A Novel Design of Wave Energy Harvest Device with Flywheel Energy Storage System

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ABSTRACT

This paper describes a novel design of a wave energy harvest device that utilizes a flywheel energy storage (FES) system to yield increased power generation. The buoy design is moored to the ocean floor via a cable; as the buoy is heaved vertically by ocean waves, the cable rotates a pulley which in turn drives the rotor of an onboard generator. A ratchet within the pulley allows the rotor to only be turned in one direction. To prevent large tensions from begin imposed on the cable by the back torque from the generator, a flywheel energy storage system is used. As the buoy is heaved vertically by incident waves, the electric load on the generator is removed, resulting in all of the energy extracted by the buoy to be stored in the flywheel system. Consequently the buoy is less restricted by high tensions and able to closely follow the motion of the waves, even while using a large generator with a high back torque coefficient. As the buoy moves downward after being heaved, the load is re-coupled to the generator, transferring the energy stored by the flywheel to the generator. Essentially the FES system trades power generation time for improved buoy motion. The focus of the paper is not to optimize the design of the buoy, but rather demonstrate the effectiveness of the FES system for the buoy design with arbitrary parameters. Simple simulations for a small buoy confirm the effectiveness of the proposed flywheel energy storage system—without it the wave energy harvest device produced only 90.0 watts of power, but with it the device produced 180.3 watts—an improvement of 100%. This improvement is based on a small generator with low back torque coefficient; for a large-scale design and stronger generator, the benefits are expected to be even greater.

Keywords: Flywheel Energy Storage, Ocean Power, Buoy, Wave Energy Harvester, Hydrodynamic Simulation

1. INTRODUCTION

The renewable energies, such as wind, wave, ocean current, solar energy, hydrogen generation, have received a great deal of attention in the past few years. Ocean waves represent an energy form created by wind passing over open water and gravitational pulls of the sun and moon, i.e. tides. A white paper by U. S. Department of the Interior [1] has estimated that the wave energy density levels can exceed 1,000 kW/m of wave crest length. The total annual average wave energy off the U.S. coastlines (including Alaska and Hawaii), calculated at a water depth of 60 m has been estimated at 2,100 Terawatt-hours (TWh) ($2{,}100 \times 10^{12}$ Wh). [2] If even a small fraction of it can be harvested, the energy crisis in the world will be greatly alleviated.

Because renewable energy from both wind and wave sources are intermittent, the periodic energy collected should be stored for more efficient output. A flywheel stores kinetic energy by rotating a disk or rotor on its axis. The use of flywheels to provide smoother power outputs is an old technology and has been applied to steam and automobile engines for over a century. In 2006, the U. S. Department of Energy published a Federal Technology Alert [3], in which describes the new application domains of the Flywheel Energy Storage (FES) systems, in particular, the uninterrupted power system (UPS) as an effective alternative to batteries.

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2. WAVE ENERGY HARVEST SYSTEM MODEL

Figure 1 shows the basic design of the wave energy harvest device, which converts the vertical linear motion of the wave into rotational motion. The device is mounted inside a buoy floating on the ocean surface.

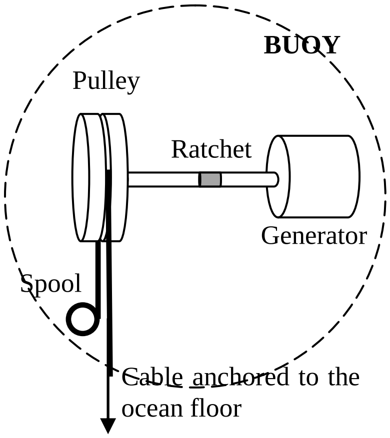

Figure 1. Wave Energy Harvest Device

An inextensible cable wraps around the pulley, with one end anchored to the ocean floor and the other end connected to a spool that keeps the cable wound up via a torsion spring. As the buoy is heaved upward by the wave, the cable comes out from the spool and rotates the pulley and the axial shaft. When the buoy moves down, the cable is retracted into the spool while the ratchet gear in the pulley prevents the shaft from rotating in the reverse direction.

