Underwater noise measurements of a 1/7$^{\mathrm{th}}$ scale wave energy converter

Christopher Bassett, Jim Thomson, Brian Polagye
Northwest National Marine Renewable Energy Center
University of Washington
Seattle, WA 98115
email: cbassett@u.washington.edu

Ken Rhinefrank
Columbia Power Technologies
Corvallis, OR 97333

***Abstract*—Field measurements of the underwater acoustic signature of Columbia Power Technologies (Columbia Power) SeaRay wave energy converter (WEC) prototype are presented. The device was deployed in the vicinity of West Point (Puget Sound, Washington State) at a depth of approximately 20 meters. The 1/7$^{\mathrm{th}}$ scale SeaRay prototype is a heave and surge, point absorber secured to the seabed with a three-point mooring. Acoustic measurements were made in order to satisfy permit requirements and assure that marine life is not adversely affected.**

A series of one-minute hydrophone recordings were collected on March 30, 2011 for approximately 4 hours. During these recordings, significant wave height varied from 0.4 to 0.7 m, peak wave periods varied from 2.9 to 3.2 seconds, and southerly winds varied from 5 to 10 m s^{-1}. These are approximately twice the amplitude of typical operating conditions for the SeaRay in Puget Sound. Shipping vessel and ferry traffic levels also were typical.

Received sound pressure levels during the experiment vary from 116 to 132 dB re 1 μPa in the integrated bands from 20 Hz to 20 kHz. At times, ship traffic dominates the signal, as determined from spectral characteristics and vessel proximity. Received sound pressure levels attributed to the WEC cycle from 116 to 126 dB re 1 μPa in the integrated bands from 60 Hz to 20 kHz at distances from 10 to 1500 m from the SeaRay. The cycling is well correlated with the peak wave period, including peaks and harmonics in the pressure spectral densities. Masking by ship noise prevents rigorous extrapolation to estimate the WEC source level at the conventional 1 m reference.

***Index Terms*—Underwater acoustics, wave energy**

I. Introduction

Underwater acoustic emissions (i.e., noise) from wave energy converters (WECs) are a potential environmental effect of wave energy development. Thus, underwater noise levels in the vicinity of WECs should be quantified during deployment. Such quantification of WEC noise will often be difficult in the presence of ship traffic noise, which is expected to be several orders of magnitude larger than WEC noise, particularly for pilot-scale installations [1]. Mechanisms for sound generation by WECs include, but are not limited to, generators, bearings, structural vibrations, and strum on mooring cables [2].

Here, we described measurements of the CPT SeaRay wave energy converter (WEC) deployed in the vicinity of West Point (Puget Sound, Washington State) at a depth of approximately 20 meters. The 1/7$^{\mathrm{th}}$ scale SeaRay prototype is a heave and surge, point absorber secured to the seabed with a three-point mooring. In contrast to the full-scale WEC, the prototype includes a gearbox and torque limiter, and these elements may contribute to noise production from the prototype.

The location of the buoy, determined during this study using GPS, is 47°39.507'N and 122°26.450'W. Noise measurements were made from 10:21 to 14:16 PDT on March 30, 2011 as a rapid response to a storm with high winds and larger than average waves in the vicinity of the device.

II. Methodology

Autonomous acoustic measurements were obtained with a free drifting buoy (APL-UW SWIFT) with a hydrophone 1 meter below the surface. The acoustic recording system used on the APL-UW SWIFT consists of a self-contained Loggerhead DSG data acquisition and storage system with an HTI-96 series Hi-Tech hydrophone with an internal preamplifier. The hydrophone, when accounting for the internal preamplifier, has an effective sensitivitiy of -165.9 dB μPa V^{-1}. Digitized 16-bit data are written to a 32 GB SD card contained in the hydrophone pressure case. The frequency response of the hydrophone and data acquisition system is flat from 20 Hz to 30 kHz. Acoustics data obtained with the drifter were recorded at 80 kHz for 60 seconds every other minute. The SWIFT was deployed from a research vessel (R/V Inferno), allowed to drift in the dominant current direction for up to 80 minutes, then recovered, and redeployed.

