Controller Design for Maximum Energy Extraction from Wave Energy Converters

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***Abstract*— In this project, two controllers for heaving body wave energy converters (WECs) are presented. One is based on the real-time control based on the control strategy proposed by Fusco et al. The second controller is a new controller based on latching technique. The oscillation of the Power Take off (PTO) system is controlled in such a way that its velocity is always in phase with the wave excitation force. In this study, it is considered that the amplitude of the oscillation is always within given constraints. Based on reference velocity estimation and Internal Model control of PTO force, a satisfactory improvement in wave energy extraction is obtained. Latching based control is also shown to extract the energy from system which can be studied for further improvement.**

***Index Terms*—Optimal control, real-time estimation, wave energy, wave forecasting.**

NOMENCLATURE

$x(t)$	Heaving position of floating body.
$v(t)$	Heaving velocity of floating body.
$f_{\mathrm{ex}}(t)$	Wave excitation force.
$f_u(t)$	Power takeoff force (control input).
$Z_i(s)$	Intrinsic impedance of floating system.
$Z_r(\omega)$	Radiation impedance of floating system.
$B(\omega)$	Radiation resistance of floating system.
$1/H$	Ratio of velocity to excitation force
$K(s)$	Controller for velocity tracking.
H_s	Significant wave height.

ASSUMPTIONS

1) Energy extraction done only through heaving motion of buoy.
2) Excitation force is contained within a restricted band of frequencies between 0.3 to 0.8 rad/s
3) Efficiency of PTO system is 100%.

I. INTRODUCTION

Ocean wave carries a significant amount of energy which can contribute to meet the power requirement for several countries worldwide. Wave energy conversion devices are still under development and there is significant scope in improvement of energy extraction capability of these devices.

For one dimensional mode of oscillation such as heave, 50% of total wave energy is theoretically available for absorption by WEC [1]. To extract maximum of available energy from ocean waves, buoy must always oscillate in such a way that its velocity is in phase with the control force. Control strategies for wave energy conversion are thus designed to meet the aforesaid goal.

This report demonstrates two controllers: first one being simple and effective real time controller as proposed by Fusco et al. [2] and second one is based on latching technique [3] hereafter mentioned as Controller-1 & Controller-2 respectively. In controller-1, the velocity tracking internal Model Control (IMC) is used, where the reference velocity used is as calculated by Extended Kalman Filter [4].

Controller-1: The controller requires bidirectional energy flow and is thus of reactive type. Typical hydraulic PTOs and linear electrical generators that have been studied for applications in wave energy have the ability of inverting the energy flow [5], [6].

It has been assumed that the Power Take Off system operates at ideal efficiency as the main focus is towards the control of system.

Controller-2: This controller is based on latching phenomenon. The control force is set to zero for all conditions where, velocity of buoy goes below zero. Thus this controller does not require bidirectional energy flow and only power input to system is to actuate latching mechanism. Available latch controls are time based, which latches the motion of buoy at zero velocity and releases the same after certain time period known as latching time. In regular waves, the latching duration is given by the relation [7],

$$T_{latch} = (T_w - T_0) / 2 \quad (1)$$

Where, T_{latch} = Latch duration, T_w = Wave period, T_0 = Resonance period

However, the latching in this controller is not time dependent but is based on actual velocity of buoy. The PTO force is switched to zero for all cases when wave velocity goes below zero. It has been assumed that the Power Take Off system operates at ideal efficiency as the main focus is towards the control of system.

The considered model of plant for both controllers is explained in Section II, while the control part has been discussed in Section III. Results of both controllers are stated in Section IV. Conclusions are discussed in Section V.

II. MODEL OF WAVE ENERGY CONVERTER

A single-body floating system, as in Fig. 1, is considered where energy is extracted from the relative motion with the sea.

The system is constrained to perform heaving motion only i.e. one degree of freedom. The external forces acting on the WEC are the excitation from the waves and the control force produced by the PTO. As mentioned earlier, it has been assumed that there is no energy loss in PTO system i.e. 100% efficiency.

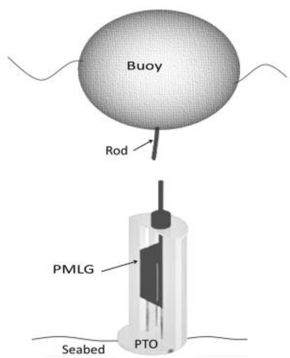

Fig. 1. Schematic of a point absorber type wave energy convertor.