To analyze the performance of the device, the equations of motion of the system are formulated based on a simple model that examines forces in the vertical direction. The motion of the buoy in the wave can be derived by

$$F_{wave} - T = ma \tag{1}$$

where F_{wave} is the sum of the forces produced by the wave, T is the tension in the cable, m is the sum of the mass of the buoy and added mass displaced by the buoy, and a is the vertical acceleration of the buoy. The tension T is positive only when the cable is driving the shaft; otherwise when the shaft is ratcheting—that is, when the driving angular velocity of the pulley is less than the actual angular velocity of the shaft—the cable is relaxed and the tension is treated as zero. The mechanical device inside the buoy can be modeled by

$$T \cdot r_{pul} - M_{gen} - M_{spo} = I\alpha \tag{2}$$

where r_{pul} is the radius of the pulley, M_{gen} is the back torque of the generator, M_{spo} is the torque produced by the spool that is constant and small, I is the total mass moment of inertia of the rotating elements, and α is the angular acceleration of the axis. If there is no slippage in the pulley when the buoy moves upward, the vertical and angular accelerations can be related by

$$a = \alpha \cdot r_{pul} \ . \tag{3}$$

It is clear that while the pulley is driving the generator rotor—i.e. while the buoy is heaved—the acceleration is limited by the generator back torque, M_{gen}. This effect of this torque can be removed completely by removing the electrical load from the generator, but this in turn causes the generator to not produce any power. However, by removing this torque while the pulley drives the system, and reapplying the load to collect energy while the pulley is ratcheting—at which time the tension in the cable is no longer affected by the back torque—the buoy system is able to achieve greater acceleration while still producing power. Thus, the use of a flywheel energy storage system to work with the wave energy harvest device is suggested.

3. FLYWHEEL ENERGY STORAGE SYSTEM

The flywheel energy storage system (FES) stores energy in the form of rotational kinetic energy. These storage systems lose energy from two sources: bearing friction and aerodynamic drag. However, new technologies can limit the effect of both of these factors. For example, magnetic bearings [4, 5] or even superconducting magnetic bearings [6] can levitate the shaft from physical contact with the bearing and hence reduce the friction to minimum. The aerodynamic drag can be minimized by enclosing the rotor in an air-tight vacuum chamber. [7] This type of set up is particularly suitable for marine applications, in which the system is subject to a corrosive, saltwater environment.

The purpose of this paper is not to design a new FES system; instead, with the already available technologies, the authors suggest a system that can improve the effectiveness of the wave energy harvest device detailed in the previous section. The suggested FES system uses the mechanical torque as the input to charge kinetic energy into the rotor, and draws energy from it through the generator to power the magnetic bearings. [8] The integrated harvest device-FES system works in the following way:

1. When the wave forces the buoy up, kinetic energy is charged into the FES system. Simultaneously, an onboard sensor recognizes the positive torque applied by the pulley to the rotor and causes the load on the generator to decouple via a switch, resulting in no current passing through the generator and a back torque of zero. The tension in the cable will be lower and allow the buoy to follow the motion of the wave more closely than if power is drawn by the generator during the upward motion.
2. When the pulley is ratcheting—that is, the angular velocity of the pulley is slower than that of the rotor—the load on the generator is re-coupled and causes the energy stored by the FES system to be drawn out as electrical power. As

the FES system discharges its stored energy through generator, the rotor slows down until the next wave crest approaches.

Similar FES systems have been demonstrated to be both feasible and practical. Hybrid performance vehicles, such as the Porsche 911 GT3 R Hybrid, utilize flywheel storage systems to capture kinetic energy produced by the engine, acting in place of a traditional battery. The flywheel system captures a portion of the energy dissipated during breaking, and then transmits it back to the electric motor when the vehicle is accelerated. These flywheels have been shown to be effective even during bumpy road conditions; even though the conditions imposed on the buoy may be more severe, the angular velocity of the flywheel in the buoy will be only several hundred rpm, as opposed to 40,000 rpm in the hybrid vehicles [9]. Additionally, the fact that the flywheel systems generally dissipate a majority of their stored energy within about 10 seconds is not a limitation for the buoy, as the energy storage is only required for the time between incident wave crests.

