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IFAC PapersOnLine 50-1 (2017) 14698–14704

The Effect of Viscosity on the Maximisation of Electrical Power from a Wave Energy Converter under Predictive Control

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Abstract: In this paper, the non-linear effects of viscosity on the performance of a Wave Energy Converter (WEC) system are analysed. A standard linear Model Predictive Control (MPC) is used to show the negative effects that the unaccounted non-linear viscosity force in the hydrodynamic system has on the power absorption. A non-linear MPC (NLMPC) is then implemented, where the non-linear viscosity effects are included in the optimisation. A linear drag coefficient estimate of the non-linear viscosity is then included in the linear MPC; creating a Linear Viscous Model Predictive Control. When constraints are incorporated, it is shown that a single choice of the linear viscous drag coefficient for use within the linear MPC can provide comparable results to the non-linear MPC approach, over a wide range of sea states.

Keywords: MPC, LPV-MPC, power maximisation, viscosity, wave energy.

1. INTRODUCTION

In recent times there has been a renewed interest in wave energy, due primarily to the drive to replace fossil fuels in an attempt to combat climate change. As a renewable source, wave energy in particular is seen as attractive due to its high energy density, (Clément et al., 2002). There are numerous wave energy converter (WEC) paradigms which can extract this energy from the wave in various ways, and can operate either in the near shore or at offshore locations, (Drew et al., 2009). This work focuses on a point absorber wave energy converter, which is relatively simple from a mechanical point of view and which is applicable for wave farm arrays, (Budal and Falnes, 1975).

Incorporating control into the WEC is crucial for maximum power extraction and to protect the device. Classical control methods such as reactive control, (Budal and Falnes, 1977) and latching, (Budal and Falnes, 1980) have been used to extract maximum or close to maximum average power. The effect of system constraints have been investigated, (Fusco and Ringwood, 2013) as well as the use of a realistic non-ideal Power Take Off (PTO), (Tedeschi et al., 2011). Both latching and reactive control were originally designed to operate in monochromatic seas, however, there have been attempts to extend their use for irregular sea conditions, (Fusco and Ringwood, 2011; Babarit et al., 2004).

Other advanced control methods have been investigated; such as fuzzy logic, (Schoen et al., 2011), bang-bang control, (Abraham and Kerrigan, 2013), pseudo spectral control, (Paparella and Ringwood, 2016) and model predictive control (MPC), (Hals et al., 2011). In this paper MPC is utilised as the control algorithm due to its ability to produce optimal results, whilst easily incorporating system constraints within the optimisation, (Maciejowski, 2002). In the most commonly used MPC approach for wave energy, the average power is maximised over a certain prediction horizon based on a model of the device, (Cretel et al., 2010). When the PTO is included in the system, (Polinder et al., 2004), a cascade control scheme can be easily implemented, where the slower outer loop sends piecewise linear reference points to the faster inner PTO force control loop, (Montoya Andrade et al., 2014; Cretel et al., 2011). In (O'Sullivan and Lightbody, 2015), it is shown that it is essential to include the PTO power losses within the cost function, as the average power can dramatically reduce when the WEC operates away from its natural frequency.

It is crucial that each design aspect of the power extraction system from wave-to-wire is designed in an integrated manner, rather than as individual subsystems. This subject of co-design has lately been highlighted, where items such as the sea spectrum suitability, (Lenee-Bluhm et al., 2011), the geometry of the WEC, (Garcia-Rosa and Ringwood, 2016), the prediction of the excitation wave, (Fusco and Ringwood, 2010), the rating of the generator, (Aubry et al., 2012), the power electronics needed for high power ratings, (Lovelace et al., 2000), the effects of the DC-link on the power extraction, (O'Sullivan and Lightbody, 2016a,b) and the aggregation of power from multiple WEC's, (Molinas et al., 2007) have been analysed. One category that has been somewhat assumed as insignificant in previous wave energy research, is the importance of including and modelling the non-linear components of the WEC system. The main non-linearity in the hydrodynamic system are the Froude-Krylov forces and the viscosity forces. In both, (Guérinel et al., 2011; Penalba Retes et al., 2015), the effects of including non-linear Froude-Krylov forces in the hydrodynamics model were demonstrated.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.2500

Whilst in, (Bhinder et al., 2011; Giorgi et al., 2016), it was shown that without the implementation of active control, the effects on the power extraction is insignificant. However, when active control is used, the performance from the non-linear model considerably diverges from the linear model, (Giorgi et al., 2016).

In this paper, the non-linear effects of viscosity on the average power absorption are investigated. It first investigates the effect that unmodelled viscosity within the WEC has on the electrical power absorption when a linear model is used within the MPC. A non-linear MPC approach based on the linear parameter-varying (LPV) method is then utilised, in which the non-linear viscosity effect is approximated within the predictive model at each prediction step. This is further simplified, utilising a linear viscous damping within the predictive model, which is optimally tuned for each sea state. When constraints are included, it is shown that the electrical power extracted in our example was actually quite insensitive to the choice of the linear viscous damping coefficient and performance close to that obtained using the non-linear MPC could be obtained across all sea states, without the added computational complexity of the non-linear MPC.