The model in figure 2 can be expressed as:

$$V(\omega) = \frac{1}{Z_i(\omega)}\left[F_{\mathrm{ex}}(\omega) + F_u(\omega)\right] \tag{2}$$

Where, $V(\omega)$ = Heaving velocity

$Z_i(\omega)$ = Intrinsic impedance of plant

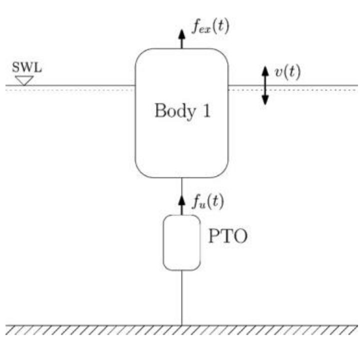

Fig. 2. One-degree-of-freedom (heave) floating system for wave energy conversion.

The specifications of WEC system are considered as below,

Heaving buoy shape	: Cylindrical
Cylinder Radius	: 3m
Cylinder Height	: 5m
Draught	: 4m
Mass	: 3.2 X 10^5 Kg

In S-domain, the model can be represented as a transfer function mentioned below.

$$\frac{1}{Z_i(s)} = \frac{1.8\times10^{-6}\cdot s(s^2+1.1s+0.4)(s^2+1.6s+1.8)}{(s^2+1.2s+0.4)(s^2+1.4s+1.6)(s^2+0.1s+1.5)} \tag{3}$$

III. Control Of PTO Force

This section outlines the control strategy used in Controller-1 and Controller-2. Both controllers are designed for the system modeled in Section II.

I. Controller-1

The approach comprises of the reference velocity generation from knowledge of the current wave excitation force acting on the system, and then imposition of such velocity, through the PTO force, via a lower-level feedback controller K(s).

In real time control, the condition for maximum energy extraction is given by relation between oscillation velocity and wave excitation force as [2]

$$V(\omega) = \frac{1}{Z_i(\omega) + Z_i^*(\omega)}F_{\mathrm{ex}}(\omega) = \frac{1}{2B(\omega)}F_{\mathrm{ex}}(\omega). \tag{4}$$

Based on (4), the velocity should always be in phase with the excitation force and it should have an amplitude that is modulated in the frequency-domain by the inverse of double the radiation resistance1/2 B (ϖ), which is non causal.

The reference velocity can be generated from the following adaptive law:

$$v_{\mathrm{ref}}(t) = \frac{1}{H(t)}f_{\mathrm{ex}}(t), \qquad \frac{1}{H(t)} = \frac{1}{2B(\hat{\omega})} \tag{5}$$

Where the value of the constant is calculated from the curve $1/2B(\omega)$, based on a real-time estimate of the peak frequency of the wave excitation force. The optimum value of oscillation velocity is obtained by implementation of Extended Kalman Filter as shown in Fig. 5. [4][8][9]

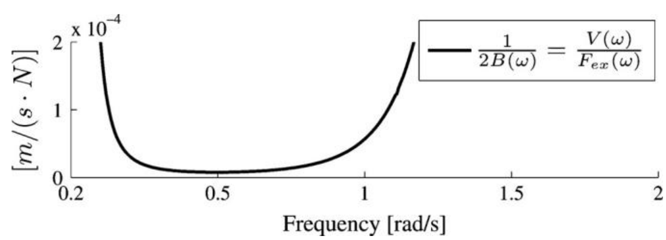

Fig. 3. Optimal relation between excitation force and oscillation velocity. The phase is zero.

In practice, the excitation force is contained within the range of 0.3 to 0.8 rad/s [10]. Since this lies in the flat part of curve shown in fig. 5, the constant value of 1/H i.e. 0.50 X 10^5 is used for reference velocity estimation.