4. SIMULATION METHOD

A mathematical simulation was developed to model the buoy motion and angular velocity of the generator rotor of the aforementioned system. The simulation creates a second-order differential equation produced by equating the sum of the forces acting on the buoy to the product of the buoy mass and its acceleration. For simplicity, the width of the waves are considered to be substantially longer than the width of the buoy so that the problem may be treated as two-dimensional, neglecting any forces acting orthogonal to both the wave propagation and the vertical directions. Additionally, the motion of the buoy is assumed to be constrained so that motion occurs only in the vertical direction, thus requiring only one differential equation to be solved.

The purpose of the simulation is to validate the ability for the suggested FES system to improve performance of the buoy system—that is, the objective is to demonstrate an increase in power output from the system when the FES system is applied to an already-working buoy system, keeping everything else constant. As a result, several of the design parameters can be given relatively arbitrary, albeit realistic, values (the values chosen are based off of the design of a related experiment that will not be discussed here as it falls outside of the scope of this paper).

The general equation of motion for a floating body under heave contains several terms, including a hydrostatic restoring force (modeled as a spring) and the vertical heaving forces imposed by the wave. The simulation models the wave as purely sinusoidal that propagates perpendicularly to the motion of the buoy. The function describing the wave height as a function of horizontal position x and time t is

$$y_{wave}(x,t) = a \cdot \sin(2\pi \cdot (\frac{t}{T_w} - \frac{x}{\lambda_w})) \ . \qquad (4)$$

Here a is the wave amplitude in meters, T_w is the period of the wave in seconds, and λ_w is the wavelength in meters. The hydrostatic force is part of the driving motion for the wave, as given by

$$F_s = \rho \cdot g \cdot V_{submerged} - m \cdot g \ . \qquad (5)$$

Density of the water is given by ρ, measured in kg/m^3. The first term is the buoyancy force, $F_b(z)$, which is a function of the buoy position with respect to the wave, as given by Archimedes' principle. The second term is the weight, W, given in Newtons.

The other portion of the driving forces for the buoy is the excitation forces caused by the interaction of the waves with the buoy. These forces include the Froude-Krylov [10], wave diffraction, and radiation forces. The latter two forces are substantially difficult to solve and may be neglected under the assumption that the wavelength of incident waves is much larger than the size and motion of the buoy. For simplification of the simulation, these terms are indeed excluded, and the wave excitation force is equal to the Froude-Krylov force, given by the surface integral

$$F_{exc} = -\rho \iint_{Sub} \frac{\partial \Phi_I}{\partial t} \hat{n} \cdot dS \ . \qquad (6)$$

The integral is taken over the *submerged* surface of the buoy, and $\hat{n}$ is the normal vector to the surface of the buoy. The term Φ_I is the incident wave potential, and for deep sea conditions it is given as

$$\Phi_I = \frac{a \cdot \omega_w}{k} e^{kz} \operatorname{Re}\{ie^{i(\omega_w t - kx)}\} \ . \qquad (7)$$

The ω_w term is the angular frequency of the wave, given in radians per second; the k term is the wavenumber, defined as 2π divided by the wavelength; i is the imaginary number, equal to $\sqrt{-1}$; and Re is the real operator that yields only the real portion of the complex value inside of the brackets.

Additionally, the buoy experiences a drag force as it moves through the fluid, which opposes the direction of the buoy velocity. This drag force can be calculated using the vertical velocity of the buoy, $\dot{z}$, and the vertical velocity of the wave, $\dot{y}_{wave}$ found through (4), and for high Reynolds number [11], is given by

$$F_d = -\frac{1}{2} \rho \cdot A_{submerged} \cdot C_d \cdot (\dot{z} - \dot{y}_{wave}) \cdot |\dot{z} - \dot{y}_{wave}| \qquad (8)$$

The submerged area, $A_{submerged}$, is the orthogonal projection of the cylinder (i.e. a rectangle) that is submerged. The drag coefficient, C_d, has been shown to be approximately equal to unity for Reynolds number up to 10^5 [12]. A damping force caused by mechanical friction is not included as the FES system is assumed to minimize frictional losses in a fashion described in the previous section. Thus, the equation of motion takes the form

$$m \cdot \ddot{z} = F_b(z) + F_{exc}(z) - W - F_d(\dot{z}) - T \ . \quad (9)$$

The level of tension, *T*, can be calculated using (2) and (3) for when the pulley is driving the rotor, and can be taken to be a low value for when the pulley is ratcheting. The back torque imposed by the generator when an electric load of 1 Ω is applied can be found experimentally. Using a GL-PMG-500A permanent magnet alternator manufactured by Ginlong Technologies [13], the back torque and power output can be modeled to closely match experimental results using

$$M_{gen} = 1.146 \cdot \omega \ , \quad (10)$$

$$P_{out} = \frac{1}{4} \cdot \omega^2 \ . \quad (11)$$

These equations are in basic SI units, with *ω* being the angular velocity of the rotor, measured in radians per second.

