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Numerical and Experimental Analysis of the Ocean Sentinel Mooring System to Enable Improved Modeling and Design

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***Abstract*— This paper presents the design and analysis of the Ocean Sentinel instrumentation buoy mooring system, including numerical modeling and experimental validation testing during the summer of 2013. The intent of this study is to gather mooring data for the Pacific Marine Energy Center – North Energy Test Site (PMEC-NETS), and increase the understanding of numerical mooring models, which will contribute to improved designs of wave energy converter (WEC) mooring systems. The Ocean Sentinel instrumentation buoy (Ocean Sentinel) was configured in a three-point moor, with load cells on each mooring line, and the system was modeled using OrcaFlex. The model predictions of the mooring line loads are compared with actual experimental loads experienced during the summer 2013 deployment and the results are presented. Based on the results of the field testing, mooring system design improvements are proposed. This paper also includes wave data recorded during the deployment that was used in the numerical model to simulate the deployed conditions, as well as the simulated power output for a WEC array installation located at PMEC-NETS.**

I. INTRODUCTION

The Northwest National Marine Renewable Energy Center (NNMREC) is a US Department of Energy (USDOE) Center partnership between Oregon State University (OSU) and the University of Washington (UW). NNMREC's mission includes facilitating the commercialization of marine energy technology, informing regulatory and policy decisions, and closing key gaps in scientific understanding with a focus on student growth and development. Thus, NNMREC's objectives include developing facilities to serve as an integrated Test Center for wave and tidal energy developers, evaluating potential environmental and ecosystem impacts, optimizing devices and arrays for deployments and increased system reliability and survivability.

NNMREC performs fundamental technological, social, and environmental research, in addition to providing unique testing facilities [1]. OSU NNMREC testing resources include a wave energy linear test bed, 2D and 3D wave tanks, an Ocean Sentinel instrumentation buoy (Ocean Sentinel) to facilitate open-ocean testing without a cable-to-shore grid connection, as well as developing cable-to-shore grid emulator and grid-connect facilities. All of NNMREC's marine energy converter testing facilities are being branded as the Pacific Marine Energy Center (PMEC), including the scaled lab testing facilities and intermediate and full-scale open water testing facilities.

Fig. 1 summarizes the NNMREC wave energy assets for testing scaled to full-scale devices, including phases of prototype development from modeling to scaled and full-scale testing. NNMREC's wave energy open-ocean testing facilities are being developed in a multi-step process. The PMEC North Energy Test Site (PMEC-NETS) is intended for wave energy converter (WEC) technologies that are ready for field trials, but are not sufficiently mature to be connected to the electrical grid for commercial power production. PMEC-NETS is now a permitted open ocean test site north of Newport, OR, ranging in depth from 45-52 m, 2-3 miles from shore (see location in Fig. 2, lower right image), where the Ocean Sentinel, described in Section II, is used to test WECs.

The next steps include the development of the PMEC South Energy Test Site (PMEC-SETS), which is the first proposed utility scale, cable-to-shore, grid-connected wave energy test site in the US, ranging in depth from 60-70 m, with up to four test berths, 5-6 miles from shore for testing individual WECs or arrays. The PMEC-SETs onshore facility will include a grid emulator to enable WEC developers to test synchronization and power delivery to a conventional power grid, characterization of electrical generator performance, power quality verification and fault testing before a device is directly connected to the actual power grid.

This paper presents the design and analysis of the Ocean Sentinel mooring system, including numerical modeling and experimental validation testing during the summer of 2013. This paper also includes wave data recorded during the deployment that was used in the numerical model to simulate the deployed conditions. Also presented is the simulated wave power output for a 5 x 80 WEC installation array of 250 kW buoys located at PMEC-NETS.

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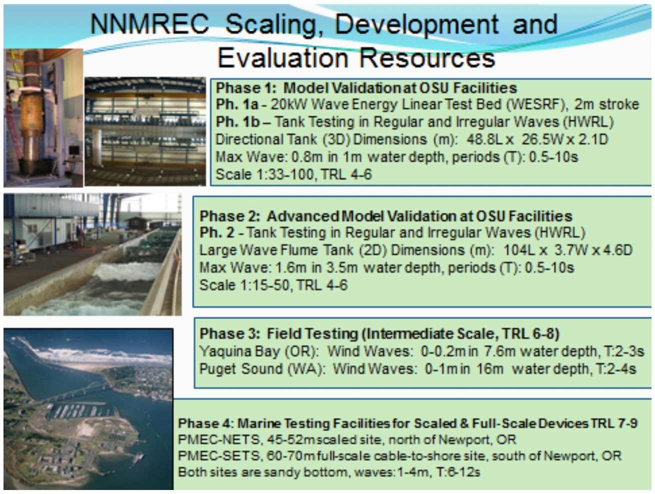


Fig. 1. NNMREC wave energy testing assets for scaled to full-scale device development.

