Circular-Slide Wave Energy Converter in Random Waves

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***Abstract* -** We propose a new wave energy converter that uses ocean wave roll/pitch motions to drive a rotating mass and spin an electric generator. Long life is achieved by sealing all mechanical parts inside a watertight structure and replacing unreliable mechanical springs by a tunable articicial spring, which keeps the system in resonance online with waves. We simulate the system dynamics in realistic ocean conditions to demonstrate performance of the new concept.

Keywords—*wave energy converter; random waves; circular sliding track; artificial spring*

I. INTRODUCTION

There are two main types of wave energy converters (WEC) for small-to-moderate power applications in the deep ocean when anchoring is not desired or impractical. The first can be called a "shaking" WEC, which is similar to a rechargeable flashlight that is energized by hand shaking. The second can be called a "direct-drive" WEC, which uses a submerged drag-device to produce a force against surface wave motion to turn a generator [1].

The direct-drive type produces much more power per unit weight in all sea conditions than the shaking type; however, in harsh environments, it is preferable to use the shaking type, because it can be hermetically sealed to reduce environmental degradation and extend operational life. Due to very low frequencies of ocean waves, the springs required to achieve resonance in shaking WECs are soft and have impractically large vertical deflections. This is a design weakness and tends to make a shaking WEC large and bulky [2].

We suggest a different type of shaking WEC with a mass that slides in a circular trajectory under gravity in response to wave-induced buoy pitch/roll, as illustrated in Fig. 1 and described in [3]. This conceptual Circular-Slide WEC includes the following components: sliding mass, circular sliding track, connecting arm, gearbox, generator, encoder, controller, etc. For protection from the harsh ocean environment, all of the components can be mounted inside a hermetically sealed box.

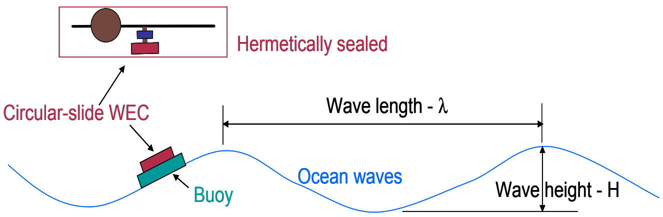

Fig. 1. Circular-slide WEC utilizing buoy pitch or roll motion.

II. DESCRIPTION OF CIRCULAR-SLIDE WEC

The principle of a circular-slide WEC (CS-WEC) can be explained using Fig. 2. The sliding mass is a weight with a circular or rectangular cross-section that slides in a low-friction track by using wheels with ball-bearings on rails. The arm is a light structure that connects the sliding mass to the input shaft of a gearbox. The gearbox increases the rotation speed and drives an electrical generator.

The encoder would be mounted on the gearbox input shaft. The angular displacement of the sliding mass, measured by the encoder, would be used to create and control an artificial torsional spring. This electro-magnetic spring would be used to force the sliding mass into rotational resonance; *i.e.,* to move back and forth on the circular track with optimal angular displacement when the buoy pitches or rolls due to wave motions. The resonating angular motion of the sliding mass would also be amplified by the gearbox to drive the generator and produce power. The optimal resonating angular amplitude of the mass on the track has been shown to be ±90°.

The zero reference for optimal feedback control should align with the buoy pitch and roll axis following each wave. If they do coincide, maximum power would be harvested. If not, during online control, the zero reference would be monitored and gradually adjusted to ensure resonance and to achieve maximum power. This activity to monitor and adjust the alignment uses negligible energy compared to that being harvested.

