Electromagnetic Spring for Sliding Wave Energy Converter

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***Abstract* — We propose a Linear Sliding Wave Energy Converter (LS-WEC) to power ocean buoys by wave energy harvesting. The concept involves a linear translator and a rotary generator that roll and pitch in ocean waves. The translator is a steel mass that is supported by wheels on rails with low-friction bearings. The translator linear motion is converted to rotary motion to spin an electric generator using a set of rack and pinion gears. The rack is fixed to the translator; the pinion is coupled to the generator shaft. An "electromagnetic spring (eSpring)" is implemented by using the generator as a motor and performing feedback control of the translator displacement. With variable stiffness, the eSpring tunes the system in resonance with changing ocean wave motions in order to maximize the power harvested. We derive the dynamic system fundamentals, which indicate a large "effective mass" associated with the polar moment of inertia of the generator rotor. We calculate power-harvesting performance by numerical simulations in sinusoidal and random waves, with and without an eSpring. The results show that without an eSpring the power decreases proportionally with the effective mass, but with the eSpring, the system uses the effective mass to store energy that is extracted by the generator. For a 3-m long LS-WEC with a 30-kg translator mass in swell conditions (1.25-m wave-height and 5-s period), the average power is 2.3w and 17.8w without and with the eSpring, respectively.**

Keywords—wave energy converter, electromagnetic spring, sliding mass, rack and pinion, swell and random waves, wave surface angular motions, polar moment of inertia.

I. INTRODUCTION

There are two kinds of wave energy converters suitable for deep ocean buoys, namely, the shaking type and the direct-driving type. The sonobuoy wave energy module (SWEM) [1] is a direct-driving type. The wave heave motions drive against a drag device, like an inverted parachute, which in turn pulls a threaded screw and turns a generator for power. A typical shaking type, previously tested by Teledyne Scientific, was well documented in reference [2]. Figure 1 shows its structure and operational principle.

The direct-driving type produces more power per unit weight; however, it cannot be totally sealed from the harsh ocean environment so it is difficult to maintain. On the other hand, the shaking-type produces less power per unit weight but it can be made totally hermetic and thus has a longer service life.

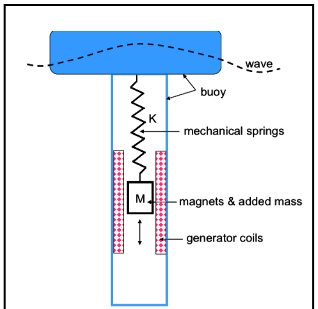

Fig. 1 - Typical shaking type WEC.

The 20-watt Teledyne device utilized 36 parallel coil springs with a total spring constant of 508 N/m. The springs hung a translation magnet assembly of 32 kg in a linear generator. The device stood about 2m high. It had a system natural period of 1.58s, where the ocean wave energy is low (see random wave spectra in Figure 2).

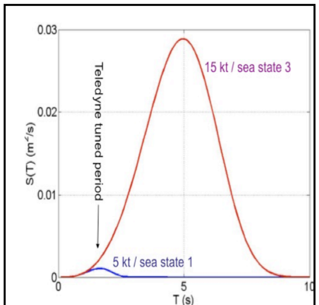

Fig. 2 - Pierson-Moskowitz spectra.

Ocean waves have naturally long periods; the average wave period is 5s for sea state 3. Energy harvesting in sea state 3, for example, would like to have the system natural period set at 5s, where the wave energy peaks. However, this would require very soft mechanical springs and cause large spring sag due to the hanging weight as explained below.

The natural frequency of the mass-spring system in Figure 1 can be represented as:

$$f = (1/2\pi)\ \sqrt{(K/M)} = 1/T \qquad (1)$$

where

f = natural frequency, Hz

K = total stiffness of parallel springs, N/m

M = mass hanging on springs, kg, and

T = natural period, s.

The weight, W, of the mass is W = M ∗ g in Newton's, where g is the gravitational constant. The mass displacement (or sag), δ, as shown in Figure 3, can be written as:

$$\delta\ = W/K = (T\ \sqrt{g}/2\pi)^2 \approx (T/2)^2 \qquad (2)$$

where we assume that $\sqrt{g}\ \approx \pi$.

