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Model predictive control of sea wave energy converters – Part II: The case of an array of devices

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ABSTRACT

This paper addresses model predictive control (MPC) of highly-coupled clusters of sea wave energy converters (WECs). Since each WEC is not only a wave absorber but also a wave generator, the motion of each WEC can be affected by the waves generated by its adjacent WECs when they are close to each other. A distributed MPC strategy is developed to maximize the energy output of the whole array and guarantee the safe operation of all the WECs with a reasonable computational load. The system for an array is partitioned into subsystems and each subsystem is controlled by a local MPC controller. The local MPC controllers run cooperatively by transmitting information to each other. Within one sampling period, each MPC controller performs optimizations iteratively so that a global optimization for the whole array can be approximated. The computational burden for the whole array is also distributed to the local controllers. A numerical simulation demonstrates the efficacy of the proposed control strategy. For the WECs operating under constraints explored, it is found that the optimized power output is an increasing function of degree of WEC–WEC coupling. Increases in power of up to 20% were achieved using realistic ranges of parameters with respect to the uncoupled case.

1. Introduction

A wave farm usually contains a number of sea wave energy converters (WECs) deployed within a region. The control targets for a farm involve maximizing energy generation, smoothing the power output for a friendly connection to a grid, reducing hardware cost, and maintaining the safe operation of the devices, etc. Most of the WECs in a farm are normally installed close to each other due to practical considerations, such as space limit, cable deployment, electricity delivery and maintenance. Since each WEC is not only a wave absorber but also a wave generator, the proximity of the WECs means that the motion of each WEC is affected by the waves generated by adjacent ones. This feature clearly complicates both the modelling and the control of the wave farm. Furthermore, the computational cost of control of the whole array can be intractable for real time operations. To address this problem, a hierarchical control system architecture can be employed, in which the overall array is partitioned first into sub-arrays, each of which contains a modest number of neighbouring devices. Thus to a first approximation, we assume strong interactions only occur within sub-arrays, while the sub-array to sub-array interactions are weak. It is then possible to treat each sub-array as a single system from a control perspective that is weakly coupled to similar adjacent ones. If necessary this process can be taken further with the weakly interacting sub-arrays themselves combined into larger scale entities and so on over multiple scales allowing a hierarchical layered control system.

This paper addresses the modelling and control of the modest-sized, highly-coupled arrays of WECs at the lower level of the hierarchical structure. The goal is to maximize the energy output for such an array of devices while guaranteeing their safe operation. Simpler, weak coupling versions, of the same approach can then be applied at each layer of the hierarchical system. The problem of linking the various layers into a multi-scale distributed control system will be the subject of a subsequent publication. In Ref. [1], a model predictive control (MPC) strategy is proposed for a single sea WEC to achieve the maximum energy output while maintaining its safe operation through the satisfaction of certain constraints. However, a direct application of the MPC strategy developed in Ref. [1] to an array of WECs coupled via WEC waves rapidly becomes computationally unrealistic even for the modest sized arrays of interest here. Such direct application of MPC to a whole system is frequently termed centralized MPC. To tackle this problem, a

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distributed MPC strategy is developed for the control of modest-sized strongly interacting arrays of WECs.

Distributed MPC has been developed in recent years to resolve constrained optimal control problems of large networked systems. The main benefits of using distributed MPC are that it can not only distribute the computational burden to each local controller, but also deliver approximately optimal solution for the whole system. There are two branches of distributed MPC strategies: communication-based distributed MPC, e.g. Ref. [2], and coordination-based distributed MPC, e.g. Ref. [3]. Both types of distributed MPC incorporate the coupling interactions among the subsystems. The main difference between them is that the communication-based distributed MPC optimizes the local objective function separately, while the coordination-based distributed MPC optimizes the overall objective function so that the optimal solution can converge to that of the centralized MPC. This paper adopts the coordination-based distributed MPC approach, which can guarantee that its optimal solution can approximate that of centralized MPC after a limit number of iterations.

In this paper, a distributed MPC algorithm is tailored for the specific requirements of the control of an array of WECs. The objective function for each individual WEC takes the same form as that adopted for the MPC of a single WEC proposed in Ref. [1]. This objective function makes the distributed MPC developed for WEC array different from most existing distributed MPC algorithms, which are mainly employed for tracking or regulation control problems [2]. A detailed model for the application of distributed MPC scheme is developed for an array of up to seven devices; however, for simplicity, numerical simulations are restricted to an array of only two WECs in order to provide ready comparisons against various alternative schemes. Numerical simulations show the following significant results. Firstly, the array controlled by distributed MPC can generate almost the same amount of energy as that controlled by a centralized MPC controller, while the computational burden of each controller does not significantly increase with the number of WECs. Secondly, if each WEC is controlled by an MPC controller without considering the WEC generated waves, reduced energy output and constraint violation can result, which demonstrates the invalidity of the application of the MPC strategy independently for each WEC. Thirdly, if the WECs are assumed to be placed far away from each other so that the influence from the WEC generated waves is insignificant, then output energy of the WECs controlled by local MPC controllers is smaller than that of the WECs when they are close enough so that the generated waves take effect; thus at least for the limited examples explored, when controlling WECs subject to constraints, the economic necessity of placing the WECs close to each other to save space and layout cost, can also result in increased energy output.

