Ocean Engineering 38 (2011) 684–698

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Processing irregular wave measurements to enhance point absorber power capture performance

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ARTICLE INFO

Article history:
Received 22 March 2010
Accepted 27 December 2010
Editor-in-Chief: A.I. Incecik
Available online 13 January 2011

Keywords:
Wave energy converter
Zero-crossing period
Reactive control
Wave force estimation
Wave elevation filtering

ABSTRACT

The paper aims at introducing practical methods for power capture performance enhancement of a heaving wave energy converter in irregular seas. The optimum control solution requires tuning to wave frequency based on wave force information. However, identification of the wave frequency in irregular seas is considered to be a complex and difficult task. This is partly due to technical difficulties in determination of the wave force. Besides, there are no clear guidelines for identification of wave frequency from an irregular sea state based wave force information. In a typical application, one of the available sources of information about the wave properties is the wave elevation record. The proposed approach presents a method for estimation of the wave frequency information from the wave elevation data by using signal processing and filtering techniques. The proposed method uses filters to generate an estimation of wave force information, which is used to identify the local wave frequency by method of a time-series analysis of the data. This wave frequency information is then used in tuning the device. The details of the proposed techniques, the model of the wave energy converter, the simulated sea states and the related simulation results are also presented.

1. Introduction

Amongst the wide variety of wave energy converter device concepts proposed in literature, a common concept is that of an oscillating rigid body whose motion, or relative motion, is constrained by a power take-off (PTO) system. Independent studies by Evans (1976) and Budal and Falnes (1975) demonstrated that such systems can capture more power from a regular wave than is incident on its width. However, such theoretical performance levels suggested by linear theory are only achievable if the optimum control conditions are met (Falnes, 2002), namely as phase and amplitude conditions. The first condition states that the oscillation velocity of the device must be in phase with the excitation force acting on the body. This is known as the optimum phase condition and, in regular waves, is satisfied when the device response is resonant. The optimum amplitude condition states that "the absorbed power is maximum when it equals the power reradiated into the sea by the oscillating system" (Falnes, 2002). In regular waves, this condition may be satisfied by defining the combined mechanical damping (due to the PTO and friction losses) equal to the hydrodynamic damping at the wave frequency.

In regular waves, it is relatively straightforward task to determine the parameters of the PTO in order to satisfy these two conditions (Eidsmoen, 1998). However, in irregular or random seas where complex wave properties are dynamic in nature, these control conditions become difficult to implement (Babarit et al., 2004). This tuning problem can be considered in two stages; prediction of wave force and wave frequency, and adjustment of device properties accordingly.

The first stage of the problem is calculation of the wave force information. The difficulty is that the calculation of wave force information suffers from some technical problems related to causality and time-history of calculation parameters. Since the wave force information comprises of both causal and non-causal components, its calculation is not a straightforward task but rather a complicated one. Prediction of the wave force requires knowledge of past and future wave information and the full time-history of device response (McCabe et al., 2005).

Assuming that the wave force information is achievable, the next question is how to estimate the wave frequency from a complex, dynamic and random signal. If one can estimate the wave frequency from the wave force signal, then the next stage is to tune the system parameters to the new settings defined by the estimated wave frequency. Subsequently, the mechanical characteristics of the device must be adjusted to maintain the required phase difference between the excitation force and device velocity. This may be achieved exactly by continuous adjustment

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doi:10.1016/j.oceaneng.2010.12.016

Nomenclature

b_{loss}	loss related damping coefficient
b_{pto}	power take-off damping coefficient, kNs/m
$b_{rad}(\omega)$	frequency dependent radiation damping coefficient, kNs/m
k_{net}	buoyancy stiffness, kN/m
k_{pto}	power take-off stiffness, kN/m
m	overall mass of body, tonne
m_n	nth moment of the power spectral density $S(f)$
$F_E^{stab}(s)$	Laplace transform of $F_E^{stab}(t)$
$F_E^{unst}(s)$	Laplace transform of $F_E^{unst}(t)$.
ω	angular frequency, rad/s
ω_p	site peak frequency, rad/s
$\omega_{t\zeta}(t)$	wave frequency estimated using time series analysis of wave elevation, rad/s
ω_{wave}	wave frequency, rad/s
$\zeta(t)$	instantaneous wave elevation, m
$\zeta'(t)$	filtered instantaneous wave elevation, m
f_{ord}	filter order
f_{pass}	pass band edge frequency, Hz
f_{stop}	stop band edge frequency, Hz
A_{rip}^{stop}	stop band ripple, dB
A_{rip}^{pass}	pass band ripple, dB
f_s	sampling frequency, Hz
$f_{s/2}$	half the sampling frequency, Hz
H_s	significant wave height, m
T_p	peak period, s
γ	peakedness

