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## Power Maximizing of Point Absorber Wave Energy Converter by Model Predictive Control

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**ABSTRACT :** Ocean wave energy is a promising renewable energy source that can be converted into useful electrical energy using wave energy converters (WECs). In order for WECs to become a commercially viable alternative to established methods of energy generation, operating the WEC in an optimal fashion is a key task. This work aims to control WEC power potential while respecting the constraints on motions and forces using Model predictive control (MPC). One subclass of WECs, namely, buoy type point absorbers uses a linear generator as the power take-off (PTO) system and MPC to optimize the generator force. On the basis of the simulated results, the MPC coupled forecasting shows system to optimize energy capture while respecting system.

**KEYWORDS:** Point absorber, Wave energy converter, Model Predictive control

### I. INTRODUCTION

The need for renewable energy sources is greater than ever before since energy demanding is more nowadays. One that has not yet been fully utilized is the energy in ocean surface waves. Wave energy originates from the wind, which in turn originates from the sun. When the wind blows over the ocean, friction gives rise to water movement and waves are generated. Even though the total energy of waves on earth is much lower than the total solar energy, it is much denser; specifically wave energy is about five times denser than solar energy; with power density up to 2–3 kW/m<sup>2</sup> on the surface [1]. This makes wave energy a good renewable energy source, but only if we can find an efficient way to extract it. The study of converting the mechanical energy in the ocean waves to useful electricity began in the 1970's [1], but still no one has found a way to make it profitable. According to [2], the ocean holds approximately 8000–80000 TWh/year or 1–10 TW, whereas Falnes in [3] quantifies the world's exploitable wave power resource to be of the order of 1 TW. Comparing this to the world's annual energy consumption of approximately 148000 TWh in 2008, shows that wave energy could play an important role in the world's energy portfolio.

The device which converts Ocean wave energy into electricity is called a Wave Energy Converter (WEC). A WEC comes in various shapes and sizes. The one that has been modelled here is a called point absorber: it has a buoy that moves with the wave motion. The buoy is connected to an energy converter called Power Take Off (PTO), so that the movement of the buoy is transmitted to the PTO. Inside the PTO, a generator converts the mechanical energy to electrical energy and transmits it to the grid.

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## II. RELATED WORK

In order for WECs to become a commercially viable alternative, operating the WEC in an optimal fashion is a key task. More work on optimizing the energy generation of WECs has been done which leads to control laws such as latching control, phase and amplitude control [4]–[6].

Furthermore, Schoen et al. [7] have proposed a hybrid control strategy to increase the energy conversion while being robust to modelling errors. The short-term tuning of the converter is done by a fuzzy logic controller, while the robust controller attempts to minimize the modelling errors.

Recently, researchers increasingly deal with MPC algorithm in order to control point absorbers. They have shown that MPC approach is very promising control method, since it is able to exploit the entire power potential of a WEC on the one hand, while respecting the constraints on motions and forces on the other hand.

All the above-mentioned control approaches requires prediction data of the wave's motion. The problem of short-term wave forecasting has already been studied by many researchers. Fusco and Ringwood [8], for example, focused on wave forecasting and prediction requirements for unconstrained phase and amplitude control. Where, the required forecasting horizon and the achievable performance of wave predictions for different properties of the floating system has been discussed. The same authors presented various wave prediction algorithms in [9]. They implemented cyclical models, autoregressive models, and neural networks in order to predict the wave's motion and validated these models against real observations from data buoys. It was shown that an accurate prediction for up to two typical wave periods into the future can be calculated. Different prediction models have been presented in [7]. A predictive Kautz model and a combination of a Kautz and autoregressive model have been proposed, where both filters have reduced orders compared to conventional prediction filters. Hence, the proposed filters can lower the computational effort in real-time applications.

This paper deals with model predictive control, where the prediction of the wave's motion is required. However, it does not focus on wave prediction and an ideal prediction is assumed. However, the above-mentioned work on wave prediction could be used to estimate the wave horizon for our model predictive controller as well.