In addition to dynamical models for the WECs and the wave–wave field the MPC scheme also requires some form of deterministic sea wave prediction algorithm (DSWP) [4–10] and far field wave data (a standard multi-directional wave model using Pierson–Moskowitz wave spectra was employed).

The focus here is not on the details of the specific WECs involved, rather on the far wider control issues. Thus for the sake of clarity, relatively simplified generic WEC models are employed, similar to those used in Ref. [1]. However given the approach employed, here the incorporation of far more detailed WEC dynamics, particular to a specific technology, is a very straightforward process.

The structure of this paper is as follows. Modelling issues are addressed in Section 2. Three candidate MPC control strategies for the control of an array of WECs are introduced in Section 3. Section 4 focuses on distributed MPC algorithm development. Finally, simulation results are shown in Section 5 to demonstrate the efficacy of the proposed distributed MPC.

2. Model establishment for an array of WECs

Consider an array of m WECs, and suppose the motion of any WEC i can be influenced by the waves generated by the remaining $m-1$ WECs. WEC i can be described by a discrete time state space model

$$x_i(k+1) = A_i x_i(k) + B_{ui} u_i(k) + B_{wi}\left(w_{f,i}(k) + \sum_{l\neq i}^{m-1} w_{i,l}(k)\right) \quad (1a)$$

$$y_i(k) = C_i x_i(k) \quad (1b)$$

$$z_i(k) = C_{z,i} x_i(k) \quad (1c)$$

Here y_i, x_i and u_i are the heave motion, state variable and control signal respectively. z_i represents a constrained state variable (constrained for safety reasons), $w_{f,i}$ is time derivative of the vertical displacement of the far field (external) wave as propagated to WEC i, which is required to be predicted by the DSWP algorithm. $w_{i,l}$ represents the time derivative of the vertical displacement of the WEC wave at WEC i that was generated by WEC l. The quantity $w_{i,l}$ is dependent on two factors: a) the locations of the WECs i and l, and b) the heave motion of WEC l. There are two approaches to obtaining $w_{i,l}$. One is via a first-principle based fluid mechanical model, in general, including nonlinearities. The other more straightforward, and perhaps more practical method, is to ignore the nonlinearities between $w_{i,l}$ and y_l, so that the dynamics can be derived using standard linear system identification methods based on experimental data. In the latter case, this relation can be expressed in the frequency domain

$$\widehat{W}_{i,l} = \widehat{H}_{i,l}\widehat{Y}_l, \quad (2)$$

where $\widehat{H}_{i,l}$ represents the frequency response function between the internal wave $\widehat{W}_{i,l}$ and the motion of WEC l, $\widehat{Y}_l$, which are the Fourier transforms of w_i, and y_l respectively.

For numerical simulation, we establish the fluid mechanical model as in Ref. [11]

$$\widehat{H}_{i,l} = j\omega\sqrt{\frac{\pi|\omega|^4}{8g^3}}a^2\frac{1}{\sqrt{d_{i,l}}}e^{-j\left\{\frac{\omega^2}{g}d_{i,l}+\frac{3\pi}{4}\right\}} \quad (3)$$

Here $d_{i,l}$ is the distance between the locations of the WEC l generating wave and the WEC i under consideration; a is the diameter of the float; $g = 9.81\ \mathrm{m/s^2}$ is the gravitational constant. It is assumed for the dynamics model (3) that $k(\omega)a \ll 1$, where $k(\omega) \approx \omega^2/g$ is the wave number for deep water. Note that care should be taken for equation (3) to ensure the correct symmetry properties such that the appropriate Fourier inverses stay real.

For $\omega > 0$, (3) can be equivalently written as

$$\widehat{H}_{i,l} = A(\omega)e^{-j\phi(\omega)} \quad (4)$$

with

$$A(\omega) = \omega^3 a^2\sqrt{\frac{\pi}{8g^3 d_{i,l}}} \quad (5)$$

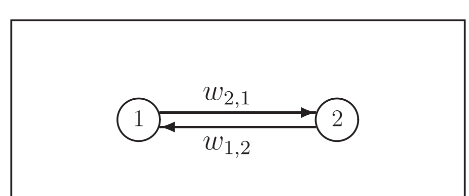

Fig. 1. The interaction between 2 WECs.