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Optimizing ocean-wave energy extraction of a dual coaxial-cylinder WEC using nonlinear model predictive control

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HIGHLIGHTS

- Constrained NMPC is applied to wave energy converter to maximize energy extraction.
- The conversion efficiency of the permanent magnet linear generator is added in NMPC.
- Time-dependent and discontinuous generator damping is suggested as control parameter.
- Active control improves absorption bandwidth and peak value of the WEC.

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ABSTRACT

Active control based on nonlinear model predictive control (NMPC) methodology is applied to a candidate but realistic dual coaxial-cylinder wave-energy extractor system with the objective of maximizing energy capture over a range of incident ocean-wave conditions. The extractor consists of an outer cylinder (floater) moving relative to a tension-tethered inner cylinder, driving a permanent-magnet linear generator (PMLG) to acquire power take-off (PTO). The floater dynamics is solved in the time domain with the NMPC to constrain maximum floater motion and simultaneously incorporating the PMLG damping capability. The numerical model of the coupled floater and PTO dynamics is formulated in the state-space representation. The mechanical to electrical conversion efficiency of the PMLG, which was experimentally determined as a function of its power-extraction damping, is considered in the numerical simulation. The NMPC process yields a time-varying profile for the generator damping as the control strategy. Simulation results indicate strongly time-dependent and discontinuous generator-damping requirements for both regular and irregular incident-wave scenarios. However, the NMPC-controlled system significantly outperforms a passive-control, constant-damping system by exhibiting higher peak values of energy-extraction and a broader capturing bandwidth, thus confirming the feasibility and success of the control strategy.

1. Introduction

A model-scale point-absorber type wave-energy converter (WEC) was developed and tested in [1]. The WEC system consists of an outer toroidal floater sliding vertically along a tension-tethered inner cylinder and a permanent-magnet linear generator (PMLG) as the power take-off (PTO) device. A specially modified floater shape significantly reduced viscous losses, and optimized operating conditions for the PMLG was found to enhance the overall energy extraction efficiency. This was accomplished without incorporating an active control system [1]. However, the performance of the dual coaxial-cylinder WEC noticeably decreased when it operated outside of its resonance frequency. This drawback can be potentially overcome by incorporating an active control, because it has the ability to increase the peak capture width and simultaneously widen the bandwidth.

Many control strategies for improving WEC energy extraction in arbitrary sea states have been studied, including well-known control methods such as reactive control and latching control [2–4]. However, these methods may not be appropriate for real-time control because they are based on frequency domain analyses. A new control strategy, model predictive control (MPC), enables the optimization of energy capture in real-time under certain given constraints, such as motion limitation and device capability [5–13]. Because MPC considers constraints in a control scheme, a MPC

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controlled-WEC system exhibits better performance than other adaptive control strategies [10]. The investigations mentioned previously have been optimized velocity and reaction force from the PTO, which allows the problem to be solved as a convex quadratic programming (QP) that has a fast execution algorithm. Moreover, nonlinear model predictive control (NMPC) was introduced to account for nonlinear effects from mooring lines [14] or a time-varying PTO damping value [15,16]. In particular, the work referenced in [16] formulated the PTO force as a function of instantaneous damping and floater velocity. The study focused on solving time-varying PMLG damping as a controllable parameter without incorporating active elements for reactive force control. This can be a more practical approach to controlling the PMLG, and it prevents feeding energy back into the waves. This strategy showed the PMLG damping to be a bang-bang type control sequence. Aside from theoretical simulations, the effectiveness of the implemented NMPC was experimentally validated by setting an electrical on–off activation period on the PMLG [17].

The current study is mainly based on the previously constrained NMPC work conducted by [16]. However, previous research on control strategies applicable to the WEC was mainly aimed at maximizing power absorption from incoming waves. In reality, the mechanical to electrical power conversion efficiency of the PTO is also a critical factor in determining the useful electrical power output [18]. Thus, an actual electrical conversion efficiency module for the PMLG, which is experimentally determined as a function of PMLG damping, is now inserted into the control algorithm so as to maximize useful electrical power output.

One of the difficulties in wave-energy extraction is the wave-forecasting problem, which is still a challenging and untapped problem. Wave climate forecasting in medium and long term certainly have a significant role to play in deployment of WEC system [19–22]. However, for real-time control of the WEC system, prediction of the incident-wave field for short term is an essential part of the control process due to the non-causal nature of the wave-exciting force. Spatial measurements using radar [23] or a LIDAR [24] can make wave predictions in a real environment. Several forecasting models have also been presented based on time series such as deterministic wave prediction [25,26], extended Kalman filter, auto regressive, and neural network [27,28]. In this study, we assume that prediction of incident-wave elevation is perfect, and so wave-exciting force is a known factor.

