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Background

- Floating wind fast becoming a new industry
- To push the TRL of new designs, validation campaigns in wave tanks common

**QUESTION:** How do you define a successful validation – how close do simulations need to match measurements?

**EXAMPLE:** In OC5, validation of a floating wind semisubmersible was performed
  - Tower-base force compared – simulations/measurements
  - Modeling tools under-predicted the loads by about 20%
  - Low-frequency response at its pitch and surge natural frequencies (nonlinear hydrodynamics) – biggest cause

**ANSWER:** Uncertainty assessment

- Define a bound on measurements
- Understand level of certainty in response characteristics
Overview

Objective: Assess uncertainty in load/motion response of OC5-DeepCwind semisubmersible, with special focus on low-frequency behavior

Approach:
- OC5-DeepCwind semisubmersible re-tested by sub-group. Two test campaigns:
  - Constrained
  - Simple moored
- Uncertainty assessment of motion response of floating configuration
  - ASME uncertainty approach
  - Random uncertainty calculated through repeat tests
  - Systematic uncertainty assessed on all components of test, and propagated to response metrics
  - Response metrics used for direct comparison between simulations/measurements – and uncertainty bounds for these metrics were calculated
### Tests and Metrics

- **RAO**: the response amplitude operator (RAO) in surge, heave, and pitch at 6 discrete frequency points within the wave energy range;

- **PSD Sum, Low Frequencies**: the integral of the power spectral density (PSD) of surge and pitch motions over the low-frequency range (pink);

- **PSD Sum, Wave Frequencies**: the integral of the PSD of surge and pitch motions over the wave-frequency range (blue)

- **Mean Surge Offset**

### Test Matrix

<table>
<thead>
<tr>
<th>Test Name</th>
<th>Waves</th>
<th>Number Repeats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular wave 1</td>
<td>H=7.1 m, T=12.1 s</td>
<td>5</td>
</tr>
<tr>
<td>Regular wave 2</td>
<td>H=4 m, T=9 s</td>
<td>2</td>
</tr>
<tr>
<td>White noise</td>
<td>Hs=7.1 m, T=6-26 s</td>
<td>2</td>
</tr>
<tr>
<td>Irregular wave</td>
<td>Hs=7.1 m, Tp=12.1 s</td>
<td>5</td>
</tr>
</tbody>
</table>

**Note:** Simulation models not fully tuned, and therefore do not represent the best results that could be obtained by the modeling tool.
## Systematic Uncertainty Sources

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline Value</th>
<th>Uncertainty Level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure Properties</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platform mass [kg]</td>
<td>1.4196E+7</td>
<td>8.75E+4</td>
</tr>
<tr>
<td>CM, x direction [m]</td>
<td>0</td>
<td>0.22</td>
</tr>
<tr>
<td>CM, y direction [m]</td>
<td>0</td>
<td>0.22</td>
</tr>
<tr>
<td>CM, vertical [m]</td>
<td>-7.53</td>
<td>0.21</td>
</tr>
<tr>
<td>Platform inertia, Ixx abt CM [kg-m²]</td>
<td>1.2898E+10</td>
<td>1.2898E+8</td>
</tr>
<tr>
<td>Platform inertia, Iyy abt CM [kg-m²]</td>
<td>1.2851E+10</td>
<td>1.2851E+8</td>
</tr>
<tr>
<td>Platform inertia, Izz abt CM [kg-m²]</td>
<td>1.4189E+10</td>
<td>1.4189E+8</td>
</tr>
<tr>
<td>Draft [m]</td>
<td>20</td>
<td>0.25</td>
</tr>
<tr>
<td>Column angle, [deg]</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Column diameter, [m]</td>
<td>12 or 24</td>
<td>0.1</td>
</tr>
<tr>
<td>Mooring stiffness [kN/m]</td>
<td>48.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Mooring pretension [kN]</td>
<td>1122.5</td>
<td>62</td>
</tr>
<tr>
<td>Anchor position x [m]</td>
<td>Radially outward</td>
<td>0.25</td>
</tr>
<tr>
<td>Anchor position y [m]</td>
<td>Radially outward</td>
<td>0.25</td>
</tr>
<tr>
<td>Anchor position z [m]</td>
<td>Up/down</td>
<td>0.25</td>
</tr>
<tr>
<td>Mooring fairlead position [m]</td>
<td>Radially outward</td>
<td>0.05</td>
</tr>
<tr>
<td>Initial position [m]</td>
<td>0</td>
<td>0.12</td>
</tr>
<tr>
<td>Initial orientation [deg]</td>
<td>0</td>
<td>0.062</td>
</tr>
<tr>
<td>Water depth [m]</td>
<td>180</td>
<td>2</td>
</tr>
<tr>
<td>Water density [kg/m³]</td>
<td>1025</td>
<td>10.25</td>
</tr>
<tr>
<td>Wave elevation – due to sensor drift [m]</td>
<td>measured</td>
<td>0.03</td>
</tr>
<tr>
<td>Wave elevation – due to probe location and tilt [m]</td>
<td>measured</td>
<td>negligible</td>
</tr>
<tr>
<td>Translation measurement [m]</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Rotation measurement [deg]</td>
<td>0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Down-selected Systematic Sources