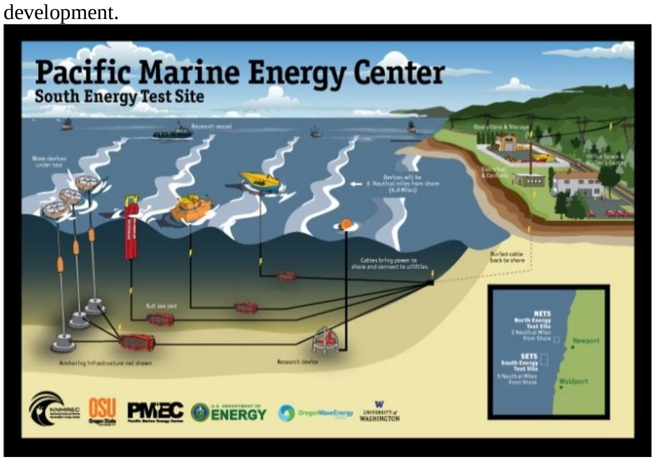


Fig. 2. Proposed Pacific Marine Energy Center South Energy Test Site (PMEC-SETS) for the Testing of full-scale wave energy devices, with the PMEC North Energy Test Site (PMEC-NETS) also shown in the image on the lower right.

II. The Ocean Sentinel Instrumentation Buoy

The Ocean Sentinel is an instrumentation buoy developed by NNMREC and AXYS Technologies for open-ocean WEC testing [2]. The Ocean Sentinel is a surface buoy, based on the 6-meter NOMAD (Navy Oceanographic Meteorological Automatic Device) buoy design that facilitates open-ocean, stand-alone testing of WECs without a utility grid connection. A concept diagram of the Ocean Sentinel testing a WEC is shown in Fig. 3, with the deployed Ocean Sentinel shown in Fig. 4. WECs under test are moored approximately 125 m from the instrumentation buoy, and are connected by an umbilical cable. Power generated by the WEC is controlled by switchgear and power conversion equipment located on board the instrumentation buoy and dissipated in an onboard load bank. Wave data measured by a TRIAXYS wave measuring buoy moored nearby is transmitted to the instrumentation buoy via wireless telemetry. The primary functions of the Ocean Sentinel are as follows:

1. Provide stand-alone electrical loading and power conversion for the WEC under test.
2. Measure and record WEC power output.
3. Collect and store data transmitted from the TRIAXYS wave measuring buoy moored nearby.
4. Conduct environmental monitoring.
5. Transmit collected data to a shore station via a wireless telemetry system.

The Ocean Sentinel was deployed for the first time in August 2012 for a 6-week period to test an experimental half-scale Wave Energy Technology New Zealand (WET-NZ) WEC. The operation of both the WET-NZ and the Ocean Sentinel were successfully demonstrated during the deployment, and the performance of the half-scale WET-NZ was characterized under a wide range of generator loading and sea conditions. The Ocean Sentinel power conversion, control, and data acquisition system (DAS) was used to control the load applied to the WET-NZ power take-off (PTO), and to collect WEC power and ocean data throughout the deployment period. This allowed experimentation with different control methods during the deployment; the results of these tests are described in [3].

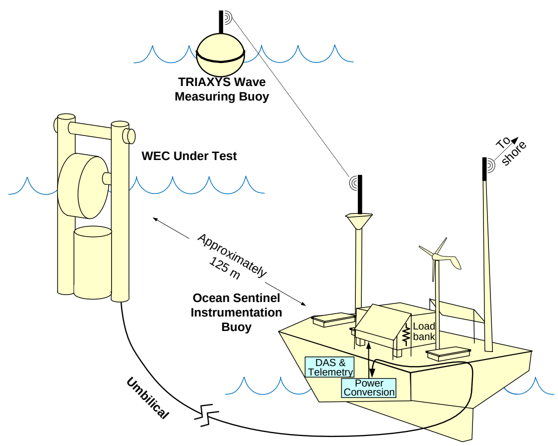


Fig. 3. WEC testing with the Ocean Sentinel instrumentation buoy.

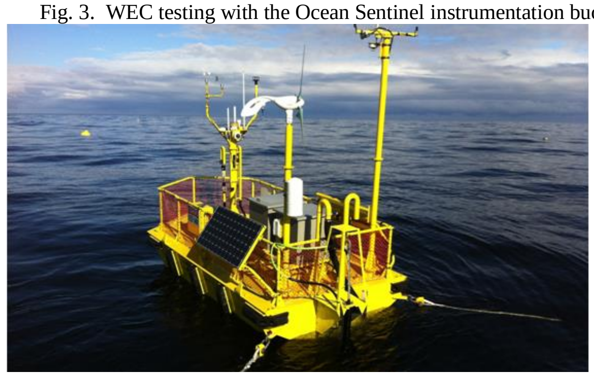


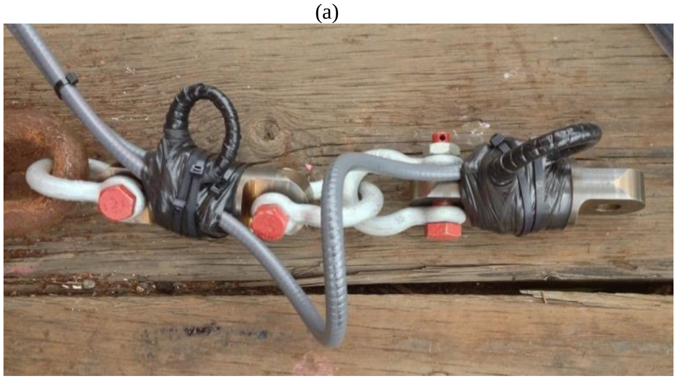
Fig. 4. Ocean Sentinel instrumentation buoy on station.

