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A comparison of WEC control strategies for a linear WEC model

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ABSTRACT

In this study, we employ a numerical model to compare the performance of a number of wave energy converter (WEC) control strategies. Each control strategy was evaluated on a single numerical model using sea states to represent a deployment site of the coast of Newport, OR. A number of metrics, ranging from power-flow characteristics to kinematics are employed to provide a comparison of each control strategy's performance.

1. INTRODUCTION

Work is currently underway to study the improvement of wave energy converter (WEC) performance through enhanced control system design. Controllers were selected to span the WEC control design space with the aim of building a more comprehensive understanding of different controller capabilities and requirements. Seven control strategies have been developed and applied on a numerical model of the selected WEC.

2. STUDY DEVICE & NUMERICAL MODEL

A WEC device test-bed was used to perform this study's control performance comparison. Figure 1 shows an illustration of the device, which will soon be tested in the Naval Surface Warfare Center, Carderock Division (NSWCCD) Maneuvering and Seakeeping (MASK) basin [1]. A numerical model, based on the formulation suggested by Cummins [2], has been developed to simulate the performance and dynamics of the test-bed WEC device [3, 4].

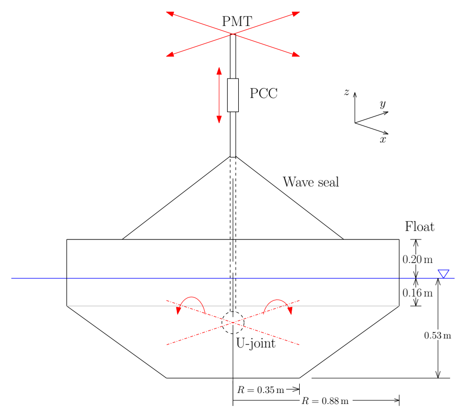

Figure 1: WEC device test-bed used for control comparison.

3. CONTROL STRATEGIES

3.1 Resistive Control

In resistive loading control the constant of proportionality between the force and velocity determines the 'resistance' offered, which is also the power absorption rate. Resistive control is the simplest feedback control strategy and that there is no reactive power; for these reasons, there are no special requirements for the PCC and no foreknowledge of the excitation force is required.

3.2 Model Predictive Control (MPC)

Model Predictive Control is an optimization based control strategy. It is primarily a feedforward strategy targeting both amplitude and phase implemented in a receding horizon fashion. The current state of the system is taken into account at every optimization step and hence there is a feedback loop present in which these states are passed directly to the optimization. The current implementation is valid for a single DOF system using deterministic and perfect wave prediction 8 seconds into the future.

3.3 Dynamic Programming (DP)

Dynamic programming is a useful mathematical technique for making a sequence of interrelated decisions. It provides a systematic procedure for determining the optimal combination of decisions [5].

There is no standard mathematical formulation of the dynamic programming problem; unlike other techniques like linear programming, DP is a general approach to problem solving. Hence the implementation of DP requires developing a tailored algorithm and equations for the particular application. In this WEC optimal control problem, the space-time domain is discretized. At each time node, the problem can be thought of as searching for the optimal control (decision) at that time such that the extracted energy is maximized over a given future horizon.

3.4 Shape-Based (SB) Control

The SB approach was recently developed for space trajectory optimization [6, 7, 8, 9], and has its roots in pseudo spectral optimal control [10, 11]. In pseudo spectral methods, the system dynamics are approximated by function series. The derivative of the state vector is approximated by the analytic derivative of the corresponding approximating function of the state.

This SB approach differs from the pseudo spectral optimal control approach in that it approximates only one state (buoy's vertical velocity) using Fourier series as opposed to approximating all the system's states and the control in pseudo spectral methods; hence the SB method is computationally faster. The SB approach benefits from a priori knowledge about the shape of one of the states to generate a good initial guess for the optimization process. In this development, the buoy's vertical velocity is selected to be the approximated state since the shape of the wave vertical velocity can be used as initial guess for the buoy's vertical velocity. In this development, a Fourier series expansion is used for approximation.

3.5 Linear Quadratic (LQ) Control

Linear Quadratic control is a pure feedback control strategy in which the feedback gain is obtained by solving an optimization problem. This is a feedback strategy targeting amplitude and phase. This strategy also includes a state estimator; the control signal is obtained by multiplying the estimated state by the gain matrix calculated offline. In the current implementation the entire state vector is being estimated, that is position, velocity and radiation states.

3.6 PD Version of CC Control (PDC3)

This control strategy suboptimally realizes Complex Conjugate (CC) control via a feedback strategy by creating a resonate generator. The theoretical underpinnings of complex conjugate control are fundamentally linear, and hence this is also linear. It targets both amplitude and phase through feedback that is constructed from individual frequency components that come from the excitation input signal. Each individual frequency uses a Proportional-Derivative (PD) control to provide both optimal resistive and reactive elements. By resonating each frequency component and summing them together the controller feedback effort that maximizes the amount of absorbed power is provided.