Drifter recordings are divided into windows (16384 points), tapered using a Hann window, overlapped 50%, Fast Fourier Transformed, and normalized to preserve variance. Windows are ensemble averaged to obtain pressure spectral densities (PSD) from 10 Hz to 20 kHz with high statistical confidence. The resulting pressure spectral densities describe the frequency content of the recordings. The minimum and maximum resolvable frequencies are dependent on the hydrophone response and data acquisition rate, respectively. The spectra are evaluated for quality control and integrated from 60 Hz to 20 kHz to determine broadband sound pressure levels (SPL), given in dB re 1 μPa, attributed to the wave energy converter. Below 60 Hz spectral levels are attributed ambient noise sources.

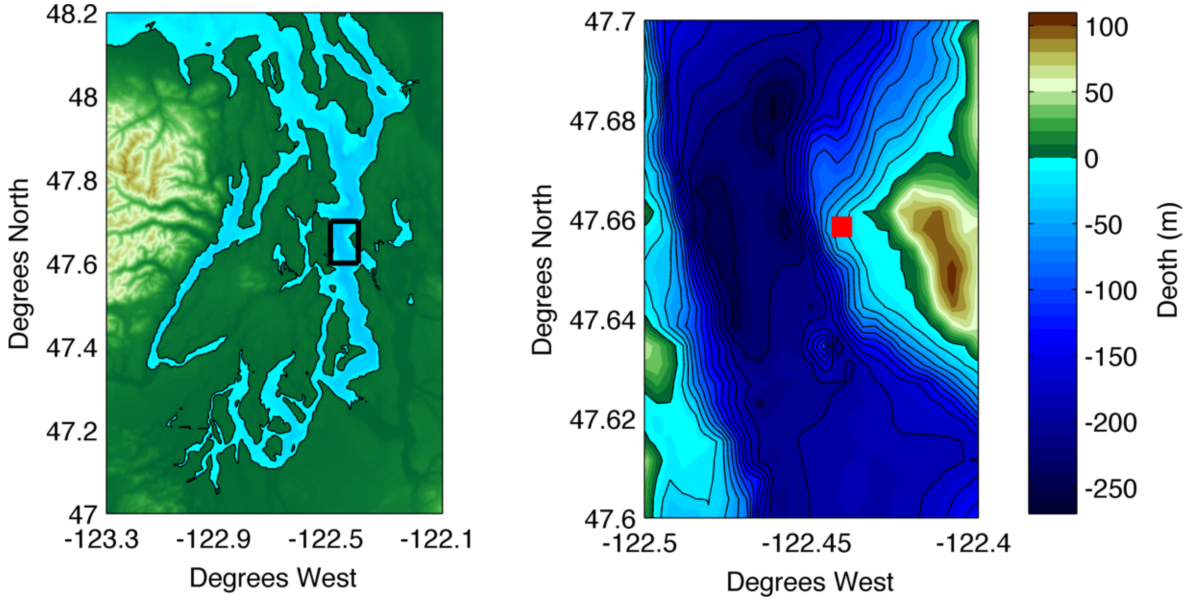

Fig. 1: Puget Sound (left inset), and Central Puget Sound (right inset) including West Point and the location on the Columbia Power Technologies prototype wave energy converter (red square).