A. 2013 Ocean Sentinel Deployment at the PMEC-NETS

NNMREC deployed the Ocean Sentinel for the second time in July 2013 for a 9-week period to perform much needed mooring analysis and testing, which included numerical modeling and experimental validation. The intent of this testing and analysis was to enable the refinement of numerical mooring models, contributing to more accurate modeling, and improved designs, of WEC mooring systems. During the mooring design process, the Ocean Sentinel mooring system was modeled and tested using the OrcaFlex numerical hydrodynamic modeling tool.

For the 2013 deployment, the Ocean Sentinel was configured in a three-point mooring with load cells integrated into each mooring line (see Fig. 5) to record all tension loads. Two load cells were placed in series on the bow leg for redundancy, due to their unserviceable location under water (Fig. 5b), with one load cell each on the port and starboard legs. One swivel was placed on each mooring line outboard of the load cells to reduce torsional forces, which could potentially damage the load cells (Fig. 5a). In addition, a TRIAXYS surface wave measurement buoy and a seafloor mounted Acoustic Wave and Current (AWAC) profiler both measured wave and ocean current data near the Ocean Sentinel. Note that the two wave and current measurement systems were deployed to enable redundancy/verification. After deployment, the recorded wave and current data is coupled with the OrcaFlex model to simulate the deployed conditions and compare with actual results as detailed in the next sections.

(a)



(b)

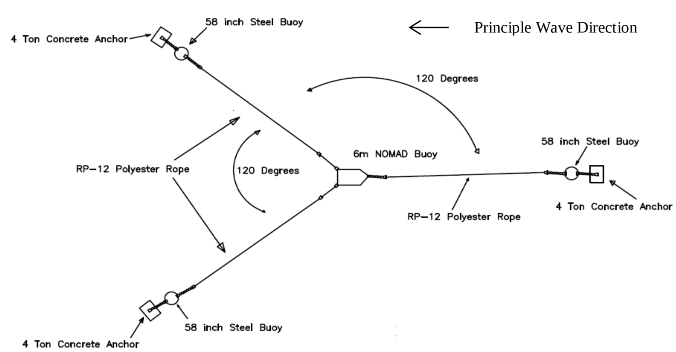
Fig. 5. Ocean Sentinel mooring system with load cells integrated into each mooring line with: (a) one load cell installed on each stern mooring line where the orange swivels are used to reduce torsional forces on the load cells, and (b) two load cells used on the bow line for redundancy (not serviceable during deployment).

B. Design and Deployment of the Ocean Sentinel Mooring System

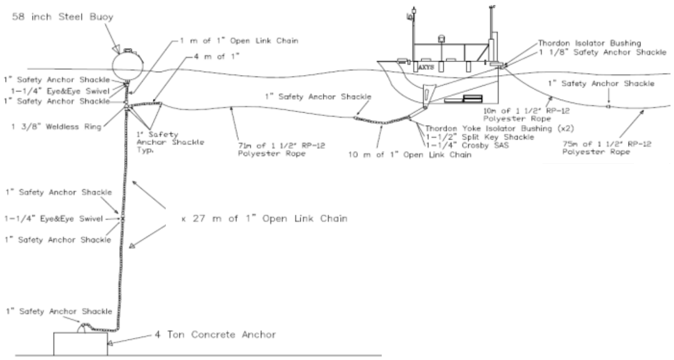
The Ocean Sentinel mooring system was designed for WEC testing using a tensioned three-point moor, as shown in Fig. 6, to prevent significant twisting of the umbilical power cable between a WEC and the Ocean Sentinel (see umbilical in Fig. 3). Components not shown in Fig. 6 include the load cells (Fig. 5) and swivels (Fig. 5a), which were used for the 2013 mooring study deployment.

The mooring system consists of three 8,500 lb. concrete anchors, connected with chain to surface floats. The surface floats are then connected to the Ocean Sentinel with synthetic line. Attachment points on the Ocean Sentinel include the bow yoke attachment using a 10 m length of chain, and shackle points at the port and starboard corners of the stern. Utilizing triangular attachment points and a tensioned system prevents significant twisting of the umbilical cable when the WEC rotation is also properly restrained. Fig. 6b shows the standard mooring leg configuration, however the actual configuration included an additional 27 m length of chain between the bow concrete anchor and surface float to increase scope. The system utilizes chain scope and yoke mass to maintain a nominal tension.

