



Citation for published version:

Cargo, CJ, Hillis, AJ & Plummer, AR 2016, 'Strategies for active tuning of Wave Energy Converter hydraulic power take-off mechanisms', *Renewable Energy*, vol. 94, pp. 32-47 .
<https://doi.org/10.1016/j.renene.2016.03.007>

DOI:

[10.1016/j.renene.2016.03.007](https://doi.org/10.1016/j.renene.2016.03.007)

Publication date:

2016

Document Version

Peer reviewed version

[Link to publication](#)

Publisher Rights

CC BY-NC-ND

Creative Commons Attribution Non-Commercial No Derivatives License

University of Bath

Alternative formats

If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Strategies for active tuning of Wave Energy Converter hydraulic power take-off mechanisms

C.J. Cargo, A.J. Hillis*, A.R. Plummer

Department of Mechanical Engineering, University of Bath, Bath BA27AY

Abstract

This paper presents a study of practically implementable active tuning methods for a Wave Energy Converter (WEC) power take-off (PTO). It is distinguished from other simulation studies by the level of detail and realism in the inputs and the PTO model. Wave data recorded at the European Marine Energy Centre is used to derive input data for a detailed component level model of a hydraulic PTO. A methodology is presented for obtaining the optimum PTO damping co-efficient for a given sea state, and an open loop active tuning method is used to adjust the PTO parameters to achieve this optimum damping in service. The investigation shows that tuning of a hydraulic PTO to an estimated wave frequency is a difficult task due to sea state estimation errors and the complex dynamics of a realistic PTO. Preview knowledge of the future waves was shown to provide no meaningful improvement in energy capture for the device under investigation. Significantly, power gains observed in similar work using simplified linear PTO models or simplified sea states are not seen here, demonstrating that over-simplification of the PTO during the simulation phase of WEC development could lead to incorrect design decisions and subsequent additional delay and cost.

Key words: wave energy, hydraulic PTO, power optimization, irregular waves

*Corresponding author

Email address: a.j.hillis@bath.ac.uk (A.J. Hillis)

1. Introduction

The optimization of wave energy converter (WEC) hydraulic power take-offs (PTO) in sea states of varying wave amplitude, direction, and frequency is a significant problem. Sub-optimal configuration can result in very inefficient energy conversion [1], so understanding the design trade-offs is key to the success of the technology. This work focuses on a generic point absorber type WEC. Previous work by the authors has considered the optimisation of this device for regular waves [2] and synthesised irregular waves [3] to gain an understanding of the fundamental issues. This paper considers real wave data from the European Marine Energy Centre (EMEC) based in Orkney, Scotland. It presents techniques to analyse the wave energy resource at a particular site by using statistics that are calculated from the raw data. A method to calculate the wave excitation force from the raw wave displacement is presented and this is then used as the input to a simulation model. This provides a prediction of how the WEC will behave and the power which can be generated in real wave conditions.

PTO tuning is investigated using the real data and compared to the results found previously [2, 3]. Real time tuning methods are analysed to determine the best method to maximise power generation by updating the PTO damping. Active and passive methods are examined which tune the PTO to a wave frequency calculated from different horizons of wave data.

2. Background

Previous work has focused on developing control methods for point absorbers to maximize the energy absorbed. Falcao [4] used a simplified hydraulic PTO unit connected to a point absorber to develop an algorithm to optimize the converter. The algorithm was shown to be weakly dependent on wave period and independent of wave height when simulated in real sea conditions and to produce power levels similar to a fully linear PTO unit. This work was continued in Falcao [5] to include a strategy for phase control by latching to increase the absorbed power further. In Babarit et al. [6] three different latching control strategies are compared to show their effectiveness in different sea states with all three strategies giving a

31 considerably increased efficiency in irregular waves. In Yavuz et al. [7] work
32 focuses on assessing the performance of a tuneable point absorber by trying to fulfil
33 the condition of resonance by varying the PTO characteristics. Results showed a
34 maximum power capture of 50 per cent of the rated power in regular waves. This
35 work was continued in Yavuz et al. [8] with irregular waves to show that power
36 capture can be maximized by continuously tuning the natural frequency of the
37 device to the incoming wave frequency. More recently, in Folley and Whittaker
38 [9], a new control method called active bipolar damping or declutching is proposed
39 which tries to shift the buoy’s velocity so it is in phase with the wave force. When
40 compared theoretically to other methods, it shows a higher power capture than
41 optimum linear damping without the requirement of reactive energy storage. This
42 control method has been investigated in Babarit et al. [10] using a hydraulic PTO
43 and compared to a control method which tries to mimic the continuous behaviour
44 of a viscous damper. Results show greater power levels from the declutching control
45 method with the added advantage of requiring a less complex system. Most of these
46 investigations use linearized models and do not consider real hydraulic circuits and
47 components in their investigations.

48 **3. Hydrodynamics of the WEC**

49 A point absorber type device is used for this study and is the same as that
50 used in [2] and [3]. A diagram of the heaving buoy is shown in Fig. 1, and it has a
51 mass of 39 tonnes, a radius of 2m and a draft of 4m. A point mass acting at the
52 centre of the buoy is assumed. The governing equation of motion for the buoy in
53 heave is

$$m\ddot{x} = f_h(t) + \Phi(t) \quad (1)$$

54 where m is the mass of the buoy, \ddot{x} is the buoy’s acceleration, $f_h(t)$ is the total
55 wave force and $\Phi(t)$ is the mechanical force created by the PTO and moorings.
56 Assuming linear wave theory, the wave force can be approximated as

$$f_h(t) = f_e(t) + f_r(t) + f_{hs}(t) \quad (2)$$

57 where $f_e(t)$ is the excitation force produced by an incident wave on an otherwise
 58 fixed body, $f_r(t)$ is the radiation force and $f_{hs}(t)$ is the hydrostatic buoyancy force.
 59 For a regular wave of frequency ω the excitation force is given by

$$f_e(t) = \text{Re}(F_e e^{j\omega t}) \quad (3)$$

60 where F_e is the complex excitation force amplitude. Following the approach de-
 61 scribed in [3] and using the assumptions of [11] and Hulme [12], for a hemispherical
 62 body that is small in comparison to the incident wavelength, F_e may be approxi-
 63 mated by

$$F_e \approx \frac{H\rho}{\omega} \sqrt{\frac{\pi}{3} g^3 r^3 \epsilon e^{-2kl}} \quad (4)$$

64 where H is the free surface elevation, ρ is the water density, g is the acceleration
 65 due to gravity, r and l are the radius and half-height of the buoy, ϵ is Havelock's
 66 dimensionless damping coefficient computed by Hulme [12] and k is the wave
 67 number ($k = \frac{\omega^2}{g}$) given by the deep water dispersion equation.

68 The radiation force $f_r(t)$ can be decomposed into components in phase with
 69 the buoy's acceleration and velocity [11] [13] so that

$$f_r(t) = -A(\omega)\ddot{x} - B(\omega)\dot{x} \quad (5)$$

70 where $A(\omega)$ is the added mass coefficient and $B(\omega)$ is the radiation damping
 71 coefficient, which may be approximated in this case to [11] [12]

$$B(\omega) \approx \omega\rho \left(\frac{2\pi}{3}\right) r^3 \epsilon e^{-2kl} \quad (6)$$

72 For small heave displacements, the hydrostatic force $f_{hs}(t)$ can be linearised so
 73 that

$$f_{hs}(t) = -\rho g \pi r^2 x \quad (7)$$

74 4. Hydraulic PTO mechanism

75 The aim of the PTO is to convert the irregular wave input into a smooth
 76 electrical power output by decoupling the power capture and power generation

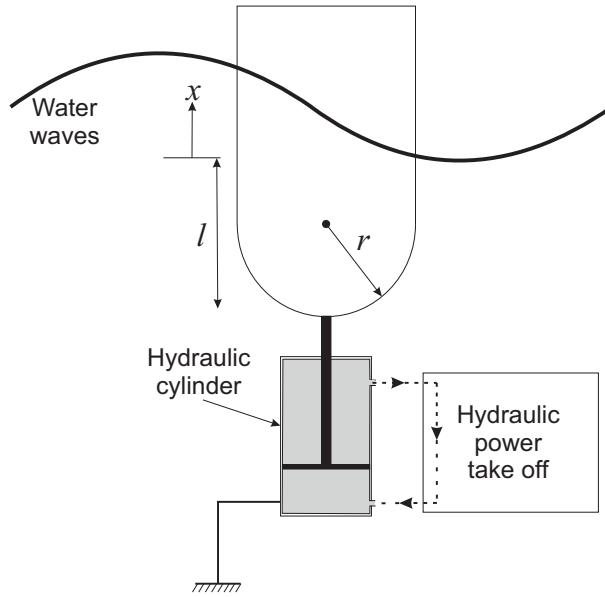


Figure 1: Schematic diagram of the WEC

77 processes. Hydraulic PTOs are generally used in WECs due to their advantages
 78 for dealing with low frequency, high force wave inputs and their high power density
 79 and robustness.

80 The hydraulic PTO used in this simulation model is shown in Figure 2. The
 81 simplified circuit excludes components such as filters and coolers which would
 82 be required in the real hydraulic system. The heave motion of the buoy drives a
 83 double-acting equal area hydraulic piston within a fixed cylinder to pump hydraulic
 84 oil through rectification circuit to provide unidirection flow through a hydraulic
 85 motor. The pressure difference between the high and low pressure accumulators
 86 drives a variable displacement hydraulic motor, which drives an electrical gener-
 87 ator. The accumulators are intended to smooth the pressure differential across
 88 the hydraulic motor and therefore achieve synchronous power generation. The
 89 thermodynamic transformations in the accumulators are assumed to be isentropic,
 90 which is a reasonable assumption considering the cycle time of the device. The
 91 generator is modelled as a simple rotational damper with variable damping coef-
 92 ficient allowing its resistive torque to be altered. In a real circuit, there will be
 93 external leakage from the motor to tank. Therefore, to replenish the circuit and
 94 avoid cavitation in the cylinder, an additional accumulator is used to maintain a
 95 minimum system pressure of 10 bar. Pressure relief valves are used to limit the

96 peak system pressure to 350 bar and protect hydraulic components.