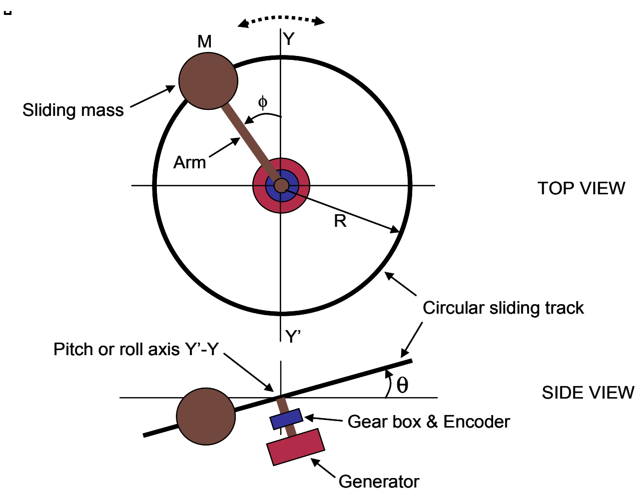

Fig. 2. Major components of the circular-slide WEC.

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One strong advantage of the CS-WEC concept is that no static spring deflection problem exists as in conventional shaking WECs. The artificial or electromagnetic spring eliminates reliability problems associated with mechanical springs and the spring constant can be modified in-situ by monitoring the dominant wave period, which keeps the system in resonance with waves for maximum power.

For some buoy applications where the center portion of the buoy is not available [4], the CS-WEC could be configured as shown in Fig. 3. The connecting arm in the original configuration would be replaced by a hub with a center hole that is supported at three points on the circular track, including one under the sliding mass. The hub is made with gear teeth, which drive a pinion connected to the generator. In this situation, there is no need for a gearbox; it is replaced by the hub ring gear and pinion. Other designs of hub and drive coupling for maximizing the center hole are possible.

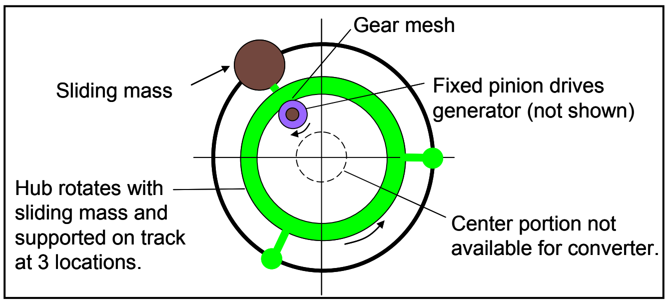

Fig. 3. Hub configuration with center hole.

III. Power Scaling Law

The relevant dynamic parameters and forces associated with the CS-WEC are presented in Fig. 4.

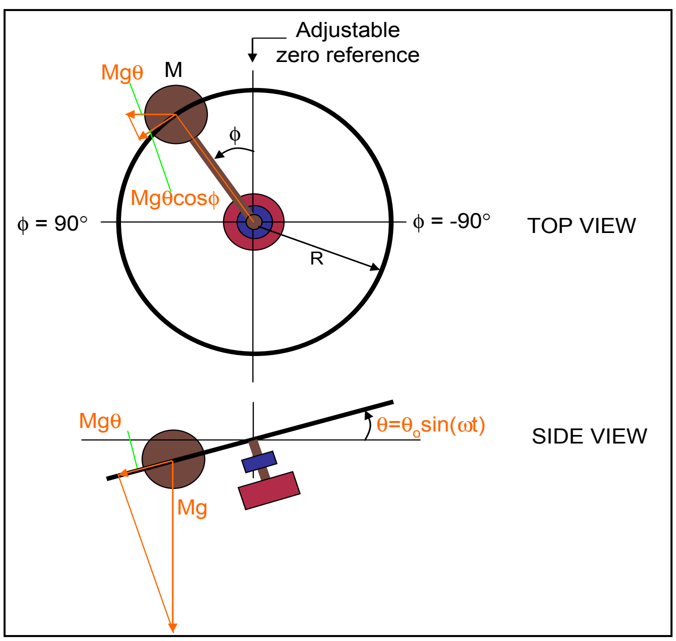

Fig. 4. Relevant parameters of a circular-slide wave energy converter.