Load cells were used to measure tension in the Ocean Sentinel mooring lines, and did not measure compression or torsion. Each load cell was rated to 10,000 lb (44.48 kN), with safe working loads up to 15,000 lb (66.72 kN). The load cells were sampled at 20 Hz, which provided a good balance between desired resolution and data storage capacity onboard the Ocean Sentinel.



(a)



(b)

Fig. 6. Ocean Sentinel mooring system: (a) top view (b) side view. [4]

C. Ocean Sentinel Numerical Model

The numerical model was built in OrcaFlex, including the Ocean Sentinel and mooring system to represent the 2013 as-deployed configuration. Simulations were run to compare model predictions of mooring line tension with field data. 20-min simulation times were used with a time step of 0.0005 seconds, and all environmental data was taken from the TRIAXYS. Model inputs included: multi-directional wave spectra, directional current-depth profiles, and constant wind magnitude and direction. Currents were constant at each depth, and linear interpolations were used from the top of the TRIAXYS current data to the sea surface and from the bottom of the data to the seabed. TRIAXYS wave data is presented in Section III

D. Field Test Results

The environmental conditions during most of the deployment were typical for summers at the NETS:

- H_s = 5.27 ft (1.61 m)
- T_s = 8.27 s
- Dominant Wave Direction = 269° (from this direction)
- Surface Current = 0.50 knots (0.26 m/s), generally North/South
- Wind = 8.43 knots (4.33 m/s), generally North/South

Toward the end of the deployment, early storms came through the area that brought unique conditions. The largest seas, currents, and wind gusts occurred during this time. Maximum values for wave height, surface current velocity, and wind gust velocity were:

- H_{max} = 39.19 ft (11.94 m) at T_{max} = 11.92 s, coming from 261°
- Surface Current = 1.96 knots (1.01 m/s), flowing to 357°
- Wind Gust = 53.46 knots (27.50 m/s), coming from 179°

The resulting three-hour average tension in each mooring line is shown in Fig. 7, and the averages for the deployment were:

- Bow line load cell #1 = 389.66 lb (1.73 kN)
- Bow line load cell #2 = 360.00 lb (1.60 kN)
- Port line = 195.01 lb (0.87 kN)
- Starboard (Stbd) line = 161.01 lb (0.72 kN)

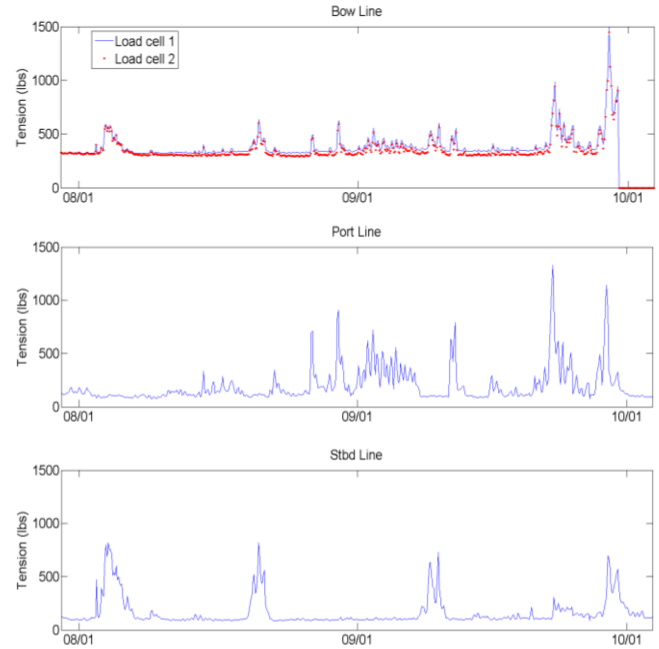


Fig. 7. Three-hour average mooring line loads during 2013 deployment.

The three-hour maximum tension in each mooring line is shown in Fig. 8 and the maximum values for the deployment were:

- Bow line load cell #1 = 7832.91 lb (34.84 kN)
- Bow line load cell #2 = 7788.87 lb (34.64 kN)
- Port line = 7999.83 lb (35.58 kN)
- Starboard (Stbd) line = 3041.32 lb (13.53 kN)

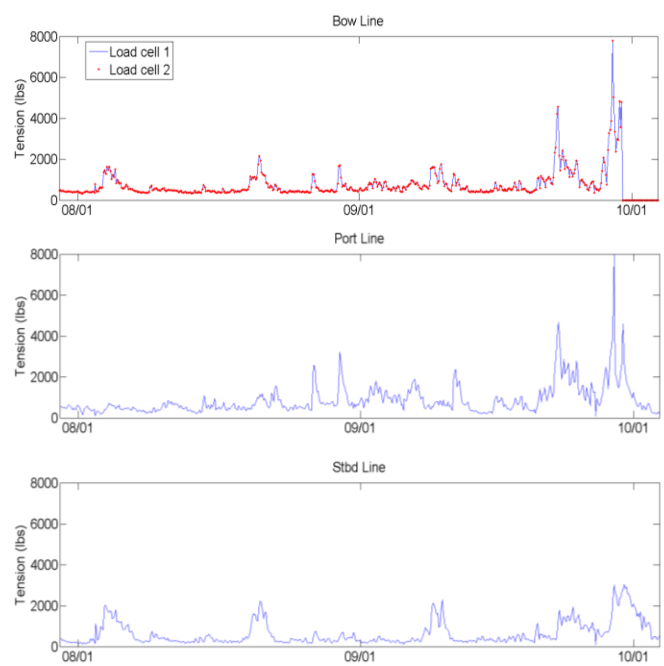


Fig. 8. Three-hour max tension in each mooring line, 2013 deployment.