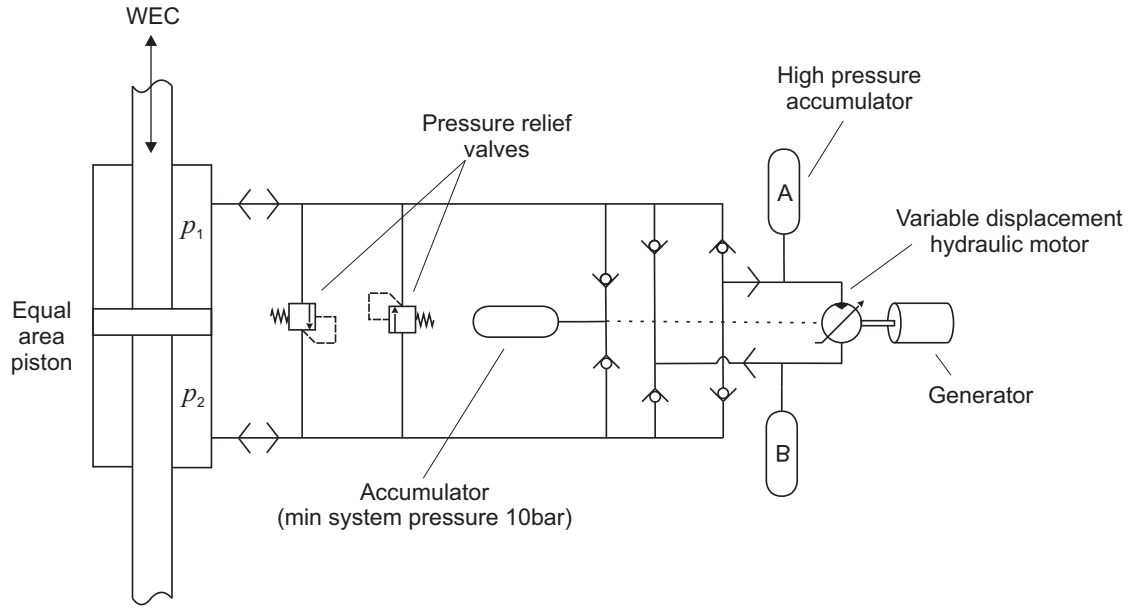


Figure 2: Hydraulic PTO circuit diagram

97 In reality there will be losses throughout the hydraulic circuit including friction
 98 in the piston and pipework, leakage in the motor and torque losses due to friction in
 99 the motor and generator. These losses will be system specific and are approximated
 100 here based on experience.

101 The PTO force is given by

$$\Phi = (p_1 - p_2)A_p - f_{fr} \quad (8)$$

102 where p_1 and p_2 are the pressures in the piston chambers, A_p is the piston area
 103 and f_{fr} is the cylinder friction force, given by

$$f_{fr} = f_c \text{sign}(\dot{x}) + f_v \dot{x} \quad (9)$$

104 where f_c and f_v are the Coulomb and viscous friction coefficients, respectively.

105 The details for calculating cylinder pressures are provided in [3].

106 The mechanical power captured by the PTO is given by

$$P_{cap} = \Phi \dot{x} \quad (10)$$

107 The power generated by the PTO is not equal to the captured power P_{cap} due
 108 to system losses in the hydraulic circuit and electrical generator. The generated
 109 power may be calculated from

$$P_{gen} = T_m \omega_m \quad (11)$$

110 where T_m and ω_m are the motor torque and angular velocity, respectively. The
 111 motor torque is calculated from [14]

$$T_m = x_m D_m (p_A - p_B) - C_f D_m (p_A - p_B) - C_v D_m \mu \omega_m \quad (12)$$

112 where x_m is the fraction of maximum displacement D_m of the hydraulic motor
 113 displacement, μ is the dynamic viscosity of the oil and p_A and p_B are the
 114 accumulator pressures. Again, the details for calculating accumulator pressures
 115 are provided in [3]. C_v and C_f are dimensionless viscous friction and Coulomb
 116 friction co-efficients representing motor losses according to the Wilson model [14].
 117 Slip losses are also included, and are calculated as [14]

$$q_m - \frac{C_s D_m (p_A - p_B)}{\mu} = x_m D_m \omega_m \quad (13)$$

118 where q_m is the flowrate to the motor and C_s is the dimensionless slip coefficient.
 119 The motor angular velocity can be calculated from rotational acceleration, which
 120 is given by

$$\dot{\omega}_m = \frac{T_m - T_g}{J} \quad (14)$$

121 where T_g and J are the torque and inertia of the generator.

122 Assuming no losses, the generator torque is given by

$$T_g = C_g \omega_m \quad (15)$$

123 where C_g is the damping coefficient of the generator.

124 Table 1 shows the component parameters in the PTO. These values are not
 125 based on any specific design but are a representation of suitable sizing for the
 126 buoy size. In this idealised case the effect of the boost pump is negligible and the

127 electrical generator is assumed to be 100% efficient so the electrical power
 128 generated can be equated to the mechanical power generated by the PTO. The
 129 high pressure accumulator ('A') has a relatively low pre-charge pressure to ensure
 130 that it charges even in calm wave conditions.

Maximum system pressure	350 bar
Equal area piston	
Area	0.007 m ²
Stroke Limit	±2.5 m
HP Gas accumulator 'A'	
Pre-charge Pressure	30 bar
Volume	200 L
γ	1.4
LP Gas accumulator 'B'	
Pre-charge Pressure	10 bar
Volume	200 L
γ	1.4
Variable Displacement Motor	
Capacity	180 cc/rev
Generator	
Damping coefficient	2.5 Nm/(rad/s)
Inertia	2 kgm ²
Oil Properties	
Viscosity	50 cSt
Density	850 kg/m ³

Table 1: PTO component values

131 Table 2 shows the parameters of all the other components required to calculate
 132 the losses.

Cylinder	
Coulomb friction (f_c)	3500 N
Viscous friction coefficient (f_v)	100 N/(m/s)
Variable Displacement Motor	
C_f	0.014
Check Valve	
Valve constant (K_v)	8.5×10^{-6}
Cracking Pressure	0.3 bar
Pipework	
Diameter (d)	50 mm
Total Length (l)	10 m

Table 2: PTO unit component loss parameters

133 **5. Wave Data Analysis**

134 Real ocean waves are random but there are key parameters which can be
135 calculated from recorded wave elevation data to analyse and compare different
136 sea states. These parameters are calculated from the frequency moments of the
137 variance spectrum (m_a) [15]. The frequency spectrum (S_n) is given by the Fast
138 Fourier Transform (FFT) of the wave elevation. Figure 3 shows the spectrum as
139 a result of taking the FFT of a 30 minute duration data packet sampled at
140 1.28Hz. The raw FFT produces a noisy spectrum which could produce erroneous
141 results when used to calculate key parameters of the underlying sea state. A
142 smoothed spectrum may be obtained by passing the raw amplitude spectrum
143 through a polynomial filter. In this case a Savitzky-Golay filter was used [16],
144 though this is arbitrary. A third order polynomial filter was used with a frame
145 size of 81. In subsequent analyses, both raw and smoothed spectra are used for
146 PTO tuning and the results are compared.

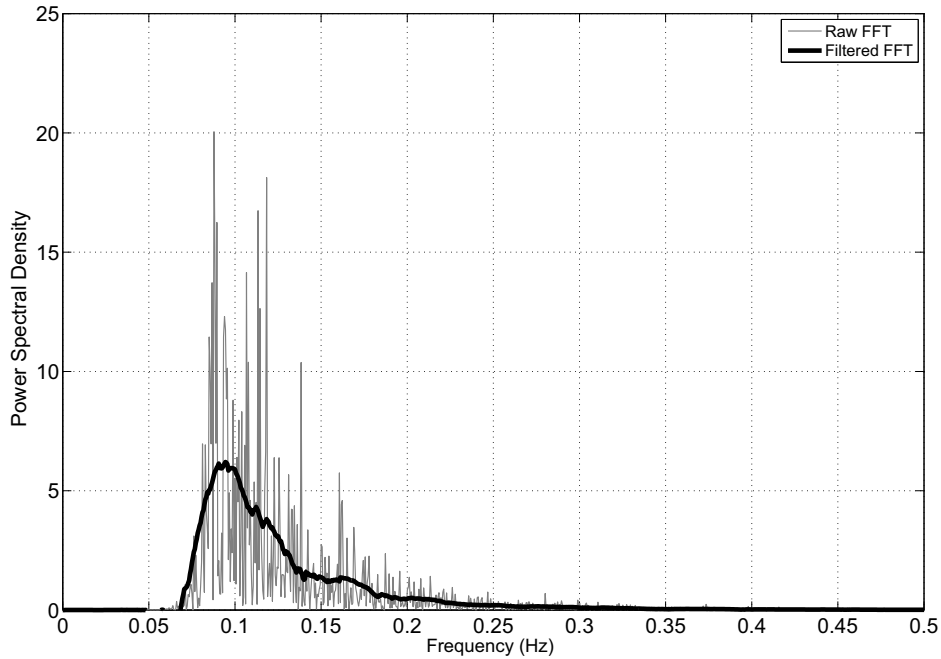


Figure 3: Example frequency spectrum of measured wave data

147 The moments of the variance spectrum (m_a) for $a=-1,0,1,2$, are calculated from

148 [15]:

$$m_a = \sum_{i=1}^N S_{n_i} \omega_i^a \Delta\omega = \int_0^{\omega_N} S_n \omega^a d\omega \quad (16)$$

149 where N is chosen so as to include the frequency range (ω_i to ω_N) containing
150 significant power (e.g. 0-0.25Hz in Figure 3.)

151 The significant wave height (H_s), peak period (T_p), energy period (T_e) and wave
152 power flux (P_{flux}) are key parameters[15]. The significant wave height is the
153 average of the wave heights of the third largest waves and the peak period is the
154 wave period corresponding to the most energetic waves in the spectrum and is
155 given by

$$H_s = 4\sqrt{m_0} \quad (17)$$

156 The peak period T_p is given by

$$T_p = \frac{1}{f_p} \quad (18)$$

157 where f_p is the frequency in Hz corresponding to maximum S_n .

158 The energy period (T_e) is given by

$$T_e = \frac{m_{-1}}{m_0} \quad (19)$$

159 The total wave power flux (P_{flux}) of the spectrum is the scalar sum over the
160 frequency range, and is found from

$$P_{flux} = \frac{1}{2a} \sum_{i=1}^N P_{wave_i} \quad (20)$$

161 Artificial irregular wave elevation and excitation force profiles can be created
162 using the random-phase method [5] though this results in periodic signals which
163 are not realistic. Alternatively, they can be generated by shaped filtering of
164 white noise [17, 18] which is more realistic. Real waves are non repeating and
165 their frequency spectrum may have more than one significant peak. This work
166 uses real wave data collected from test sites to determine if the trends and
167 methods which have been found previously [2] are applicable to real waves.
168 EMEC has a number of data collection buoys in different locations around their

169 site in Orkney. Data for the months of April and October 2011 were obtained for
170 one of the locations (Billia Croo Buoy E). The data is for the wave heave
171 displacement and it is split into 30 minute packets with a sampling frequency of
172 1.28 Hz.