of device mass or restraining stiffness through complex conjugate or reactive control (Nebel, 1992; Pizer, 1993; Eidsmoen, 1996, 1998; Korde, 2001; Yavuz et al., 2006, 2007; Falcao, 2007) or approximately by techniques such as latching (Korde, 2002; Babarit et al., 2004).

A solution to the above stated tuning problem in irregular seas was earlier considered to be the use of approximate tuning methods. However, these methods earlier employed by Yavuz et al. (2007) aim at removing high frequency components in the wave elevation record only to improve the performance of time-series analysis where these components cause misleading results.

These tuning methods are based on the use of a local (in time) wave frequency that is obtained from the surface elevation records (Yavuz et al., 2007). This wave frequency is then used in adjustment of the power take-off (PTO) unit parameters (stiffness and damping) of a heaving device. It is also reported that the proposed active tuning methods improve power capture significantly relative to passive types where PTO unit parameters are fixed for the duration of simulation. This approach is attractive in such that it does not require any wave prediction method (period is estimated from the preceding two wave cycles only), yet significantly improves power capture relative to the performance of passive techniques.

On the other hand, the optimum control theory suggests the use of wave frequency of the wave force for tuning applications. Besides, wave force information differs from surface elevation information. Thus, both active and passive tuning techniques suggested by Yavuz et al. (2007) suffer from performance limitation due to the use of wave frequency of the surface elevation instead of the frequency of the wave force. It is clear from this observation that there is a need for practical estimation of the wave force signal from wave elevation information for further improvement of power capture performances of the suggested control techniques. This statement essentially defines the objective of the present study.

It is reported that some floating objects like heaving wave energy converters (WECs) demonstrate roughly the behaviour of a low pass filter (Lindegaard et al., 2002) in response to wave elevation spectrums. The scope of the present work is to investigate the device response spectrum and to improve the power capture performance of an oscillating type one degree-of-freedom (DOF) heaving WEC. The present study aims at developing a method for estimation of the wave force information from wave elevation data and also at examining additional approaches for further improvement of the technique.

The present study also aims at providing a practical method for wave force estimation and wave frequency identification processes. Therefore, main contributions of this study are the introduction and implementation of an estimation method for wave force information from wave elevation data and the identification of wave frequency from estimated wave force information.

In addition, the present study provides details of the simulation process and the related results in irregular seas for reactive control of a heaving WEC. The presented estimation method employs an online processing technique that enhances the power capture of a single DOF device. It is also shown that the proposed technique is superior to the ones suggested earlier by Yavuz et al. (2007). The presented results include an online wave frequency estimation technique that enables wave period estimation used in reactive control of the heaving WEC. The results indicate that the power capture performance of the heaving WEC can be enhanced further. It is also shown that the proposed technique improves the power capture performance of the device in such a way that it performs as well as the system tuned with estimated wave frequency of the wave force information. Besides, it is worth pointing out that the proposed technique is very much practical and straightforward to apply to other types of devices provided that appropriate method of processing techniques are identified which might differ for other motion modes.

To provide the necessary background for discussions, a brief review of the time-series analysis method is presented in the following section. Subsequently the wave force and wave elevation data sets are analysed for the investigation of common and differing spectral properties. The mathematical model of the system is presented in Section 4. The outline of the system structure and simulation model is discussed in Section 5. In Section 6, simulated sea states and related properties are presented. A range of sea-states are considered as defined by the JONSWAP spectrum with peak periods, in the range of 6.5–12 s, to demonstrate the increase in device power capture that may be attained. In Section 7, simulations of device performance are conducted using a time-domain (TD) model (McCabe et al., 2005) of a single degree of freedom (DOF) heaving WEC in which the diffraction and radiation forces are computed by use of Laplace transfer functions. Finally, conclusions are presented in Section 8.

2. Estimation of wave frequency

The proposed wave period estimation technique is based on the zero crossing principle. Implementation of the technique is presented in Fig. 1 (Yavuz et al., 2007). As illustrated in the figure, the transient wave frequency ($\omega_{t\zeta}$) is obtained by interpolation