E. Field Test Notable Events

The first notable event during the 2013 deployment occurred on 9/22/2013, during the first storm event, when the Ocean Sentinel strayed out of its watch circle and established a new position approximately 460 ft (140.2 m) to the North. This occurred because the Ocean Sentinel dragged its port anchor. The new anchor position was measured via the anchor surface float during recovery operations, so there was ± 93 ft (28.3 m) of uncertainty in the measurement due to the anchor buoy's watch circle. However, the port anchor was measured approximately 430 ft (131 m) to the Northwest of its original position, which clearly indicated that the anchor had been dragged (see Fig. 9). The Ocean Sentinel maintained this new position throughout the end of the deployment, so it is unlikely that any significant additional anchor movements occurred.

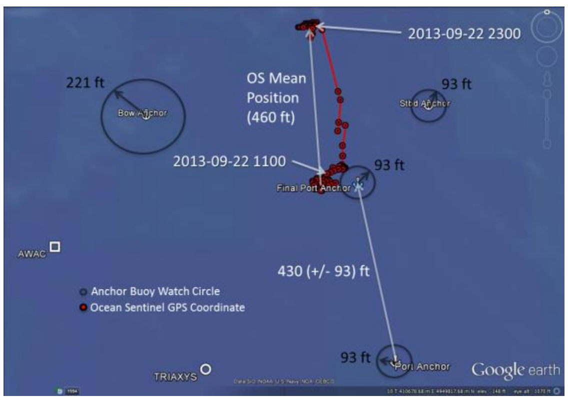


Fig. 9. Ocean Sentinel anchor movement.

The second notable event during the 2013 deployment occurred on 9/30/2013, when the cables connecting both bow load cells to the CompactRIO DAS were damaged, and the load cells began providing inaccurate data. The cables were routed through double conduit, ½ in (1.3 cm) and 1 in (2.5 cm), for protection from abrasion and impact. The ½ in (1.3 cm) conduit broke where it came out of the 1 in (2.5 cm) conduit near the end of the yoke, and the individual wires in the cables were worn down to the conductors (see Fig. 10). This most likely caused a short circuit through sea water, which led to inaccurate readings after 9/30/2013. Therefore, data from the bow load cells after 9/29/2013 was not used in this study.

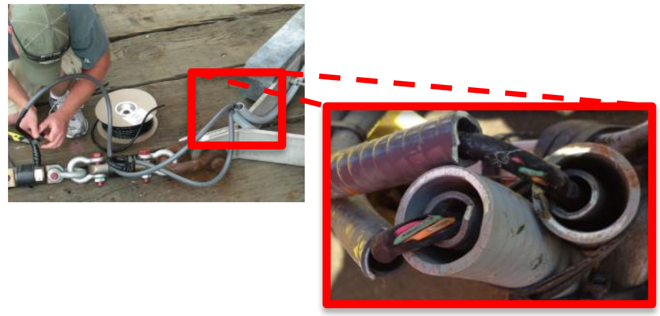


Fig. 10. Bow load cell cable damage.

F. Model Correlation with Field Data

In this study two cases were compared with field data, which is considered a preliminary correlation. The first case was an operational condition, which represented the typical environmental conditions experienced by the Ocean Sentinel during the deployment. The second case was the storm condition on 9/22/2013, which was chosen to estimate forces on the port anchor before it was dragged.

For Case 1, the time period of 1240–1300 on 8/24/2013 was chosen because environmental conditions and mooring line loads were close to average deployment values. Conditions during this time were:

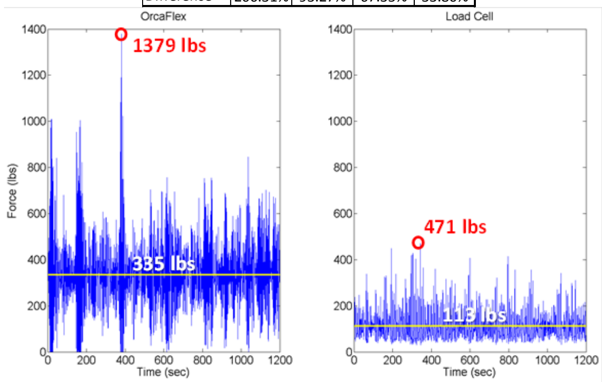
- Hs = 5.33 ft (1.62 m)
- Ts = 7.90 s
- Dominant Wave Direction = 263° (from this direction)
- Surface Current = 0.148 knots (0.076 m/s), to 296°
- Wind = 1.56 knots (0.80 m/s), from 34°

Actual mooring line forces (tension) during this time period are shown in comparison with results from the numerical model in Table 1. Time history and spectral comparisons for the port mooring line are shown in Fig. 11. Note that the time-series wave data at the Ocean Sentinel is not known, so only spectral data is used for correlation between actual and simulated data. Time history data is shown in Fig. 11a only for qualitative comparison.

