A study on Prediction Requirements in time-domain Control of Wave Energy Converters ⋆

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Abstract: Wave energy converters (WECs) based on oscillating bodies or oscillating water columns would earn huge benefits from a time-domain control on a wave by wave basis. Such a control would allow efficient energy extraction over a wider range of frequencies than what could possibly be achieved when no real-time control is adopted, thus increasing the economical attractiveness of the WECs. Almost every control strategy that showed some potential, however, suffers from the problem that future knowledge of the incident wave elevation, or wave excitation force, is required. In this paper a general control framework for oscillating WECs is presented and a methodology to understand and quantify the wave excitation force prediction requirements, along with the achievable prediction accuracy, is discussed. The two features are compared against each other and linked to the dynamic characteristics of a device. Along with the qualitative discussion, the methodology is applied to some heaving cylinders when reactive control and linear passive control are applied, under different sea conditions.

Keywords: Wave energy, controller constraints and structure, time series forecasting.

1. INTRODUCTION

The principle of most wave energy conversion systems is based on the relative oscillation between bodies or on oscillating pressure distributions within fixed or moving chambers. Such Wave Energy Converters (WECs) act as resonators with respect to the incident wave elevation and offer efficient power absorption only over a restricted range of frequencies around the resonance. It is crucial for the improvement of the economic viability of WECs, therefore, the design of a proper control system which is able to alter the oscillator dynamics such that the efficient energy conversion occurs over a wide range of wave conditions, as highlighted in Korde (2000).

The traditional approach to WECs control consists of frequency domain relationships which can be used to tune the device to the predominant wave frequency of the occurring wave conditions, as extensively reviewed in Korde (2000), Falnes (2002). Frequency domain relationships, however, do not allow, in general, a real-time control on a wave by wave basis, which would have the potential to significantly raise the productivity of a device. A conversion in the time domain produces, however, a non-realisable control, where non-causal impulse response functions require future knowledge of the incident wave elevation or of any other effect of it on the system (excitation force, oscillating velocity, pressure distribution,...), as discussed in Falnes (1996) and Fusco (2009).

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Therefore, a truly effective time-domain control of an oscillating system for wave power production cannot disregard the problem of short-term prediction (typical forecasting horizons of some seconds) of the incident wave elevation, or of any other effect of it on the system. In this study a methodology to analyse, qualitatively and quantitatively, the problem of prediction in the time-domain control of a simple floating body in heaving mode, is presented, where the prediction is focused on the excitation force.

In particular, section 2 presents a general time-domain control framework, to which most of the current control approaches can be reduced, and specifies it for our test case of a floating cylinder in heaving mode. The prediction problem is then dealt with in section 3, with the definition of the requiremets and the analysis of the achievable prediction, based on the results presented in Fusco and Ringwood (2009, 2010). The results and the conclusion of this study are outlined in sections 4 and 5.

2. TIME-DOMAIN CONTROL OF WECS

The dynamics of a floating body moving in heaving direction, under the influence of the wave exciting force $f_{ex}(t)$ and of a controllable load force $f_u(t)$, with absence of friction and viscous forces, can be described by the following linear integro-differential equation:

$$m\dot{v}(t) + \int_0^t k(t-\tau)v(\tau)d\tau + K_s \int_0^t v(\tau)d\tau = f_{ex}(t) + f_u(t), \quad (1)$$

where $v(t)$ is the heaving velocity, $k(t)$ is the causal impulse response of the radiation and K_s is the buoyancy coefficient. Note that it was supposed $v(t) = 0$ for $t < 0$.

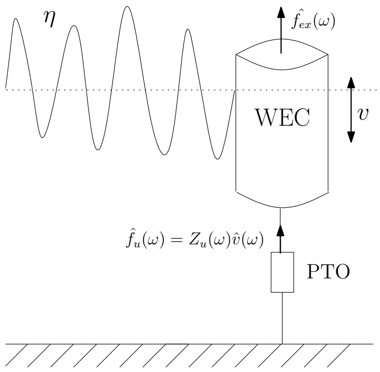

Fig. 1. WEC consisting of a cylinder oscillating in heaving mode.