Because the differential equation is nonlinear as a result of the drag term, the differential equation given by (9) is approximated using a fourth-order Runge-Kutta method [14]. The accuracy of the approximation can be improved by choosing a suitably small time-step for evaluation.

5. SIMULATION RESULTS

In order to evaluate the effectiveness of the proposed FES design, two simulations were ran—one that simply extracts power throughout the entire motion, and one that decouples the electrical load on the generator in the previously described fashion. Both simulations model the ocean waves as a sine function with 1-meter amplitude and 5-second period. The buoy used is a horizontal cylinder with a 0.3-meter radius and unit length, the mass of the system is 200 kg, the moment of inertia is 0.25 kg-m^2, and the radius of the pulley is three centimeters. Again, these values are arbitrarily chosen based off of expected values for real design.

The two systems are completely identical except for the application of the load on the generator. For the system without the proposed FES concept, the resistive back torque from the generator is always active, creating additional tension in the mooring cable as the pulley drives the rotor. For the system with the FES device, the load on the generator is decoupled as the pulley drives the shaft, removing the additional tension cause by the moment described in (8). The tradeoff, however, is that during this time the generator does not draw any power. The simulation demonstrates that even though there is less time at which power is produced, the FES system yields a greater overall average power.

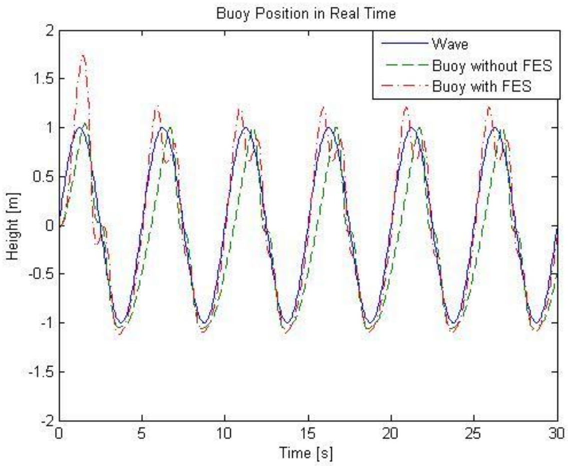

Figure 2. Simulation buoy height with respect to time for both the system without FES and the system with FES

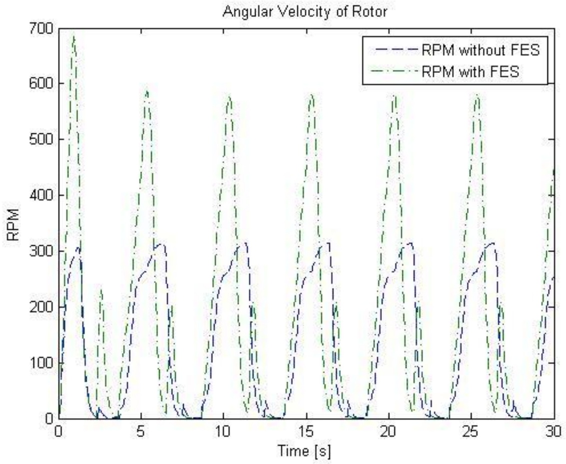

Figure 3. Simulation rotor velocity for both the system without FES and the system with FES