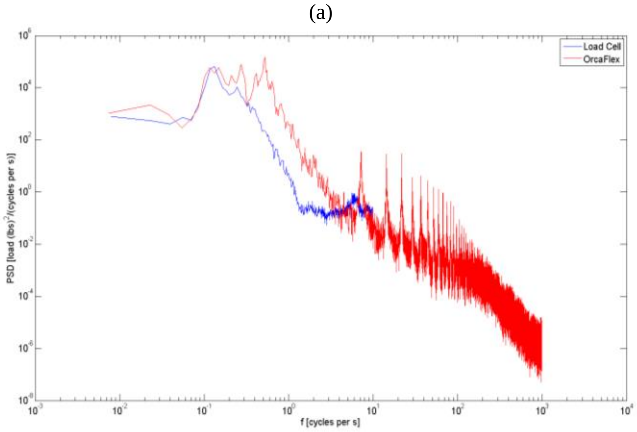
Table. 1. Case 1 mooring line tension statistics

	Port				Stbd			
	F_{max} (lbs)	$F_{1/10}$ (lbs)	$F_{1/3}$ (lbs)	F_{avg} (lbs)	F_{max} (lbs)	$F_{1/10}$ (lbs)	$F_{1/3}$ (lbs)	F_{avg} (lbs)
Load Cell	470.97	247.84	182.15	112.54	375.77	188.88	142.94	99.26
OrcaFlex	1379.05	584.50	473.87	334.92	2299.84	604.29	412.78	209.66
Difference	192.81%	135.84%	160.15%	197.60%	512.03%	219.93%	188.78%	111.22%

	Bow			
	F_{max} (lbs)	$F_{1/10}$ (lbs)	$F_{1/3}$ (lbs)	F_{avg} (lbs)
Load Cell 1	413.81	368.02	350.45	324.13
Load Cell 2	383.43	339.08	321.38	294.68
OrcaFlex	1221.00	683.3	562.16	413.99
Difference	206.31%	93.27%	67.35%	33.80%



(a)



(b)

Fig. 11. Case 1 port line tension comparison: (a) time history, (b) spectra.

The Ocean Sentinel began moving out of its watch circle on 9/22/2013 between 1000 and 1100, and most likely began dragging its port anchor during this time. The time period of 1020–1040 on 9/22/2013 was chosen for Case 2 to analyze tension in the mooring lines and predictions of forces on the port anchor before it moved. Conditions during this time were:

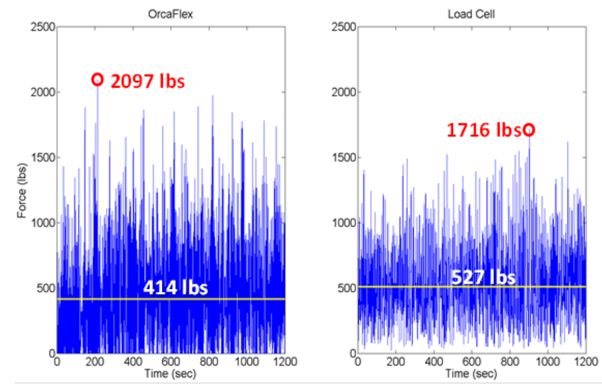
- Hs = 6.63 ft (2.02 m)
- Ts = 10.20 s
- Dominant Wave Direction, from 272°
- Surface Current = 0.86 knots (0.44 m/s), to 342°
- Wind = 16.35 knots (8.40 m/s), from 178°

Actual mooring line forces (tension) during this time period are shown in comparison with results from the numerical model in Table 2. Time history and spectral comparisons for the port mooring line are shown in Fig. 12.

Table. 2. Case 2 mooring line tension statistics

	Port				Stbd			
	F_{max} (lbs)	$F_{1/10}$ (lbs)	$F_{1/3}$ (lbs)	F_{avg} (lbs)	F_{max} (lbs)	$F_{1/10}$ (lbs)	$F_{1/3}$ (lbs)	F_{avg} (lbs)
Load Cell	1715.58	1084.29	852.75	527.08	297.97	162.95	134.91	102.63
OrcaFlex	2096.71	1139.00	841.97	414.24	2808.81	1431.48	994.33	461.30
Difference	22.22%	5.05%	1.26%	21.41%	842.65%	778.48%	637.03%	349.48%

	Bow			
	F_{max} (lbs)	$F_{1/10}$ (lbs)	$F_{1/3}$ (lbs)	F_{avg} (lbs)
Load Cell 1	1010.98	677.89	567.85	441.36
Load Cell 2	970.78	638.88	529.05	402.68
OrcaFlex	1549.97	692.57	556.66	394.78
Difference	56.42%	5.19%	1.50%	6.45%