173 The wave parameters defined in equations 17 to 20 were calculated for each
174 individual data packet and the results for both months are compared in Figures 4
175 to 7. They reveal that the average power available in April was lower than
176 October. October had more occurrences of the lowest level of wave power
177 (<30 kW/m) but there were also more large wave powers (>100 kW/m), which
178 indicates more variable weather (Figure 7). The average values of terms relating
179 to wave period are lower for October but the variance is lower in April. In
180 particular, there are more short period waves in October (Figure 5). This may
181 indicate a changing of the dominant wave frequency through the year in this
182 location.

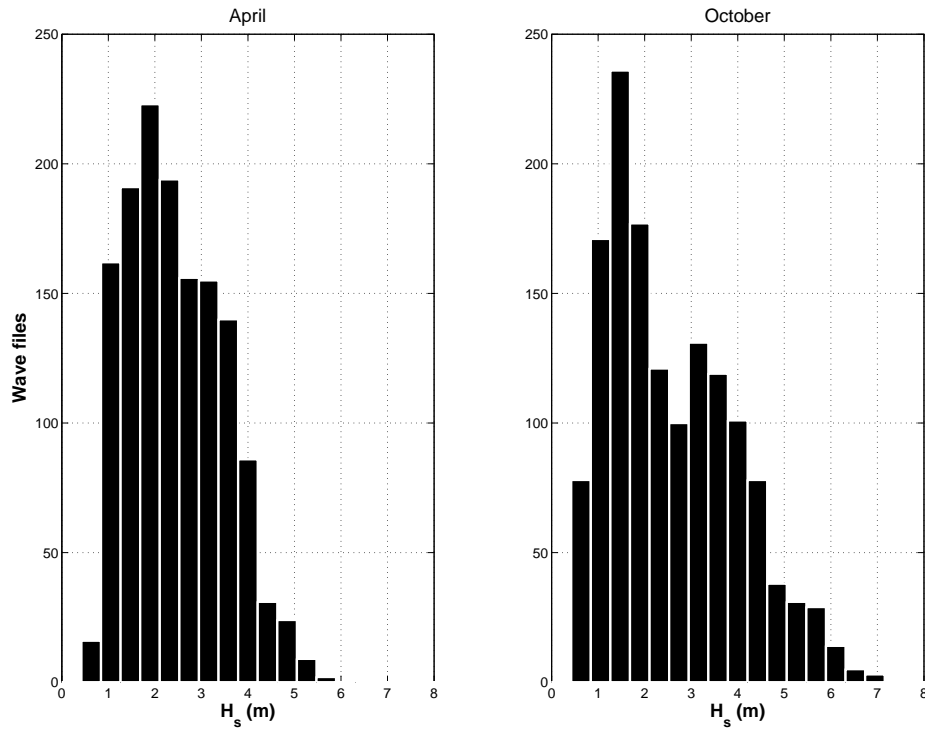


Figure 4: Frequency histogram showing the significant wave height in April and October

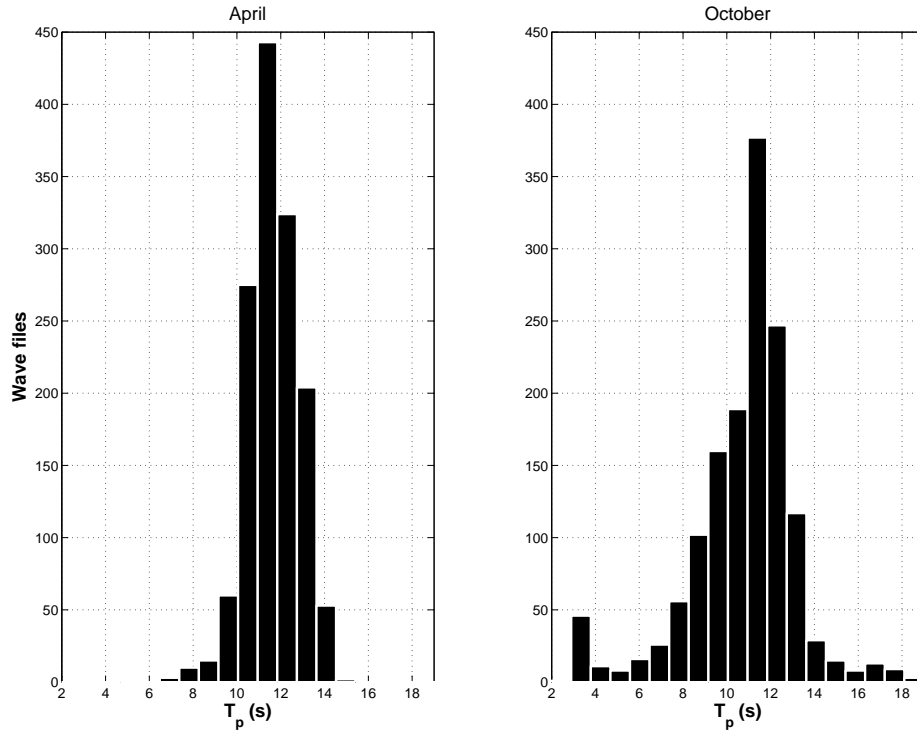


Figure 5: Frequency histogram showing the peak period in April and October (from filtered spectrum)

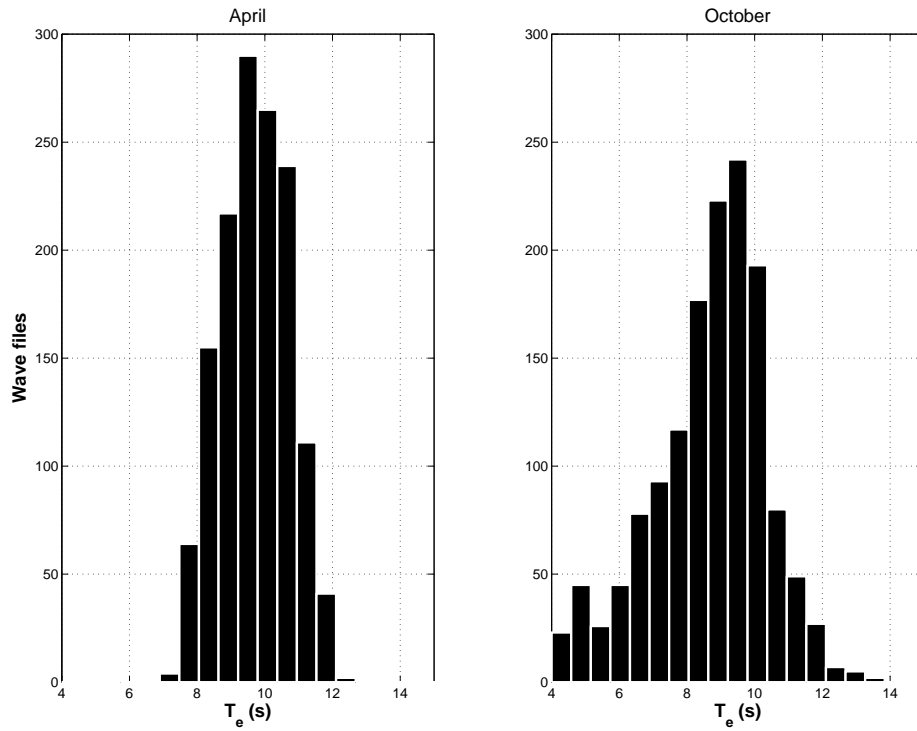


Figure 6: Frequency histogram showing the energy period in April and October

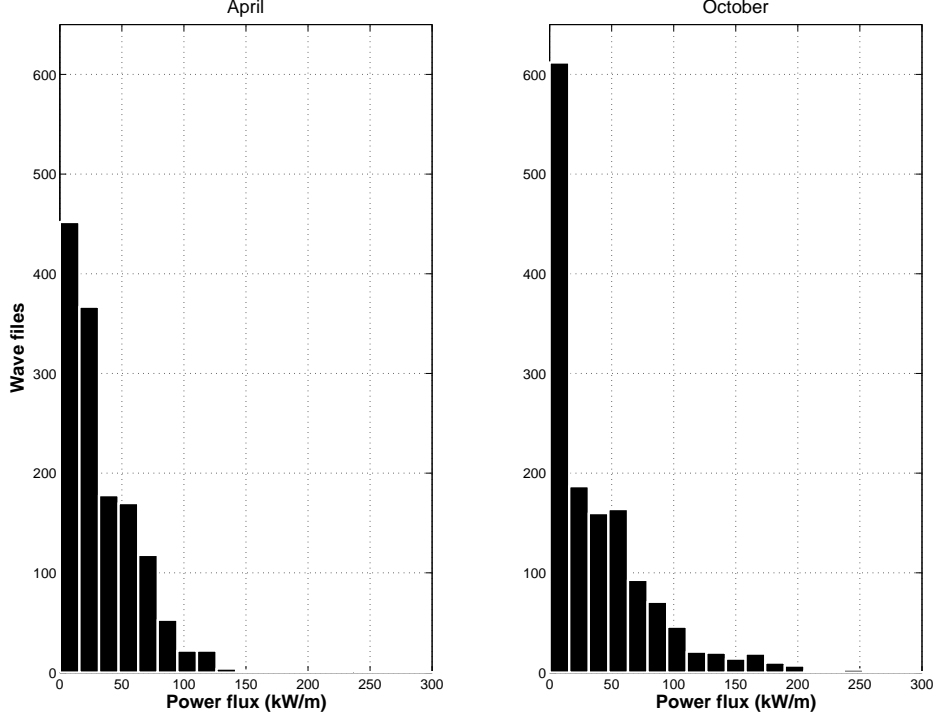


Figure 7: Frequency histogram showing the wave power flux in April and October

183 6. Generating a Wave Excitation Force Signal from wave elevation 184 data

185 The simulation model uses wave excitation force as the input to the
186 hydrodynamic model so it is necessary to create a wave excitation force signal
187 from the wave elevation data. The FFT of the wave displacement gives the
188 discrete frequency components (ω_i) and their corresponding amplitude (X_{w_i}) and
189 phase (ϕ_i). Assuming a finite number of wave components, the wave excitation
190 force coefficient $\Gamma(\omega_i)$ of each wave component can be calculated as follows.
191 Equations 4 and 6 can be combined to obtain an expression for the wave
192 excitation force amplitude F_e as a function of the radiation damping coefficient
193 $B(\omega)$:

$$F_e \approx H \sqrt{\frac{B(\omega)g^3\rho}{2\omega^3}} \quad (21)$$

194 According to Falnes [11], F_e can be expressed in terms of the wave excitation
195 force coefficient $\Gamma(\omega)$ as:

$$F_e = \Gamma(\omega) \frac{H}{2} \quad (22)$$

196 Comparing equation 21 with equation 22, it can be seen that

$$\Gamma(\omega_i) = \frac{2}{H} F_e \approx \sqrt{\left(\frac{2g^3 \rho B(\omega_i)}{\omega_i^3} \right)} \quad (23)$$