Neglecting the polar moments of inertia of the connecting arm, generator rotor, *etc.,* the equation of motion of a CS-WEC is:

$$MR^2\frac{d^2\phi}{dt^2}+B\frac{d\phi}{dt}+K\phi = Mgsin(\theta)cos(\phi)R \qquad (1)$$

where

ϕ = sliding mass angular displacement on track, rad

t = time, s

M = sliding mass, kg

R = circular track radius, m

B = damping coefficient associated with friction and power output, Nm-s/rad

K = artificial torsional spring constant from feedback control, Nm/rad

g = gravitational constant = $9.81\ m/s^2$

$\theta=\theta_o sin(\omega t)$ = instantaneous incline angle, rad

$\omega=\frac{2\pi}{T}$ = dominant wave frequency, rad/s

T = dominant wave period, s

$\theta_o=\frac{H}{2}\frac{2\pi}{\lambda}=\frac{(2\pi)^2}{2g}\frac{H}{T^2}\approx 2\frac{H}{T^2}$ = buoy incline angle, rad

H = significant wave height, m

$\lambda=\frac{gT^2}{2\pi}$ = deep water wave length, m

Equation (1) is nonlinear because the forcing function on the right hand side contains the term *cos(ϕ)*. When we average over the track angle ϕ, assuming it is extended to ± π/2, we get

$$\frac{1}{\pi}\int_{-\pi/2}^{\pi/2}\cos(\phi)d\phi=\frac{2}{\pi} \qquad (2)$$

Substituting (2) into (1) and assuming a small wave angle θ, we have an approximated linear dynamic system as represented by (3).

$$MR^2\frac{d^2\phi}{dt^2}+B\frac{d\phi}{dt}+K\phi = Mg\theta_o\sin(\omega t)(\frac{2}{\pi})R \qquad (3)$$

Let's make the artificial spring constant, *K,* such that the system is in resonance. Then, the inertial force cancels the spring force, and (3) becomes

$$V=\left.\frac{d\phi}{dt}\right|_{\max}=Mg\theta_o(\frac{2}{\pi})R/B=\frac{g\theta_o(\frac{2}{\pi})}{2\xi\omega R}=\omega(\frac{\pi}{2}) \qquad (4)$$

where

V = angular velocity amplitude at resonance,

$B=\xi(2\omega MR^2)$, and

ξ = damping ratio.

Using (4), the average power, P, at resonance is:

$$P = \frac{1}{2} B V^2 \eta = \frac{1}{2} [\xi (2 \omega M R^2)] [\frac{g \theta_o (\frac{2}{\pi})}{2 \xi \omega R}]^2 \eta \qquad (5)$$

or

$$P = (1/2) M g R \theta_0 \omega \eta \qquad (6)$$

where η = system efficiency, *e.g.,* 0.75. Equation (6) can be written as:

$$P = 20 \ \pi \eta M R H / T^3 \qquad (7)$$

The scaling law (7) indicates that the average power of a tuned circular-slide wave energy converter is directly proportional to the sliding mass (M), the circular sliding track radius (R), the significant wave height (H) and inversely proportional to the wave period (T) cubed.

On average, world-wide ocean waves have a significant height of about 2m and dominant period of about 10s. For those average conditions, our circular-slide WEC would produce average power (watts) as listed in the following table.

TABLE I. Power (watts) for various masses and radii.

	Radius (m)		
Mass (kg)	0.5	1	2
25	1	2	5
50	2	5	9
100	5	9	18

Note that the artificial torsional spring constant, K, in (1) is set equal to $MR^2\omega^2$ for all time, where MR^2 is the approximate polar moment of inertia of the sliding parts and ω is the wave circular frequency. Mathematically, the control system causes a motor to produce a torque, T_q, such that:

$$T_q = - K \phi_m \qquad (8)$$

where

$K = I_p \omega^2$

$I_p \approx MR^2$, and

ϕ_m = sliding mass angle, ϕ, measured by the encoder.

This implies the controlled spring torque is always equal to the inertial torque, which is a requirement for system resonance.