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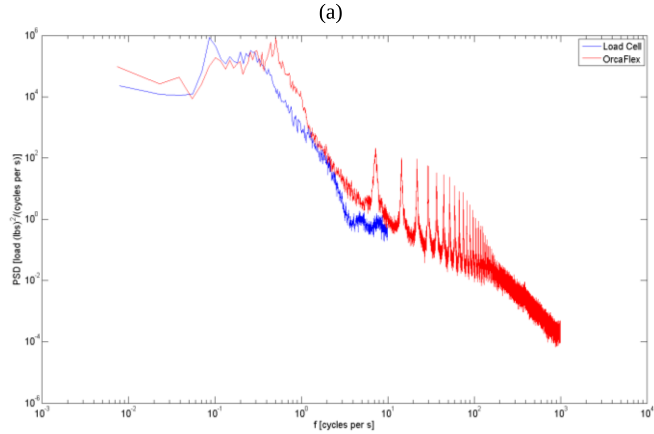

(b)

Fig. 12. Case 2 port line tension comparison: (a) time history, (b) spectra.

The numerical model showed mixed correlation with the field data. In almost all cases, it over-predicted forces in the mooring lines. The model did not show good correlation with Case 1, and the poor correlation during this time period may be due to a mismatch of model properties and environmental inputs, requiring further numerical simulation to resolve. The model showed good correlation with the field data for Case 2, especially in the bow and port mooring lines; both $F_{1/10}$ and $F_{1/3}$ were within 5.2% of actual loads. The correlation was not as good for the starboard line, where sources of error may be due to a difference between the model and the actual mooring system anchor locations during this time. The Ocean Sentinel may have already begun dragging its port anchor, which would put slack in the starboard line due to the direction of surface current. If this occurred, the model as it is currently configured would no longer be valid. The actual time of anchor movement is unknown, and will require further numerical simulation to resolve.

G. Mooring System Design Improvements

Mooring systems for wave energy devices must be designed to operate in extreme conditions, while also ensuring the safety of equipment and the environment. The Ocean Sentinel's mooring system experienced conditions near design maximums, and behaved as noted. Umbilical power and communications cables may also be at risk should mooring systems fail. Improvements to the mooring system might include the addition of drag anchors extending from the existing gravity anchors, or the installation of permanently installed subsurface anchors (e.g., embedment anchors). Anchoring systems must also be designed for ease of installation, maintenance, and reduced costs.

III. TRIAXYS WAVE DATA AND SIMULATED WAVE INSTALLATION OUTPUT AT PMEC-NETS

The TRIAXYS surface monitoring buoy wave data measured near the Ocean Sentinel at the PMEC-NETS during the summer 2013 deployment (from July 29th to October 4th) is presented here. Fig. 13 shows the Probability Mass Function (PMF) of the significant wave height for the duration of the 2-month deployment. The Fig. 13 graph shows that significant wave heights between 0.7 m and 2 m are the most likely to occur. Fig. 14 displays the PMF for wave period where it can be seen that no wave periods of less than approximately 6 seconds were recorded, with the most likely period being between 6 and 10 seconds.

Fig. 15 shows the significant wave height (averaged over 20 minute intervals) for the duration of the deployment. For the majority of the deployment, significant wave heights ranged in the expected summertime levels, i.e., between 1 m and 2 m. However, early storms occurred towards the end of the deployment, leading to significantly elevated wave heights.

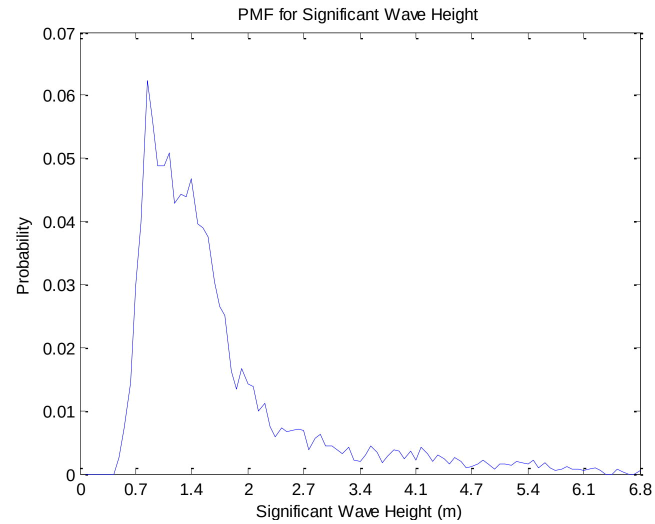

Fig. 13. PMF of significant wave height.