197 The excitation force can then be calculated from

$$f_e(t) = \sum_{i=1}^n \Gamma(\omega_i) X_w(\omega_i) \cos(\omega_i t + \varphi_i) \quad (24)$$

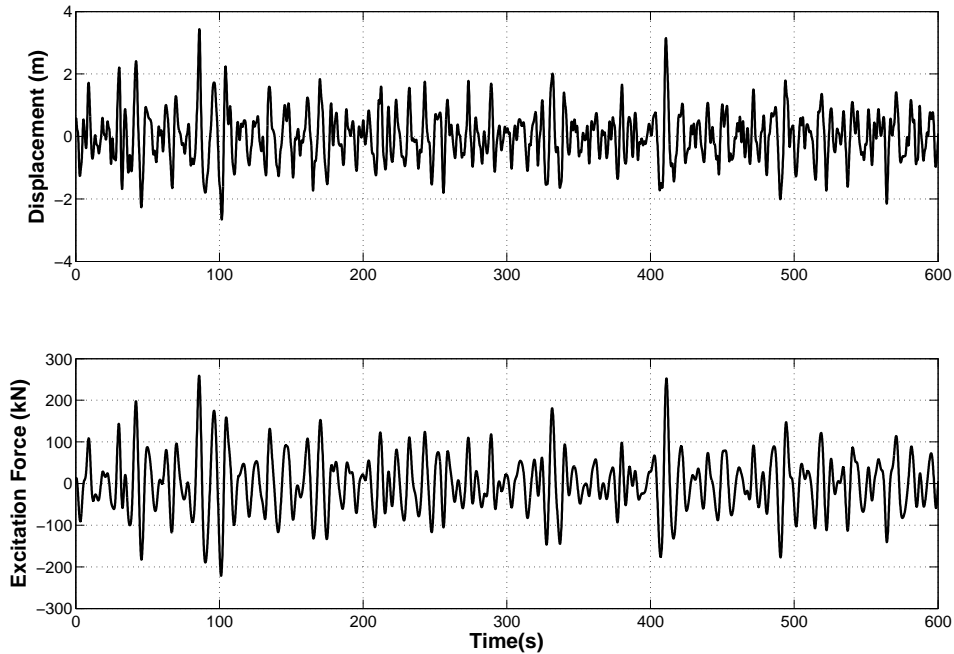


Figure 8: Wave displacement and excitation force for an example EMEC file

198 Figure 8 shows a 600 s section of an example EMEC file with the wave
 199 displacement and the calculated wave excitation force. In the time domain,
 200 Figure 9 shows that the WEC behaves in a similar manner to that in irregular
 201 waves produced by the random phase method [2], with induced body stall and
 202 Coulomb type PTO force evident.
 203 Since the wave profile is non-repeating the energy stored in the accumulators will
 204 not achieve a pseudo-steady state over a fixed time period as seen with a

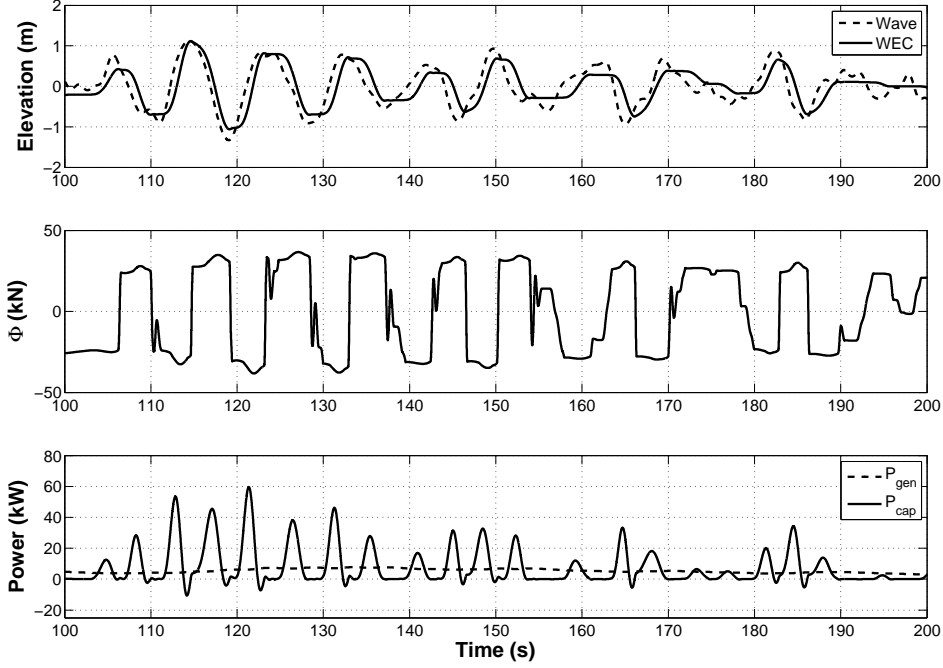


Figure 9: WEC and PTO behaviour in the example EMEC file

205 repeating wave force input [3]. Therefore, to negate the effect of the added
 206 energy stored in the accumulators giving an inaccurate result for the generated
 207 power (P_{gen}) and PTO efficiency (η_{pto}) the model is analysed over the largest
 208 possible time period.

209 7. PTO Tuning in Real Seas

210 Previous work [3] demonstrated a relationship between the peak wave period (T_p)
 211 and the optimum PTO damping (α_{opt}) for waves created using the
 212 Pierson-Moskowitz spectrum and the random phase method:

$$\alpha_{opt}(T_p) = C_g \left(\frac{x_m D_m}{A_p} \right)^2 \quad (25)$$

213 where A_p represents the piston area, C_g is the generator damping coefficient, D_m
 214 is the hydraulic motor capacity and x_m is the fraction of maximum motor
 215 displacement. Here, the piston area is fixed and the PTO damping is optimised
 216 for a given T_p by varying the motor capacity and generator load.

217 It is important to determine if this, or any other relationship, exists for real wave

218 data. Therefore, a number of wave packets were chosen in both months with
 219 $H_s \approx 2.5$ m and T_p ranging from 8-14s approximately. For each of the wave
 220 packets an optimisation algorithm was used to maximise P_{gen} and give α_{opt} to
 221 determine any trends between it and the wave parameters.

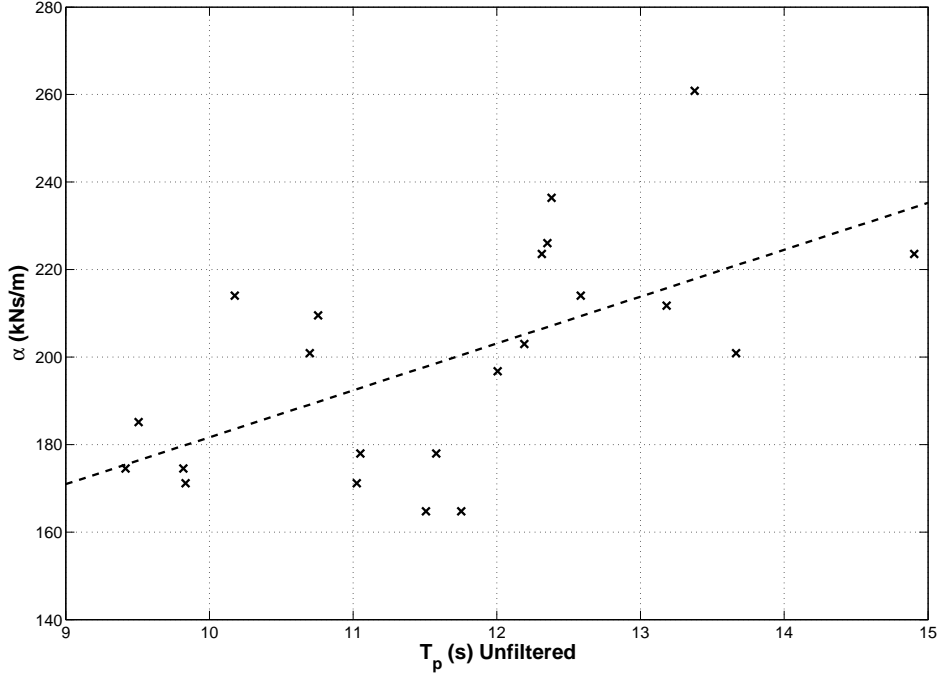


Figure 10: Optimum PTO damping vs peak wave period with filtered spectrum

Wave Parameter	Hydraulic PTO
T_p (Filtered)	74.9
T_p (Unfiltered)	95.3
T_e	56.1

Table 3: Norm of the residuals for the fit between the optimum PTO damping and the different wave parameters

222 Figures 10, 11 and 12 show that the correlation between T_p and α_{opt} is better
 223 when T_p is calculated from the filtered spectrum. However, Table 3 shows that
 224 the norm of the residuals, an indicator of the goodness of the correlation, is
 225 lowest for the fit between the energy period (T_e) and α_{opt} .