Equation (2) indicates that the mechanical spring sag would be 6.2m if designed for a natural period of T = 5s. To allow a 6.2-m sag, without breaking the spring, the original spring length would need to be on the order of 10m, and the total WEC height might be impractical. That is why the Teledyne system had a high natural frequency of 0.63Hz (or a low period of 1.58s) and correspondingly lower sag of 0.58m.

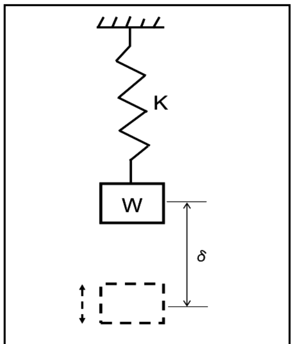

Fig. 3 - Mechanical spring sag.

II. LS-WEC Description

Herein we propose another hermetic shaking-type called the Linear-Sliding Wave Energy Converter (LS-WEC [3]) as presented in Figure 4. It was conceived to circumvent the above problem. The translator weight of a LS-WEC rests on a horizontal sliding rail. Therefore, there is no sagging problem due to gravity. Gravity is utilized for our benefit to drive the translator on the rail back and forth in wave rolling and pitching motions. In order to avoid using any mechanical springs, which suffer from constant stiffness, the LS-WEC applies an in-situ tunable electromagnetic spring; one may call it an "eSpring". With this eSpring, the system can vary its natural frequency in-situ to suit the wave conditions all the time and maximize power harvested.

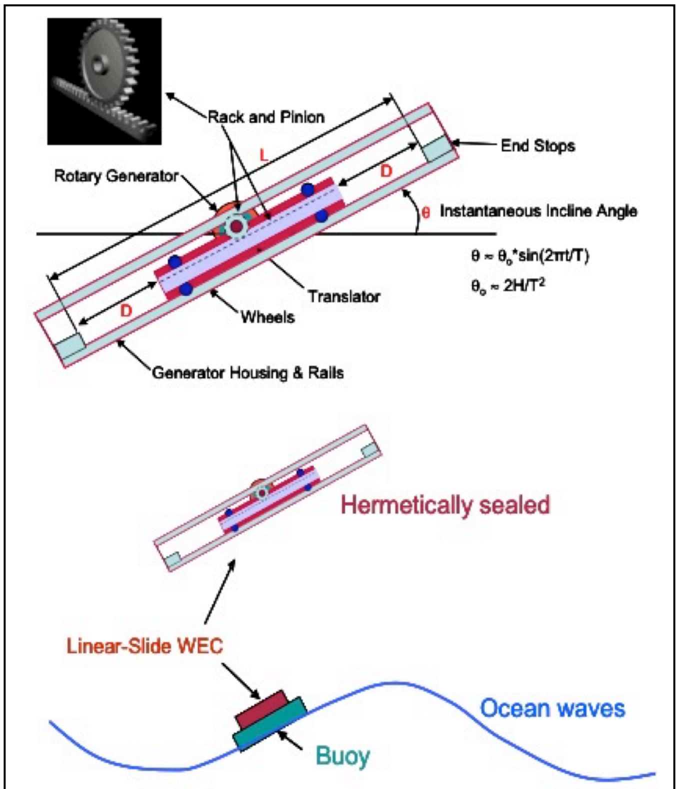

Fig. 4 - Linear Slide Wave Energy Converter.

The translator linear displacement is transformed into rotary motion by using a rack and pinion, which drives a conventional rotary generator. This set-up avoids mechanical problems, such as alignment, contact friction, and bulkiness associated with a linear generator, which has heavy magnets and yoke plates to provide high magnetic flux density in narrow air gaps.

There are two European WECs [4] applying the same wave roll/pitch principle:

1. IS (www.waveforenergy.com/technology),

and

2. Penguin (www.wello.eu/en/penguin).

The IS-WEC has a gyroscope rotor with controllable rpm ("IS" stands for Inertia Sea). The gyroscope precesses when the WEC housing rolls and pitches in waves. The precession drives an electric generator. The gyroscope is a complicated mechanical system that can consume a significant amount of energy.

