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# Session 3 Presentation - Circular-Slide Wave Energy Converter

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# Circular-Slide Wave Energy Converter

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***Abstract***—We introduce a new concept for wave energy harvesting that is robust to harsh weather conditions and relevant to long-life ocean buoy applications.

## 1. Introduction

For small-to-moderate power applications in the deep ocean where anchoring is impractical, such as charging batteries on weather buoys [1], two types of wave energy converters (WEC) are possible. The first type can be called a "shaking" WEC, which is similar to a rechargeable flashlight that is energized by hand shaking. A conventional linear shaking WEC consists of a generator mass that hangs from springs [3] and moves with linear motion in response to wave heaving motion. The natural frequency of a linear, mass-spring system must be close to the predominant wave frequency so that large vibration amplitudes can be achieved for effective energy harvesting. However, ocean wave frequencies are naturally low, so soft springs are required to achieve low frequencies, which leads to impractically large vertical deflections of the generator mass. Therefore, a conventional shaking WEC is long and bulky and the springs represent a design weakness.

The second type can be called a "direct-drive" WEC, which uses a relatively stationary submerged drag-device to produce a force against surface wave motion to turn a generator [2]. The authors have successfully designed, built, and tested a prototype deep-water direct-drive version called the Sonobuoy Wave Energy Module (SWEM) for Navy applications, as shown in Fig. 1.

This design includes a drag plate attached to the bottom of the buoy with a rod that keeps the buoy stationary. At the center of the buoy is a screw driving a generator that is fixed to the buoy. A float is attached to the top of the screw; it heaves with the waves. To extend the drag plate to deeper and calmer water, the concept was later modified as follows:

- The float was mounted on top as a fixed part of the sonobuoy cylindrical hull.
- The generator assisted with a constant-force torsion spring and power control electronics were used to charge a lithium-polymer battery, and
- A ball-screw mechanism was used to drive the generator, with a long flexible line at the end connected to a drag structure that provides a "floating anchor".

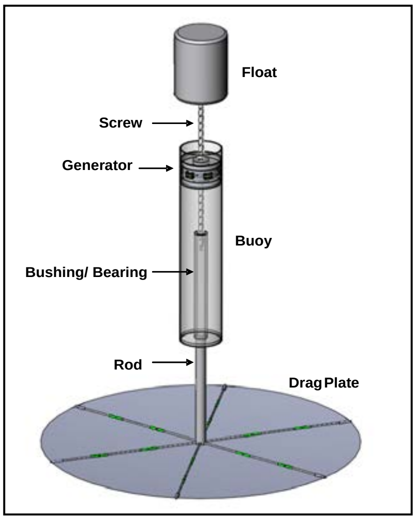


*Figure 1. SWEM concept.*

When a wave crest approaches, the surface float pulls the sonobuoy upward. At the same time, the drag body resists the upward motion due to its inertia and drag, pulls the ball-screw out of the buoy, spins the generator, and produces electrical power. During a wave trough the torsion spring retracts the ball-screw back into the buoy while an attached weight returns the drag body to the original depth, thereby finishing a wave cycle.

We demonstrated that the prototype system produces about 5 watts of average power in random sea waves driven by a 15-kt wind. That is to say that SWEM produces about 1 watt per foot of wave height at a wave period of 5 sec. Given the limited space available in an A-size sonobuoy, this is a remarkable achievement.

The direct-drive type can produce 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 to extend operational life.

We now 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. 2. This conceptual WEC includes the following major components: sliding mass, circular sliding track, connecting arm, gearbox, generator, and encoder. For protection from the harsh ocean environment, all of the components would be mounted inside a hermetically sealed box.

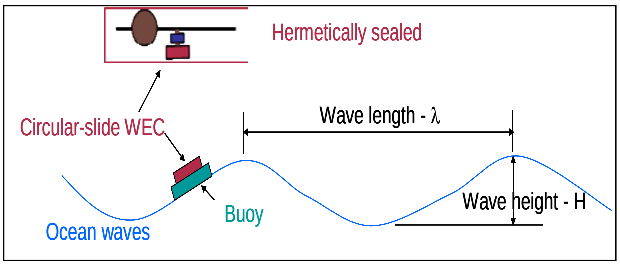


*Figure 2. Circular-slide WEC utilizing buoy pitch or roll motion.*

## 2. Description of Circular-Slide WEC

The concept of a circular-slide WEC (CS-WEC) is depicted in Fig. 3. 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 would be measured by the encoder and used for feedback control to create an artificial torsional spring. This spring would make the sliding mass resonate, or move back and forth on the circular track when the buoy pitches or rolls due to wave motions. The resonating angular motion of the sliding mass would be amplified by the gearbox to drive the generator and produce power. The optimal resonating angular amplitude of the mass on the track is ±90°.