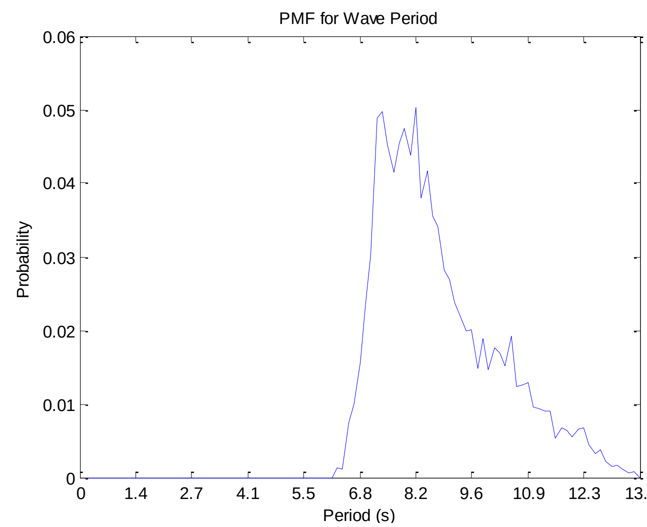

Fig. 14. PMF of wave period.

To better understand the wave resource potential of the PMEC-NETS, the power output of a generic WEC installation at the site was simulated. The simulated WEC installation had 400 buoys, arranged in a 5 x 80 grid, where each device was rated at 250 kW, with capacity factors of 0.5. These ratings can be altered to better simulate the performance of specific WEC devices. Much like a well-spaced wind farm, it was assumed that each buoy is able to operate without interfering with the other devices. While there are different types of WECs, a linear model for an oscillating body WEC was used, and a Power Take-Off (PTO) model was applied to the outputs of the linear model. Since each WEC was assumed to not interfere with others, the array power is the sum of each individual WEC's power. This time series plot is shown in Fig. 16.

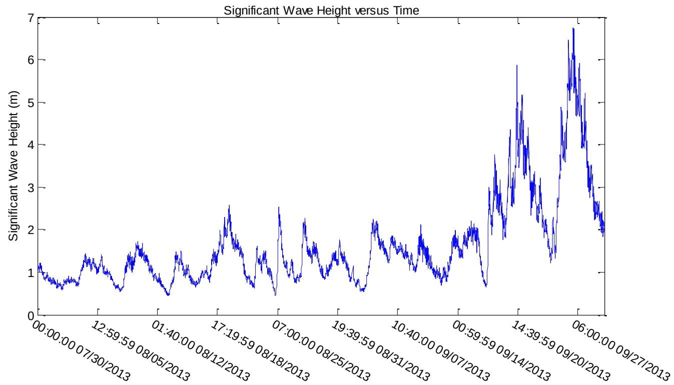

Fig. 15. Significant wave height for duration of deployment.

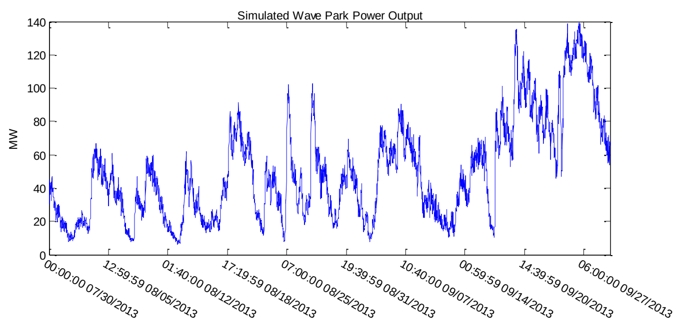

Fig. 16. Power time series of simulated WEC installation at the PMEC-NETS deployment location.

Again, at the end of the deployment early storms occurred that were uncharacteristic of standard summer wave conditions. For the majority of the deployment, the simulated WEC installation consistently produced above 30 MW in summertime conditions. In the stormy conditions, more characteristic for winter weather, the power output of the WEC farm increased significantly. The average power produced over the deployment was 49 MW.

IV. Conclusions

This paper presented the mooring design and analysis of the Ocean Sentinel instrumentation buoy, a mobile test platform for testing Wave Energy Converters (WECs), developed by the Northwest National Marine Renewable Energy Center (NNMREC). The Ocean Sentinel was deployed from July 29th, 2013 to October 4th, 2013 at the NNMREC Pacific Marine Energy Center – North Energy Test Site (PMEC-NETS) located 2 – 3 nautical miles offshore of Yaquina Head, north of Newport, OR. The Ocean Sentinel was configured in a three-point moor, with load cells on each mooring line. Prior to deployment, the numerical model was used for design and testing of the Ocean Sentinel mooring system. After deployment, recorded environmental conditions were coupled with the model to simulate deployed conditions, and model predictions of tension in the mooring lines were compared and preliminary simulations showed mixed results in comparison to actual field data. Follow on work to this study will include verification and validation of the numerical model, as well as uncertainty quantification for the model and field data. In addition, based on the results of the field testing, mooring system design improvements were proposed.

During the field observation, the Ocean Sentinel experienced a maximum wave height of 39.19 ft (11.94 m), the largest summer (July – September) wave recorded in the area during the last ten years, and a maximum mooring line tension of 7999.83 lb (35.58 kN). The port anchor was dragged during an early storm event on 9/22/2013, which is considered a minor mooring system failure. This paper also presented simulated power output for a 5 x 80 buoy wave installation array located at PMEC-NETS. Each WEC was rated at 250 kW, with capacity factors of 0.5, and the wave energy installation consistently yielded above 30 MW, with an average power of 49 MW produced over the summer 2013 deployment period.

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