Optimized Latching Control of Floating Point Absorber Wave Energy Converter

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Abstract. There is an increasing demand for energy in today’s world. Currently main energy resources are fossil fuels, which will eventually drain out, also the emissions produced from them contribute to global warming. For a sustainable future, these fossil fuels should be replaced with renewable and green energy sources. Sea waves are a gigantic and undiscovered vitality asset. The potential for extricating energy from waves is extensive. To trap this energy, wave energy converters (WEC) are needed. There is a need for increasing the energy output and decreasing the cost requirement of these existing WECs. This paper presents a method which uses prediction as a part of the control scheme to increase the energy efficiency of the floating-point absorber WECs. Kalman Filter is used for estimation, coupled with latching control in regular as well as irregular sea waves. Modelling and Simulation results for the same are also included.

1. Introduction

Sea waves are gigantic, to a great extent undiscovered energy asset, and the potential for separating energy from waves is significant. The energy contained in sea surface waves is wind energy gathered over an endless range of the sea's surface and transported to the shorelines in the concentrated type of gravitational waves.

Progressing endeavors are made keeping in mind the end goal to decide reasonable strategies to discover areas where the harvest of this energy is beneficial and actually feasible. These requirements limit’s the choices of appropriate areas down to the most part of the Atlantic and Pacific seas, where there is high density of waves along with consistency, particularly in the winter months is common[1].

This paper presents the general status of wave energy and assesses the devices that represent current wave energy converter (WEC), and a portion of the control techniques to improve efficiency of point absorbers. The dimensions of point absorbers are smaller than the sea wavelengths, making them less demanding to handle. For the most part, point absorbers work best when in resonance with the approaching waves, i.e., when the angular frequency of device is same as that of incoming wave. As a result of the randomness of sea waves and their large frequency and amplitude spectrum, control strategies are required to extract maximum power from incoming wave.

2. Wave Energy Converter

There are various techniques for wave energy conversion, the devices used in energy conversion are called as wave energy converters. There are various types of wave energy converters [1], [2]. Some of the predominant types of wave energy converters are as follows:

2.1. Point Absorber

A point absorber is a wave energy converter which has smaller wavelength respect to incident wavelength of sea waves. They can be floating structure that hurl all over on the surface of the water or submerged beneath the surface depending on pressure differential. In view of their small size, the direction of incoming wave is not essential for these devices.

A typical kind of point absorbers, which are studied here are heaving float WECs. They get excited by the heave motion of waves to produce electrical energy. In general, these gadgets include a kind of floating
body, the float, whose motion is the function of incoming wave. Most devices of this kind have a second body, the spar, which is more inert to the incoming waves than the buoy, so that the difference in motion of the two bodies can be utilized to generate power. The second body is generally much heavier than the float and creates a lot of drag force. Moreover, it is moored to the seabed to limit its movement and to keep it on position.

2.2. Attenuators
It has various floaters on its arms. The energy of the movement of the arms is again used in hydraulic line which can be converted into electric current. This device has a high endurance for rough sea conditions. A significant advantage of these sorts of devices is the negligible contact with water, preventing corrosion's and preventing electrics far from any of the waves.

2.3. Terminators
Terminator devices lie parallel to the wave front and physically intercept waves. These terminator devices incorporate a stationary part and a moving part that moves due to incoming waves. The "stationary" part could be tied to the ocean bottom or shore. It must stay still, as opposed to the mobile part, to produce sufficient drag.

2.4. Submerged pressure differential
The submerged pressure differential converters are a submerged point safeguard that uses the pressure difference over incoming wave’s peaks and troughs. It involves two fundamental parts: an ocean bed fixed air-filled cylinder-shaped chamber with a moveable upper cylinder. As a crest passes over the converter, the water pressure over then pressurizes the air inside the chamber, causing the movement of the upper cylinder downward. As a trough passes over the converter, the water pressure on the device decreases and the upper chamber rises. Favorably this converter is completely submerged, it is not exposed to the hazardous pummeling forces experienced by floating wave energy converters, and decreases the visual effect of the device.

2.5. Overtopping devices
An overtopping device can capture ocean water of incoming waves in a reservoir over the ocean level, then discharges the water back to ocean through turbines. A case of such a device is the Wave Dragon. These converters utilize a couple of expansive reflectors to assemble waves into the central part, where they stream up a slope and over the top into a raised reservoir, from which the water is permitted to come back to the ocean by means of various low-head turbines.