In certain conditions, the optimal excitation force can be well beyond the physical limitations of the system. For such a case below condition is used.

$$\frac{1}{H} \le \frac{\omega X_{\mathrm{lim}}}{A}. \tag{6}$$

Where, X_{lim} is the limit of displacement.
Estimate of the frequency $\hat{\omega}$ And amplitude $\hat{A}$ Of the excitation Can be obtained through the EKF [8],[9]

$$\frac{1}{H(t)} = \begin{cases} \frac{1}{2B(\hat{\omega})}, & \text{if } \frac{\hat{\omega}X_{\text{lim}}}{\hat{A}} > \frac{1}{2B(\hat{\omega})} \\ \frac{\omega X_{\text{lim}}}{\hat{A}}, & \text{otherwise.} \end{cases} \tag{7}$$

However, in this study it is considered that our system never works in constrained form i.e. actual value of displacement never exceeds the limit.
The control architecture used is based on Internal Model Control (IMC). Term IMC indicates that the controller uses the model of plant for calculations. Controller block diagram is as displayed in fig. 3 and fig. 4

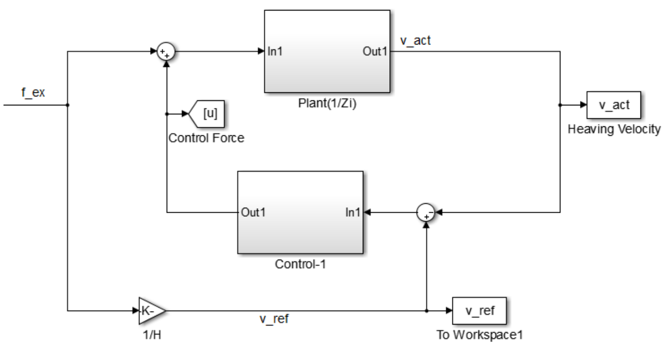

Fig. 4. Simulink model of WEC system with use of Conteoller-1.

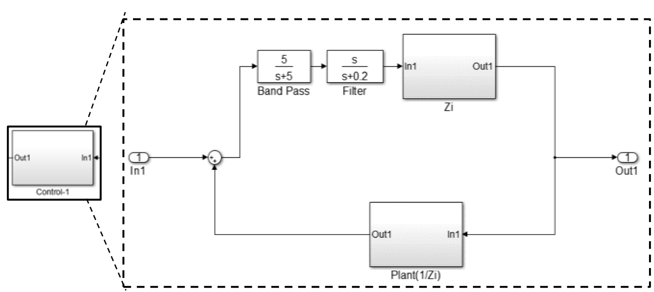

Fig. 5. Architecture of Controller-1

The bandpass filter is used to maintain the stability of the closed loop system, with 0.2 and 5 rad/s as its cutoff frequencies.

II. Controller-2

This controller is based on latching mechanism. However, it is not time controlled. The control logic used for this controller is to set the control force zero for all negative values of velocity. This controller is different from the Controller-1 in a way that, it does not any reference velocity. The same can be observed in fig 6. This controller however tries to maintain the zero phase between control force and velocity. The control architecture for controller-2 is shown in fig 7.

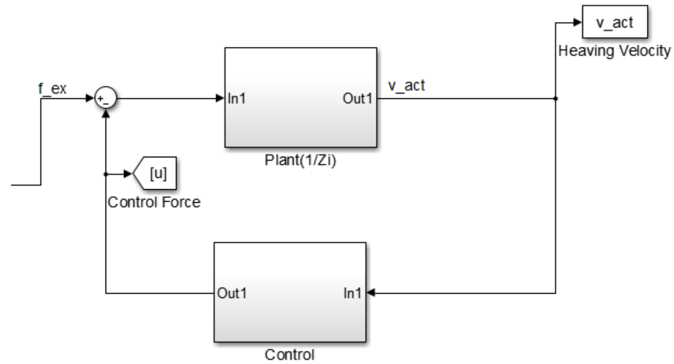

Fig. 6. Simulink model of WEC system with use of Conteoller-2.

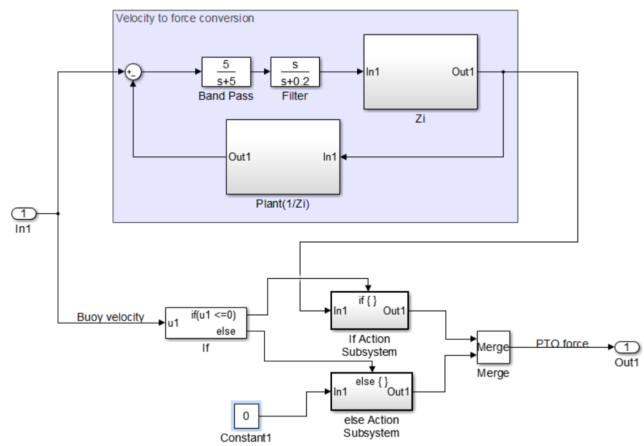

Fig. 7. Architecture of Controller-2

IV. RESULTS

A. Wave Data

The proposed control method is validated on the heaving cylinder as specified in Section II under regular wave condition.