To make the artificial torsion spring practical, the motor must be a low power consumption device. We suggest that the motoring function be implemented in the generator to keep the hardware simple and to reduce weight and volume. Since CS-WEC is potentially applicable to drifting buoys, we consider a generator sized for a 3m Discus buoy [4], for example. Using the scaling law (7), we have the average power of 113 watts for a sliding mass of 100kg, track radius of 1.5m, wave height of 2m at a period of 5s. For this purpose, a permanent magnet brushless generator was sized to produce 0.2 HP (150 watts) at 200rpm. The generator core had a rotor outside diameter of 100mm, a stator outer diameter of 160mm, and a length of 150mm. The generator had six rotor permanent magnets and three phases of stator windings. It had a torque constant of 4.3Nm/A, and a coil resistance of 0.57ohm per phase. As discussed later, nonlinear simulations of (1) will include these generator/motor properties.

IV. SIMULATION OF CIRCULAR-SLIDE WEC RESPONSE IN RANDOM WAVES

Previously [3] we simulated energy harvesting in an ocean swell with a 2-m height and 10-s period. In this paper, we present further power simulation results in random waves. Based on a Pierson-Moskowitz wave spectrum [5], random wave heights were computed at five different wind speeds, *i.e.,* 5, 10, 15, 20 and 25kt, as presented in Fig. 5. The associated significant wave heights and average periods are tabulated on top of the figure.

Wind speed (kt)	Significant wave height (m)	Average wave period (s)
5	0.14	1.65
10	0.56	3.30
15	1.27	4.95
20	2.26	6.60
25	3.53	8.25

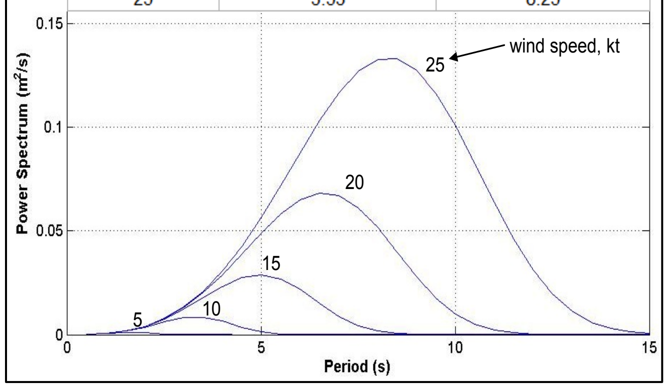

Fig. 5. Pierson-Moskowitz wave-height spectra for several wind speeds.

The random waves at each wind speed consist of components in a range of frequencies. For example, at a wind speed of 15kt, the wave frequency content may be approximated, as shown in Fig. 6.

Since no phase information was available, the phases of the wave components are assumed to be random. The wave amplitude versus time for the 15-kt case is shown in the upper plot of Fig. 7. It shows a wave height of more than 1m, which is consistent with the "significant wave heights tabulated in Fig. 5. The lower plot of Fig. 7 is the random wave surface tilt angle at 15-kt wind, which appears to have high frequency content. An FFT of the signal revealed the frequency spectrum of Fig. 8.

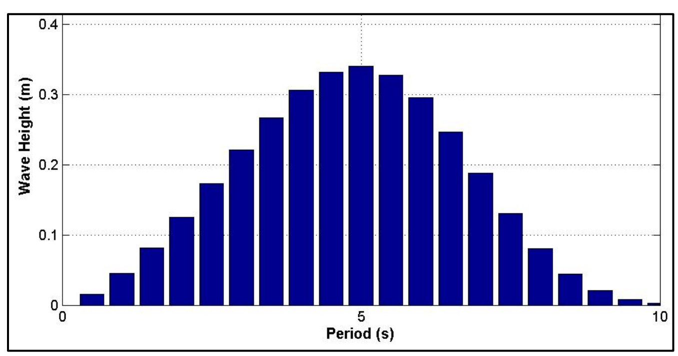

Fig. 6. Random wave frequency content for 15-kt winds.