Current research into MPC for wave energy applications exclusively focuses on linear MPC. Brekken in [10] and Hals et al. in [11] successfully applied linear MPC to one-body WEC models. Moreover, the application to a linear two-body model with mooring was demonstrated in [12]. The proposed controllers are validated and compared through simulation for irregular sea states.

## III. POINT ABSORBER MODEL

The point absorber model L10, developed at OregonStateUniversityisconsideredinthiswork. It consists of a float, also called buoy, floating on the ocean surface and a second body consisting of a spar and a ballast tank where the spar's motion is damped through mooring. The relative motion of the two bodies can be converted into usable energy through a power takeoff (PTO) system.

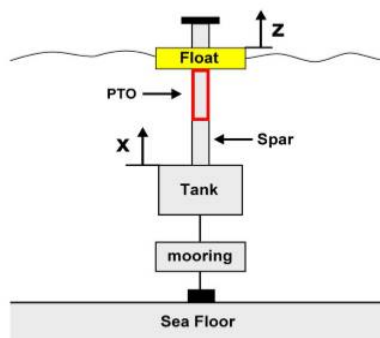


Figure.1. Schematic diagram of L10 Wave Energy Converter

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A schematic diagram of the L10 point absorber wave energy converter is shown in Fig.1, which denotes the positions of the spar and the float, respectively. The L10 shows an example of a direct-drive WEC. Here, the wave energy is converted directly into electrical energy by means of a linear generator without converting wave energy into mechanical energy as in hydraulic PTO systems first. In what follows, the point absorber is simply considered as an axis-symmetric float connected to a stationary reference body through an electric linear generator, as considered in This is also comparable to the assumption of perfect mooring of the spar as the reference body.

## Equations of Motion

The proposed nonlinear two-body model follows the work in [11]. Thus, impulse response functions are used in order to calculate the radiation forces. Using impulse response functions yields convolution terms in the expressions for the radiation forces. Furthermore, a highly nonlinear mooring force law [12] is used.

The motion of the buoy and the spar is denoted by  $x$  and  $z$ , respectively. The equation of motions (EOMs) can be derived using Newton's second law. The formulation is based on linear wave theory (LWT). Assuming linear hydrodynamics, the force on the L10 float can be written in the frequency domain as

$$-\omega^2 z(\omega)m = F_e(\omega) + F_r(\omega) + F_b(\omega) + F_{gen}(\omega) \quad (1)$$

where  $\omega^2 z(\omega)$  is the frequency domain second derivative of the L10 float heave (vertical) position,  $m$  is the float mass,  $F_e(\omega)$  is the wave excitation force on the float,  $F_r(\omega)$  is the float radiation force,  $F_b(\omega)$  is the float buoyancy force, and  $F_{gen}(\omega)$  is the generator (i.e., power take off) force (reacted against the spar).

As a first order approximation of the radiation force to ease the MPC formulation, it is assumed that the frequency dependent L10 float added mass and damping can be approximated by a constant. Therefore

$$F_r(\omega) = (\omega^2 A - j\omega B)z(\omega) \quad (2)$$

This is expressed in the time domain as

$$F_r(t) = -A\ddot{z}(t) - B\dot{z}(t) \quad (3)$$

The buoyancy force is

$$F_b(t) = -g\rho\pi r_{float}^2 z(t) = -kz(t) \quad (4)$$

Where  $g$  is the acceleration of gravity,  $\rho$  is the density of seawater, and  $r_{float}$  is the float radius. For the simulations, a simple method for determining  $F_e(t)$  is used based on a linearized Morison approach as shown in Patel (1989) [13].

$$F_e(t) = A\dot{\eta}(t) + B\ddot{\eta}(t) + k\eta(t) \quad (5)$$

where  $\eta(t)$  is the water surface elevation. This then gives a simple model for determining the excitation force, and the float motion profile from the water surface elevation  $\eta(t)$ . As stated earlier, it is assumed the spar is held relatively stationary, thus providing a reaction point for the generator, and that there are no significant radiated wave interactions between the float and the spar.

