>60°</td>
<td>140 (30°)</td>
<td>grade 3</td>
<td>90 (30°)</td>
<td>grade 3</td>
<td>140 (60°)</td>
<td>grade 3</td>
<td>100 (60°)</td>
<td>grade 3</td>
<td>Stable</td>
<td>Resistant</td>
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</tbody>
</table>
The final «best scheme»

<table>
<thead>
<tr>
<th></th>
<th>PreTens</th>
<th>$F_{\text{mean}}$</th>
<th>$F_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>17.06 kN</td>
<td>47.5 kN</td>
<td>1213.7 kN</td>
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<tr>
<td>Back</td>
<td>62.06 kN</td>
<td>44.9 kN</td>
<td>2610.7 kN</td>
</tr>
<tr>
<td>Lat1</td>
<td>17.14 kN</td>
<td>51.2 kN</td>
<td>2477.7 kN</td>
</tr>
<tr>
<td>Lat2</td>
<td>17.14 kN</td>
<td>19.7 kN</td>
<td>50.7 kN</td>
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</tbody>
</table>

**Degree of freedom**

<table>
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<tr>
<th></th>
<th>Surge</th>
<th>Roll</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>6.4 m</td>
<td>21°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(dim/4)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sway</td>
<td>10 m</td>
<td>13°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(dim)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heave</td>
<td>3.8 m</td>
<td>32°</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1.5 dim)</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
The final «best scheme»
What about a WEC-WAB?

<table>
<thead>
<tr>
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<th>PreTens</th>
<th>$F_{\text{mean}}$</th>
<th>$F_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Front</strong></td>
<td>18.5 kN</td>
<td>47.7 kN</td>
<td>1332.0 kN</td>
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<tr>
<td><strong>Back</strong></td>
<td>39.2 kN</td>
<td>21.4 kN</td>
<td>20.7 kN</td>
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<tr>
<td><strong>Lat1</strong></td>
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<td>24 kN</td>
<td>48.5 kN</td>
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<tr>
<td><strong>Lat2</strong></td>
<td>16.5 kN</td>
<td>16.1 kN</td>
<td>23.2 kN</td>
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</tbody>
</table>
What is next?

- Fatigue analysis
- CALM configuration (device-buoy link)
- Validation and calibration of AQWA
Thank you for your kind attention

Giovanna Bevilacqua & Barbara Zanuttigh
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