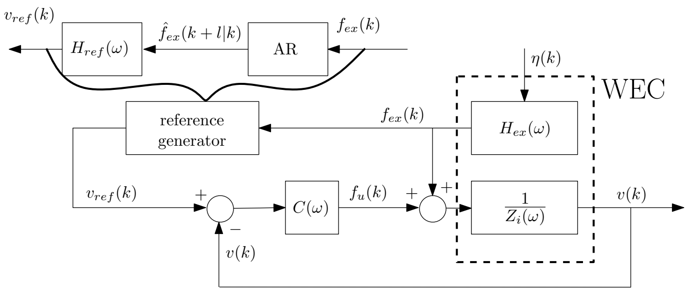

Fig. 2. Time domain control of oscillating Wave Energy Converter (WEC)

In the frequency domain, for $\omega \neq 0$, the model in (1) becomes:

$$\left\{ j\omega \left[m + m_a(\omega) + m_\infty - \frac{K_s}{\omega^2} \right] + \mu(\omega) \right\} \hat{v}(\omega) = \hat{f}_{ex}(\omega) + \hat{f}_u(\omega), \quad (2)$$

where the notation $\hat{x}(\omega)$ indicates the Fourier transform of the signal $x(t)$, $\hat{x}(\omega) = \mathscr{F}\{x(t)\}$. The transfer function of the radiation has been decomposed as:

$$K(\omega) = \mathscr{F}\{k(t)\} \triangleq \mu(\omega) + \jmath\omega[m_a(\omega) + m_\infty], \quad (3)$$

where $\mu(\omega)$ is the radiation resistance, $m_a(\omega)$ is the added mass and m_∞ is the mass at infinite frequency. Introducing the intrinsic mechanical impedance $Z_i(\omega)$:

$$Z_i(\omega) = \mu(\omega) + j\omega \left[m + m_a(\omega) + m_\infty - \frac{K_s}{\omega^2} \right], \quad (4)$$

the frequency domain model in (2) can be simplified to:

$$Z_i(\omega)\hat{v}(\omega) = \hat{f}_{ex}(\omega) + \hat{f}_u(\omega) \quad (5)$$

As shown in Fig. 1, the oscillating dynamics of the system can be controlled through a power takeoff (PTO) mechanism, that we assume able to realise any load impedance $Z_u(\omega)$, such that:

$$\hat{f}_u(\omega) = Z_u(\omega)\hat{v}(\omega) \quad (6)$$

In this case relative motion with respect to the sea bottom is considered, without loss of generality.

It can be shown, Falnes (2002), that maximum power absorption at the load occurs under the condition

$$\hat{f}_u^{(1)}(\omega) = -Z_i^*(\omega)\hat{v}(\omega) \quad \Leftrightarrow \quad Z_u^{(1)}(\omega) = -Z_i^*(\omega), \quad (7)$$

where the notation * indicates the complex-conjugate. This condition is named *reactive* or *complex-conjugate* control. Note that the reactive part of $Z_i(\omega)$ requires that the load injects some power into the system for parts of the cycle, which makes the potential of this approach less attractive in case of inefficiencies in the bi-directional power flow.

With the constraints of a passive load, and of a linear relationship between the load force and the oscillating velocity, the maximum power absorption occurs when:

$$\hat{f}_u^{(2)}(\omega) = -|Z_i(\omega)|\hat{v}(\omega) \quad \Leftrightarrow \quad Z_u^{(2)}(\omega) = -|Z_i(\omega)|, \quad (8)$$

but this maximum is much lower than the one achievable through reactive control.

Relationships (7) and (8) could be converted into the time domain and used for real-time tuning of the load force $f_u(t)$. The resultant impulse response functions, however, are noncausal, so that prediction of the oscillation velocity is required. This direct approach was proposed in Korde (1999) and Korde (2000) and it is our opinion that it suffers from two main complications: it is a feed-forward approach so that it does not offer the flexibility of a feed-back control loop to deal with the unavoidable prediction errors; the variable to predict, oscillation velocity, is dependant on the control and on the system dynamics, so that the prediction problem can not be dealt with separately from the control.