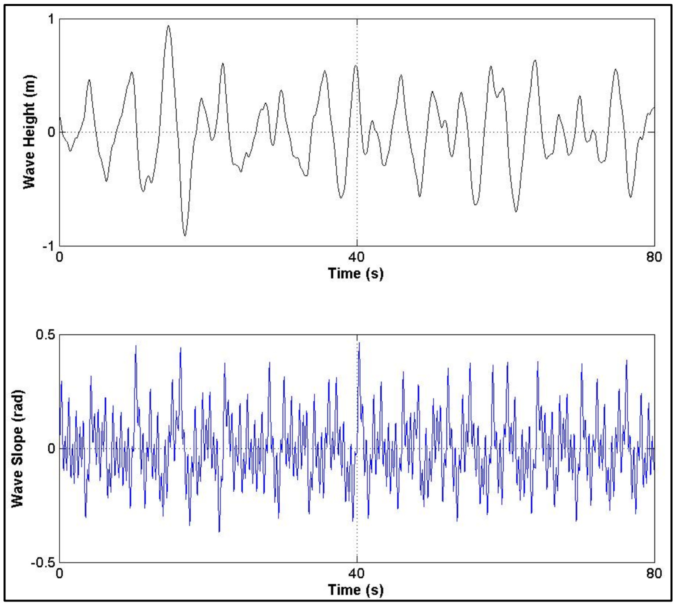

Fig. 7. Simulated 15-kt random wave heights and surface slopes.

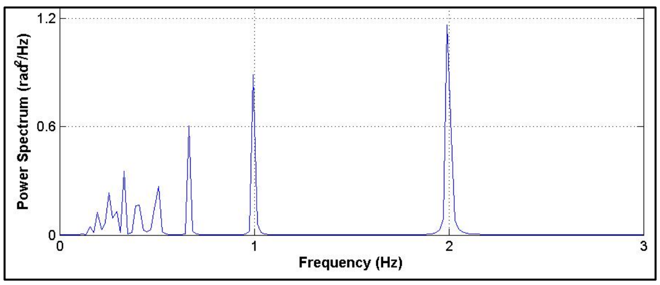

Fig. 8. Spectrum of random wave surface tilts in 15-kt winds.

The frequency peaks at 0.67, 1 and 2Hz appear due to the components at the digitizing periods at 0.5, 1.0 and 1.5s as shown in Fig. 6. These relatively high-frequency components are associated with short wave lengths of 0.39, 1.56, and 3.51m, respectively. A buoy (or buoy floatation) might have a diameter larger than these wavelengths and/or natural mode frequencies too low to respond to these relatively high frequencies. In order to avoid the complication of undefined dynamics that are associated with a specific buoy size, we assumed that the system would not respond to high frequency (> 0.5 Hz) wave components. We then filtered the wave spectra for all wind speeds. Figs. 9, 10, and 11 represent the filtered random wave results at a 15-kt wind speed.

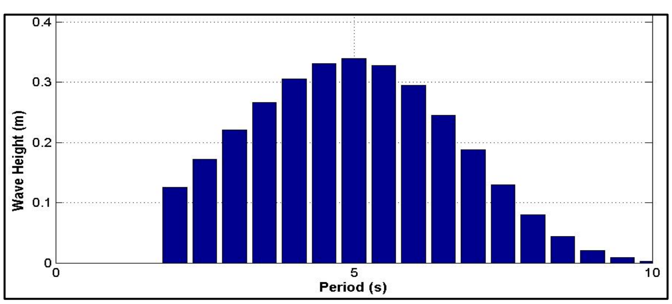

Fig. 9. 15-kt random wave frequency content with 3 short periods eliminated.

