Applicability of a Toroidal Hull Structure for Floating Wind

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Offshore Wind

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Self Introduction

• Mr Kurt Delpeche
  - Pacifico Energy K.K., Offshore Wind, Japan
  - Foundations Package Manager
  
  - MSc in Offshore Engineering, 2008
  - Newcastle University, UK, Marine department
  - Hydrodynamic and Experimental Analysis on a Novel Hybrid Floating Offshore Renewable Energy Structure
Outline

• Background
  – Context
  – Historical concepts
  – Current concepts
  – Toroidal hull concept

• Design and hydrodynamics

• Experimental setup

• Results
Background

• Context – Design and Modelling Process

LCOE

Expensive foundations

Low motion response

Hybrid Floater

Toroidal Hull

Need

Analysis of problem

Statement of problem

Conceptual design

Selected scheme

Embodiment of scheme

Detailing

Working drawings etc.

Design of model test

Scaling laws

Model parameters

Calibration of wave tank

Design of instrumentation

Calibration of instrumentation

Model design and drafting

Model construction

Model Calibration

Decay test

Run wave test
Background

• Historical concepts

- Taut moored SPAR (Susuki et al)
- Shim wind-wave device (Cho and Shim, 1999)
- Box girder (Ohta et al, 2003)
- TLP concept (Musial et al, 2004)
- Multi-turbine floater (Henderson, 1997)
- Hywind concept, (Equinor, 2005)
Background

- Current concepts

  ![Semi-sub](image1.png)

  ![Spar-buoy](image2.png)

  ![TLP](image3.png)

  Other Variations
Background

• Toroidal hull – a historical concept

- The toroidal hull concept was first suggested by ERNO Raumfahrttechnik GmbH and partners as a new design of semi-submersible called the RS 35 for rough weather operation (Source: The naval architect, 1980)

- The symmetrical arrangement is said to give good motion characteristics and eliminated the need for cross bracing.

- The toroidal form was suggested for the design of underwater missile launches and an underwater space station (Ross, 2005)
Background

- **Toroidal hull – scale of the structure**
  - **Ring-hull**: overall diameter of about **100 m**
  - **Tubular sections**: diameter of about **10 m**
  - **Vertical columns**: diameter of about **12 m**
  - In its operational mode the ring-hull is submerged to a depth of about **20 m**
Background

• Toroidal hull – historical results of seakeeping tests
  – The transfer function of *heave*, *surge* and *pitch* prove the *excellent response characteristics* of this design
  – In the period range of 5-12 the platform motions are extremely small since the forces acting on the submerged torus are nearly cancelled by the forces on the columns.
  – The *drag resistance* of the ring structure is about half of the transverse resistance of a comparable twin hull semi-submersible.
Design and Hydrodynamics

- Toroidal hull applied to a hybrid wind and wave energy structure
Design and Hydrodynamics

- Specifications, Motions and Forces
Design and Hydrodynamics

• Forces
  1. The variation in pressure due to the passage of the wave – the Froude-Krylov force
  2. Inertia forces due to the effects of the acceleration of the particles within the wave on the added virtual mass of the body

  o Surface wave ➞ \[ y = \zeta_0 \cos(kx - \omega t), \text{ where } \zeta_0 = 0.5H_u \]

  o Heave response ➞ \[ (M + M_{AVM,y})\ddot{y} + c\dot{y} + ky.y = F_{WAVE} \]

  o Solution ➞ \[
  y = \left( \frac{F_{\text{wave}}/K_{y}}{\omega_d} \right) \cos(\omega t + \phi)
  \]

  \[
  RAO(\omega) = \frac{F(\omega)}{-m\omega^2 + k}
  \]

  \[
  \sqrt{1 - \left( \frac{\omega}{\omega_n} \right)^2}^2 + \left( \frac{2\omega}{\omega_n} \omega_d \right)^2
  \]
Design and Hydrodynamics

• Torus

- The *added mass* and *drag coefficients* are two critical parameters for accurate prediction of hydrodynamic forces on the floater.
- The added mass can be deduced from a simple strip theory, as the product of the two dimensional added mass and the circumference of the torus.
Design and Hydrodynamics

- Evaluation of Added-Mass and Forces on a Torus

\[ b_{33} \approx \pi c B_{33} \]
\[ m_{33} \approx 2\pi c M_{33} \approx \left[ \frac{(1-4)}{(3\pi Ka)m} \right] \]

\[ F_{hull} = -2\pi R \omega^2 \zeta_0 e^{-kz} \left[ \cos(KR \cos \theta) \right] \]

\[ J_0(Z) = \frac{1}{2\pi} \int_0^{2\pi} \cos(Z \cos \theta) d\theta \]

\[ J_1(Z) = \frac{1}{2\pi} \int_0^{2\pi} \cos \theta \sin(Z \cos \theta) d\theta \]
Experimental Set-up

- Modelling Criteria
  - Using Froude’s law and the sale as $\lambda$ (1:200)