The Penguin WEC utilizes the wave pitch and roll of a floating hull, which houses a rotating eccentric mass and drives an electrical generator. A prototype animation demonstration of this "rotating-mass" WEC showed the eccentric mass rotates in full circles; the power control appeared without using an artificial spring or resonance. Its asymmetrically shaped hull appears able to amplify rolls and pitches with passing waves.

III. LS-WEC Dynamics

The LS-WEC relies on the wave-created potential energy of a translator for driving a generator using a rack and pinion. The side view of Figure 5 shows the rack and pinion separated for clarity. The tangential force exerted on the pinion is F, which is equal to and opposite to the force on the translator. The center of gravity of the translator is displaced by X, which corresponds to a pinion angular displacement, ϕ, which is measurable by an encoder on the generator/motor shaft.

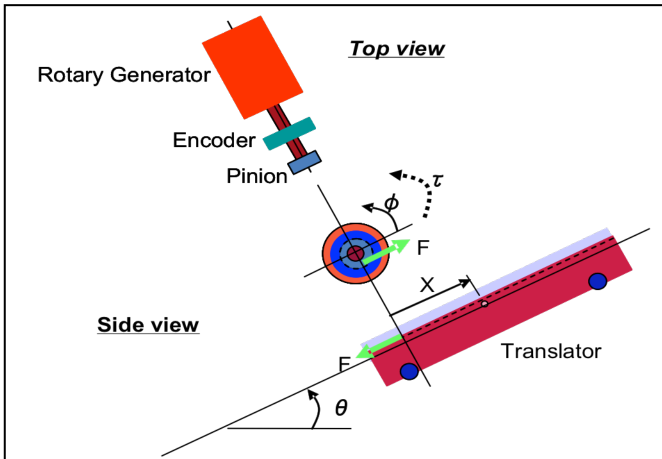

Fig. 5 - LS-WEC dynamic parameters.

The purpose of the following analysis is to explore the inertial effect of the generator/motor rotor on the system dynamics, which are represented by (3) and (4):

$$M_t X'' = - F - M_t g \theta_o \sin(\omega t) \quad (3)$$

$$J \phi'' = F r + \tau \quad (4)$$

where

' = differentiation once with respect to time

'' = differentiation twice with respect to time

X = translator displacement, m

ϕ = pinion angle measured by encoder, rad

M_t = translator mass, kg

J = polar moment of inertia of generator rotor, kg-m^2

F = force exerted on the translator by the pinion, N

τ = generator and motor torque, Nm

r = pinion pitch radius, m

g = gravitational constant, 9.8 m/s^2

θ_o = wave surface angle, rad ($\approx 2H/T^2$ for swell [5])

H = wave height, m, and

ω = wave frequency, rad/s.

Assuming that the system generator and motor are two separated, but structurally identical devices, and that they are mounted back to back on the same shaft with the pinion and encoder, the torque on the shaft would be:

$$\tau = - K_\phi \phi - B_\phi \phi' \quad (5)$$

where

K_ϕ = torsion stiffness coefficient provided by the motor, Nm/rad, and

B_ϕ = equivalent torsion damping coefficient of the generator, Nms/rad.

There is no slip between the pinion and rack, so:

$$\phi = X / r. \quad (6)$$

Combining (4), (5) and (6), we have:

$$M_e X'' = F - K_e X - B_e X' \quad (7)$$

where M_e, K_e, and B_e, are the effective rotating generator mass, system stiffness, and generator damping coefficient. Adding (7) to (3), the system equation becomes:

$$X'' + (B_e /M) X' + (K_e /M) X = - (M_t /M) g \theta_o \sin(\omega t) \quad (8)$$

where the total mass, M, is the sum of the actual translator mass plus the effective mass of the rotating generator. Then:

$$M = M_t + M_e \quad (9a)$$

$$M_e = J / r^2 \quad (9b)$$

$$K_e = K_\phi / r^2 \text{, and} \quad (9c)$$

$$B_e = B_\phi / r^2 \quad (9d)$$

To make the system resonate at a particular wave period, T, we set:

$$\sqrt{(K_e / M)} = 2\pi / T = \omega \quad (10)$$

which is equivalent to:

$$K_e = (M_t + M_e) (2\pi / T)^2. \quad (11)$$

Equation (11) shows that the effective system stiffness is larger with the generator-motor rotor inertia than without by the amount of $(J / r^2) (2\pi / T)^2$.