- Parameters down-selected based on their influence on the response metrics according to simulations.
- Thresholded by examining the total combined systematic uncertainty of the response metrics.
  - Parameters causing less than 10% change in total combined systematic uncertainty on any metric were removed.
- Original set of 24 parameters down-selected to 8
- Parameters were adjusted to try to make them independent of each other

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Center of mass, x direction</td>
<td>CMx</td>
</tr>
<tr>
<td>2 Center of mass, vertical</td>
<td>CMz</td>
</tr>
<tr>
<td>3 Mooring stiffness</td>
<td>Stiff</td>
</tr>
<tr>
<td>4 Draft</td>
<td>Draft</td>
</tr>
<tr>
<td>5 Column diameter</td>
<td>ColDia</td>
</tr>
<tr>
<td>6 Wave elevation – due to sensor drift</td>
<td>WaveElev</td>
</tr>
<tr>
<td>7 Platform inertia, Iyy abt CM</td>
<td>Iyy</td>
</tr>
<tr>
<td>8 Platform mass + Displaced Volume</td>
<td>Mass+Buoy</td>
</tr>
</tbody>
</table>
Systematic Uncertainty Propagation

INPUT
(Wave Elevation)

TEST SPECIMEN
(CMx, CMz, Stiff, Draft, ColDia, lyy, Mass+Buoy)

OUTPUT

• Systematic uncertainty of the response metrics due to a given uncertainty source:
  – Simulate model using the baseline properties and calculate associated response metrics.
  – Simulate model using a new value for given uncertain parameter, and calculate response metrics.
  – Difference between response metrics calculated using baseline properties and when changing one of the uncertain parameters is the systematic uncertainty for that parameter.
  – Variations performed in positive and negative directions -> asymmetric uncertainty bounds

• Sum all propagated uncertainty sources
Modeling Approaches

Propagation affected by the fact we are using a model. Addressed by:

- Using multiple models
- Using multiple modeling approaches
- Taking largest variation across all approaches

<table>
<thead>
<tr>
<th>Model ID</th>
<th>Global linear and quadratic drag</th>
<th>Morison drag on vertical columns</th>
<th>Morison drag on heave plates</th>
<th>Wave loads above still water level</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAST</td>
<td></td>
<td>x</td>
<td>x</td>
<td>Morison-type drag up to 1st order free surface based on constant potential</td>
</tr>
<tr>
<td>FAST_PQ</td>
<td></td>
<td>x</td>
<td></td>
<td>Morison-type drag up to 1st order free surface based on constant potential</td>
</tr>
<tr>
<td>SIMA</td>
<td></td>
<td>x</td>
<td>x</td>
<td>Morison loads applied on heave plate only, Therefore, no wave loads act above still water level.</td>
</tr>
<tr>
<td>aNySIM</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>aNySIM_PQ</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Total Uncertainty Calculation