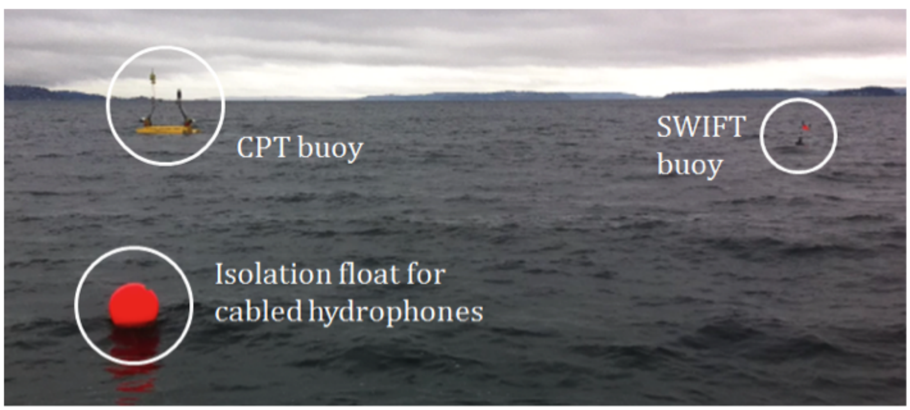

Fig. 2: The CPT SeaRay in operation, as well as a hydrophone and APL-UW SWIFT.

The SWIFT is also equipped with an accelerometer, a high resolution Digital Video Recorder (DVR), and a GPS recorder. The SWIFT motion is recorded at 5 Hz in 300 second windows, and the motion is used to construct wave height spectra by applying Linear Finite Depth Theory [3] to covert velocity energy spectra $S_u(f)$ to elevation energy spectra $S_\eta(f)$, where f is frequency (i.e., $(2\pi f)^{-2} S_u(f) = S_\eta(f)$ in deep water). A detailed description of the SWIFT methodology is forthcoming in [4]. The spectral wave energy flux, or spectral power density along a wave crest, is estimated as $P(f) = \rho g c_g S(f) = \rho g^2 (4\pi f)^{-1} S_\eta(f)$, where c_g is the group velocity, ρ is the density of seawater and g is gravity, and the result can be integrated in frequency to obtain the total power density of the wave field.

GPS logs for the SWIFT are used to calculate the distance between the hydrophone and the SeaRay. GPS coordinates are recorded at 5 Hz. Field notes on the positions of nearby ships monitored by a stand-alone AIS receiver are used to interpret spatial patterns of broadband SPLs.

The CPT SeaRay mooring system is also equipped with a Nortek Acoustic Wave and Current meter (AWAC) and instruments for monitoring the operating conditions of the device. During the noise measurements (March 30, 2011), the SeaRay telemetry unit was not functioning so information about operating parameters of the buoy is not available. Instead, operational data from comparable wave conditions on March 14, 2011 are used. Time series of generator torque, generator shaft speed, wave spectra are calculated in the fore and aft directions. The signal processing techniques used for spectral analysis of the SeaRay operating parameters the are the same as those used for the the hydrophone data. Generator torque, and generator shaft speed data are sampled at 25 Hz and processed using data windows with 2048 data points.