3.7 Latching

Latching is a type of switching control, the origins of which in wave energy conversion can be traced back to early studies on small heaving point absorber buoys with short natural resonant periods. The technique consisted of locking the buoy displacement until the approach of a crest (or a trough) and releasing it so it achieved full velocity at the crest (or trough) and then re-locking the displacement until the approach of a crest or trough. The presence or absence of a full-valued braking force was thus the only control required. A formal theoretical foundation was established in the mid-eighties through the work of Hoskin and Nichols [12]. In practice, the objective of latching control can be seen as to maximize the absorbed power by "keeping" the velocity of the buoy in phase with the excitation force. The strategy is most effective when the incoming wave has a period greater than the resonance period of the oscillating body because by holding the device in a latched state for a given amount of time, the net result can be understood as "shifting" the resonance period of the device to a larger value.

4. COMPARISON METHODOLOGY

Following IEC guidelines, a set of 10 irregular were selected to represent a deployment climate offshore of Newport, OR. In addition to these 10 sea-states which will define average annual metrics, 7 sea-states were also chosen to lie along constant steepness isolines. Figure 2 shows the irregular waves considered.

5. RESULTS

5.1 Tabular Comparison

Table 1 summarizes the relative performance of the assessed control strategies in irregular waves. All values are given as the average annual value for the quantity defined. Further, all units are metric and all results are shown in model scale. Quantities presented in Table 1 are defined as follows:

- **Power production characteristics** - Quantities relevant to power production.

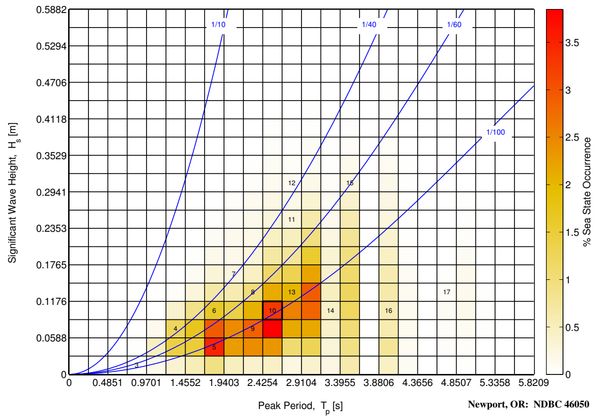

Figure 2: Irregular waves used to perform control strategy performance comparison. NOTE: sea-states 1,2 and 3 fall in the same bin.

- **Average power-in** - Average annual power used to motor the device (i.e. "reactive power").
- **Average power-net** - Average annual net power from the device.
- **Average energy-stored** - Average annual stored power (only necessary for reactive strategies). Storage is calculated as the amount of energy necessary to provide the reactive power required by the control strategy without absorbing power from other sources (e.g. power from the electrical network).
- **Power-in, peak†/RMS** - Peak power-in divided by RMS power-in.
- **Power-net, peak†/RMS** - Peak power-net divided by RMS power-net.
- **Total absolute power flow** - Indication of stress on PCC. Is is calculated as the annual weighted average of the absolute value of the power flowing through the PCC.

- **PCC requirement** - Quantities relevant to PCC capability requirements.
  - **PCC force, peak†** - Peak force applied by PCC.
  - **Slew rate requirements** - Average annual rate change in force applied by PCC (i.e. $\frac{\partial F}{\partial t}$)
  - **PCC force, RMS** - RMS of force applied by PCC.
  - **PCC Force, peak†/RMS** - Peak PCC force divided by RMS PCC force.
- **Mechanical loading** - Measures of requirements for device drive train structure (e.g., bearing surfaces, motor extension limits)
  - **Oscillation amplitude, peak†** - Peak of float vertical motion amplitude.
  - **Oscillation amplitude, peak†/RMS** - Peak of float vertical motion amplitude divided by RMS of float vertical motion amplitude.
  - **Oscillation velocity, peak†** - Peak of float vertical velocity.
  - **Oscillation velocity, peak†/RMS** - Peak of float vertical velocity divided by RMS of float vertical velocity.
  - **Oscillation acceleration, peak†** - Peak of float vertical velocity
  - **Oscillation acceleration, peak†/RMS** - Peak of float vertical acceleration divided by RMS of vertical acceleration.

†Here, the term "peak" refers to the 98$^{\text{th}}$ percentile of the identified response's peaks.

The control strategies are then divided into four main categories: the bounding cases, the cases that target phase (TP), the cases that target amplitude and phase with a predominantly feedback strategy (TAP-FB), and the cases that target amplitude and phase with a predominantly feedforward strategy (TAP-FF).

5.2 Sample Time-History

Figure 3a shows a sample time-history from select control strategies for the irregular sea-state 15 ($H_s = 0.32\,\text{m}$, $T_p = 3.6\,\text{s}$). It is interesting to note that all the control strategies attempt to improve the "phase matching" between velocity and excitation force, when compared to resistive control. The plots also show how the control strategies try to keep velocity in phase with excitation: latching locks the device in order to match the peaks of the velocity with the peaks of the excitation force while MPC and LQ force the device to follow excitation with a smoother profile, by using reactive power (Figure 3d), that is by accelerating the device by means of the actuator force. The smoother motion resulting from applying MPC and LQ can be observed also by looking at the time profiles of the position (Figure 3b) and the force exerted by the actuator (Figures 3c).