226 When comparing all the trend lines, it is clear from Figure 13 that the filtered T_p
 227 and unfiltered T_p trends are very similar. It also shows that the trend for T_e and
 228 T_p using a Pierson-Moskowitz spectrum are similar. In terms of power, Figure 14

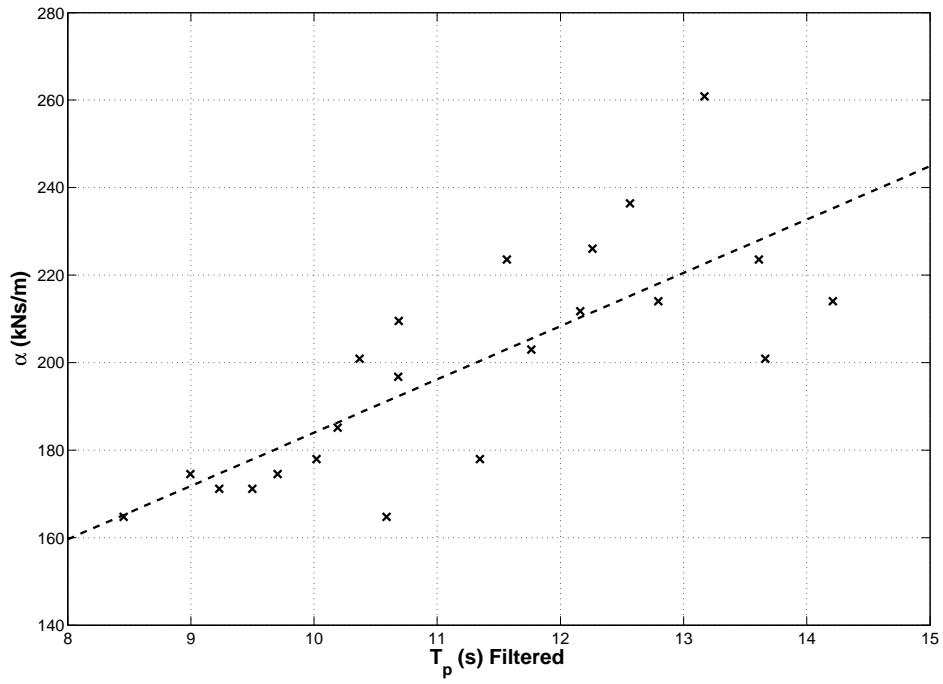


Figure 11: Optimum PTO damping vs peak wave period with unfiltered spectrum

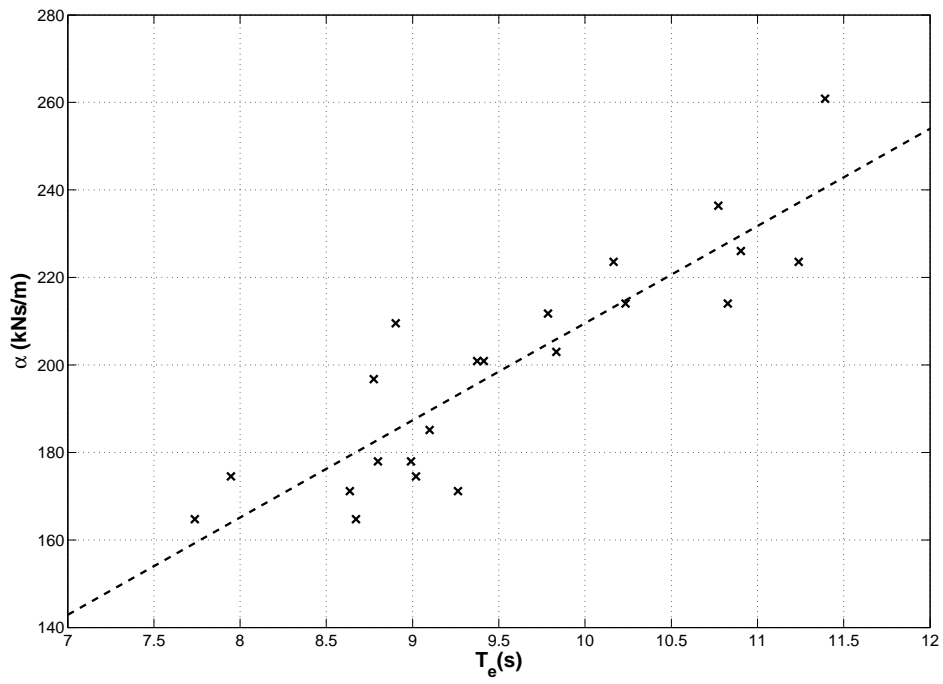


Figure 12: Optimum PTO damping vs energy period

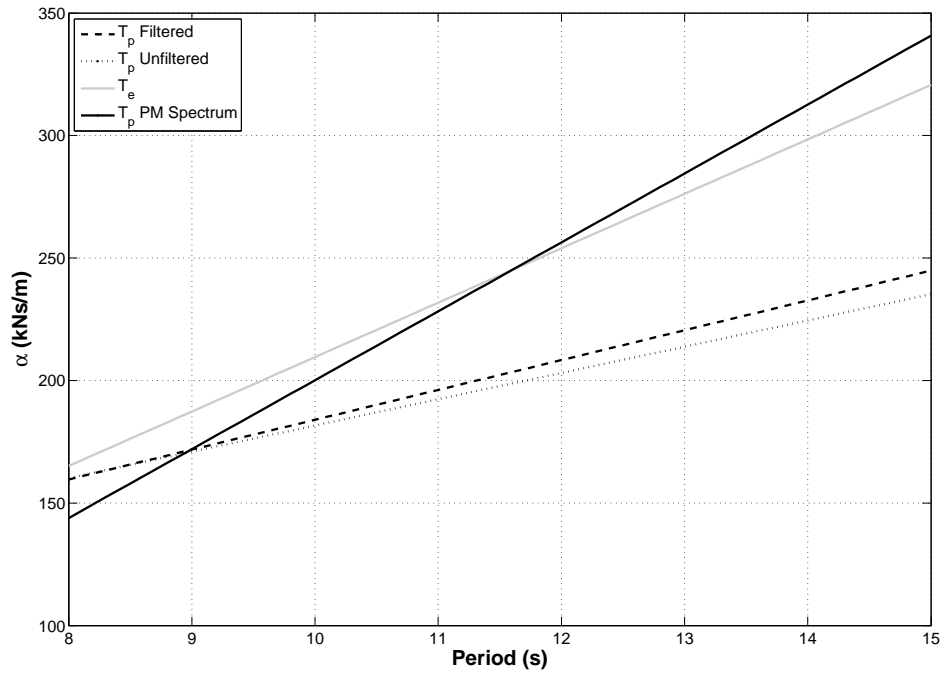


Figure 13: Comparison of the optimum PTO damping trends for the hydraulic PTO for different wave parameters

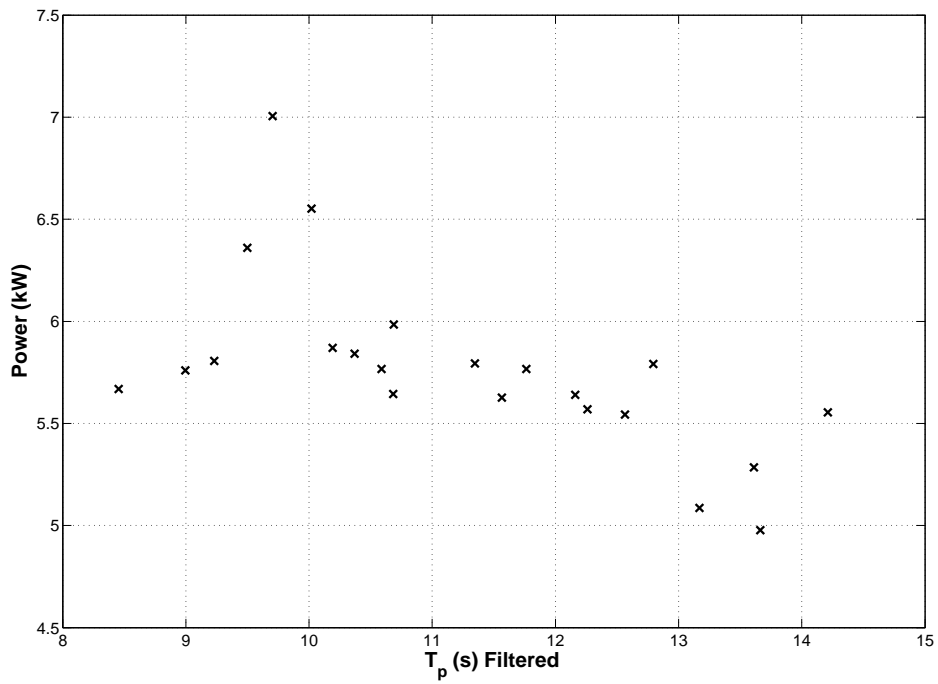


Figure 14: Maximum power generated (P_{gen}) vs peak wave period for the hydraulic PTO

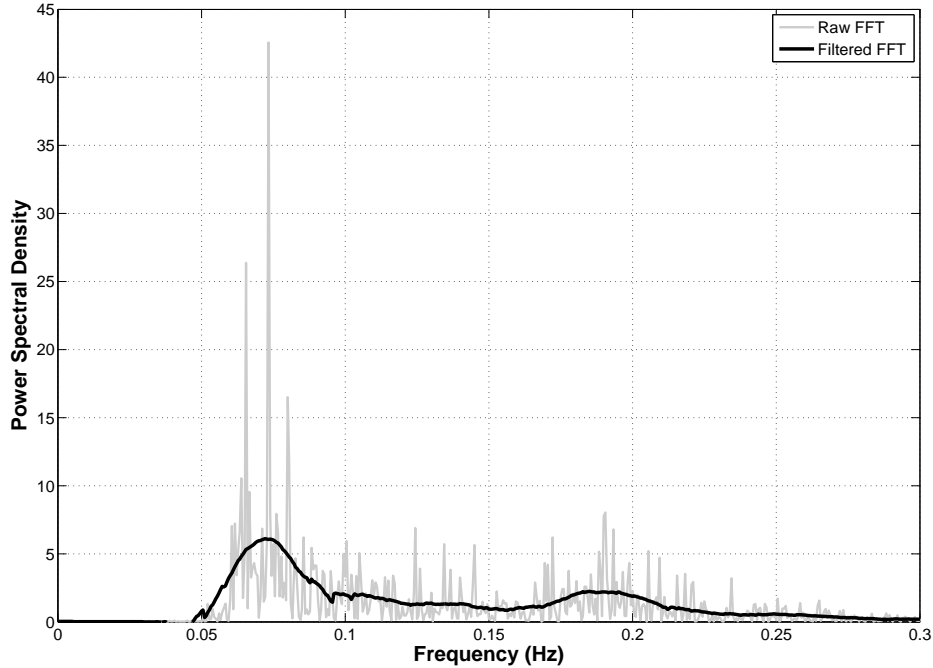


Figure 15: Frequency spectrum of one EMEC file with two distinct peaks

229 indicates that P_{gen} displays a minor drop with T_p , as previously demonstrated
 230 in [3].