IV. The Artificial Spring

A spring is essential for a one-mass dynamic system to have a natural resonance mode. The benefit of the artificial spring, compared to a mechanical spring, is that its stiffness can be electronically adjusted to match the system natural resonance frequency with varying wave frequencies. When the LS-WEC resonates with the waves, the system inertial force cancels the spring force continuously and the wave force is applied solely for power generation. Therefore, the translator displacement becomes larger and larger until the translator finally hits the stroke limiting stops.

Our concept is to implement the eSpring in the generator. In other words, the generator would be used as a motor to produce the feedback resistance torque of the eSpring. At any instance, a resistance torque (τ, Nm) would be created in the motor/generator by performing feedback control of an encoder-measured pinion/generator shaft angle (ϕ, rad). The resistance torque should be:

$$\tau = \phi \; K_e r^2 \quad (12)$$

Treating the generator as a brushless dc motor, this feedback torque corresponds to an amount of dc phase current, *i.e.*, $I_{ph} = \tau / K_T$, where K_T is the motor torque constant, Nm/A. The LS-WEC also has a system controller, not shown in the Figure 5, which performs several functions, including the feedback control of the encoder signal to create the reaction torque in the generator. The control process is illustrated in Figure 6.

V. Sizing the Motor/Generator

Now we compare M_t and M_e by sizing the generator/motor. For a 3-m long LS-WEC with a 30-kg translator mass on the ocean surface with a 1.25-m wave-height and 5-s period wave, we would design a rotary generator with a 75-w capacity at 200 rpm ($30kg * 9.8m/s^2 * 1.25m/5s \approx 74w$). We assume the following reasonable parameters: stator outer diameter = 0.2m; rotor outer diameter =0.12m; generator length = 0.1m; efficiency = 85%; 3 phase construction with 6 magnets and 6 coil per phase. The result of the sizing analysis is:

Torque = 3.56 Nm

Current = 1.04 A/phase, and

Resistance = 0.28 Ω/phase.