## IV. MPC FORMULATION

### Prediction Model

The WEC equation motion given in (1) can be expressed in time-domain state-space form as

$$\frac{d}{dt} \begin{bmatrix} \dot{z} \\ z \end{bmatrix} = \begin{bmatrix} \frac{-B}{m+A} & \frac{-k}{m+A} \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{z} \\ z \end{bmatrix} + \begin{bmatrix} \frac{1}{m+A} \\ 0 \end{bmatrix} [F_{gen}] + \begin{bmatrix} \frac{1}{m+A} \\ 0 \end{bmatrix} [F_e] \quad (6)$$

The "(t)" notation is dropped for simplicity. This model can be discretized into the form

$$x(k+1) = Ax(k) + B_u u(k) + B_v v(k) \quad (7)$$

Where  $x(k)$  is the current state vector (WEC float velocity and position),  $u(k)$  is the generator force  $F_{gen}$ , and  $v(k)$  is the estimated excitation force from the waves  $F_e$ .

A sequential model can be found by solving the system forward in time and back-substituting in (7)

$$x(k+2) = Ax(k+1) + B_u u(k+1) + B_v v(k+1) \quad (8)$$

$$= A(Ax(k) + B_u u(k) + B_v v(k)) + B_u u(k+1) + B_v v(k+1) \quad (9)$$

This can be expressed in matrix form

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$$\begin{bmatrix} x(k+1) \\ x(k+2) \end{bmatrix} = \begin{bmatrix} A \\ A^2 \end{bmatrix} x(k) + \begin{bmatrix} B_u & 0 \\ AB_u & B_u \end{bmatrix} \begin{bmatrix} u(k) \\ u(k+1) \end{bmatrix} + \begin{bmatrix} B_v & 0 \\ AB_v & B_v \end{bmatrix} \begin{bmatrix} v(k) \\ v(k+1) \end{bmatrix} \quad (10)$$

The Output equation is given by

$$y(k) = Cx(k) \quad (11)$$

We get

$$\begin{bmatrix} y(k+1) \\ y(k+2) \end{bmatrix} = \begin{bmatrix} CA \\ CA^2 \end{bmatrix} x(k) + \begin{bmatrix} CB_u & 0 \\ CAB_u & CB_u \end{bmatrix} \begin{bmatrix} u(k) \\ u(k+1) \end{bmatrix} + \begin{bmatrix} CB_v & 0 \\ CAB_v & CB_v \end{bmatrix} \begin{bmatrix} v(k) \\ v(k+1) \end{bmatrix} \quad (12)$$

## Optimization Formulation

The desired trajectory of the outputs  $Y(k)$  is  $T(k)$ . The control objective is to find the control action  $\Delta U(k)$  over the prediction horizon  $H_p$  that will minimize the quadratic sum of tracking error and controller effort. The sum is weighted by the  $Q$  and  $R$  matrices.

$$J(k) = (Y(k) - T(k))^T Q (Y(k) - T(k)) + (\Delta U(k))^T R (\Delta U(k)) \quad (22)$$

The free evolution of the system  $\gamma(k)$ , that is, the evolution of the outputs if no control action is taken (i.e.,  $\Delta U(k)=0$ ) is expressed as

$$\gamma(k) = S_x x(k) + S_{u1} u(k-1) + H_v V(k) \quad (23)$$

$$= Y(k) - S_u \Delta u(k) \quad (24)$$

The free evolution error  $E(k)$ , that is, the evolution of the tracking error if no control action is taken is expressed as

$$E(k) = T(k) - \gamma(k) \quad (25)$$

$$= T(k) - Y(k) + S_u \Delta U(k) \quad (26)$$

This is then substituted into the cost function so that it can be expressed in terms of the control action  $\Delta U(k)$

$$J(k) = (S_u \Delta U(k) - E(k))^T Q (S_u \Delta U(k) - E(k)) + (\Delta U(k))^T R (\Delta U(k)) \quad (27)$$

$$J(k) = E(k)^T Q E(k) - 2 \Delta U(k)^T S_u^T Q E(k) + \Delta U(k)^T (S_u^T Q S_u + R) \Delta U(k) \quad (28)$$

The minimization of (28) yields the optimal control action vector  $\Delta U(k)$ , such that the tracking error and control action are minimized with consideration of the weights given by the  $Q$  and  $R$  matrices. As is typical in MPC, the first control action of this vector,  $\Delta u(k)$ , is chosen as the control action for time  $k$  and the entire process is repeated the next sample time.