231 Even with filtering, two distinct peaks may remain in the spectrum, like Figure
 232 15, so the PTO may best be tuned to a frequency between these two peaks,
 233 instead of the peak frequency, so it can benefit from the high energy at both
 234 these frequencies. These types of spectrum are mainly responsible for the outliers
 235 in Figures 10 and 11 and are the reason for the poorer correlation. The energy
 236 period is less affected by these types of spectrum and therefore produces a better
 237 correlation. It should be noted that sea states may exist in which little energy is
 238 concentrated at T_p [19], in which case an iterative learning scheme aiming to
 239 maximise measured power output by varying PTO and generator parameters
 240 would likely perform better.

241 8. Real Time PTO tuning

242 Results suggest that a PTO can be tuned to maximise power generation by using
 243 T_e over a 30 minute time period. It is therefore beneficial to investigate the most
 244 suitable time period to use for tuning the PTO. Four EMEC files, that were not

245 used previously to determine the tuning trends, are chosen to investigate real
 246 time PTO tuning. Their parameters are presented in Table 4 and their filtered
 247 spectra are shown in Figure 16.

Wave Parameter	Sea States			
	1	2	3	4
Date & Time	10/04 03:30	21/04 20:30	05/04 13:30	12/04 13:30
H_s (m)	1.24	1.98	3.10	4.34
(Filtered) T_p (s)	11.92	10.34	11.61	12.95
T_e (s)	10.18	9.72	8.83	10.45

Table 4: Parameters of the four EMEC files chosen for the real time PTO tuning

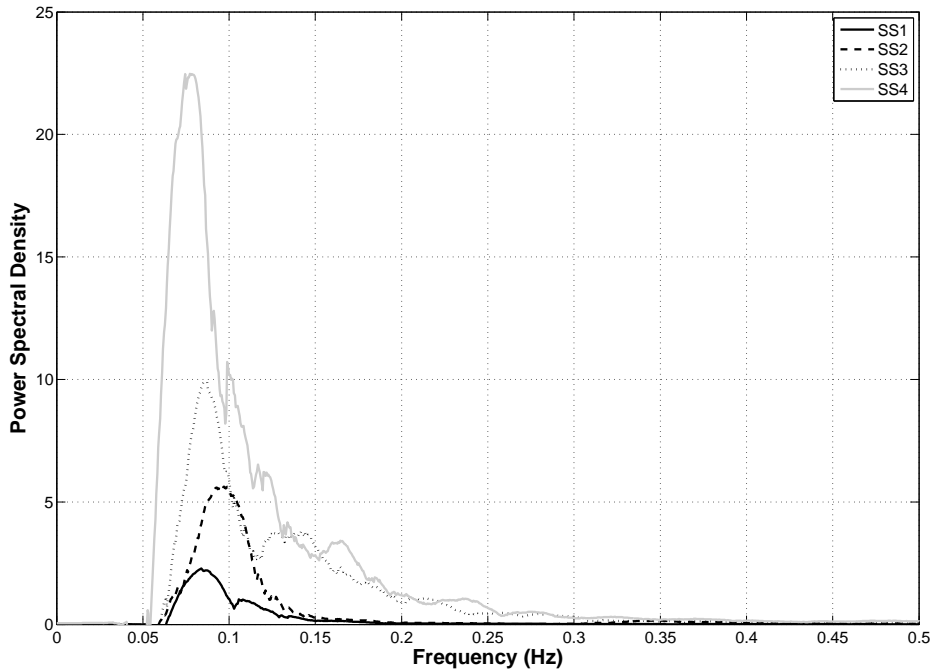


Figure 16: Filtered spectra of the four EMEC files chosen for the real time PTO tuning

248 Previous work into real time PTO tuning has shown an approximate doubling in
 249 power capture with a linear PTO by using an estimated wave frequency,
 250 calculated on a 20s moving average, rather than the constant energy frequency of
 251 the spectrum [7]. The estimated wave frequency is calculated using a windowed
 252 FFT of the wave displacement. Furthermore, it has been shown that active
 253 tuning methods generally outperform passive methods with a linear PTO. Passive
 254 methods assume the PTO settings to be fixed whereas the active methods

255 assume that PTO settings can be constantly varying. In [8], an active tuning
 256 technique is used with a 200 s window sliding FFT of the wave displacement.
 257 Most recently, work has been presented which illustrates the advantages of
 258 estimating the suitable wave frequency information by using signal processing
 259 and filtering of the wave displacement signal [20]. It estimates the wave
 260 frequency information without future knowledge of the wave profile using the
 261 zero-upcrossing method to update the linear PTO settings every 2-3 s. The
 262 zero-upcrossing method measures each point at which the wave profile crosses
 263 the zero line upward. That point is taken as the start of an individual wave and
 264 the next zero-upcrossing point is taken as the end of that wave. The time period
 265 between the two adjacent zero-upcrossing points is defined as the wave period for
 266 that individual wave and the vertical distance between the highest and lowest
 267 points between the adjacent zero-upcrossing points is defined as the wave height.
 268 In all these examples it is assumed that the PTO is linear and the desired
 269 settings are achieved instantly. This work investigates methods to calculate wave
 270 frequency information which is then used as the input to an open loop controller
 271 for the tuning of the hydraulic PTO. Due to the good linear relationship, the
 272 PTO damping (α) is adjusted according to wave energy period T_e (see Figure 12).
 273 A base-line passive method uses the PTO damping for the mean site energy
 274 frequency ($T_e=9.20$ s). The mean site energy frequency is calculated from the
 275 two months of data which have been collected. Four active methods are
 276 investigated which assume that future prediction of wave displacement at the
 277 WEC is not possible, so the PTO is tuned to the energy frequency calculated
 278 from a time period (window length) of preceding wave displacement data which
 279 is updated every 20 s.

Strategy	Notation	Window Length
Passive	P	Site Average
Active	A1	30 mins
	A2	10 mins
	A3	3 mins
	A4	30 s

Table 5: Parameters of the five tuning strategies for the hydraulic PTO

280 The use of a doubly-fed induction generator (DFIG) is assumed (as is commonly

281 used in wind turbines) because they offer variable speed generation in an efficient
 282 manner by using a frequency converter [21]. DFIGs have an operational range of
 283 approximately $\pm 30\%$ around the synchronous speed of 1500rpm, so it is assumed
 284 that if the hydraulic motor speed is outside of this range no power can be
 285 transmitted (P_{trans}) to the grid and the generated power is wasted. A generator
 286 efficiency of 100% is assumed. To maximise transmitted power, it is necessary to
 287 maintain the hydraulic motor speed within the generator speed limits at all times
 288 irrespective of wave conditions. The motor speed is controlled by adjusting its
 289 displacement (x_m) using a proportional-integral (PI) controller acting on the
 290 error in motor speed ω_m from the synchronous value ω_m with $0.1 < x_m < 1.0$.
 291 Empirically tuned proportional and integral gains of 0.05 and 0.01 were used.
 292 Changes to motor displacement (x_m) will be subject to the dynamics of the
 293 swash plate positioning system of the hydraulic piston motor. It is assumed that
 294 these dynamics can be modelled as a first order transfer function ($R(s)$) with a
 295 time constant, $\tau = 0.1$ s, such that

$$R(s) = \frac{1}{1 + 0.1s} \quad (26)$$

296 To ensure P_{cap} remains at its maximum, $\alpha_{opt}(T_e)$ must be maintained whilst
 297 controlling the motor speed. To maintain α_{opt} it is necessary to continually
 298 adjust the piston area or generator load at the same rate as x_m . Adjusting the
 299 generator load is the only feasible option so it must be varied alongside x_m to
 300 maintain α_{opt} according to [3]

$$C_g = \alpha_{opt}(T_e) \left(\frac{x_m D_m}{A_p} \right)^2 \quad (27)$$

301 Therefore, in the simulation model the signal to alter the generator load is passed
 302 through the same transfer function ($R(s)$ or, in practice, an estimate of the real
 303 transfer function) to ensure both signals are in phase. The block diagram of this
 304 control strategy is shown in Figure 17.

305 In general, the results show that there is only a marginal gain, if any, from using
 306 active tuning methods (Tables 6 to 10). The captured power (P_{cap}) is very
 307 similar for all the methods but there are slight variances in the generated (P_{gen})

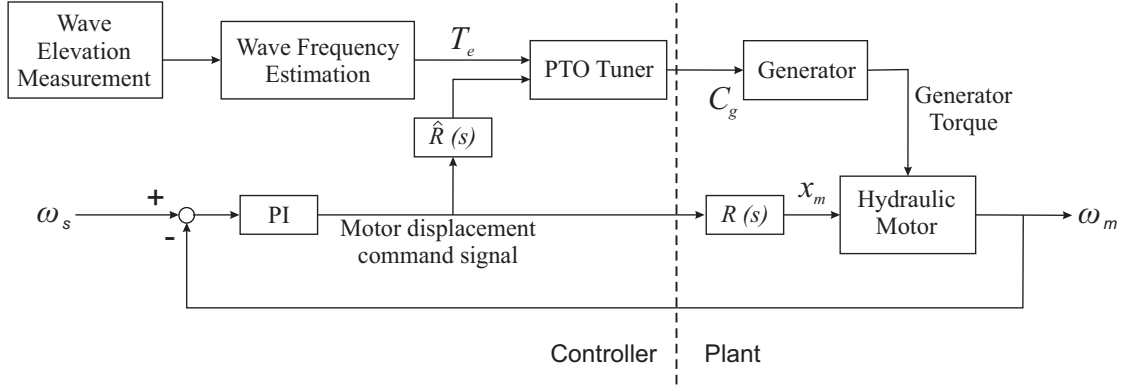


Figure 17: PTO Tuning and Motor Control Block Diagram

Strategy	Power (kW)			Efficiency (%)		
	P_{cap}	P_{gen}	P_{trans}	η_{pto}	η_{trans}	η_{tot}
P	1.13	0.18	0.18	16.2	98.7	16.0
A1	1.11	0.17	0.17	15.6	98.4	15.4
A2	1.12	0.18	0.17	15.7	98.6	15.5
A3	1.10	0.16	0.16	14.6	98.6	14.4
A4	1.10	0.16	0.16	14.6	98.5	14.4

Table 6: Results for SS1 comparing the different tuning methods

Strategy	Power (kW)			Efficiency (%)		
	P_{cap}	P_{gen}	P_{trans}	η_{pto}	η_{trans}	η_{tot}
P	6.21	3.41	3.40	54.8	99.7	54.7
A1	6.17	3.42	3.42	55.4	100	55.4
A2	6.16	3.42	3.42	55.4	100	55.4
A3	6.15	3.41	3.41	55.5	100	55.5
A4	6.16	3.41	3.38	55.3	99.2	55.3

