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Towards realistic non-linear receding-horizon spectral control of wave energy converters

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ABSTRACT

Non-linear, power-maximising control of wave energy converters (WECs) can be achieved within a receding-horizon control framework, whereby an upper loop calculates a reference trajectory in real-time, ensuring maximal power absorption under operational constraints, while a tracking loop drives the device along the generated trajectory. This paper articulates the four fundamental components of such a control strategy: *reference generation* calculations, *tracking loop*, and wave excitation *estimation* and *forecasting*. The upper-loop optimisation problem is efficiently solved through a Fourier spectral method, taking into account non-linear dynamics and constraints. Tracking is achieved through a linear state feedback, combined with a non-linear feed-forward term. An extended Kalman filter is used for excitation force estimation, based on noisy WEC position and acceleration measurements. Finally, wave excitation forecasts are based on a linear predictor, whose coefficients are derived from the wave spectrum (on a sea-state-by-sea-state basis). The practical issues and trade-offs, which arise when the four components listed above are combined within a practical implementation, are investigated by means of realistic numerical simulations, using a WEC model comprising a combination of static and velocity-dependent non-linear forces.

1. Introduction

Power-maximising control has the potential to significantly improve the economic competitiveness of WECs (Ringwood, Bacelli, & Fusco, 2014). However, the practical implementation of real-time WEC control faces significant technical barriers, including the following:

- Due, in particular, to radiation force memory effects, the optimal control law for WEC power maximisation is, in general, non-causal, i.e. the knowledge of future wave excitation is required (Falnes, 2002);
- As stressed in Penalba Retes, Mérigaud, Gilloteaux, and Ringwood (2015), hydrodynamic non-linearities tend to be highlighted under actively controlled conditions compared to, for example, passive linear damping. In addition, non-linear dynamics may also stem from the characteristics of the power take-off (PTO) machinery or from other physical components, such as the mooring system. Therefore, a realistic WEC control system should be able to accommodate non-linear effects where appropriate;
- Operational constraints must be taken into account, to prevent the WEC or PTO system from exceeding its physical limitations.

Receding-horizon control provides a relevant framework to address these challenges, via the following characteristics:

- Taking into account wave excitation forecasts over a finite time horizon, the optimal control force or WEC trajectory is calculated in real time, and updated as new wave input forecasts become available (Gieske, 2007);
- The optimal control force or trajectory calculation, which is in essence an optimisation problem, can take into account non-linear WEC dynamics and operational constraints.

The general receding-horizon WEC control philosophy is illustrated in Fig. 1, showing the reference WEC velocity (optimal velocity prediction) updated at two consecutive time steps. The true optimal velocity is the one which would maximise power absorption, if the true wave excitation signal was perfectly known over an infinite time horizon. As illustrated in the figure, the optimal velocity, which is calculated within a finite-horizon window, differs from the true optimal velocity.

Due to the consecutive updates of the reference trajectory or control input, a receding-horizon control scheme involves sequential use of an efficient optimisation algorithm. Regardless of whether such an algorithm generates a reference trajectory, control force, or both, it will be termed 'reference generator' (RG).

Receding-horizon WEC control strategies are reviewed in Faedo, Olaya, and Ringwood (2017). The majority of studies use linear or non-linear model predictive control (MPC) as a RG, where the variables

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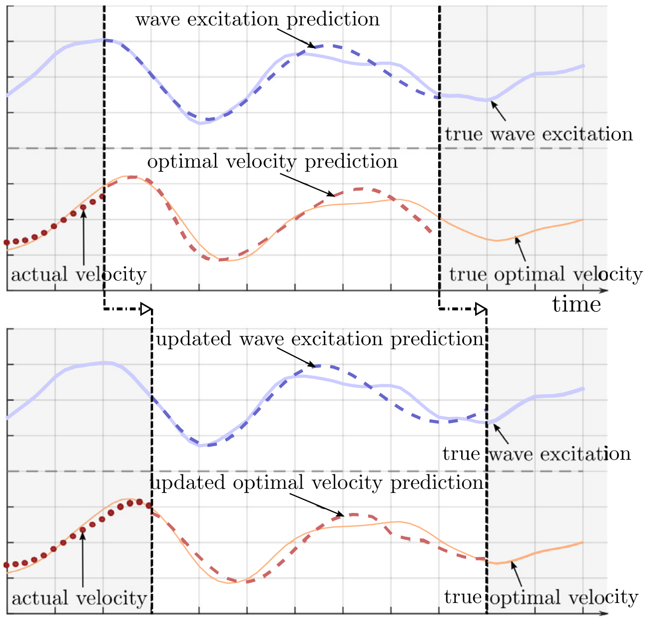

Fig. 1. Receding-horizon WEC control philosophy — optimal velocity trajectory updates at two consecutive time steps. Solid blue (resp. orange): true wave excitation (resp. true optimal WEC trajectory). Dashed blue (resp. red): predicted wave excitation (resp. predicted optimal WEC trajectory). Dotted red: actual trajectory followed by the WEC (trying to track the predicted optimal trajectory).

(state variables, control input) are discretised in time, and the RG yields a sequence of control inputs over the receding time window. The computational difficulties associated with a real-time implementation of MPC are highlighted by a number of authors (for example Li, Weiss, Mueller, Townley, & Belmont, 2012, Richter, Magana, Sawodny, & Brekken, 2013, Tona, Nguyen, Sabiron, & Creff, 2015), and tend to reduce the time-horizon which can be effectively used as a receding window length.