An alternative control framework is proposed here, as from Falnes (2002), where an equivalent of optimal relationships (7) and (8) is utilised to generate a reference oscillation velocity, imposed on the system through a standard feedback, as in Fig. 2. In particular, the reference generator would realise an approximation, by means of a prediction of the excitation force, of the following non-causal relationships, equivalent to (7) and (8):

$$\hat{v}_{ref}^{(1)}(\omega) = \frac{\hat{f}_{ex}(\omega)}{2\mu(\omega)} \triangleq H_{ref}^{(1)}(\omega)\hat{f}_{ex}(\omega), \quad (9)$$

in the case of reactive control and

$$\hat{v}_{ref}^{(2)}(\omega) = \frac{\hat{f}_{ex}(\omega)}{Z_i(\omega) + |Z_i(\omega)|} \triangleq H_{ref}^{(2)}(\omega)\hat{f}_{ex}(\omega), \quad (10)$$

in the case of passive and linear load. Within this framework, the presence of a controller $C(\omega)$ offers some flexibility to treat the prediction error. Also, the prediction is focused on the excitation force, which only depends on the incident wave elevation and on static excitation properties of the system, but not on its motion.

In this study the requirements of the wave excitation force prediction are analysed and quantified, in relation to the general control framework of Fig. 2 and to its two possible realisations through conditions (9) and (10).

Note that, by changing the physical quantities involved, most approaches to the control of a WEC of the oscillating type could be reduced to the logic scheme proposed in Fig. 2, where an *optimal* (in some sense) reference is generated on the basis of some logic requiring future knowledge of some effect of the wave elevation on the system, e.g. latching (Babarit and Clement (2006)), declutching (Babarit et al. (2009)), Model Predictive Control (MPC) (Bacelli et al. (2009)).

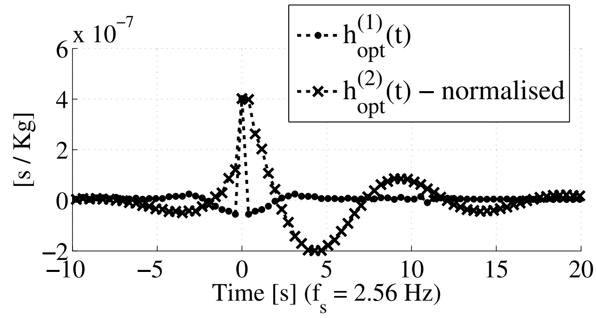

Fig. 3. Impulse response functions to generate optimal reference for the oscillation velocity are non causal

3. PREDICTION REQUIREMENTS AGAINST ACHIEVABLE PREDICTION

3.1 Prediction requirements

The expression for the two optimal reference oscillation velocities, in (9) and (10), are converted into the timed domain:

$$v_{ref}^{(1)}(t) = \int_{-\infty}^{t} h_{ref}^{(1)}(\tau) f_{ex}(t-\tau) d\tau$$
$$v_{ref}^{(2)}(t) = \int_{-\infty}^{t} h_{ref}^{(2)}(\tau) f_{ex}(t-\tau) d\tau, \quad (11)$$

where the kernel functions $h_{ref}^{(1,2)}(t)$ are noncausal, as in the example in Fig. 3, and future knowledge of the wave excitation force $f_{ex}(t)$ is required for real-time computation.

In order to quantify the importance of the future excitation force, its influence on the power potentially extracted from the sea is determined. In particular, a reference oscillation velocity is assumed to be generated through equations (11), where the impulse responses are truncated for $t < -L_t$ (i.e. at each time step, excitation force up to L_t seconds into the future is considered), for some L_t:

$$\hat{v}_{ref}^{(1,2),L_t}(\omega) = H_{ref}^{(1,2),L_t}(\omega) \hat{f}_{ex}(\omega) \quad (12)$$

In (12), $H_{ref}^{(1,2),L_t}(\omega)$ is the Fourier transform of the kernels $h_{ref}^{(1,2)}(t)$, truncated for $t < -L_t$.

To maintain the focus of the paper, the reference velocity thus calculated is supposed to be ideally imposed on the system by the control loop in Fig. 2. The average mechanical power transferred from the sea to the load, in the frequency domain, is finally calculated as:

$$P_u(\omega) = \frac{1}{2} \Re \left\{ Z_u(\omega) \hat{v}_{ref}^{(1,2),L_t}(\omega) \hat{v}_{ref}^{(1,2),L_t}(\omega)^* \right\} \quad (13)$$

or, taking into account (12):

$$P_u(\omega) = \frac{1}{2} |H_{ref}^{(1,2),L_t}(\omega)|^2 |\hat{f}_{ex}(\omega)|^2 \Re \left\{ Z_u(\omega) \right\}, \quad (14)$$

which depends of course on the control logic applied, reactive (1) or passive (2), and on the truncation time L_t. From (5) and introducing the relationship between excitation force and incident wave elevation, $H_{ex}(\omega) \triangleq \hat{f}_{ex}(\omega)/\eta(\omega)$, a final expression for the average power transfer from the sea to the load can be written:

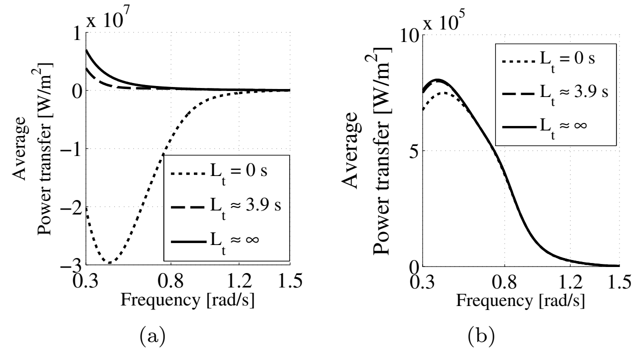

Fig. 4. Power for different forecasting horizons: *(a)* reactive control; *(b)* passive control.

$$\frac{P_u(\omega)}{|\hat{\eta}(\omega)|^2} = \frac{1}{2} |H_{ref}^{(1,2),L_t}(\omega)|^2 |H_{ex}(\omega)|^2 \cdot \Re \left\{ Z_i(\omega) - \frac{1}{H_{ref}^{(1,2),L_t}(\omega)} \right\} \quad (15)$$

As an example, Fig. 4 shows the average power transfer, in the case of a heaving cylinder, for some L_t, when reactive control, Fig. 4(a), and passive control, 4(b), are applied. Note how the reactive control is dramatically affected by non considering any future information about the excitation force, while the passive control is more robust in this respect, although the achievable power transfer in this case is smaller by one order of magnitude.

It is important to note that the influence of future excitation force on achievable power transfer depends exclusively on the shape of $H_{ref}^{(1,2),L_t}(\omega)$, and therefore on the dynamics of the considered system, as from (9) and (10). In the particular case of reactive control, equation (9), only the radiation $\mu(\omega)$ has an influence on the importance of considering future excitation force. This is very interesting and it follows, intuitively, that a floating system with larger-bandwidth radiation means a impulse response $h_{ref}^{(1)}(t)$ going more quickly to zero and, therefore, that the excitation force is required for a shorter time horizon.

3.2 Excitation force prediction

Here we discuss the actual predictability of the wave excitation force, that is how well it can be predicted and how long into the future and we will relate it to some properties of the system. In particular, the wave excitation force is a direct effect of the incident wave elevation on a floating body and it is low-pass filtered by its frequency characteristics, as from:

$$f_{ex}(\omega) = H_{ex}(\omega) \hat{\eta}(\omega) \quad (16)$$

Note that the transfer function $H_{ex}(\omega)$ depends exclusively on the shape of the floating body and it is usually a low-pass filter, as from Falnes (2002).

The prediction problem is considered, here, as a purely stochastic time series approach, where the future excitation force is estimated from current and past observations, as extensively studied in Korde (1999), Fusco and Ringwood (2010) and Fusco and Ringwood (2009). Alternative solutions propose a more deterministic approach where the dynamic behavior of the system is predicted from an array of distant wave elevation measurements, see for example Belmont et al. (2006), van den Boom (2009) and an overview in Fusco (2009). These alternatives are not considered here, as the paper is focused more on the prediction requirements than on the solutionw for the prediction.

In Fusco and Ringwood (2010) it was concluded that filtering out the high frequency waves can significantly improve the wave elevation time series prediction. In particular it was shown how Auto Regressive (AR) models allow the achievement of very accurate predictions of the low frequency swell for up to 2 wave periods into the future. Being the excitation force a wave elevation low-pass filtered by $H_{ex}(\omega)$, we expect that, given a certain sea state, more accurate predictions, and further into the future, can be obtained for floating systems characterised by a narrower-banded and sharper excitation frequency characteristics.

3.3 Radiation-Excitation relationship for a floating body

In section 3.1 it has been shown how the wave excitation force needs to be predicted some time into the future in order to generate an optimal reference oscillation velocity to control an oscillating WEC. The prediction horizon is strictly connected to the radiation properties of the system and it is expected to get larger as the radiation gets narrower-banded in the frequency domain, particularly in the case of reactive control.