Table 7: Results for SS2 comparing the different tuning methods

Strategy	Power (kW)			Efficiency (%)		
	P_{cap}	P_{gen}	P_{trans}	η_{pto}	η_{trans}	η_{tot}
P	15.7	9.38	6.75	59.6	72.0	42.9
A1	15.8	9.26	6.48	58.6	70.0	41.0
A2	15.8	9.26	6.43	58.6	69.4	40.7
A3	15.8	9.32	6.67	59.0	71.5	42.2
A4	15.7	9.27	6.64	58.9	71.6	42.2

Table 8: Results for SS3 comparing the different tuning methods

Strategy	Power (kW)			Efficiency (%)		
	P_{cap}	P_{gen}	P_{trans}	η_{pto}	η_{trans}	η_{tot}
P	28.2	16.5	4.81	58.5	29.1	17.0
A1	28.3	17.4	6.43	61.4	37.0	22.7
A2	28.3	17.4	6.51	61.6	37.5	23.1
A3	28.3	17.3	6.27	61.2	36.2	22.2
A4	28.2	17.1	5.89	60.5	34.5	20.8

Table 9: Results for SS4 comparing the different tuning methods

Strategy	Sea States				Average
	1	2	3	4	
P	0.18	3.40	6.75	4.82	3.79
A1	0.17	3.42	6.48	6.43	4.12
A2	0.17	3.42	6.43	6.51	4.13
A3	0.16	3.41	6.67	6.27	4.13
A4	0.16	3.38	6.64	5.89	4.02

Table 10: The transmitted power in kW for each sea state using the active and passive tuning methods

308 and transmitted power (P_{trans}). The biggest gain is for the highest energy sea
309 state (SS4) where the active methods out perform the passive method by at least
310 20% (in terms of P_{trans}). This is because T_e for SS4 has the biggest difference
311 from the site average value.

312 Figure 18 shows how the estimated energy period (T_e) and PTO damping (α)
313 vary with time for the different control strategies. For A4 there are large
314 fluctuations in T_e between consecutive discrete values but these variations reduce
315 as the window length of the strategies increases. For SS4 the largest P_{trans} is for
316 method A2. For shorter window lengths, like A4, there can be large transient
317 waves which have a major affect on the estimated T_e . A2 gives a good balance
318 between tracking changes in T_e whilst not being biased by large individual waves.
319 The advantage of using a shorter window length is the reduction in the capacity
320 required to store preceding data but with the passive method there is no
321 requirement for data storage or online calculations. The results for these sea
322 states show only a minor reduction in transmitted power with the passive
323 method, but this would be exacerbated if the energy period differs significantly
324 from the average site value.

325 By way of illustration, Figure 19 shows a comparison of motor displacement

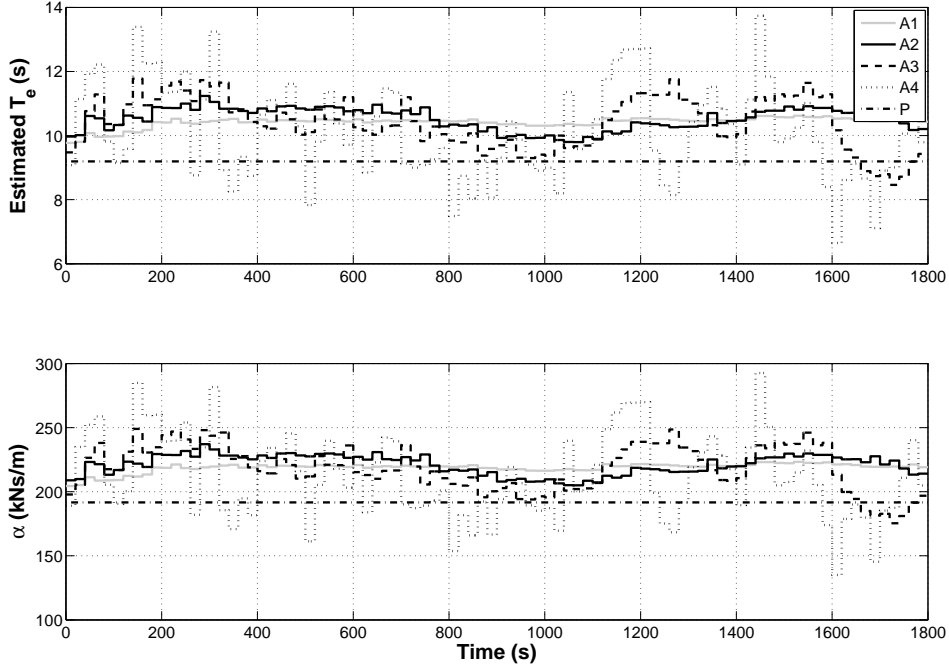


Figure 18: Estimated T_e and corresponding α for the control strategies for SS4

326 fraction and motor speed for control strategies P and A4 for SS3. This shows how
 327 the motor displacement is varied in order to attempt to maintain the synchronous
 328 speed of the generator. Figure 20 shows the corresponding transmitted power for
 329 the different control strategies. It is clearly seen that transmitted power drops to
 330 zero when the synchronous speed limit of $\pm 30\%$ is violated.

331 9. PTO Tuning To Future Wave Data

332 Results show that active tuning of the PTO using preceding wave displacement
 333 data does not provide a meaningful gain in P_{trans} compared to passive tuning to
 334 a mean sea state. If the incident wave displacement could be predicted then
 335 power increases could potentially be achieved. Previous work has shown this to
 336 be true for a linear PTO [8]. Here we investigate if this is also true for a realistic
 337 hydraulic PTO model.

338 The tuning method predicts T_e from a future window length of 20s and it uses
 339 the previously identified trend to modify α accordingly. The results, presented in
 340 Table 11, indicate that there is only a small gain from using a future wave
 341 prediction method when compared to the passive tuning method. The future

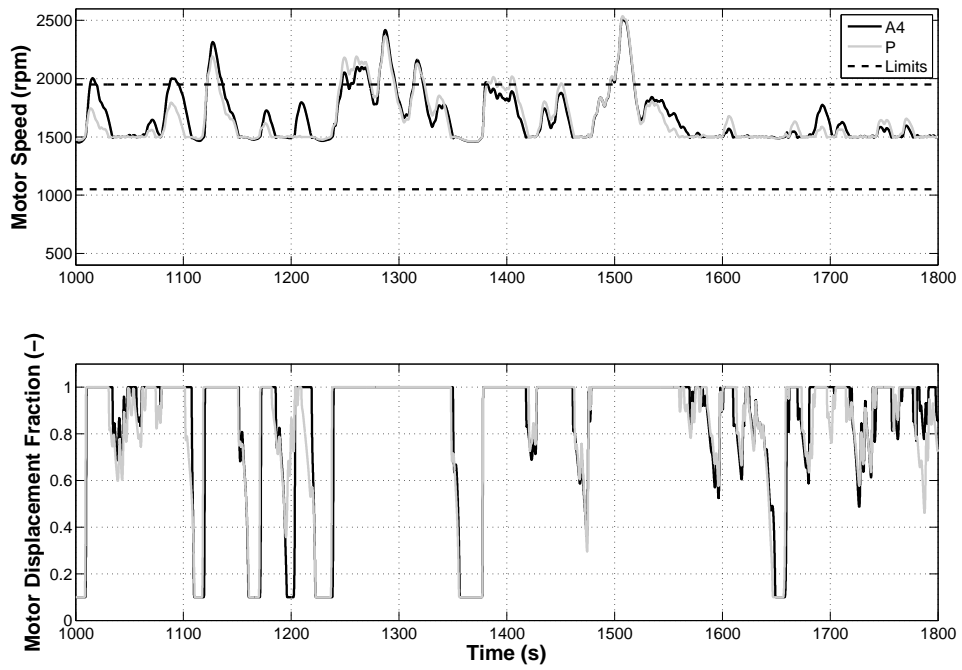


Figure 19: Comparison of motor displacement fraction and motor speed for control strategies P and A4 for SS3

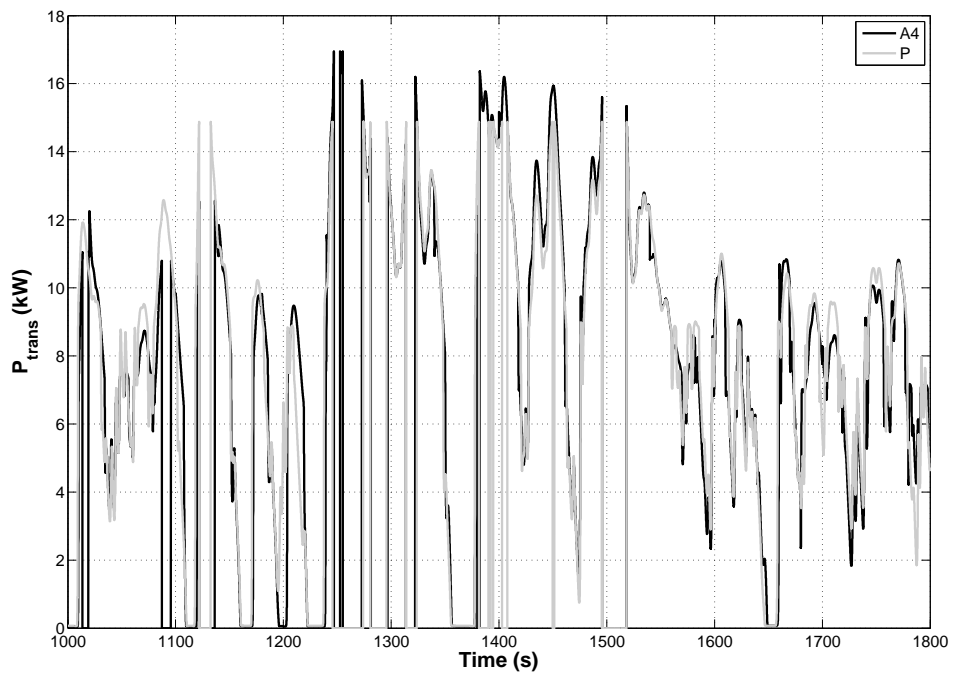


Figure 20: Comparison of transmitted power for control strategies P and A4 for SS3

342 prediction method only gives a higher transmitted power for SS4 compared to
 343 the passive method, but broadly speaking there is minimal change.