## V. SIMULATION RESULTS

The proposed method is verified by using MATLAB simulation model and its results are validated. The MPC algorithm is set up to allow the maximum speed to be relaxed by a factor of two to  $\pm 2$  m/s, and the maximum generator force by a factor of two if the minimization problem is unfeasible. If the minimization problem is still unfeasible, the second strategy of de-emphasizing far future predictions is done.

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TABLE I

SIMULATION PARAMETERS

Variable	Explanation	Value
A	Added mass	5660kg
m	Mass	1997kg
B	Radiation damping	11,400N/(m/s)
k	Hydrostatic stiffness	88,970N/m

The hydrodynamic parameters and control parameters of the point absorber used in the simulation are given in Table I. The position constraint is equivalent to the stroke length of the generator and is taken from [11]. The generator constraint is chosen so that the MPC control can be effectively tested.

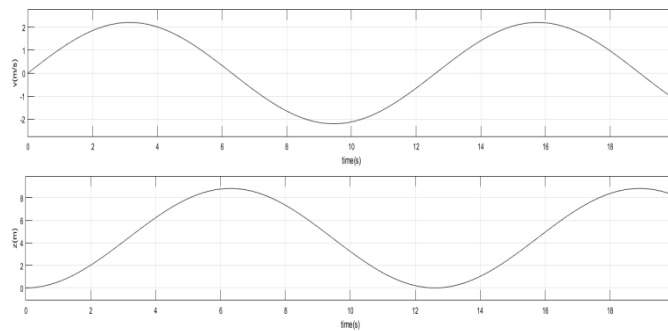


Figure.2. Simulation results of position and velocity during monochromatic sinusoidal wave as input signal.

The simulation result of position and velocity with respect to time is shown in Fig.2, which shows that the position,  $z$  and velocity,  $v$  trajectory has a sinusoidal shape. The position,  $z$  is always positive while the velocity  $v$  is symmetric about zero. The maximum and minimum values of  $z$  are 8.834 m and 0, respectively. The velocity  $v$  has a maximum of 2.1 m/s and a minimum of -2.1 m/s.

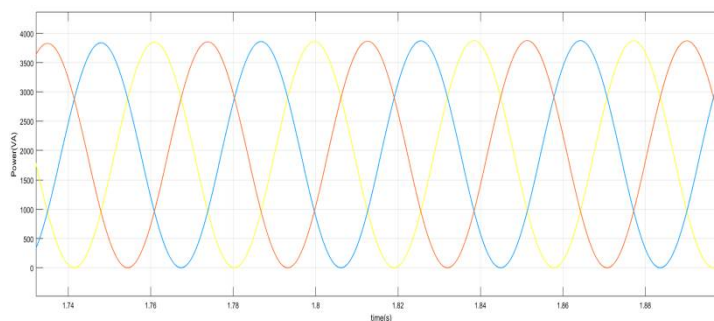


Figure.3. Simulation result of power with linear MPC

The simulation result of power output of the system for all the three phases is shown in Fig.3. The power is non-negative since it is calculated using the formula  $P = i^2 RL$ . During one period there are two peaks. The average power obtained is 3.8KW.

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## VI. CONCLUSION

This paper presents a formulation of a prediction model for a simple point absorber WEC, Model Predictive Control implementation details, and simulation results. The prediction model is used to implement a Model Predictive Control algorithm that tracks an optimal velocity trajectory while respecting system velocity and position limits, and generator force limits. Additionally, the algorithm implements excitation force prediction. The simulation results demonstrate that the control approach is able to generate power while avoiding possibly destructive velocities and excursions in position. It has also been demonstrated that MPC provides a method of realizing power-shedding when operating in especially energetic seas, and that MPC is a promising approach for ocean wave energy applications.

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