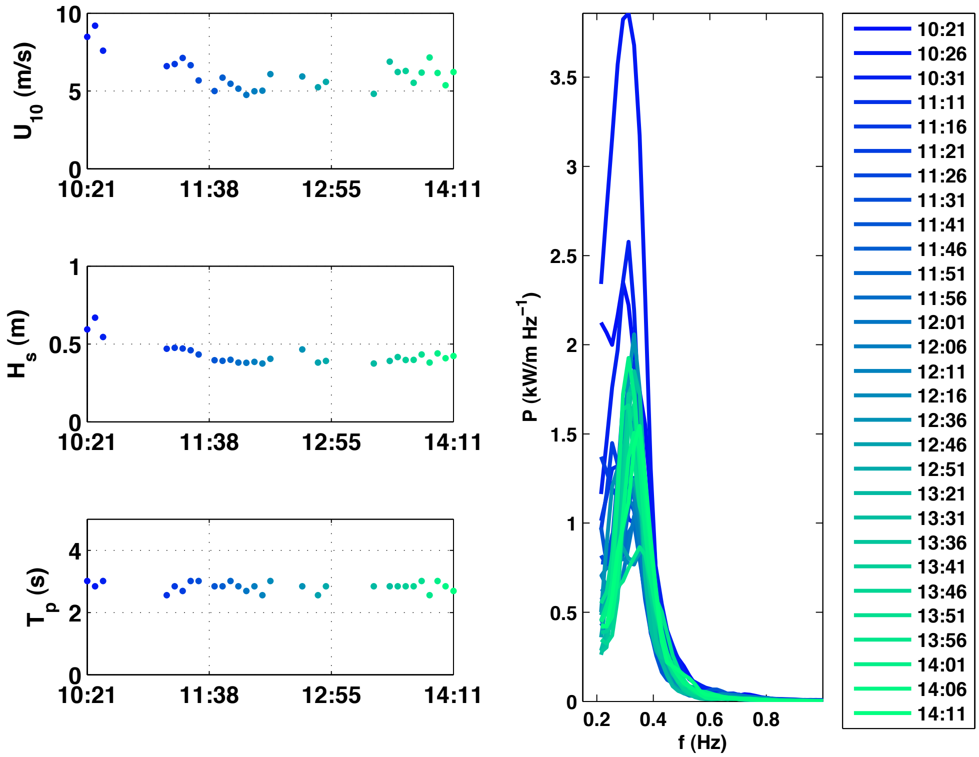

Fig. 3: a) Wind speeds, b) Significant wave heights, and c) Peak wave periods and d) Wave power density spectra during the study on March 30, 2011

III. Results

A. Wave Climate and Operating Conditions

During the acoustic measurements, significant wave heights (H_s) ranged from 0.4 to 0.7 m, peak wave periods (T_p) from 2.9 to 3.2 seconds, and southerly winds at reference height of 10 m (U_{10}) from 5-10 m s^{-1}; approximately twice the amplitude of typical operating conditions for the SeaRay in Puget Sound. For a full-scale device, comparable operating conditions would be a significant wave heights between 2.8 and 4.9 meters and wave periods between 7.7 and 8.5 seconds. Figure 3 shows the wave conditions and spectra power density estimated using the APL-UW SWIFT during the study. Digital Video Recordings (DVR) of the SeaRay in operation during hydrophone recordings indicate full travel on the buoy surge mechanism.

Figure 4 includes time series and spectra, normalized by their maximum values, for the generator torque and generator shaft speed in the fore and aft direction for comparable wave conditions on March 14, 2011. Spectra for generator torques and shaft speeds show peaks at the dominant wave period, and the a priori expectation is for noise generation to peak at similar intervals. In addition, the aft components show a secondary peak at twice the dominate wave period, which again is expected to contribute to noise production.

B. Sound Pressure Spectral Densities and Received Sound Pressure Levels

Shipping traffic, which is known to be a substantial contributor to ambient noise in Puget Sound (e.g. [5]), dominates the overall broadband sound pressure levels (20 Hz to 20 kHz), as determined from relative distances and acoustic spectral characteristics. Many vessels, including local ferries operating regularly within 4 km, as well as container vessels, tugs, and a recreational vessel within 100 m, were recorded near the site throughout the data collection on March 30, 2011.

Figure 5 shows a spectrogram of a one minute recording taken from the SWIFT at 13:41 PDT on March 30, 2011 at a distance of 0.3 km from the SeaRay. In addition, Figure 5 includes a time series of the broadband SPL (60 Hz to 20 kHz) for each window in the spectrogram. Below 1 kHz there are increases in spectral levels that occur approximately once per wave period (Figure 4). Above 800 Hz there are additional short increases in spectral levels that occur approximately twice per wave period, a pattern consistent with WEC torque and shaft speed in the fore generator (Figure 4).

In addition to modulation of the broadband SPL, the harmonics (i.e., frequency content) of the acoustic signature are modulated within each wave period. Figure 6 includes the same one minute spectrogram plotted in linear scale with different colormap threshold. The spectrogram in linear space reveals approximately 10 identifiable harmonics that oscillate together in time. Although the frequencies of these harmonics