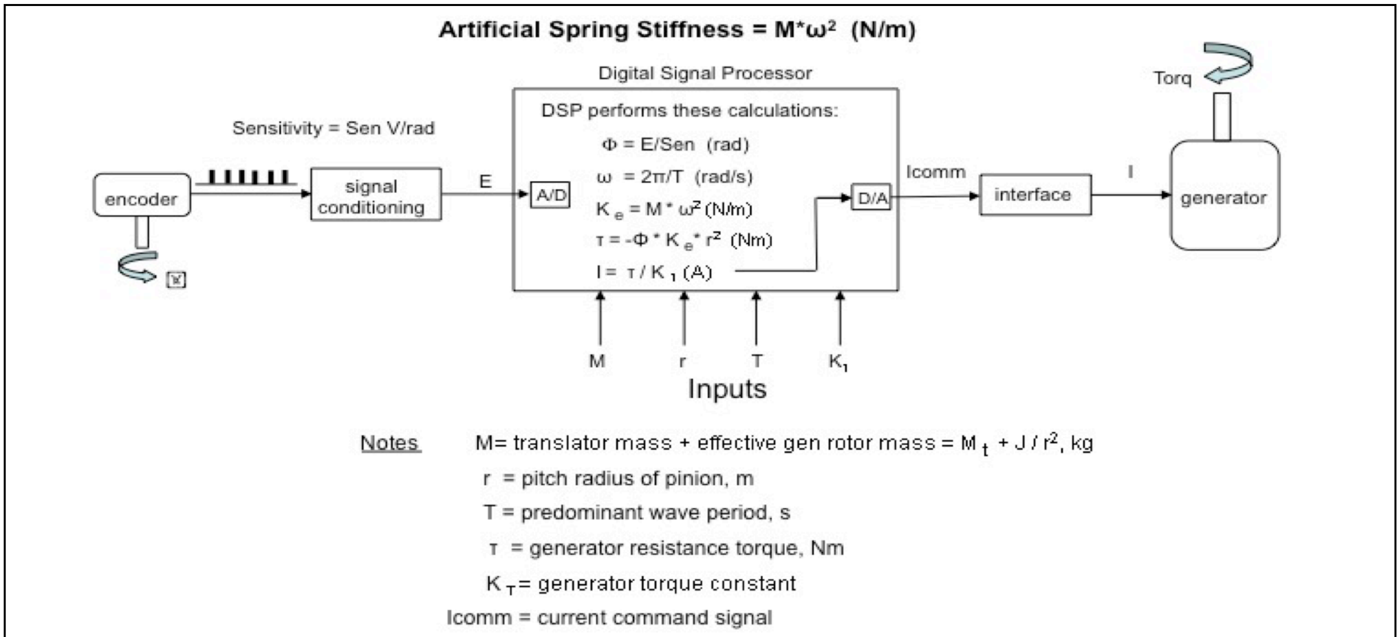

Fig. 6 - Feedback control for artificial spring.

Neglecting the contribution of the components with small diameters, such as shaft, pinion, encoder, etc., the polar moment of inertia, J, of the generator rotor was calculated as:

$$J = M_e R^2 / 2 = [\pi R^2 L \rho] R^2/2 = 0.016 \text{ kg-m}^2 \qquad (13)$$

where R is the generator rotor radius = 0.06m,

L = generator rotor length = 0.1m, and

ρ = steel rotor density = 7830 kg/m^3.

Assuming the pinion pitch radius (r) is 0.025m, the effective rotor mass is:

$$M_e = J / r^2 = 0.016 / 0.025^2 = 25.6\text{kg}, \qquad (14)$$

which is nearly the same as the 30-kg translator mass. We now investigate whether energy from the translator, which is needed to drive the rotary inertia, will significantly reduce the overall system power harvesting.

VI. POWER HARVESTING SIMULATIONS

A power simulation program was written in Matlab Simulink. Two simulation examples are given below: first, for a sinusoidal (*i.e.,* swell wave) sea surface, and second for a locally wind-driven random sea.

Figure 7 shows the net power potential of a 3-m long LS-WEC with and without an artificial spring: in a) a sinusoidal swell with a 1.25-m wave-height and a 5-s period (left column) and b) a random sea driven by a 15-kt wind (right column). We have assumed that the translator mass is 30kg and the stroke limit is ±1.4m. The top (green) curves show the time series of sea surface wave angles during 100s.

Let's first consider the swell results on the left side. Without the eSpring, the translator moves back and forth, but stays at one side of track and the average power is 2.33w (center left red curve). With the eSpring set for resonance at T=5s, the system fully utilizes the stroke limits and the net average power becomes 17.83w, which is a 665% increase of power. The power consumed by the eSpring was shown to be directly proportional to the translator mass and inversely proportional to the wave period. In most cases, the motor spring consumed only a few percent of the gross power, which is very "affordable".

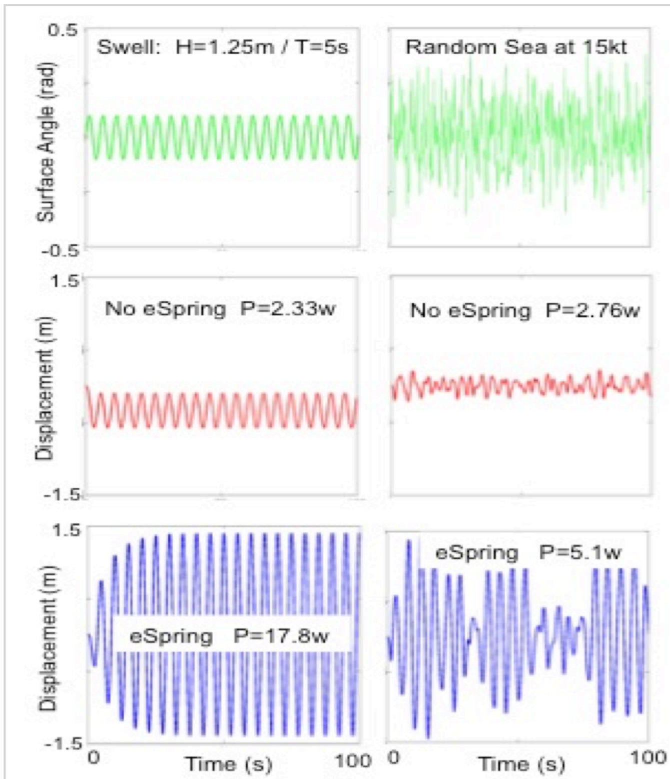

Fig. 7 - eSpring effect on power harvesting.