- Combined random and propagated systematic uncertainty
  \[ u_C = \sqrt{(b_R)^2 + (s_x)^2} \]

- Expanded uncertainty: multiply standard uncertainty by a coverage factor
  - \( k = 2 \), level of confidence of approximately 95%

  \[ U = ku_C \quad X = \bar{X} \pm U \]  
  Response metric uncertainty band

- For asymmetric uncertainty:

  \[ q_i = \frac{(\bar{X} + b_i^+) + (\bar{X} - b_i^-)}{2} - \bar{X} \]

  \[ X = \left( \bar{X} + \sum_{i=1}^{N} q_i \right) \pm U \]
Metric: Mean Surge

- Uncertainty in mean surge in regular wave case 1 is probably overstated
  - large variation was only seen for one of the simulation tools
  - much of the difference is likely related to static effects (which would have been zeroed out in the experimental measurements)
Metric: RAOs

- RAO calculations shown based on all waves
  - 6 points chosen for uncertainty assessment
- Frequencies on low end showed most uncertainty
  - Closeness to natural frequencies
  - Cancellation effects in the excitation
- Pitch response shows larger uncertainty than other DOFs
Metric: PSD Sum

\[ S_{sum} = \sum_{i=j}^{k} S_{res} \left( f_i \right) \Delta f \]

- Uncertainty levels vary between the two irregular waves (irregular and white noise)
  - Difference especially pronounced in the low-frequency surge metric

- Amplitude of the total uncertainty:
  - wave-frequency: <20%,
  - low-frequency: 30-40%
Contributions to Uncertainty

- Random uncertainty negligible
- Surge (Wave):
  - Wave elevation
  - Column diameter
- Surge (Low):
  - Mooring stiffness
    (affects natural frequency)
  - Wave elevation
- Pitch (Wave)
  - Draft
  - CM – x-dir
- Pitch (Low):
  - CM – z-dir
    (affects natural frequency)
  - Draft
Variability of Propagated Uncertainty

- Largest change in metric across all simulation approaches taken -> conservative
- No single simulation approach consistently had larger uncertainties than others
- While levels varied between simulations, mainly agreed on the parameters that are the most sensitive
Conclusions

• The total experimental uncertainty for a set of hydrodynamics model tests with a rigid semisubmersible wind turbine has been estimated through propagation of the systematic uncertainties using several numerical simulation tools.

• Wave frequency responses are found to have smaller uncertainty than low-frequency responses.

• Random uncertainty, which was found through repeated measurements, is negligible compared to the systematic uncertainty.

• Low-frequency responses were most sensitive to model characteristics that affected the stiffness (natural frequency):
  – Surge: mooring system stiffness
  – Pitch: platform draft and vertical center of gravity

• Simulation tools showed good agreement regarding which parameters were most important, although the magnitude of the propagated uncertainty differed significantly.

• The results from this study give a measurement of uncertainty that can be used in future validation efforts.
  – The results from previous OC5 study do not fall in the uncertainty bands calculated
  – The data from the present tests will be studied further using both engineering and high-fidelity models through the OC6 project.


Thank You
Systematic Uncertainty Propagation

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- Sum all propagated uncertainty sources

- Propagation affected by the fact we are using a model. Addressed by:
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\[
\theta_i = \frac{\partial X}{\partial p_i}
\]

\[
b_i = \theta_i d_i
\]

\[
b_R^2 = \sum_{i=1}^{N} b_i^2
\]

\[
b_i = \text{systematic uncertainty of output metrics}
\]

\[
b_R = \text{total combined systematic uncertainty}
\]

\[
p_i = \text{parameter values}
\]

\[
d_i = \text{systematic uncertainty sources}
\]

\[
X = \text{output response metric}
\]

\[
\Theta = \text{sensitivity coefficients}
\]