The zero reference of the feedback control points to the buoy pitch or roll axis following the wave. When the initial reference is set, the controlled axis may or may not coincide with the actual buoy axis. If they coincide, maximum power would be harvested. Therefore, during online control, the zero reference would be monitored and gradually changed to achieve maximum power.

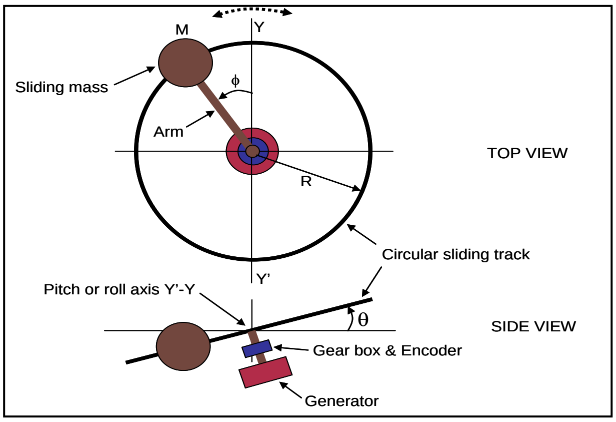


*Figure 3. Major components of the circular-slide WEC.*

For some buoy applications where the center portion is not available, the CS-WEC could be configured as shown in Fig. 4. The connecting arm in the original configuration is replaced by a hub with a center hole that is supported at three points on the circular track including the one at the sliding mass. The hub is made with gear teeth, which drive a pinion connected to the generator. 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.

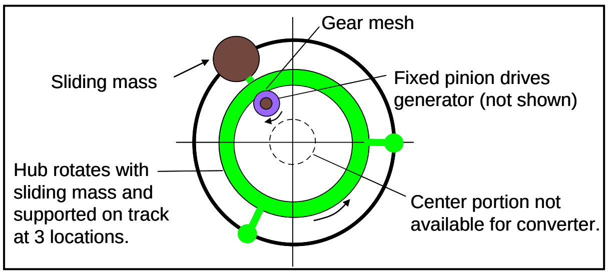


*Figure 4. Hub configuration with center hole.*

## 3. Advantages of Circular-Slide WEC

There is no static spring deflection problem as in the conventional shaking WEC. In fact, this concept utilizes an artificial or electromagnetic spring, which eliminates all reliability problems associated with mechanical springs. In addition, the artificial spring rate can be modified in-situ by monitoring the dominant wave period or frequency. This will keep the system in resonance all the time for maximum power.

To describe other advantages of the new concept, it is appropriate to present an old concept, *i.e.,* the Linear-Slide (LS) WEC, as shown in Fig. 5. The LS-WEC has limited stroke length (L); the new CS-WEC has no such limit. Therefore, possible pounding damage at end stops can be avoided.

Secondly, being fixed on buoy, the LS-WEC cannot follow the changing pitch or roll axis. Another identical LS-WEC would be needed to place in a perpendicular position and compensate for the loss of power as the buoy pitch/roll axis changes. The CS-WEC can follow the changing axis by re-setting the zero reference of feedback control automatically. Therefore, the new concept is a lighter system recognizing that the major weight contribution to the system is the sliding mass.

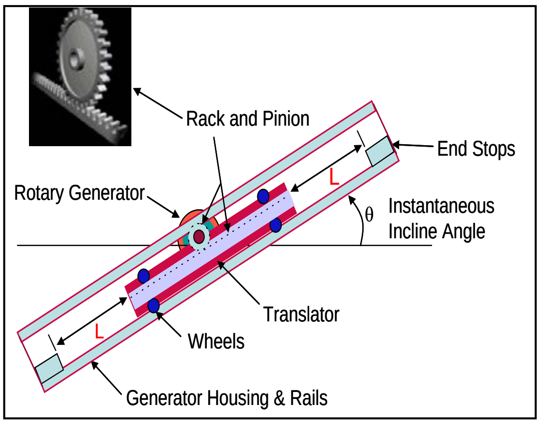


*Figure 5. Previous concept - linear-slide WEC.*

## 4. Scaling Law

The relevant dynamic parameters of the CS-WEC are presented in Fig. 6.