Some remarks on the sinusoidal wave simulation are:

1. The initial small displacements with the eSpring occur during the time needed to overcome system inertia and to achieve steady state motion.

2. The translator mass delivers energy to the system and the effective inertia mass absorbs energy and runs along with the translator. Without an eSpring, the power generated by the LS-WEC is proportional to the ratio $M_t/(M_t + M_e)$. From the simulations, the power is 4.31w when the effective mass is neglected and 2.33w, when the effective mass of 25.6kg is included {4.31*[30/(30+25.6)]}.

3. The generator rotational speed is inversely proportional to the pinion pitch radius, while the effective mass is proportional to the speed squared. Therefore, making the generator run fast is not necessarily beneficial for wave power harvesting without using the eSpring.

4. The system resonance control using the eSpring makes the effective mass useful. In other words, the resonance makes the effective mass store energy instead of wasting it. The stored energy is extractable by the generator.

5. The effective mass makes the eSpring stiffness proportionally larger than that with no effective mass. Therefore, the effective mass increases the eSpring power consumption.

Now, let's consider the random wave results on the right side. We know from Figure 2 that random waves at 15-kt wind speed have a broadband spectrum with a significant wave-height of 1.27m and an average period of 4.95s, respectively. Assuming the random wave components at different periods have random phases relative to each other, the calculated composite wave surface angle, as a function of time, is presented in the top right green curve. Using this wave surface angle time series as input, the LS-WEC translator displacement, without an eSpring, is shown in the middle right red curve. The displacement is in general slightly smaller than for the sinusoidal wave case. The corresponding average power harvested is 2.76w, which is slightly larger than for the sinusoidal wave case (2.33w), probably due to high frequency components. The random wave result, with an eSpring set at 4.95s, is shown in the bottom right blue curve, which shows that the translator does not often move to near the end stops. The corresponding average power harvested is 5.13w, or 86% more than without an eSpring. As expected, the power is smaller than with the sinusoidal wave excitation, where only a single resonance frequency is needed.

It worthwhile to mention that for low wind speeds, the random waves have low amplitudes at low periods (or high frequencies). In this situation, the eSpring power consumption may become significantly large.

VII. Conclusions

A LS-WEC consists of a translator, which is coupled to a rotary generator, with a set of rack and pinion gears. The translator slides back and forth on a rail, thus turns the generator in pitching/rolling wave motions, and generates electrical power. It works without a spring, mechanical or artificial, but poorly. One of the reasons is that the generator rotor is an additional inertial force burden on the dynamic system.

With an artificial or electromagnetic spring, the system resonates at the frequency of predominate waves. The inertial forces due to the translator mass and the generator rotor are always cancelled by the spring force. This dedicates all of the wave forces to drive the translator and make its displacement grow until hitting the stops.

Power simulations for sinusoidal waves indicate that power harvested with the artificial spring is close to eight times the power without the spring. In random wave simulation, the power with the spring is about 80% more than power without the spring.

The electromagnetic spring does consume power, which is proportional to the sum of the translator mass and the effective mass of the generator rotor, and inversely proportional to the wave period squared. Therefore, power consumed by the spring can be significant when wave period is very low, say less than 5s.

In summary, the LS-WEC concept alleviates the mechanical spring sagging problem of conventional heaving types of wave energy converters. The hermetic LS-WEC armed with the enabling technology of an electromagnetic spring becomes a power-efficient converter for charging batteries in ocean buoys.

References

[1] DelBalzo, D.R., Sonobuoy Wave Energy Module, Final Report, QinetiQ North America, March 2012.

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

[3] Chen, H.M. and DelBalzo, D.R., "Linear Sliding Wave Energy Converter," Presented at Ocean15 at Genova, Italy, 18 May, 2015.

[4] SI Ocean report, Ocean Energy: State of the Art, Dec, 2012, pages, 15, 16 and 30 (http://www.emec.org.uk/marine-energy/wave-devices/).

[5] McCormick, M. E., Ocean Wave Energy Conversion, Dover Publication Inc., 2007, Chapter 2.