2.6. Oscillating water columns
The working of the oscillating water columns wave energy converters (OWCs) is fundamentally the same as that of a wind turbine, being founded on the functioning of wave induced air pressurization. The device is set upon an air chamber, which is closed and is set over the water. The section of waves changes the water level inside the closed chamber and the rising and falling water level increments and declines the pneumatic force inside the chamber, causing a bidirectional wind stream. By setting a turbine on top of this chamber air will go all through it with the changing air pressure levels. There are two choices to isolate the bi-directional stream: a) Wells turbine to make suction or b) the pressure producing valves. OWC converters can be moored seaward or be set on the shoreline where waves break.

3. Sea Waves
Sea waves with consistent wave amplitudes and periods are rarely found. Normal sea conditions are more mathematically represented by Stochastic-wave time series that considers the superposition of various wave forms with different amplitudes and periods. This superposition of waves is portrayed by an ocean spectrum. Through factual investigation, spectra are described by particular parameters, for example, significant wave amplitude, peak period, wind speed, fetch length, and others. The general kind of spectrum
that are utilized for sea waves are as follows. The Eq. (1) gives the general equation of the sea wave spectrum for irregular sea.

\[ S(f) = Af^{-5} \exp[-Bf^{-4}] \]  

(1)

3.1. Pierson-Moskowitz spectrum

It is one of the simplest spectra, proposed by Pierson and Moskowitz [4]. It assumed that after the wind blew relentlessly for quite a while over a substantial territory, the waves would come into harmony with the wind. The spectrum is calculated from Eq. (2).

\[ S(f) = \frac{\alpha_{pm} \sigma^2}{(2\pi)^3} f^{-5} \exp\left[-\frac{5}{4} \left(\frac{f_p}{f}\right)^4\right] \]

\[ A = \frac{\alpha_{pm} \sigma^2}{(2\pi)^3}, \quad B = \frac{5}{4} (f_p)^4 \]

(2)

Where \( \alpha_{pm} = 0.0081 \) was calculated such that the required wave height is met, \( g \) is gravity and \( f_p \) is peak frequency of the spectrum.

3.2. Bretschneider spectrum

This is a two-parameter spectrum, based on peak wave frequency and significant wave height. The spectrum is calculated from Eq. (3).

\[ S(f) = \frac{H_{m0}}{4} \left(1.057 f_p\right)^4 f^{-5} \exp\left[-\frac{5}{4} \left(\frac{f_p}{f}\right)^4\right] \]

Here \( A = \frac{H_{m0}}{4} \left(1.057 f_p\right)^4 \approx \frac{5}{16} H_{m0}^2 f_p^4 \), \( B = \left(1.057 f_p\right)^4 \approx \frac{5}{4} f_p^4 \).

Where ‘\( H_{m0} \)’ is significant wave height, which is generally defined as the mean height of the one third highest waves.

3.3. JONSWAP (Joint North Sea Wave Project) Spectrum

The spectrum was proposed by Hasselmann et al. [5], and the original formulation of the spectrum is given in Eq. (4). Which was later on changed at International Towing Tank Conference (ITTC).

\[ S(f) = \frac{\alpha_j \sigma^2}{(2\pi)^4} f^{-5} \exp\left[-\frac{5}{4} \left(\frac{f_p}{f}\right)^4\right] f^{\gamma} \exp\left[-\left(\frac{f_p}{f}\right)^{2}\right], \quad \gamma = \begin{cases} 0.07 & f \leq f_p \\ 0.09 & f > f_p \end{cases} \]

Here \( A = \frac{\alpha_j \sigma^2}{(2\pi)^4}, \quad B = \frac{5}{4} f_p^4 \).

Where \( \alpha_j \) is the non-dimensional variable, that is a function of wind speed and fetch length.