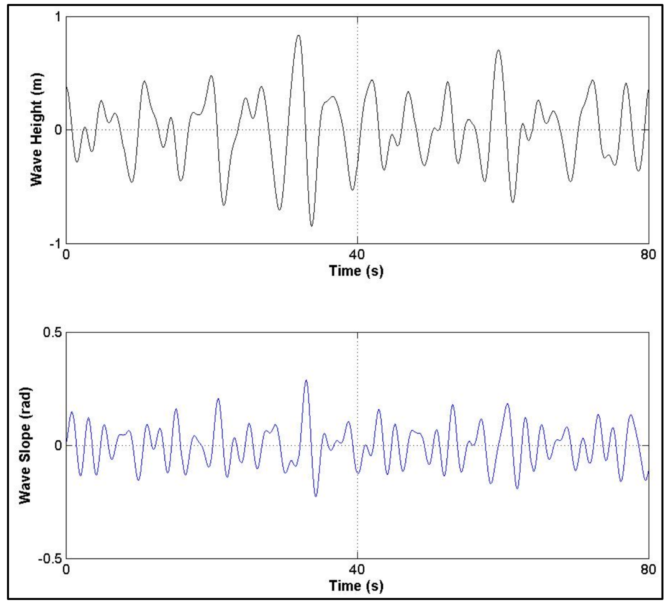

Fig. 10. Filtered 15-kt random wave heights and surface slopes.

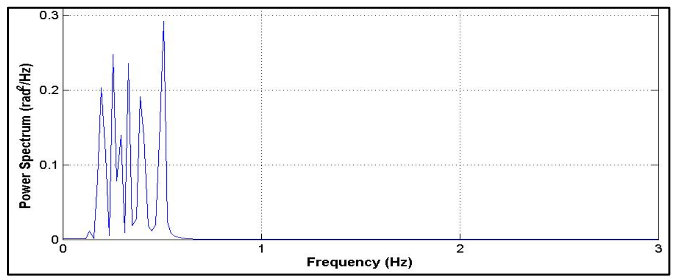

Fig. 11. Filtered frequency content of random wave surface tilts.

The Matlab Simulink results for a 2-m high swell with 10-s period (upper row) and random waves from a 15-kt wind speed (lower row) are presented in Fig. 12. The left column shows the system excitation; *i.e.,* the wave surface tilt angle and the right column shows the response; *i.e.,* the angle of the sliding mass, both versus time. The swell simulations showed sinusoidal variation in the mass sliding angle and the random cases showed irregular response, because the random wave excitation has many components at different frequencies.

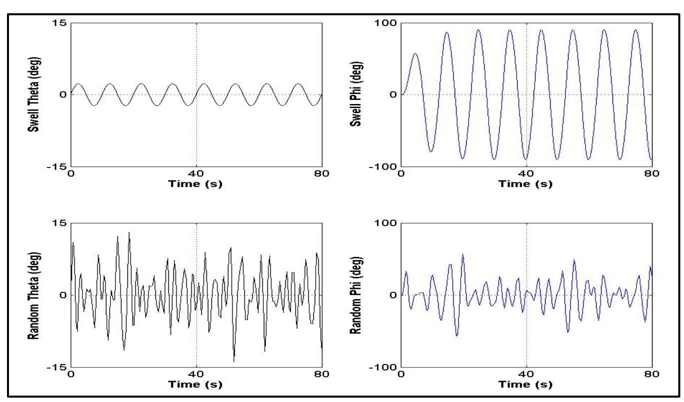

Fig. 12. Wave tilt (left column) and sliding mass angle (right column) for 2-m swells at 10-s period (upper row) and random waves (lower row).

For the random wave simulations, we can assume that an artificial spring will cause resonance and maximize net power harvested at a period near the average period, for a given wind speed. Net power is defined as the residual average power after removing the small amount of power needed to control the artificial spring. Equation (5) shows that power is proportional to the damping ratio and to the angular velocity squared, but large damping can reduce the velocity and thus reduce power (see Fig. 13).

Net power versus the artificial spring period is presented in Fig. 13 for a 15-kt wind and two damping ratios, 0.3 and 0.4. Note that power is greatest when the damping ratio is 0.3 and the artificial spring period is near 4s, despite the fact that the average random wave period is 4.95s for 15-kt winds (see Fig. 5), which is consistent with the observation that energy from random waves is spread over a broad range of periods.