On the other hand, in section 3.2, it was highlighted how the excitation properties of the system, enclosed in the transfer function $H_{ex}(\omega)$ between the incident wave elevation and the excitation force, determine the predictability of the excitation force. In particular, the excitation force is expected to be predictable longer into the future and with a better accuracy for a narrower-banded excitation frequency response.

Excitation and radiation, however, are both properties of a floating system and, therefore, they must be related in some way. Investigating this relationship can give us some important insight about the relationship between the prediction horizon required for the excitation force and the achievable prediction accuracy.

In the particular case of axisymmetric bodies and deep water, for the heave motion, excitation force transfer function and radiation resistance are related through the reciprocity relation, derived in Falnes (2002):

$$\mu(\omega) = \frac{\omega^3}{2\rho g^3}|H_{ex}(\omega)|^2, \tag{17}$$

where ρ is the water density and g is the gravity acceleration.

Equation (17) is the direct relationship between radiation resistance and excitation that we are interested in. We may conclude, from it, that if the excitation is narrow-banded, so it will be the radiation resistance. This is exemplified in Fig. 5, where the radiation resistance and the excitation transfer function for a wide-banded and a narrow-banded floating cylinder are shown.

It may be concluded that systems for which the prediction is required longer into the future present narrower-banded

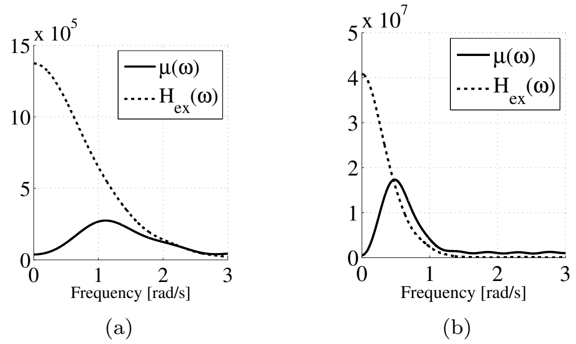

Fig. 5. Radiation resistance and excitation transfer function for two different heaving cylinders.

Cyl	$\omega_0\,[rad/s]$	$T_0\,[s]$	$\Delta\omega\,[rad/s]$	$r\,[m]$	$b\,[m]$
1	1.49	4.20	0.46	6.72	2.16
2	1.03	6.10	0.37	17.55	3.91
3	0.88	7.13	0.28	21.07	5.96
4	0.64	9.79	0.17	20.44	12.10

Table 1. Characteristics of the floating cylinders analysed in this study: resonance frequency/period ω_0/T_0, bandwidth $\Delta\omega$, radius r and draught b.

radiation characteristics, but also have stronger low-pass filtering properties on the incident waves, thus allowing for better predictions of the excitation force.

4. RESULTS

According to the methodology outlined in section 3, here the prediction requirements for the time-domain control of a WEC and the achievable prediction of the excitation force are quantified here, in relation to a range of specific heaving cylinders under two different sea conditions.

Table 1 summarises the characteristics of different cylinders, all presenting the same mass distribution, in terms of resonance period/frequency, bandwidth, radius and draught. Note how the cylinders range from higher resonance frequency and wider bandwidth to lower resonance frequency and narrower bandwidth. The two real sea states considered are shown in Fig. 6: wave data set 1, Fig. 6(a), is from the Pico Island, in the Azores Archipelago (Esteves et al. (2009), Azevedo and Rodrigues (2008) and Barrera et al. (2008)), and it is more concentrated at the low frequencies with a well defined swell; wave data set 2, Fig. 6(b), comes from the Galway Bay, off the West coast of Ireland, and it has a relatively small swell mixed with some high frequencies wind waves.

Given a specific time horizon L_t and a specific control logic, reactive or passive control, the average power transfer in (15) is determined. The total average power absorbed at the load, for a given incident wave spectrum $|\hat{\eta}(\omega)|^2$, is then calculated as:

$$\overline{P_l} = \int_{-\infty}^{+\infty} \frac{P_u(\omega)}{|\hat{\eta}(\omega)|^2}|\hat{\eta}(\omega)|^2 d\omega \tag{18}$$

Fig. 7 shows the results obtained, for the two sea states, when reactive control is applied. The considered future horizon, L_t, ranges from 0 (no future excitation force