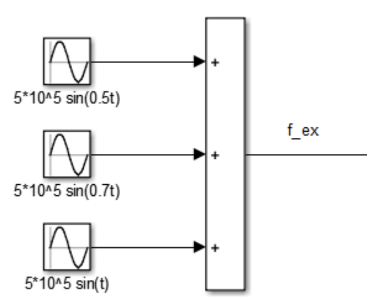

Fig. 8. Excitation force used for simulation of controllers

The spectrum if excitation of waves have been used from 0.5 rad/s to 1 rad/s.

B. Performance of Controller-1

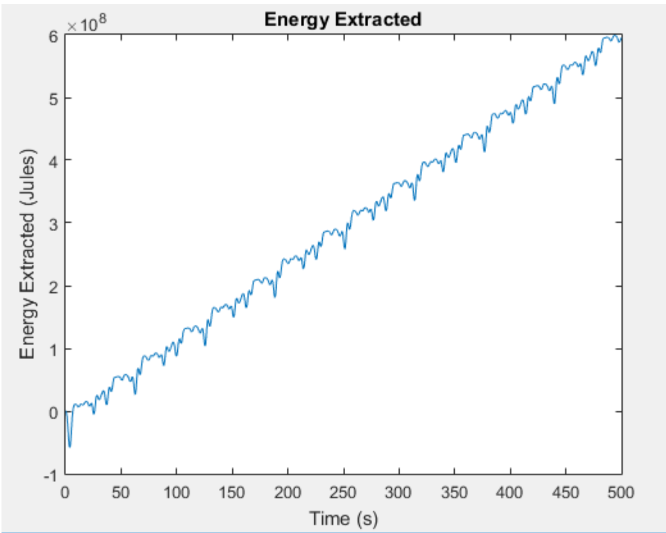

Fig. 9. Energy extracted in 500s with use of Controller-1

Overall energy extracted over a time of 500s by the use of controller-1 is around 6 X 10^8 Jules.

C. Performance of Controller-2

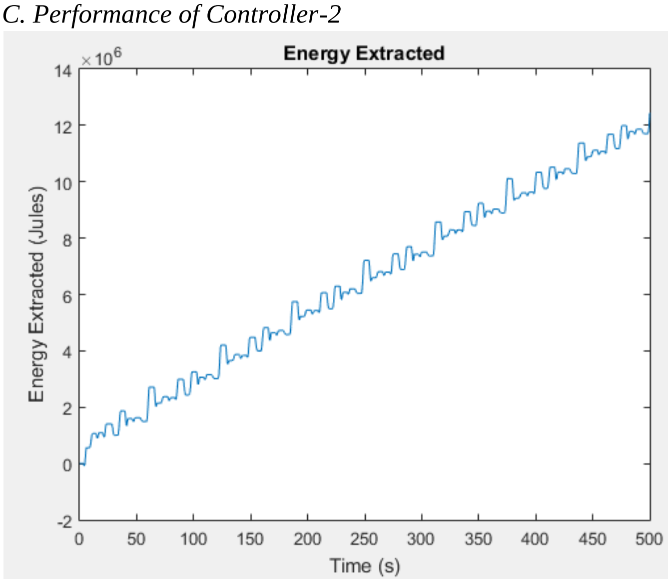

Fig. 10. Energy extracted in 500s with use of Controller-2

Overall energy extracted over a time of 500s by the use of controller-1 is around 1.4 X 10^7 Jules.

V. Conclusion

A strategy for the control of bottom-referenced oscillating WECs has been exercised. Both controllers set the velocity of the oscillator to be in phase with the excitation force and with an amplitude proportional to the wave force. Based on a regular wave function, both controller demonstrates the accumulation of energy. However, the energy accumulation in Controller-1 is much larger than that from controller-2. The controller-2 is a new control proposed in this project and is not optimized for maximum energy extraction. There is a scope for improvement in the proposed control strategy. As per results, both controllers require bidirectional energy flow however there is a possibility that controller-2 can be optimized to work only with positive one directional energy flow.

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