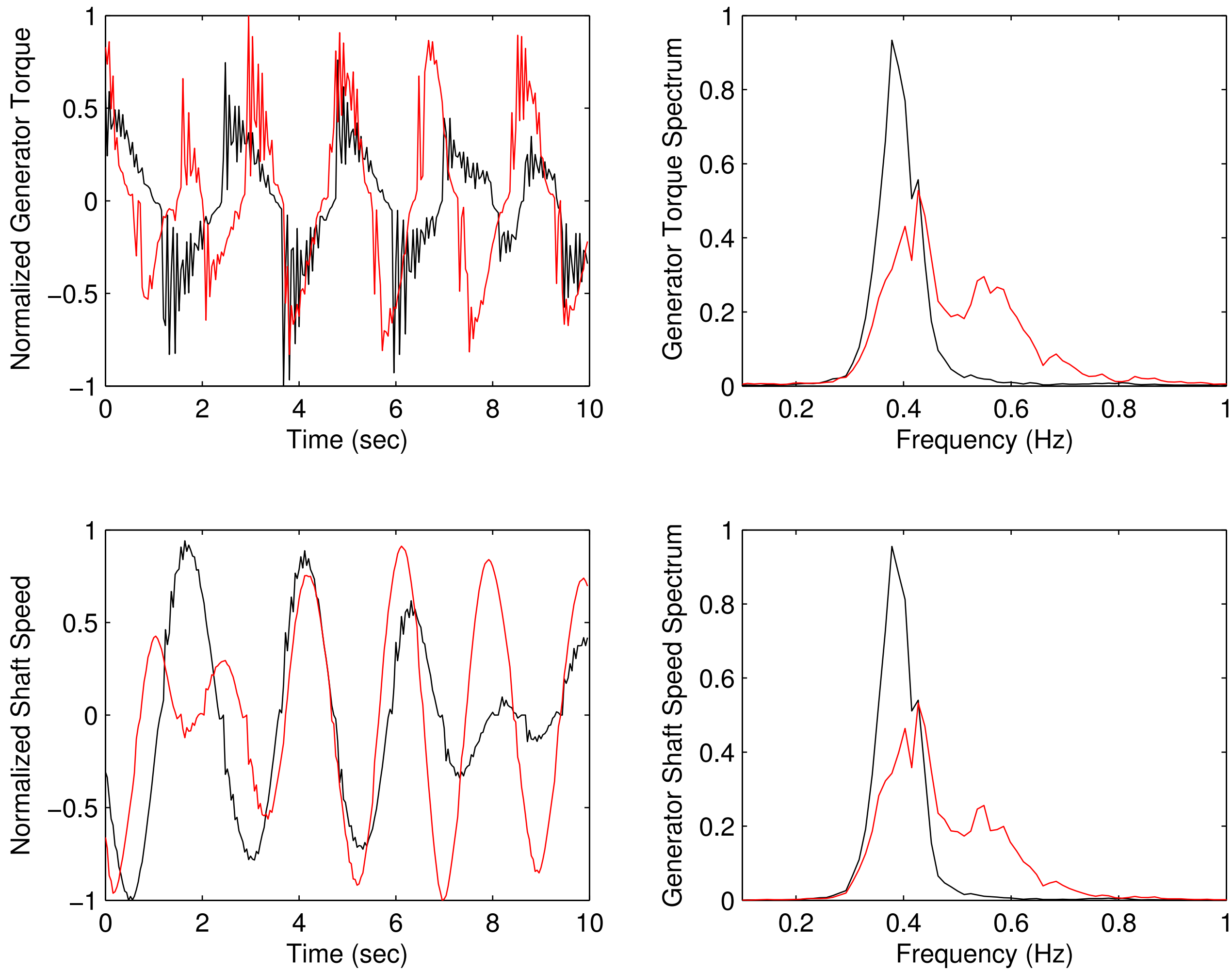

Fig. 4: Normalized time series and spectra for the generator torque and generator shaft speed in the fore and aft direction on March 14, 2011. Black lines correspond to aft generator and red lines correspond to the fore generators.

vary with time, the energy contained by each individual harmonic typically reaches a minimum when the frequency of the harmonics reaches a minimum. These minima are co-temporal with brief increases in energy above 800 Hz occurring twice per wave period.

One explanation for the modulation of the harmonics is the ramp up and down of the generator shaft speed with the passage of each wave. The high intensity pulse at the harmonic minimum may be attributed to the aft portion of WEC slapping the water surface, as confirmed by digital video recordings of the WEC in operation (and the spectra in Figure 4). These hypothesis cannot be rigorously tested without coherent operational data from the WEC, because other sources of noise are always present. For example, the occasional increases in broadband noise may be attributed to surface waves breaking locally on or near the SWIFT.