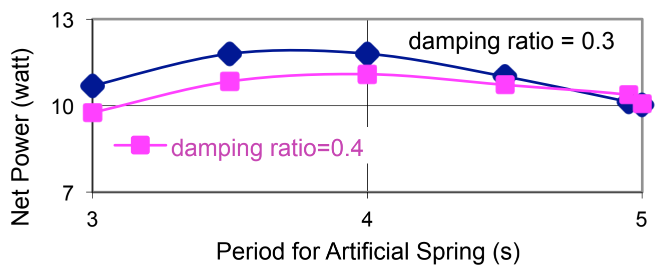

Fig. 13. Net power vs. artificial spring period.

Simulated net power results for a 50-kg sliding mass on a track with a 1-m radius are shown in Fig. 14 for random waves (from 5-25 kt winds) and swells (2-m high at 9, 10, 11, and 12-s periods). For the random wave calculations, we used damping ratios in the range of 0.2 to 0.55 and artificial spring periods near the average wave periods to maximize net power for each wind speed separately. For the swell calculations, we used a damping ratio of 0.225 and artificial spring periods equal to the swell periods, again to maximize net power. Net powers for the random wave cases are plotted as a function of the average wave period for each wind speed, as noted in Fig. 5. Random waves produce more power than long-period swells for wind speeds above 10kt, which is consistent with the CS-WEC power-scaling law that indicates that harvested power is inversely proportional to wave period cubed.

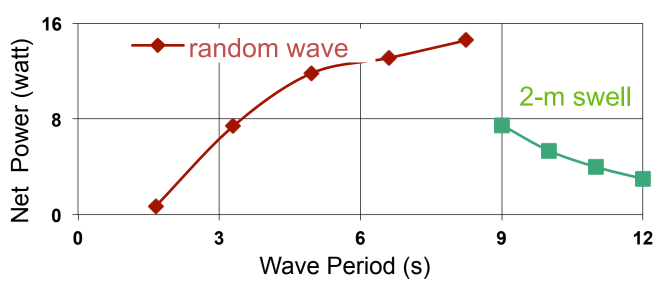

Fig. 14. CS-WEC power in random waves (1.5 - 8.5s average periods) and in swell (9 - 12s periods).

IV. CONCLUSIONS

The Circular-Slide Wave Energy Converter is a shaking WEC, which can be mounted under or on top of a drifting buoy. It utilizes wave pitch/roll instead of heave motions. A mass slides on a low-friction circular track due to gravity when the track is tilted by waves, and spins a generator to produce electrical power. The average power harvested is proportional to the mass, the track radius, the wave height, and inversely proportional to the wave period cubed. The CS-WEC does not use mechanical springs. Instead, it measures the angular motion of the sliding mass, performs feedback control of the generator torque, and in essence creates an artificial torsion spring. The spring torque is tuned to cancel the inertial torque so that the dynamic system is always in a resonant state, which ensures maximum power harvesting.

In simulating the CS-WEC response to random waves, the Pierson-Moskowitz wave spectrum was used at five wind speeds, *i.e.,* 5, 10, 15, 20 and 25kt. Each of the five spectra was approximated by a sum of wave components at discrete periods and random phases. From these wave components, the instantaneous surface tilt angle was derived as the excitation input to the simulation program.

In a deep sea, the wave surface tilt angle is inversely proportional to the wave period squared. Therefore, the low-period wave components have short wave lengths but large tilt angles. If a buoy or a surface float has large-enough horizontal dimensions, it will not respond to these short waves and high frequencies. For this study, we filtered out waves with periods less than 2s in order to mitigate any concerns about buoy dynamics.

The random wave simulations indicate that wind waves have more harvestable energy over a wide range of periods when compared to long period swells, especially for wind speeds greater than 10kt, which is the primary historical ocean condition. At any wind speed, the chosen period for creating or tuning the artificial spring can vary over a large range without sacrificing much power. The results are consistent with the CS-WEC power scaling law that wind waves generate more power because their periods are lower than those for swells.

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