Strategy	Power (kW)	Sea States			
		1	2	3	4
Future	P_{cap}	0.97	6.19	15.7	28.4
	P_{gen}	0.11	3.38	8.99	17.1
	P_{trans}	0.10	3.37	5.79	5.41
Passive	P_{cap}	1.13	6.21	15.7	28.2
	P_{gen}	0.18	3.41	9.38	16.53
	P_{trans}	0.18	3.40	6.75	4.82

Table 11: The power for each sea state for the future and passive tuning methods

344 Therefore, this indicates that there is no gain from using algorithms or nearby
 345 measurement buoys to predict the future wave behaviour. Overall, the best
 346 tuning method is an active method which determines only a fundamental change
 347 in the energy frequency of the waves and therefore gradually changes the PTO
 348 damping to tune the device correctly. It is important to note that the presented
 349 P_{trans} values are still subject to the inefficiencies of the generator.

350 10. Conclusions

351 Wave data for two months in 2011, recorded at the European Marine Energy
352 Centre, was used to derive input data to evaluate tuning strategies for a realistic
353 model of a hydraulic power take-off for a wave energy converter. The model was
354 then used to determine the relationship between the peak wave and energy
355 period and the optimum PTO damping for a number of sea states with varying
356 parameters. An open loop active tuning method was investigated, in which past
357 wave displacement data was used to adjust the PTO damping according to the
358 wave energy frequency. Different window lengths were analysed for the active
359 methods and compared to a passive method in which the PTO is fixed and tuned
360 to the site average frequency. The investigation shows that the tuning of a
361 hydraulic PTO to an estimated wave frequency is a difficult task. Even if the
362 wave frequency can be estimated accurately and the PTO damping adjusted
363 immediately, the PTO force will not change instantly due to the dynamics of the
364 hydraulic PTO. The most effective active method analyses a sufficiently long
365 preceding period of data to determine any change in significant wave frequency
366 but not react to an individual wave. Power generation is expected to improve
367 using active tuning as the energy frequency of the waves deviates further from
368 the average site value. Preview knowledge of the future waves was shown to
369 provide no meaningful improvement in energy capture for a point absorber WEC
370 with a realistic PTO, though it would likely be of value for a wave-by-wave
371 strategy such as latching control.

372 Finally, the results have illustrated that there is a large power loss in the PTO.
373 This is due to significant power loss in the components of the PTO (especially
374 the hydraulic motor). For example, in low energy seas the small motor
375 displacement required to maintain the synchronous speed means that the motor
376 efficiency is always very low, so the mechanical power that is captured by the
377 PTO can not be converted efficiently. Also, in high energy seas, there is a
378 significant drop between the generated power and the transmitted power because
379 the motor displacement is not large enough to maintain the synchronous speed.
380 Therefore, even though the PTO efficiency may be adequate, a significant

381 portion of the generated power is lost. Significantly, power gains observed in
382 similar work using simplified linear PTO models and/or simplified sea states are
383 not seen here, demonstrating that over-simplification of the PTO during the
384 simulation phase of WEC development could lead to incorrect design decisions
385 and subsequent additional delay and cost.

386 References

- 387 [1] A.R. Plummer and M. Schlotter. Investigating the Performance of a
388 Hydraulic Power Take-Off. In *Proceedings of the 8th European Wave and*
389 *Tidal Energy Conference (EWTEC)*, Uppsala, Sweden, 2009.
- 390 [2] CJ Cargo, AR Plummer, AJ Hillis, and M Schlotter. Determination of
391 optimal parameters for a hydraulic power take-off unit of a wave energy
392 converter in regular waves. *Proceedings of the Institution of Mechanical*
393 *Engineers, Part A: Journal of Power and Energy*, 226(1):98–111, 2012.
- 394 [3] CJ Cargo, AJ Hillis, and AR Plummer. Optimisation and control of a
395 hydraulic power take-off unit for a wave energy converter in irregular waves.
396 *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of*
397 *Power and Energy*, 228(4):462–479, 2014.
- 398 [4] A.F.O. Falcão. Modelling and control of oscillating-body wave energy
399 converters with hydraulic power take-off and gas accumulator. *Ocean*
400 *Engineering*, 34(14-15):2021–2032, 2007.
- 401 [5] A.F.O. Falcão. Phase control through load control of oscillating-body wave
402 energy converters with hydraulic PTO system. *Ocean Engineering*,
403 35(3-4):358–366, 2008.
- 404 [6] A. Babarit, G. Duclos, and A.H. Clément. Comparison of latching control
405 strategies for a heaving wave energy device in random sea. *Applied Ocean*
406 *Research*, 26(5):227–238, 2005.
- 407 [7] H. Yavuz, A. McCabe, G. Aggidis, and M.B. Widden. Calculation of the
408 performance of resonant wave energy converters in real seas. *Proceedings of*

- 409 *the Institution of Mechanical Engineers, Part M: Journal of Engineering for*
410 *the Maritime Environment*, 220(3):117–128, 2006.
- 411 [8] H. Yavuz, T.J. Stallard, A.P. McCabe, and G. Aggidis. Time series
412 analysis-based adaptive tuning techniques for a heaving wave energy
413 converter in irregular seas. *Proceedings of the Institution of Mechanical*
414 *Engineers, Part A: Journal of Power and Energy*, 221(1):77–90, 2007.
- 415 [9] M. Folley and T. Whittaker. The control of wave energy converters using
416 active bipolar damping. *Proceedings of the Institution of Mechanical*
417 *Engineers, Part M: Journal of Engineering for the Maritime Environment*,
418 223(4):479–487, 2009.
- 419 [10] A. Babarit, M. Guglielmi, and A.H. Clément. Declutching control of a wave
420 energy converter. *Ocean Engineering*, 36(12):1015–1024, 2009.
- 421 [11] J. Falnes. *Ocean Waves and Oscillating Systems: Linear Interactions*
422 *including Wave-Energy Extraction*. Cambridge University Press, Cambridge,
423 UK, 2002.
- 424 [12] A. Hulme. The Wave forces acting on a floating hemisphere undergoing
425 forced periodic oscillations. *The Journal of Fluid Mechanics*, 121:443–463,
426 1982.
- 427 [13] S. Barstow, G. Mørk, D. Mollison, and J. Cruz. The Wave Energy Resource.
428 In J. Cruz, editor, *Ocean Wave Energy: Current Status and Future*
429 *Perspectives*, chapter 4, pages 93–132. Springer, 2008.
- 430 [14] W.E. Wilson. Performance criteria for positive displacement pumps and
431 fluid motors. *Trans. Am. Soc. Mech. Eng*, 71(2):115–120, 1949.
- 432 [15] Edward Pitt. Assessment of Wave Energy Resource. Technical report,
433 European Marine Energy Centre, 2009.
- 434 [16] A. Savitzky and M.J.E. Golay. Smoothing and Differentiation of Data by
435 Simplified Least Squares Procedures. *Analytical Chemistry*,
436 36(8):1627–1639, 1964.

- 437 [17] M.J. Ketabdari and A. Ranginkaman. Simulation of Random Irregular Sea
438 Waves for Numerical and Physical Models Using Digital Filters. *Transaction*
439 *B: Mechanical Enginerring*, 16(3):240–247, 2009.
- 440 [18] AJ Hillis. Active motion control of fixed offshore platforms using an
441 extended state observer. *Proceedings of the Institution of Mechanical*
442 *Engineers, Part I: Journal of Systems and Control Engineering*,
443 224(1):53–63, 2010.
- 444 [19] A.D. de Andrés, R. Guanche, J. Weber, and R. Costello. Finding gaps on
445 power production assessment on wecs: Wave definition analysis. *Renewable*
446 *Energy*, 83:171–187, 2015.
- 447 [20] H. Yavuz, S. Mistikoglu, and T. Stallard. Processing irregular wave
448 measurements to enhance point absorber power capture performance. *Ocean*
449 *Engineering*, 38(4):684–698, 2011.
- 450 [21] A. Petersson. *Analysis, Modeling and Control of Doubly-Fed Induction*
451 *Generators for Wind Turbines*. PhD thesis, Chalmers University of
452 Technology, 2005.

453 **Nomenclature**

454 **Nomenclature**

$A(\omega)$	frequency dependent added mass	[kg]
A_p	piston area	[m ²]
r	buoy radius	[m]
$B(\omega)$	frequency dependent radiation damping coefficient	[Ns/m]
C_f	motor coulomb friction coefficient	[-]
C_g	generator damping coefficient	[Nm/(rad/s)]
C_v	motor viscous friction coefficient	[-]
D_m	motor capacity	[cc/rev]
f_c	coulomb friction	[N]
f_e	wave excitation force	[N]
f_{fr}	cylinder friction	[N]
f_h	wave force	[N]
f_{hs}	wave hydrostatic force	[N]
f_v	viscous friction coefficient	[Ns/m]
f_r	wave radiation force	[N]
$F_e(s)$	Laplace transform of wave excitation force	[N]
g	gravitational acceleration	[ms ⁻²]
H	wave height	[m]
H_s	significant wave height	[m]
J	generator inertia	[kgm ²]
K_v	valve coefficient	[m ³ /s bar]
k	wave number	[m ⁻¹]
l	half height of buoy	[m]
m	mass of buoy	[kg]
n	number of wave components	[-]
p_i	piston chamber pressure (i = 1,2)	[bar]
p_A	accumulator 'A' pressure	[bar]
p_B	accumulator 'B' pressure	[bar]
P_{cap}	captured power	[kW]
P_{gen}	generated power	[kW]

P_{trans}	transmitted power	[kW]
P_{wave}	wave power	[kW]
q_m	flow rate to the motor	[m ³ /s]
S_n	spectral density	[m ² s]
t	time	[s]
T_m	motor torque	[Nm]
T_p	peak period	[s]
x	buoy displacement	[m]
x_m	fraction of motor displacement	[-]
α	PTO damping	[Ns/m]
α_{opt}	optimum PTO damping	[Ns/m]
Δt	wave cycle time	[s]
$\Delta\omega$	wave frequency band	[rad/s]
ϵ	Havelock's coefficient	[-]
η_{pto}	PTO efficiency	[%]
$\Gamma(\omega)$	wave excitation force coefficient	[N/m]
μ	oil dynamic viscosity	[Ns/m ²]
ρ	water density	[kg/m ³]
Φ	PTO force	[N]
ω	wave frequency	[rad/s]
ω_m	angular motor velocity	[rad/s]
ω_s	generator synchronous velocity	[rad/s]
φ	wave phase component	[s]