3.4. White Gaussian Noise

White Gaussian noise can be combined with the system to make system more random. Gaussian noise is statistical noise having a probability density function (PDF) equal to that of the normal distribution, which is also known as the Gaussian distribution. In other words, the values that the noise can take on are Gaussian-distributed. Gaussian noise has a fixed power spectral density and it is also sometimes referred as white noise because it affects all frequency component equally, like a white light, which basically has all the frequency components. Since it has Gaussian distribution its probability density function depends on mean and variance of the random variable. The sea wave spectrums generated by simulation for regular as well as irregular sea is as shown in figure 1.
Figure 1. Sea Wave Spectrums, as generated by simulation. (a) Regular Sea Wave (b) Irregular Sea Wave.

4. Floating Point Absorbers

4.1. Coordinate System and Dynamics

The coordinate system of a floating-point absorber subject to incoming waves in water, is so chosen that the X-axis is in the direction of wave propagation, with the wave heading angle equal to zero. The Z-axis is in the vertical upwards direction, and the Y-axis direction is defined by the right-hand rule. Surge (x), sway (y), and heave (z) correspond to the first, second and third position respectively. Roll (Rx), Pitch (Ry), and Yaw (Rz) correspond to the fourth, fifth and sixth position respectively. This is illustrated in figure 2(a).

Figure 2. Floating Point Absorbers: (a) Coordinate System and the six directions of motion (b) Dynamic Model.

While considering hydrodynamics and wave-float interaction in preparatory hypothetical analysis, we normally consider its vertical movement i.e. only one degree of motion of wave-energy converter and that is in Z direction [3]. As illustrated in figure 2(b). The Force equation of the system in time domain can be obtained as below

\[(m + m_{\omega})\ddot{z} + (b + c_{PTO})\dot{z} + (\rho gS + k_{PTO})z = f_{ext}\]  (5)

Where ‘m’ is mass of the system, ‘m_{\omega}’ is the added mass, ‘k_{PTO}’ is ‘f_{ext}’ is the external force because of sea waves, ‘c_{PTO}’ is the power take off constant, ‘\rho’ is sea water density, ‘g’ is gravity, ‘S’ is surface area of the buoy, ‘b’ is viscous damping constant, and the Power Take Off force is considered to be linear
\[ F_{PTO} = -K_{PTO}X_{rel} - C_{PTO}\dot{X}_{rel}. \]

Here \( k_{PTO} \) is stiffness of the Power Take Off and \( X_{rel} \) relative motion of the two bodies. The power consumed by the Power Take Off is given by Eq. (6).

\[ P_{PTO} = -F_{PTO}\dot{X}_{rel} = (K_{PTO}X_{rel}\dot{X}_{rel} + C_{PTO}\dot{X}_{rel}^2) \]

The displacement of the float in frequency domain can be written as in Eq. (7). The average power consumed by the Power Take Off can be formulated as in Eq. (8). This gives us a condition for maximizing the power out, Eq. (9).

\[ Z = \frac{F_{ext}}{(\rho g S + k_{PTO})-(m+m_\infty)\omega^2+(b+c_{PTO})\omega} \]

\[ P = \frac{1}{2}c_{PTO}\omega^2|Z|^2 = \frac{1}{2B}F_{ext}^2 - \frac{B}{2}\left[\omega Z - \frac{F_{ext}}{2B}\right]^2 \]

\[ \omega = \sqrt{\frac{\rho g S + k_{PTO}}{m + m_\infty}} \quad \text{and} \quad c_{PTO} = b. \]

Hence relative motion and velocity between two bodies is out of phase by 90 degrees. The conditions thus obtained are condition for maximum power transfer between incoming wave and wave energy converter.

4.2. Control Strategy for Point Absorbers

There are various control strategies which can also be used, like latching control, declutch control, latching operating declutch control, Reactive control, Model predictive control. We have used the latching control method [4]. Latching is sub-optimal kind of phase control [6]. The principle behind is to latch and unlatch the relative velocity at appropriate time instances for achieving optimal phase and also optimal output power. The optimum power output is achieved if the motion is unlatched in a time instance such that the oscillatory motion is at its maximum at the same time as the excitation force is at its maximum [7]. By using this we can force our wave energy converter in the resonance with the incoming wave. The resonance maximizes the power output of the device. Latching is done when the relative velocity is zero. If a wave is periodic like sinusoidal, we can easily find the appropriate latching time, but if wave is irregular then, the knowing the appropriate latching time is not trivial. We have used Kalman filter to find the optimal latching time of WEC.