Figure 7 includes three 1-minute averaged spectra representative of the conditions recorded on March 30, 2011. When averaging over the entire minute, the well-defined frequency peaks apparent in Figures 5 and 6 are smeared together, resulting in broad peaks with relatively low signal-to-noise ratios. Because of this, a description of WEC noise produced by averaging spectra over multiple wave periods is incomplete. Additionally, the tug spectrum included in Figure 7 demonstrates that masking of all frequencies produced by the wave energy converter occurs in the presence of ship traffic.

The spectrograms shown in Figures 5 and 6 are among those with the highest WEC acoustic signal to ambient noise ratios. In the absence of loud ship noise, the same periodic acoustic signature is identifiable up to 1.5 km from the WEC the device with diminishing signal-to-noise ratios. Figure 8 includes the locations and broadband SPLs (60 Hz - 20 kHz) for all recordings taken on March 30, 2011. One minute averaged broadband SPLs range from 132 dB re 1 μPa at less than 100 meters from the device to 116 dB 1 μPa 1.1 km from the device.

Figure 9 shows the received SPLs as a function of distance to the WEC. The simple expectation from the SONAR

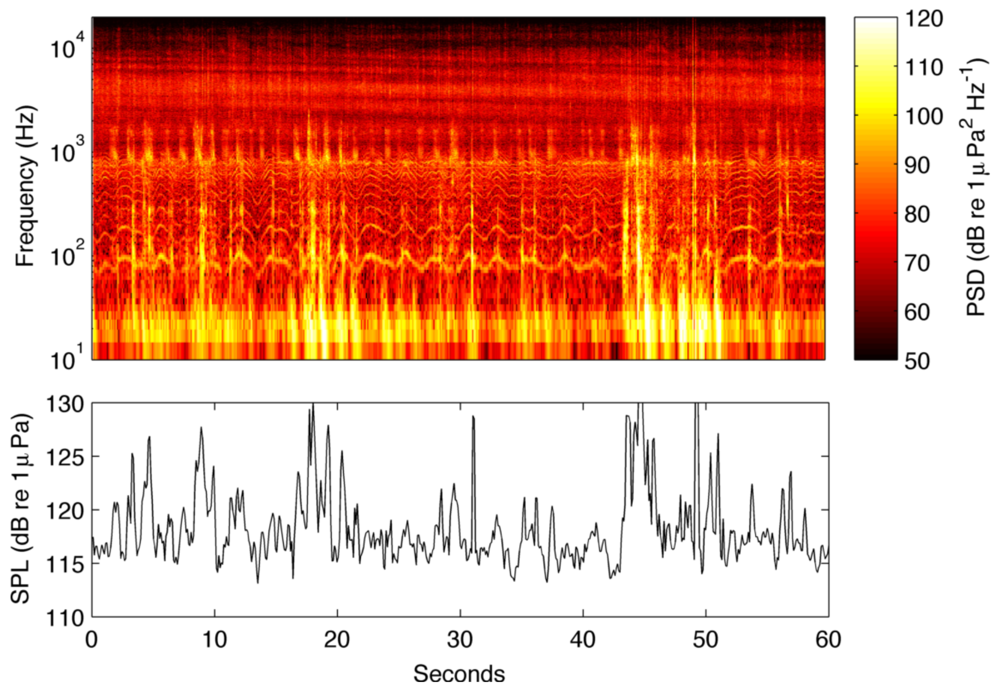

Fig. 5: top) Spectrogram for one-minute recording taken at 13:41 on March 30, 2011 at a distance of 0.3 km from the SeaRay. bottom) Broadband received SPLs (60 Hz - 20 kHz) for each window of the spectrogram.