Alternatively, recent years have witnessed the development of spectral (S) and pseudo-spectral (PS) techniques for WEC control applications (Faedo et al., 2017) which, instead of resorting to a time discretisation, describe the optimisation variables using sets of basis functions of various kinds. Fig. 2 shows several examples of such basis functions, in comparison to the (more usual) time discretisation (i.e. zero-order hold, or ZOH, in the figure), for the approximation of a signal f which could be, for example, the wave excitation force contained within the receding window. As can be seen in Fig. 2b, all other methods require less basis functions than ZOH for the same level of signal fidelity. This is a well-known property of spectral methods: for a sufficiently smooth target function, the accuracy of the spectral approximation improves more than linearly with the number of basis functions (Boyd, 2001).

S and PS methods have shown some promise in efficiently solving the WEC control problem (Bacelli, Genest, & Ringwood, 2015; Bacelli & Ringwood, 2014; Genest & Ringwood, 2017; Li, 2015; Mérigaud & Ringwood, 0000a, 2017). In addition to the computational benefits resulting from a potentially smaller number of variables involved in the RG optimisation (since, as seen in Fig. 2b, less functions are required to accurately describe input signals and variables), spectral and pseudo-spectral techniques also provide a natural way to modulate the degree of smoothness of reference trajectories or control inputs.

In particular, assuming a Fourier spectral control (FSC) formulation – i.e. using harmonic sinusoids as a functional basis – (Mérigaud & Ringwood, 0000a) details how the solution speed of the FSC problem can be significantly improved by explicit computation of the gradient and Hessian of the objective function. However, such a functional basis assumes periodicity of the wave input, while the finite-length wave excitation signal contained in the receding window is, in general, non-periodic

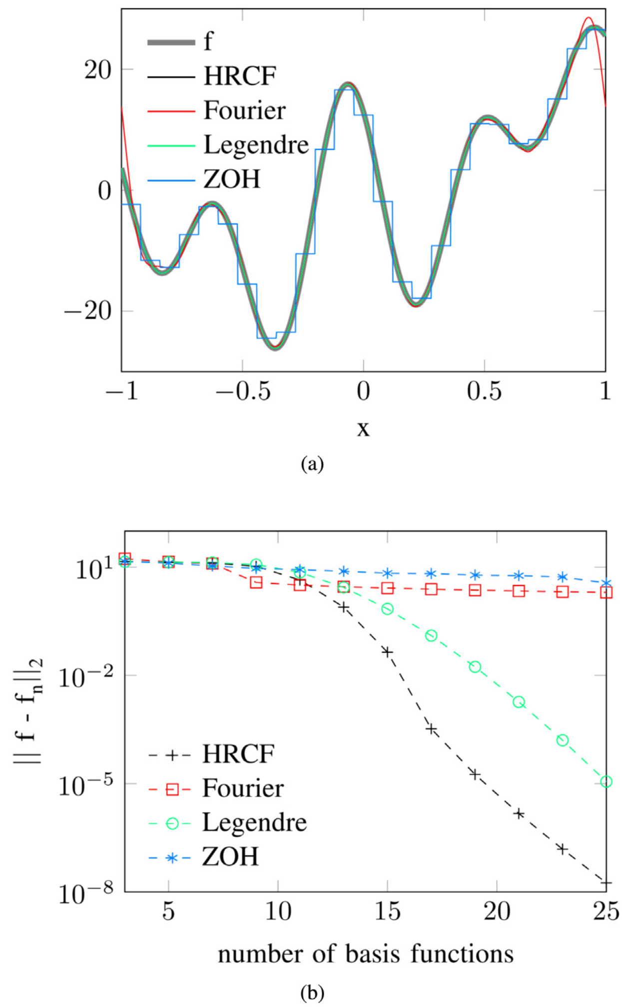

Fig. 2. (a) shows the approximation of a signal f using different sets of orthogonal functions — reproduced from (Genest & Ringwood, 2017). (b) shows the approximation error as a function of the number of basis functions. HRCF: half-range Chebyshev Fourier basis functions; Fourier: Fourier basis functions; Legendre: Legendre polynomials; ZOH: zero-order hold.

(in the example of Fig. 2, the Fourier basis yields larger approximation errors than HRCF and Legendre polynomials). Nevertheless, applying a windowing function to the finite-length wave excitation signal, spanned by the receding horizon, prior to the corresponding control calculation, can make the Fourier description appropriate (Auger, Mérigaud, & Ringwood, 0000). In this paper, a FSC solution method, applied to the windowed wave signal, is used as the RG optimisation algorithm. More detail is given in Section 3 about the FSC solution technique, and its practical implementation in a receding-horizon fashion.

In a receding-horizon WEC control implementation, as mentioned above, the RG calculations may directly provide the required control input (Faedo et al., 2017) (typically, the PTO force). Alternatively, the RG may compute a reference WEC trajectory (in terms of WEC position and/or velocity), which is subsequently followed by means of a tracking loop (TL), making use of feedback control (Fusco & Ringwood, 2014). The latter indirect approach could offer several potential benefits:

- It has been highlighted in Mérigaud and Ringwood (2017) and Nielsen, Zhou, Kramer, Basu, and Zhang (2013) that, under some conditions, calculations of the optimal WEC trajectory are independent of inertial terms and (linear or non-linear) static forces. Therefore, RG calculations naturally exhibit robustness to modelling errors in inertial and static terms, and, by ignoring such modelling terms where appropriate, may be made more efficient.