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>UNIT</th>
<th>SCALE FACTOR</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>L</td>
<td>$\lambda$</td>
<td>Any characteristic dimension of the object</td>
</tr>
<tr>
<td>Displacement</td>
<td>L</td>
<td>$\lambda$</td>
<td>Position at rest is considered as zero</td>
</tr>
<tr>
<td>Natural Period</td>
<td>T</td>
<td>$\lambda^{1/2}$</td>
<td>Period at which inertia force = restoring force</td>
</tr>
<tr>
<td>Force</td>
<td>MLT$^{-2}$</td>
<td>$\lambda^3$</td>
<td>Action of one body on another tend to change the state of motion on the body</td>
</tr>
<tr>
<td>Wave Height</td>
<td>L</td>
<td>$\lambda$</td>
<td>Consecutive crest to trough distance</td>
</tr>
<tr>
<td>Density</td>
<td>ML$^{-3}$</td>
<td>$\lambda$</td>
<td>Mass per unit volume</td>
</tr>
</tbody>
</table>
## Experimental Set-up

- **Scaled components**

<table>
<thead>
<tr>
<th>Item</th>
<th>Geometry</th>
<th>Prototype Dimension [m]</th>
<th>Model Dimensions [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pontoon</td>
<td>Diameter 1</td>
<td>120</td>
<td>0.600</td>
</tr>
<tr>
<td></td>
<td>Diameter 2</td>
<td>4.48</td>
<td>0.022</td>
</tr>
<tr>
<td>Column</td>
<td>Diameter</td>
<td>5.58</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>22.58</td>
<td>0.113</td>
</tr>
<tr>
<td>Deck</td>
<td>Length</td>
<td>95.3</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>10</td>
<td>0.050</td>
</tr>
<tr>
<td>Tower</td>
<td>Length</td>
<td>80</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>Diameter</td>
<td>5</td>
<td>0.025</td>
</tr>
<tr>
<td>Turbine</td>
<td>Rotor Diameter</td>
<td>40</td>
<td>0.200</td>
</tr>
</tbody>
</table>
## Experimental Set-up

### Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flume length</td>
<td>11 m</td>
</tr>
<tr>
<td>Width</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Water depth</td>
<td>1 m</td>
</tr>
<tr>
<td>Air Clearance</td>
<td>1 m</td>
</tr>
<tr>
<td>Central measurement section</td>
<td>3 m</td>
</tr>
<tr>
<td>Water velocity</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Wind velocity</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Period Range</td>
<td>0.8 – 4 sec</td>
</tr>
<tr>
<td>Wave height</td>
<td>0.02 - 0.2m (Period Dependent)</td>
</tr>
</tbody>
</table>
Experimental Set-up

- Environment
- Incident waves and currents
- Velocity probe
- Wave probe
- Mooring Spring
- Load cell
- Motion targets monitored by camera
Experimental Set-up

- Instrumentation
  - QUALYSIS motion tracking system
    - Displacement
  - Ventrino+ velocity probe
    - Water particle velocity
  - Capacity probe
    - Wave motion
Experimental Set-up

• Instrumentation
  - Load cells
  - Data acquisition system- LabView
Results

- **Decay test**
  - Computation of the damped frequency motion
  - Extinction curve for the structure in heave
  - Added mass and damping

\[
\begin{align*}
  m &= -\xi\omega_N \\
  \omega_d &= \omega_N \sqrt{1-\xi^2} \\
  \xi &= 0.0468 \\
  \omega_N &= 6.75 \text{ rad/sec} \\
  M_{\text{cm}} &= M - M_0 = \frac{k}{\omega_N^2} - M_0 \\
  &= 28.6 \text{ kg} \\
  C &= 2M_0\xi\omega_N \\
  &= 2(15.17)(0.0468)(6.75) \\
  &= 9.58 \text{ kg rad/sec}
\end{align*}
\]
Results

Low waves, long period
High waves, short period
Medium current only

Medium waves, long period
High waves, long period
Low current only
Results

- **SURGE**
  - Displacement (mm) vs Frequency (rad/sec)
  - Colors represent different wave heights: Hs=2cm, Hs=4cm, Hs=8cm

- **SWAY**
  - Displacement (mm) vs Frequency (rad/sec)
  - Colors represent different wave heights: Hs=2cm, Hs=4cm, Hs=8cm

- **HEAVE**
  - Displacement (mm) vs Frequency (rad/sec)
  - Colors represent different wave heights: Hs=4cm, Hs=8cm

- **ROLL**
  - Rotation (deg) vs Frequency (rad/sec)
  - Colors represent different wave heights: Hs=2cm, Hs=4cm, Hs=8cm

- **PITCH**
  - Rotation (deg) vs Frequency (rad/sec)
  - Colors represent different wave heights: Hs=2cm, Hs=4cm

- **YAW**
  - Rotation (deg) vs Frequency (rad/sec)
  - Colors represent different wave heights: Hs=2cm, Hs=4cm, Hs=8cm
Results

- RAOs (Heave, Surge, Pitch)
Results

- Heave RAO
Results

- Pitch RAO
Results

- Surge RAO
Results

- Motions with current only

<table>
<thead>
<tr>
<th>Test number U</th>
<th>Test speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.365</td>
</tr>
<tr>
<td>3</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Conclusion

• The torus is unique in several aspects.
• The results gives an overview of the hydrodynamic properties of the deep submerged toroidal displacement structure with its circular cross section combined with a barge type structure.
• Possible application with large renewable energy structures such as floating islands as well as using VAWT.
• Detailed numerical modelling is required including the combined wind turbine dynamics and a comparison with other floater types.
Thank you for your time!

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