As previously mentioned, the goal of this study is to investigate the benefits of NMPC technology by incorporating the electrical conversion efficiency of the PMLG for the model-scale dual coaxial-cylinder WEC system. In addition, we aimed to solve this non-convex problem directly in order to determine the optimal generator damping value in a time series subject to the allowable damping capacity and maximum motion limitation. The performances of the dual coaxial-cylinder WEC system with ideal or actual electrical conversion efficiency in an objective function are compared to each other and to that of a constant PTO damping value, which is the passive system.

2. Theoretical modeling of the coupled system of PTO and floater motion

To implement the NMPC methodology on the WEC, time-domain analysis, instead of frequency-domain analysis, is needed to allow for a controller input on a wave-by-wave basis. This section reviews the floater dynamics in the time domain for the dual coaxial-cylinder WEC, which is coupled with the PMLG, under linear-theory assumptions. The conversion of the time-domain model into the more efficient state-space representation is also explained; see [29–31].

2.1. Floater dynamics in time domain

Fig. 1 shows the dual coaxial-cylinder system considered in this work. An inner cylinder is tension-moored down, while the outer cylinder (or the toroidal floater) is heaving. The wedge-shaped bottom of the floater, adapted from The Berkeley Wedge[1] [32], has improved performance by significantly reducing viscous losses [1]. Wave energy is extracted from the relative heave motion between the cylinders using the PMLG PTO that links the two cylinders together. The UC-Berkeley in-house built PMLG consists of a magnet array translator, which is connected to the heaving floater and a stator, which consists of two sets of coils installed inside of the inner cylinder, as shown in Fig. 2. Electrical current is induced in the coils owing to the relative motion between the translator and the stator. The electrical power is captured at the applied load resistor, which is connected to the coils. Since the inner cylinder is effectively stationary in the vertical direction by having excessive buoyancy, only the heave motion of the floater is needed to formulate the system dynamics (see [33]):

$$m_2\ddot{\zeta}_3(t) = F_h(t) + F_r(t) + F_e(t) + F_g(t) \tag{1}$$

where m_2, $\ddot{\zeta}_3(t)$ are the displaced mass and acceleration of the floater in heave. The forces, $F_h(t)$, $F_r(t)$, $F_e(t)$ and $F_g(t)$, are the hydrostatic restoring force, wave-radiation force associated with body motion, wave-exciting force induced by waves, and generator force from the PMLG, respectively.

The hydrostatic restoring force against the floater displacement $\zeta_3(t)$ is given by

$$F_h(t) = -\rho g A_{wp}\zeta_3(t) \tag{2}$$

with ρ, g, and A_{wp} being the fluid density, gravitational acceleration, and water-plane area of the floater, respectively.

The wave-radiation force in the time domain from [34,35] can be expressed as

$$F_r(t) = -\mu_{33}(\infty)\ddot{\zeta}_3(t) - \int_0^t K_r(t-\tau)\dot{\zeta}_3(t)d\tau \tag{3}$$

where $\mu_{33}(\infty)$ is the added mass at infinite frequency. The convolution integral represents the fluid memory effect where K_r is the causal radiation impulse response or retardation function. It can be evaluated by performing the inverse Fourier transform of either the added mass μ_{33} or wave damping λ_{33} in the frequency domain as follows:

$$\begin{aligned} K_r(t) &= -\frac{2}{\pi}\int_0^\infty \sigma[\mu_{33}(\sigma) - \mu_{33}(\infty)]\sin\sigma t d\sigma \\ &= \frac{2}{\pi}\int_0^\infty [\lambda_{33}(\sigma) - \lambda_{33}(\infty)]\cos\sigma t d\sigma \end{aligned} \tag{4}$$

We note that the wave damping at infinite frequency vanishes, i.e., $\lambda_{33}(\infty) = 0$.

The wave-exciting force can be expressed as

$$F_e(t) = \int_{-\infty}^{\infty} K_e(t-\tau)\eta(0,t)d\tau \tag{5}$$

where $\eta(0,t)$ is the incident-wave elevation at the cylinder axis. The impulse response function K_e can be obtained from the inverse Fourier transform of the complex wave-exciting force amplitude per unit incident-wave amplitude $X_3 = |X_3|e^{i\delta}$ with δ being the phase of the force relative to the wave elevation:

$$K_e(t) = \frac{1}{2\pi}\Re\left\{\int_{-\infty}^{\infty} X_3(\sigma)e^{i\sigma t}d\sigma\right\} \tag{6}$$

[1] Energy-capturing floating breakwater, USPTO #9,416,766 <http://pdfpiw.uspto.gov/.piw?Docid=09416766>.