6. CONCLUSIONS

This study provides a comparison of a number of control strategies for simple 1-DOF WEC using a linear model. Future research is needed to expand on these strategies and re-evaluate their relative performance with updated models.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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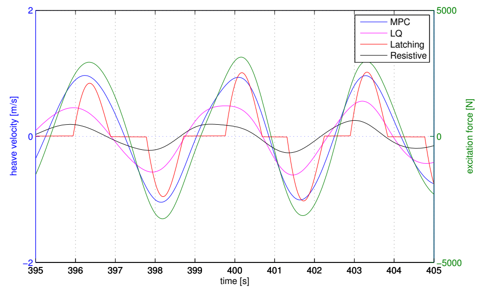
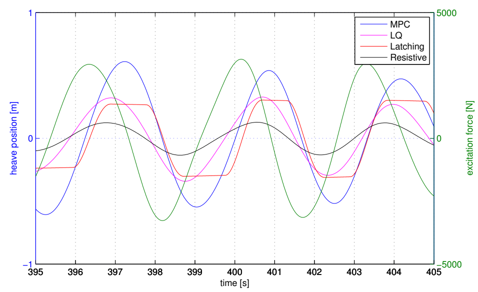
Table 1: Comparison of control strategy performance.

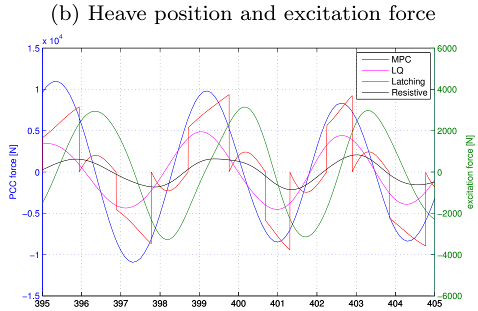
	Bounding cases		TP	TAP-FB		TAP-FF		
	Resistive	**CCC**	**Latching**	**LQG**	**PDC3**	**Linear MPC**	**DP**	**SB**
Power production characteristics								
Average power-in	0	279	0	46.5	45.8	98.8	374.8	39.0
Average power-net	15.5	52.5	28.8	39.8	25.5	46.1	38.4	22.6
Average energy-stored	0	251	0	27.5	42.9	76.4	332.9	23.8
Power-in, peak/RMS	0.0	5.8	0.0	5.6	5.1	5.6	5.4	4.3
Power-net, peak/RMS	7.3	38.8	6.2	14.3	17.3	20.2	60.1	16.2
Total absolute power flow	15.5	313.3	28.8	76.0	91.5	131.8	384.9	54.5
PCC requirements								
PCC force, peak	739	4312	2099	1970	1854	2653	5850	2500
Slew rate requirements	2.8 E+3	1.1 E+3	1.5 E+6	5.9 E+3	4.5 E+3	7.0 E+3	1.2 E+3	5.5 E+3
PCC force, RMS	315	2367	923	915	1086	1401	2730	1010
PCC Force, peak/RMS	2.35	1.82	2.27	2.15	1.71	1.89	2.14	2.49
Mechanical loading								
Oscillation amplitude, peak	0.06	0.25	0.10	0.14	0.11	0.17	0.28	0.12
Oscillation amplitude, peak/RMS	2.52	1.97	2.05	2.27	1.89	2.09	1.99	2.52
Oscillation velocity, peak	0.14	0.47	0.30	0.31	0.22	0.35	0.50	0.22
Oscillation velocity, peak/RMS	2.63	2.20	2.77	2.43	2.30	2.33	2.17	2.6
Oscillation acceleration, peak	0.39	1.02	0.45	0.78	0.22	0.46	1.27	0.64
Oscillation acceleration, peak/RMS	2.70	2.39	1.21	2.58	2.30	1.95	2.36	2.56



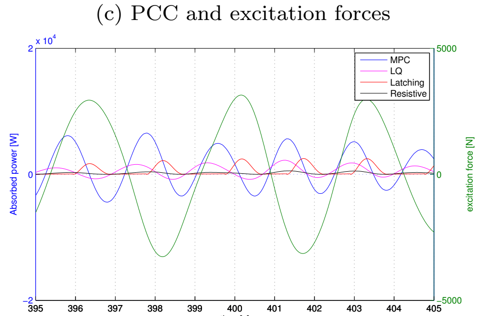
(a) Heave velocities and excitation force



(b) Heave position and excitation force



(c) PCC and excitation forces



(d) Instantaneous absorbed power and excitation force

Figure 3: Sample time histories from irregular sea-state 15 ($H_s = 0.32\,\mathrm{m}$, $T_p = 3.6\,\mathrm{s}$)

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