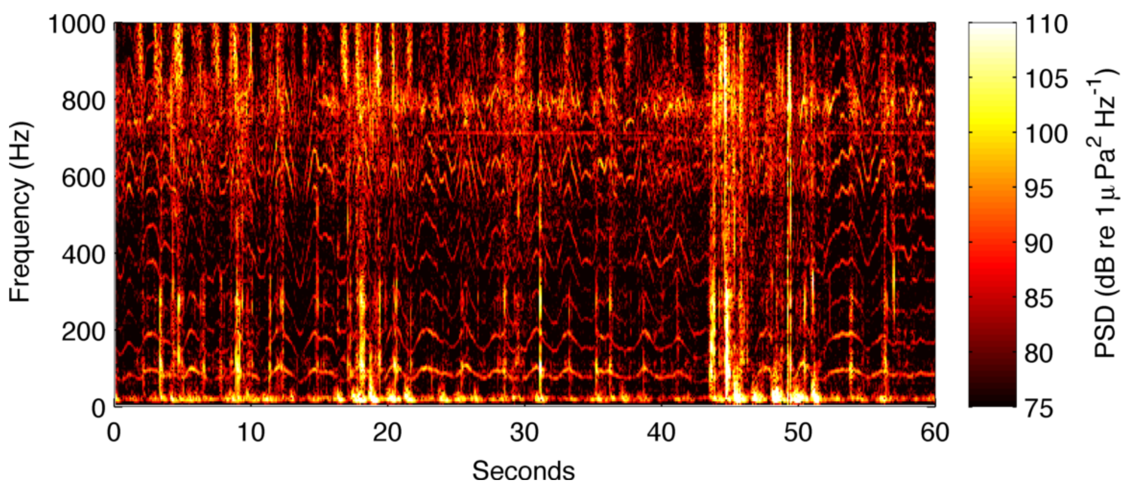

Fig. 6: A portion of the spectrogram for the recording taken at 13:41 on March 30, 2011 at a distance of 0.3 km from the SeaRay.

equation is that received SPLs will decrease with distance from the WEC. However, masking by ship noise obscures this pattern. For example, received broadband SPL from a large cargo vessel may be greater than 120 dB at a range of 20 km [5] and have a similar spectral distribution to the WEC, while received levels from the WEC are only detectable, under otherwise quiet conditions, to a range of 1.5 km (as observed here). Reducing the data to a short drift containing recordings without ships nearby identifies the highlighted points in Figure 9, which do show the expected decrease with increasing range. However, there are insufficient points to extrapolate the observations to a source level at the 1 m reference distance.

IV. Conclusion

The acoustic signature of the Columbia Power Technologies SeaRay wave energy converter is measured using an APL-UW SWIFT buoy equipped with an autonomous hydrophone. Spectrograms reveal an acoustic signature dependent on the dominant wave period. An acoustic source level could not be estimated during operation due to significant levels of anthropogenic noise from shipping and limited variation in received levels with distance from the WEC.

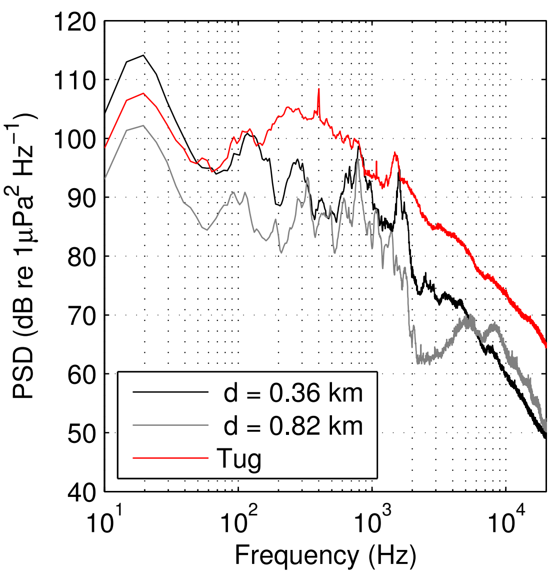

Fig. 7: Three 1-minute spectra representative of acoustic conditions recorded on March 30, 2011.