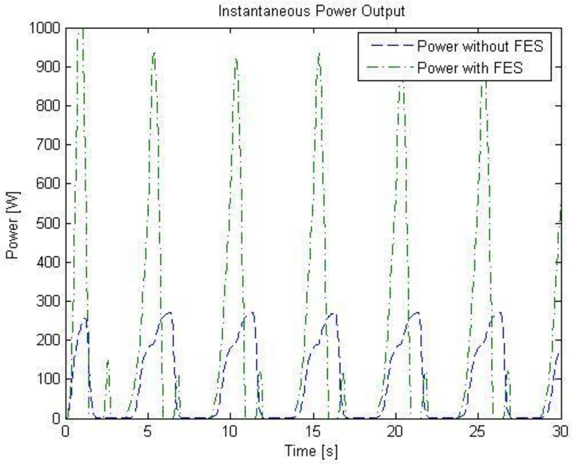

Figure 4. Simulation instantaneous power output by the generator for both the system without FES and the system with FES

The previous figures demonstrate the results of the simulation. Figure 2 presents the buoy height for both scenarios over a 30-second simulation, as well as the height of the wave for reference. Figure 3 presents the angular velocity of the generator rotor as a function of time for both systems and Figure 4 depicts the instantaneous power output by the generator for both systems.

The average power produced by the energy harvest device without the FES system was 90.0 watts, while the average power produced by the buoy with the FES was 180.3 watts. As such, the simulation demonstrates that more energy can be drawn from the system by sacrificing time during which the load is applied to the generator for higher angular velocities of the rotor. The effectiveness of the proposed flywheel energy storage system is dependent on many of the system parameters, but will generally be more valuable for larger generators that have higher startup torques back torque coefficients.

6. DISCUSSION AND CONCLUSION

The simulation results in the previous section demonstrate the effectiveness of utilizing a FES system to control power output in a wave energy harvest device. Figure 2 illustrates the physical effect that removing the electrical load during the heaving motion has on the movement of the buoy. The device without the FES system lags behind the wave crest position, remaining mostly submerged as it is heaved by the hydrostatic wave force. This limits the velocity that it achieves, and in turn, reduces the instantaneous power developed, as shown in Figures 3 and 4. The device with the FES system, on the other hand, follows the wave crest position much more closely. In fact, it is projected a small distance out of the water at the peak of the wave; although, realistically, the overshoot is undesirable, the optimized device will correct for this. The ability for the buoy to follow the wave closely allows for it to achieve peak rotor velocities of 600 rpm—double of that for the device without the FES system.

Figure 4 illustrates the tradeoff imposed by the suggested FES system—time for power to be generated. While the device without the system generates power while it has a positive angular velocity imposed on the motor, the device with the FES does not—instead much of the time the power output is zero. Nevertheless, the increase in buoy velocity is such that the FES system provides for triple the instantaneous power output peaks. As a result, the average power of the system is higher overall, experiencing an increase by 100% over the system without the FES system.

After comparing the power produced by the system with the total power available from a wave, it is clear that the device can benefit greatly from optimization. The total energy density per unit horizontal area for a purely sinusoidal wave can be described by

$$E = \frac{1}{2} \cdot \rho_{water} \cdot g \cdot a^2 \qquad (12)$$

where a is the wave amplitude [14]. For a deep ocean wave (depth greater than half of the wavelength), the wavelength and group wave velocity can be written as:

$$\lambda = \frac{g}{2\pi} \cdot T^2 \ , \qquad (13)$$

$$v_g = \frac{g}{4\pi} \cdot T \ . \qquad (14)$$

For the wave modeled, a is 1 meter, T is 5 seconds, and the density of water is taken as 997 kg/m^2. The power available in the wave per unit width of wave is

$$P = E \cdot v_g \ . \qquad (15)$$

Thus, the total power available to be captured by the cylindrical buoy (width 1 meter) is 19.1 kW. The 180 watts produced by the buoy is less than 1% of the energy available.

The effectiveness of the FES system is dependent upon the amount of back torque produced by the generator. Conceptually, as the back torque imposed by the generator increases, the effectiveness of the proposed FES system will increase as well. The simulations model a small generator rated for 500 watts of power output, which has a low back torque coefficient of 1.146 kg-m^2/s. However, with a larger generator the power output can increase substantially. Moreover, high gear ratios, larger-sized flywheels, larger buoys, and higher waves can all improve power output dramatically for the wave energy harvest device and integrated flywheel energy storage system.

Acknowledgement

This work is supported by the Korea Research Foundation Grant funded by the Korean Government (MEST) (KRF-2009-220-D00034).

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