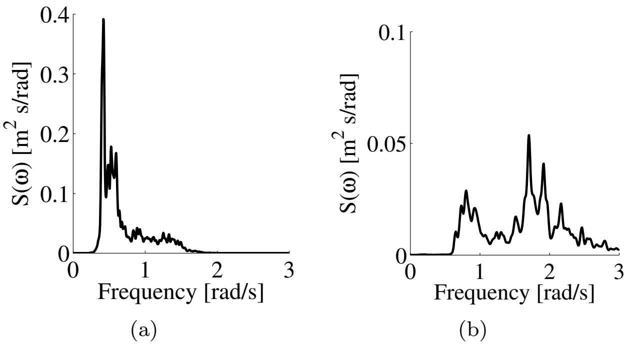

Fig. 6. Wave data considered in this study: *(a)* Data set 1; *(b)* Data set 2

needed) to nearly 20 seconds (future excitation force required up to 20 seconds). For an equal comparison of the different cylinders, the load power $\overline{P_l}$ is normalised with respect to the incident wave power, which depends on the diameter of the device, thus yielding the capture width. For both the sea states the trend is similar, with the wide-banded and higher resonance frequency cylinder giving higher capture width and approaching the theoretical maximum (infinite future horizon) when $L_t < 5\,s$. This was expected from the qualitative analysis in section 3.1, where it emerged how floating bodies with wider-banded characteristics require predictions shorter into the future. Note also how the performance of the cylinder 4 (lowest resonance frequency and narrowest band) is dramatically affected by the future horizon considered and the prediction is required for very long time horizons.

The results obtained for the case of passive control, Fig. 8, show how linear passive control does not really benefit from considering the future excitation force in the calculations for the optimal oscillation velocity. The overall capture width achievable is, however, 2-3 times smaller than what was obtained in the case of reactive control. Also, in the case of passive control, the trend of the cylinders for the two sea states is opposite and the best performance is obtained with the cylinder whose characteristics are closest to the wave spectrum. This can be explained with the fact that passive control is not able to change the resonance of the device, while reactive control can alter the device dynamics to match, in theory, any incident wave spectrum.
As regards the achievable prediction, the wave excitation force time series acting on the 4 cylinders, when each of the 2 sea states of Fig. 6 is considered, is predicted through an AR model of order $n = 32$, identified and estimated according to the methodology presented in Fusco and Ringwood (2010). The accuracy of the prediction is measured with the following goodness-of-fit index, for each forecasting horizon l:

$$\mathcal{F}(l) = \left(1 - \frac{\sqrt{\sum_k \left[\eta(k+l) - \hat{\eta}(k+l|k)\right]^2}}{\sqrt{\sum_k \eta(k)^2}}\right) \cdot 100 \quad (19)$$

Here $\eta(k+l)$ is the wave elevation and $\hat{\eta}(k+l|k)$ is its prediction based on the information up to instant k. A 100% value for $\mathcal{F}(l)$ means that the wave elevation time series is perfectly predicted l steps into the future.

Fig. 9 shows how the prediction accuracy is, in general, much higher for the lower frequency sea state, Fig. 9(a),

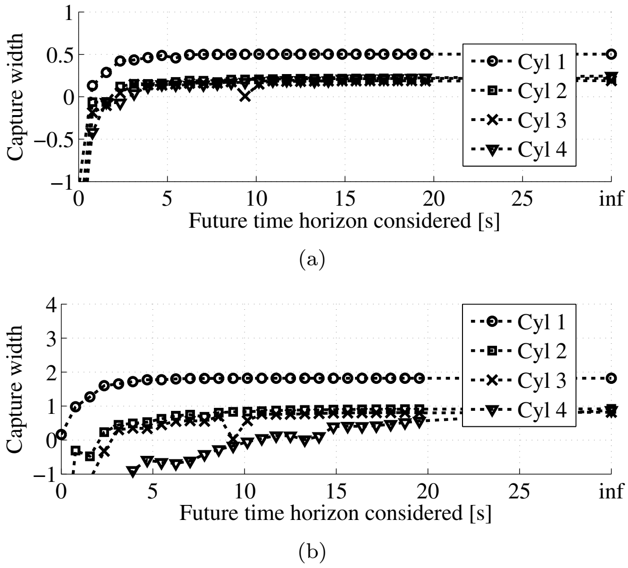

Fig. 7. Capture width for different forecasting horizons with reactive control: (a) Wave data set 1; (b) Wave data set 2