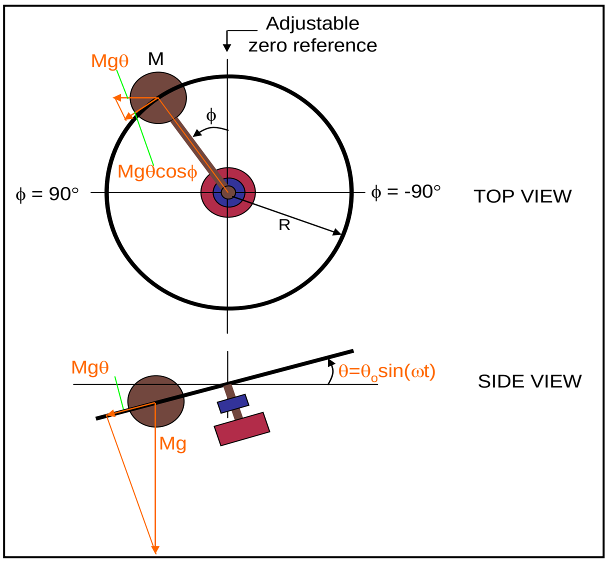


*Figure 6. Relevant parameters of a circular-slide WEC.*

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

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

where

$\phi$ = 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 = $9.81\ m/s^2$

$\boldsymbol{\theta = \theta_o \sin(\omega t)}$= 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 $cos(\phi)$. When we average the RHS over the track angle $\phi$, assuming it is extended to $\pm\pi/2$, 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 $\theta$, 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 $K$ 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
$\xi$ = damping ratio.

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

$$P = \frac{1}{2}BV^2\eta = \frac{1}{2}[\xi(2\omega MR^2)][\frac{g\theta_o(\frac{2}{\pi})}{2\xi\omega R}]^2\eta \quad \text{or}$$

$$P = \frac{1}{2}MgR\theta_o\omega\eta \qquad (5)$$

where $\eta$ = system efficiency, *e.g.*, 0.75. Equation (5) can be written as:

$$P = 20\ \pi\eta MRH/T^3 \qquad (6)$$

The scaling law (6) indicates that the average power of a tuned circular-slider 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 (in watts) as listed in the following table.

| | Radius (m) | | |
|---|---|---|---|
| Mass (kg) | 0.5 | 1.0 | 2.0 |
| 25 | 1 | 2 | 5 |
| 50 | 2 | 5 | 9 |
| 100 | 5 | 9 | 18 |

## 5. Dynamic Simulation

The scaling law (6) is based on a simple linear concept. To confirm its validity, the original nonlinear model represented by equation (1) was programmed in Simulink. The program and the corresponding result for $M$ = 100kg and $R$ = 2m are presented in Fig. 7. Note that the artificial torsional spring constant, $K$, is set equal to $MR^2\omega^2$ all the time, where $MR^2$ is the approximate polar moment of inertia of the sliding parts