2. MODELLING

2.1 Hydrodynamics

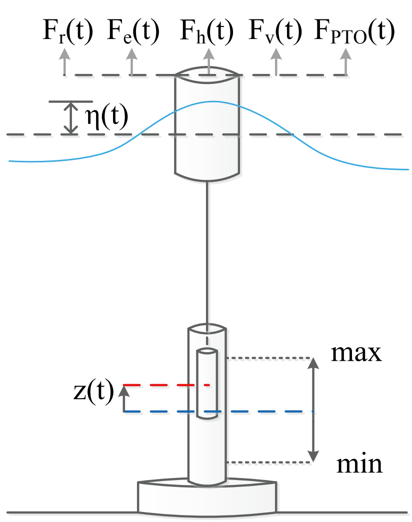

Fig. 1. System model with WEC and PTO

In this work, a cylindrical point absorber of mass M moving in heave motion is modelled. The model is based on linear wave theory but also includes the non-linear effect of viscosity. The hydrostatic force $F_h(t)$, the radiation force $F_r(t)$, the excitation force $F_e(t)$, the non-linear viscous force $F_v(t)$ and the controlled PTO force $F_{PTO}(t)$ as shown in Fig. 1, are all components of the hydrodynamic equation (1),

$$M\ddot{z}(t) = F_h(t) + F_r(t) + F_e(t) + F_v(t) + F_{PTO}(t) \quad (1)$$

The hydrodynamic system (1) is represented by the heave displacement $z(t)$, velocity $\dot{z}(t)$, the wave elevation $\eta(t)$ and the wave velocity $\dot{\eta}(t)$, where these are with respect to the equilibrium position. As this is a cylinder, the hydrostatic force is a linear function of the displacement $z(t)$, where β is the linear hydrostatic spring constant. The radiation force $F_r(t)$ is represented by a convolution integral from the Cummins transformation (Cummins, 1962), where the radiation kernel $h_r(t)$ and the added mass m_μ were found using WAMIT (Lee, 1995). The viscous force $F_v(t)$ is a non-linear component which depends on the relative velocity between the WEC and wave. The PTO force $F_{PTO}(t)$ is a force created by the control system. The non-linear mechanical model of the WEC is as follows,

$$(M + m_\mu)\,\ddot{z}(t) + \int_0^t h_r(\tau)\dot{z}(t-\tau)d\tau + \beta z(t) \quad (2)$$
$$+C_{vis}(t)\left(\dot{z}(t) - \dot{\eta}(t)\right) = (M + m_\mu)\left(u_q(t) + v(t)\right)$$

where the scaled forces, $u_q(t)$ and $v(t)$ are,

$$u_q(t) = \frac{F_{PTO}(t)}{M + m_\mu} \qquad v(t) = \frac{F_e(t)}{M + m_\mu} \quad (3)$$

The excitation force $F_e(t)$ is a non-causal convolution integral of the wave elevation $\eta(t)$, where the excitation kernel $h_e(t)$ was found using WAMIT (Lee, 1995).

$$F_e(t) = \int_{-\infty}^{t} h_e(\tau)\eta(t-\tau)d\tau \quad (4)$$

The radiation kernel $h_r(t)$ can be expressed as a weighted sum of complex exponentials (5), where the parameters can be identified from the impulse response $h_r(t)$ using Prony's method,

$$h_r(t) \approx \tilde{h}_r(t) = c_1 e^{\mu_1 t} + c_2 e^{\mu_2 t} + c_3 e^{\mu_3 t} + ... + c_n e^{\mu_n t} \quad (5)$$

The radiation force, $F_r(t)$, can then be represented in the Laplace domain as $F_r(s) = sH_r(s)Z(s)$, where,

$$H_r(s) = \mathscr{L}\{\tilde{h}_r(t)\} = \frac{b_m s^m + b_{m-1}s^{m-1} + ... + b_0}{s^n + a_{n-1}s^{n-1} + ... + a_0} \quad (6)$$

A finite state space approximation can then be produced from (6), as;

$$\begin{aligned} \dot{\boldsymbol{x}}_{\boldsymbol{r}}(t) &= A_r \boldsymbol{x}_{\boldsymbol{r}}(t) + B_r \dot{z}(t) \\ F_r(t) &= C_r \boldsymbol{x}_{\boldsymbol{r}}(t) + D_r \dot{z}(t) \end{aligned} \quad (7)$$

where $\boldsymbol{x}_{\boldsymbol{r}}(t) \in \mathbb{R}^n$,$A_r \in \mathbb{R}^{n\times n}$,$B_r \in \mathbb{R}^n$,$C_r \in \mathbb{R}^{1\times n}$.

The non-linear viscosity force $F_v(t)$, is based on the semi-empirical Morison equation (Morison et al., 1950),

$$F_v(t) = -C_{vis}(t)\left(\dot{z}(t) - \dot{\eta}(t)\right) \quad (8)$$

where,

$$C_{vis}(t) = \frac{1}{2}\rho C_d A \left|\dot{z}(t) - \dot{\eta}(t)\right|.$$

Here ρ is the density of water, C_d is the drag coefficient (Bhinder et al., 2011) and A is the sectional area of the point absorber which is orthogonal to the direction of the force.

The non-linear hydrodynamic model (2) can then be represented in the state space form,