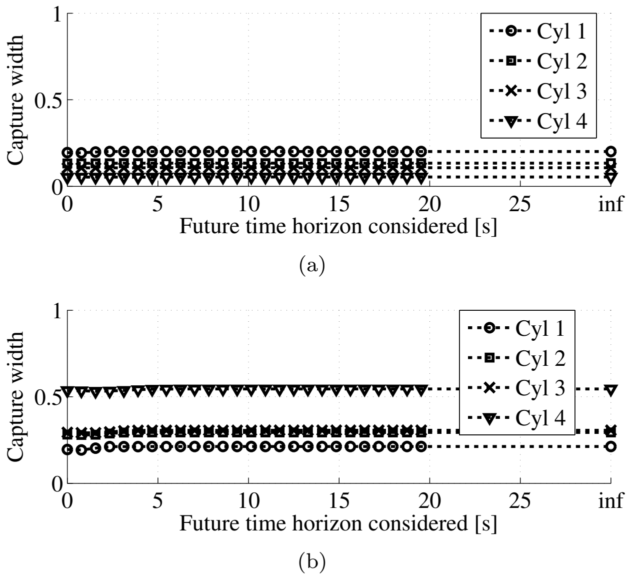

Fig. 8. Capture width for different forecasting horizons with passive control: (a) Wave data set 1; (b) Wave data set 2

which is dominated by a low frequency swell. The prediction accuracy increases as the bandwidth of the cylinder characteristics decreases, as it was expected from the discussion in sections 3.2 and 3.3. In the case of the high frequency sea state, with strong wind waves, the prediction is poor for more than $2-3$ seconds in the future, but this seems enough to get a reasonable capture width through reactive control, particularly with the wide bandwidth cylinder 1, as from Fig. 7(b)

5. CONCLUSIONS

This paper attempts to build a framework within which the prediction requirements on the excitation force signal may be examined. Accurate prediction of future excitation

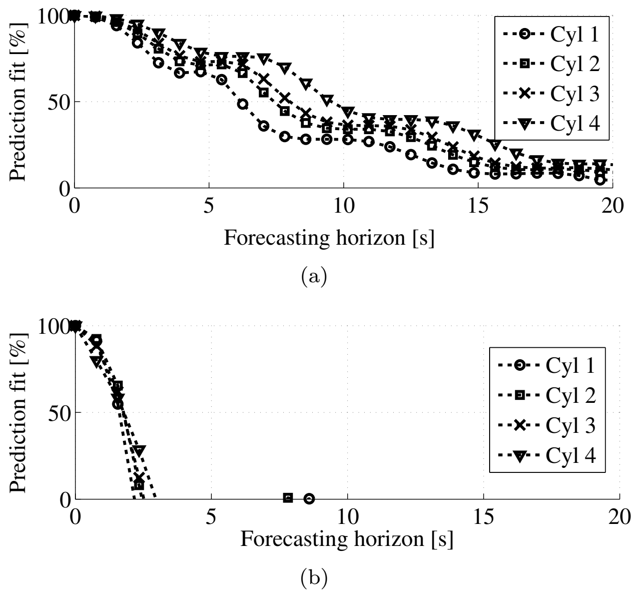

Fig. 9. Wave excitation force prediction accuracy, for the different cylinders, with AR models: (a) Wave data set 1; (b) Wave data set 2

force values are crucial to generating optimal velocity setpoints for the WEC control system, which attempts to optimise the energy capture for the WEC.

We confirm two important features of the prediction problem:

- The required prediction *horizon* for the excitation force depends only on the radiation damping properties of the system, and
- The achievable prediction *accuracy* over a particular horizon depends on the excitation force kernel for the WEC system, with narrow-banded kernel functions providing better accuracy possibilities.

For simple systems, consisting of axi-symmetric bodies in deep water subject to heave motion only, a link can be established between the prediction *horizon* requirements and available *accuracy*. In general, WEC systems with relatively slow dynamics require a relatively long excitation force prediction horizon, but permit better prediction accuracy. This suggests that a natural synergy exists between the prediction horizon and accuracy requirements.

A further important conclusion can be made in relation to the prediction requirements for systems with *active* WEC control, where power can be returned to the WEC by the PTO system, during part of the wave cycle. In such a situation, accurate excitation force prediction is very important, while future knowledge of the excitation force is of little consequence to a passive control system.

Future work will extend the work here, performed in the frequency domain, to the time domain, allowing alternative control strategies to be compared, while also looking at the effects of excitation force prediction accuracy on the WEC velocity control system.

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