4.3. Kalman Filter

Kalman filter is a predictor for linear quadratic problem, which is basically problem of predicting the next or instantaneous state of a linear dynamic system, Table 1. Which can have white Gaussian noise, it is statistically optimal than any quadratic function for error estimation. Kalman filter provides a means to get any missing piece of information in noisy environments [8]. The solution of the Kalman filter gives the dependence of the output on the input and it also the functionally depended on the coefficients of the system.

![Figure 3. The incoming wave (red), latched WEC (blue) and the latching time.](image)
Table 1. Mathematical model of the dynamic systems

| Time invariant | Continuous | Discrete |
|----------------|------------|----------|
| Linear         | \( \dot{x}(t) = Fx(t) + Gu(t) \) | \( \dot{x}_k = \Phi x_{k-1} + \Gamma u_{k-1} \) |
| General        | \( \dot{x}(t) = f(x(t), u(t)) \) | \( \dot{x}_k = f(x_{k-1}, u_{k-1}) \) |

4.4. Linear Kalman Filter

Input output model of linear dynamic system, inputs of the system are assumed to be in control, or at least could be measured by us. The algorithm used to predict the output is as given in figure 4.

![Figure 4. Kalman Filter recursive algorithm](image)

State variables can’t be measured directly and could be inferred from the variables which could be measured and output of the system could be measured.

4.5. Extended Kalman Filter

The principle downside when utilizing a linear Kalman filter estimator on the nonlinear model of the WEC is the quick deviation of the linearized mooring power from the real one over the happening scope of plant states. As a well-known instrument for noisy systems of loud frameworks, different expansions and changes of the Kalman filter exist. It basically linearizes the nonlinear system before applying state estimation by a linear Kalman filter.

5. Modelling and Simulation Results

The WEC Parameter values used for simulation are available in [8] and given in Table 2 below. The plant model was made using Solidworks [9], the testing of the model was done using MATLAB SimMechanics [10] and the simulation was done on MATLAB Simulink [9].

Table 2. The Characteristics of the Wave Energy Converter

| Property        | Value  | Property       | Value  |
|-----------------|--------|----------------|--------|
| Buoy mass       | 1000 kg| Pole width     | 50 mm  |
| Translator weight| 1000 kg| Winding resistance | 0.44 Ω |
| Buoy Type       | Cylinder| Vertical stator length | 1264 mm |
| Buoy Radius     | 1.5m   | Vertical translator length | 1867 mm |
| Buoy Height     | 0.8m   | Winding inductance | 11.7 mH |
| Buoy draft      | 0.4m   |                |        |
The regular and irregular wave spectrum, were fed into the system and the response of the system was measured, with and without the use of Kalman Filter. The efficiency is calculated on the basis of the average power of the input wave spectrum and the response wave generated by the system. The simulation results for Latching control without using Kalman Filter is as illustrated in figure 5. The input wave to the system is denoted by the blue curve and the response of the system by the yellow curve. Next the Kalman Filter was used for estimation of sea waves, the results obtained are as illustrated in figure 6. The input wave to the system is denoted by the blue curve, the Kalman Filter predicted wave by the Yellow curve and the orange curve depicts the response of the system.

![Figure 5. The input and output wave of the system without latching control.](image)

![Figure 6. The input and output wave of the system with latching control and Kalman filter.](image)

The simulation results show that a 100% power efficiency for regular wave spectrum and an efficiency of 74% for irregular wave spectrum is obtained. Thus, the adaptive control technique of prediction using Kalman Filter gives better results than the traditional Latching Control techniques.

6. Conclusion
The Sea wave energy is one of alternative energy sources which can be exploited for meeting the energy demand. This paper describes a novel method to increase the power efficiency of a floating-point absorber wave energy converter. Latching control is used to increase the gain of bring to wave energy converters. In this paper, Latching Control coupled with Kalman filter are employed to estimate the sea wave spectrum. This method was applied to both regular and irregular sea waves and an increase in the power efficiency was observed in both the cases.

Simulation results show that the Latching Control and Kalman Filter combination has increased the power conversion significantly in irregular waves, whereas in regular waves the technique can achieve perfectly optimal power conversion. Thus, the adaptive control technique of prediction using Kalman Filter gives better results than the traditional Latching control techniques. Further work on real time implementation of this method in a full-scale device can be done.

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