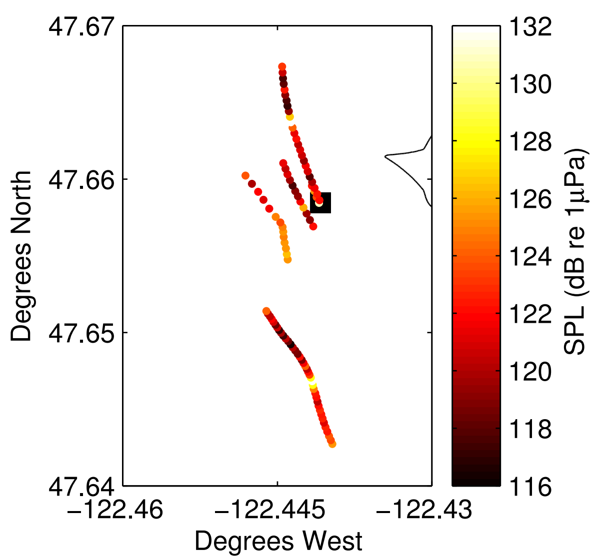

Fig. 8: A map of the locations of the recordings taken by the SWIFT and the broadband received SPLs (60 Hz - 20 kHz).

As WEC devices continue to develop and are deployed in ocean environments there will be a need to further study the acoustic signatures during operation. Given the periodic nature of surface waves, noise emissions from devices are likely to exhibit periodicity and, in a regulatory context, occupy a middle ground between continuous and pulsed noise sources. A standard method describing frequency content and sound pressure levels for devices that operate periodically under different wave conditions should be developed to facilitate a greater understanding of the potential environmental effects.

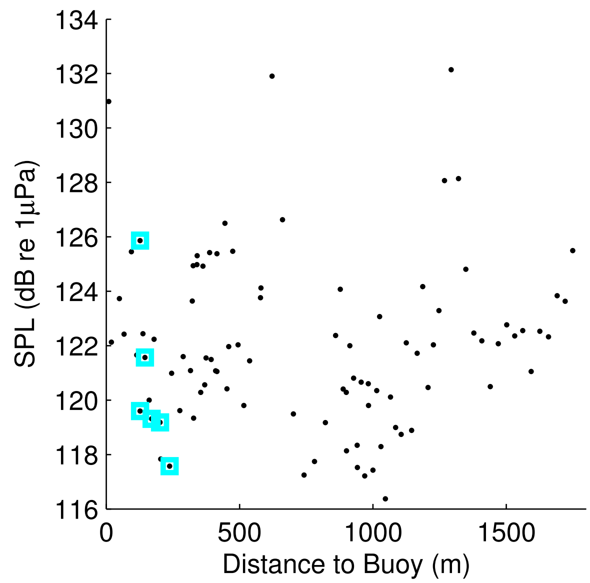

Fig. 9: Received Sound Pressure Levels (integrated from 60 Hz to 20 kHz) versus range to the WEC. Observations with minimal ship noise masking are outlined in light blue squares.

V. Acknowledgments

We thank Columbia Power Technologies for funding, as well as WEC operational data and permission to disseminate results. Columbia Power Technologies is supported by the U.S. Department of Energy (USDOE DE-EE0002647). C. Bassett is funded by the National Science Foundation (DGE-0718124).

References

[1] G. B. et al, "Ecological effects of wave energy development in the pacific northwest: A scientific workshop," NOAA, Tech. Rep., 2008.

[2] S. Patricio, A. Moura, and T. Simas, "Wave energy and underwater noise: state of art and uncertainties." Bremen: MTS/IEEE Oceans 2009 conference, May 2009.

[3] C. Mei, *The Applied Dynamics of Ocean Surface Waves*, ser. Advanced Series on Ocean Engineering. World Scientific, 1989, vol. 1.

[4] J. Thomson, "Observations of wave breaking dissipation from a swift drifter," *J. Atmos. Ocean. Tech.*, in review.

[5] C. Bassett, B. Polagye, and J. Thomson, "A vessel noise budget for Admiralty Inlet, Puget Sound, Washington," *(in preparation)*.