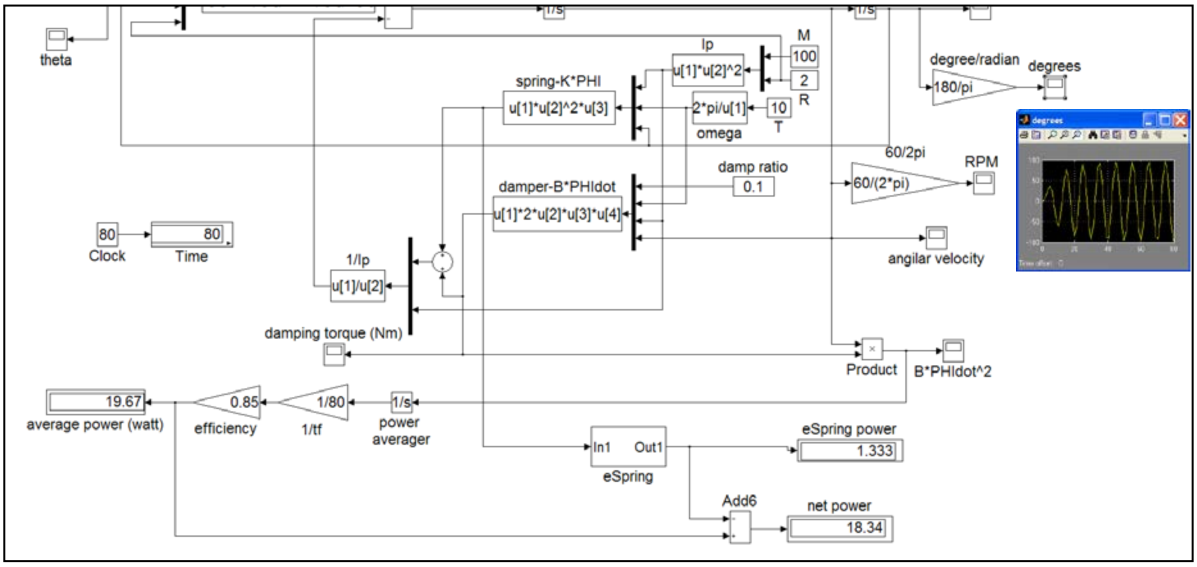


*Figure 7. Dynamic simulation of a circular-slide WEC.*

and $\omega$ is the wave circular frequency. Mathematically, the control system makes a motor produce a torque ($T_q$), such that:

$$T_q = - K\phi_m \qquad (7)$$

where,

$K = I_p\omega^2$

$I_p \approx MR^2$, and

$\phi_m$ = sliding mass angle $\phi$ measured by encoder.

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

The net power predicted by the Simulink program was 18.34 watts, which is close to the power predicted (18 watts) by using the scaling law.

The damping ratio $\xi$, was set at 0.1 in the simulation; the sliding mass slides back and forth on the track in a semi-circle, or with $\phi \approx \pm 90°$ as indicated by the inserted scope plot in Figure 7. This implies that by changing the generator load, the system will find the maximum harvested power occurs when the mass swings back and forth of a semi-circle.

A permanent magnet brushless generator was sized to produce 0.2 HP (150 watts) at 200 rpm. The generator core had a rotor outside diameter of 100 mm, a stator outer diameter of 160 mm, and a length of 150 mm. The generator had six permanent magnets and three phases of windings. It had a torque constant of 4.3 Nm/A, and a coil resistance of 0.57 ohm per phase. We assumed that the motoring function is implemented in the generator to keep the hardware simple.

In this simulation, the mechanical efficiency was assumed to be 85%, and the electrical loss is predominantly due to the copper loss of the spring feedback control. The power consumption of the spring function was calculated to be 1.3 watt, which is much smaller than the harvested power; *i.e.*, 19.7 watts.

## 6. Conclusions

Direct drive WECs can produce much more power per unit weight than the shaking type; however, in harsh environments, it is preferable to use the shaking type because they can be hermetically sealed to reduce environmental degradation.

We introduce a new shaking WEC concept; *i.e.*, the Circular-Slide Wave Energy Converter, which can be mounted under or on a buoy. It utilizes wave pitch and roll instead of heave. A mass slides on a low-friction circular track due to gravity when the track is tilted by waves. The sliding mass spins a generator to produce electrical power. The average harvested power is directly proportional to the mass, the track radius, and 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 a sliding mass and performs feedback control of the generator torque. The feedback creates an artificial torsion spring, which is tuned to cancel the inertial torque so that the dynamic system is always in resonance. The zero reference of the feedback control can be adjusted in-situ to respond to pitch/roll axis changes due to waves. These ensure maximum power harvesting through changing wave conditions. The power consumption of the artificial spring is proportional to the polar moment of inertia associated with the sliding mass; it can be kept low and affordable by properly designing the generator/motor.

## 7. References


[1] NOAA, Physical Characteristics of NDBC Buoys, Stennis Space Center, Mississippi, August 1994.

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[3] Cheung, J.T. & Childress, E.F. III, Ocean Wave Energy Harvesting, DARPA Phase 3 Final Report, Teledyne Scientific & Imaging, April 2008.