Comparison of Model and Measured Power from a WEC Ocean Deployment

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Background: OPT PowerBuoy®

• Ocean Power Technologies Inc.
  – Moored buoys which capture power from ocean waves
  – Periodic ocean testing since 1997
  – Ongoing optimization of Power Takeoff and structure
  – Upcoming ocean tests off NJ in 2015

• PowerBuoy
  – Surface float moves along spar; drives thrust rod into PTO inside spar. Linear motion translated to rotation of generator. Seek to minimize conversion stages and component losses.
  – Resulting power output supplied to payload or grid
  – Long-term operation, so system and mooring must withstand marine environment
Role of Modeling in PowerBuoy Development

- Analysis needs
  - Power, load performance of candidate geometry concepts
  - Mooring design
  - Effect of PTO limits, PTO efficiency/losses, braking behavior
  - Design and fatigue load specification for PTO, structure, and mooring
  - Towout

- **STORM (Simulink to OrcaFlex Realtime Model)**
  - Replaces prior OPT models. Main benefit: more flexible.
  - Combines WAMIT (hydrodynamic coefficients), OrcaFlex (PowerBuoy motions in irregular waves), Simulink (PTO behavior), Matlab (scripting/analysis)
  - Can vary PowerBuoy geometry, mooring components, MetOcean conditions, PTO control
  - Validation against tank measurements (Bretl et al., June 2015 OMAE: 3 PowerBuoy geometries, 3 PTO controls)
Example Comparison of STORM to Tank Results

• Scale model of PB150 PowerBuoy, compliant 3-leg mooring, resistive PTO control
• OPT Tank test data collected at Memorial University of Newfoundland
• Tank generated waves with desired wave statistics, Bretschneider spectra
• STORM simulations reasonably close to tank measurements
• Similar performance for other geometries (Bretl et al. 2015).

<table>
<thead>
<tr>
<th>Hs (m)</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<td>Ta (s)</td>
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<td>7</td>
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OrcaFlex Screenshot
# How Ocean Test Differs from Tank

<table>
<thead>
<tr>
<th></th>
<th>Tank Test</th>
<th>Ocean Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waves</strong></td>
<td>Idealized spectral shape, controlled conditions, full set of sea states</td>
<td>Multiple peaks, biased toward common sea states</td>
</tr>
<tr>
<td><strong>Friction</strong></td>
<td>Can minimize (lubrication, adjustments)</td>
<td>Components selected for additional criteria (longevity, availability)</td>
</tr>
<tr>
<td><strong>Measurements</strong></td>
<td>Extensive</td>
<td>Limited by bandwidth, data handling</td>
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</table>
Ocean Test

• LEAP (Littoral Expeditionary Autonomous PowerBuoy) – First APB350 generation
  – Power source for HF radar payload
  – Rutgers and CODAR: coastal radar network
  – Naval Undersea Warfare Center Keyport funded

• Completed 3-month ocean test (Oct 2011)
  – Site in 37m water depth off New Jersey
  – Measured power flow, system health
  – Powered payload continuously per operational plan
  – On station and operational during Hurricane Irene
  – Sufficient range of sea states to fill out power matrix; can then project power performance for any known wave climate.
APB-350 2011 Ocean Test Off the Coast of NJ

- **Customer:** US Navy
- **Location:** New Jersey
- **Purpose:** Maritime Surveillance (High Frequency)
- **Results:**
  - 400W Continuous Power
  - 1500W Peak Power
  - Survived Hurricane
  - Fully Autonomous Operation
PowerBuoy Measurements

- Sensors to measure system health, behavior, power flow
  - Data transmitted to shore and captured in archive

- Focus: Power at input to generator, $P_{Mech} = \beta_{PTO} v^2$
  - Constant PTO damping commanded throughout deployment, $\beta_{PTO}$
  - Does not include friction upstream of generator

- During 3-month deployment, covered most 'typical' sea states
  - Bin data by sea state and obtain power matrix
  - How does STORM compare?
Ocean Test: Wave Data Collection

- ADCP (Acoustic Doppler Current Profiler)
- Data processed with WavesMon software (Teledyne RDI, B. Strong)
- Calculates spectra from 3 sources: surface tracking, velocity, and pressure sensor.
  - Surface tracking preferred since does not attenuate short-period waves, but requires wind-roughened surface
  - Wave statistics (Hs, Ta) derived from best spectrum
• STORM did not include friction upstream of measurement point (frictional damping or constant friction force)

• Greater differences between STORM and measurements (0.5-1.3) than tank comparison (0.8-1.1) for same sea states
  - Greatest misfit at common sea states, which are heavily weighted in site average power

• Data binned based on Hs, Ta (simulations generated with idealized spectral shape, Bretschneider)
Some Improvement when Friction Included

- Tuned frictional damping and constant friction force to reduce misfit in common sea states (before 0.4-0.7, now 0.7-1.1), but increased misfit in higher sea states (before 0.7-0.9, now 1.2-1.4)

- Investigation ongoing, to better understand source of misfit (friction and other factors)
Scatter of Mechanical Power from Ocean Test

**Scatter Of Power Measurements**
Max-min Range Within Sea State Bin, Divided by Bin Average

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- Range of measured values is highest in sea states (low/moderate) where STORM misfit is greatest
- Need to understand the source of scatter within a sea state bin
  - Measurements: Bin all data based on ADCP Hs/Ta
  - Differs from STORM: Generate ideal spectra with bin’s central Hs/Ta
Adequacy of Ideal Spectra Shape for Site?

- One measure of fit of spectral shape: Expect Tp/Ta=1.29 for Bretschneider
- Close to most commonly occurring value, but wide variance
- Wave statistics from ADCP measurements calculated by RDI WavesMon software
• From ADCP spectra, estimate wave statistics (Hs, Tp)
• Using same statistics, generate idealized spectra (Bretschneider). Expect Tp/Ta=1.29, here 0.79.
• Misfit expected to matter for power output; device most responsive at T≤7s
• For each hour of deployment, used measured ADCP spectra to run STORM simulation. Does power prediction improve?
Compare Measured Power to STORM Simulations

• Black line: Measured mechanical power from ocean test
• Dots: STORM time-averaged mechanical power using ADCP spectra as input. (Tuned friction not applied.)
• Color indicates whether ADCP estimated spectra from surface tracking, velocity, or pressure sensor
  - Reasonable performance *unless* pressure sensor (green) is used, due to poor resolution of shorter wave periods (attenuation in 37m water depth)
Better Model Performance from Real Spectra

- Average data in bins of $H_s$ and $T_a$
- Scatter reduced if ADCP spectra are used. Ocean test/STORM = 0.8.
• Compared to ocean test, closer (0.7-1.1) than original (0.4-1.0), especially in common sea states

• Still binning by sea state
How to Incorporate Spectral Shape?

- Power matrix: easy to use (function of 2 variables, Hs and Ta); independent of site
- If must incorporate spectral shape, how?
- Active research area
  - Saulnier et al. (2011): Wave groupiness and spectral bandwidth as relevant parameters for the performance assessment of WECs, Ocean Eng. 38(1), 130-147.
Summary

• **Lesson learned**
  − For upcoming deployments (summer 2015), use measured spectra as simulation input
  − Measure mechanical power as far upstream of friction as possible

• **Next steps: Weighing how to summarize PowerBuoy performance**
  − Simple Hs/Ta description inadequate, but convenient
  − Want power performance information which is independent of site
Acknowledgements

- LEAP (Naval Undersea Warfare Center Keyport, USCG, Rutgers, CODAR)
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