Techno-Economic Optimisation for Wave Energy Converters

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Abstract

Successful development of Wave Energy Conversion technology is made difficult by a combination of factors, these include; the inaccessible nature of the target ocean locations; the relatively high cost of fullscale device testing; the stochastic nature of ocean waves; the strong interaction between subsystem designs; and, the apparent gulf between required and, so far, demonstrated performance. These difficulties taken together mean that design optimisation in software should assume a greater importance in wave energy than it does in other industries at comparable maturity.

This paper presents a techno-economic optimisation of a generic wave energy converter, namely a hinged barge. The optimisation is techno-economic in the sense that the optimisation algorithm manipulates the technical parameters of the device in order to improve the value of an economic objective function. The economic objective function used is the estimated net present value of a large array deployment. The technical parameters included are device geometry, power transmission equipment design and control parameters. A comparison between the techno-economic optimisation and an optimisation using a purely technical objective function is presented. The results show that the techno-economic optimisation results in a superior economic performance and significantly different optimised designs.

Keywords: Ocean Wave Energy Conversion, Linear-Array, Techno-Economic, Optimisation, Hinged Barge, Net Present Value, Power Take Off, CapEx, OpEx, Revenue.

1. Introduction

Numerical evaluation and optimisation of wave energy converter (WEC) technology has, to date, largely focused on technical or physical and not economic value measures. The objective functions commonly used in optimisations have included; average absorbed power [1-3] and annual energy productivity per unit displacement [4]. Other choices that have been suggested include; capture width, relative capture width, annual energy productivity per unit surface area, annual energy productivity per unit width or length and annual energy productivity per unit draught. However, the relevance of these performance measures to the ultimate commercial viability of wave energy farms is not well established.

Rather than attempt to establish the relationship between any of the non-economic value measures and the viability of a WEC device we propose that it is better to develop an economic value measure and use this as an objective function in optimisation of the technical parameters of the WEC.

We present here a comparison of optimisation results with two alternative objective functions, these alternatives are firstly *annual energy productivity per unit surface area of device* and secondly *net present value of a 100MW wave farm project*. The optimisation is applied to a generic device.
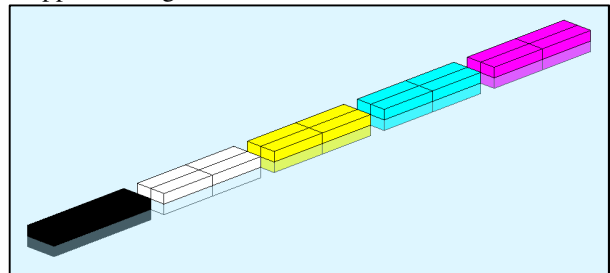

Figure 1: Generic device to be optimised.

2. Generic Device

The generic device under consideration is a hinged barge, somewhat similar to devices proposed by Cotteral [5], Farley [6] and McCabe [7]. The device is composed of a number of identical rectangular pontoons or barges arranged in a linear array with equal spacing. The spacing of the linear array is such that there is a gap between each barge and the next. Adjacent barges are joined by hinges and the axis of each hinge is horizontal, in the water plane, perpendicular to the centreline of the linear array and

mid-way through the gap. For simplicity the barges are given equal draught and freeboard.

It is intended that the device operates as an attenuator (as categorised by [8]) with the centreline of the linear array parallel to the principal wave direction. Power is removed from the oscillating bodies, for onward transmission to the electricity grid or other end customer, through a power take off (PTO) system attached to each hinge which resists the relative motion at the hinge. It follows that an *n*-body device having *n*-1 hinges will also have *n*-1 PTO sub-systems.

The geometry of a sample instance of this device is presented in table 1 and shown in figure 1.

Property	Value	Unit
Length, (overall)	200	m
No-Body	5	-
Beam	10	m
Draught	3	m
Freeboard	3	m
Gap between barges	5	m

Table 1: Geometrical parameters of sample device.

3. Technological Component

The techno component of the techno-economic objective function is composed of three parts; firstly a power absorption calculation which characterises the energy productivity in a predefined set of relevant sea states, secondly a list of cost drivers, and thirdly a table of reliability information.

3.1 Energy Absorption

To simplify the calculations unidirectional wave spectra with wave heading parallel to the longitudinal axis of the hinged barge are assumed. This simplification allows four of the six modes of rigid body motion to be neglected (surge, sway, roll & yaw) thereby significantly reducing the size of the matrices which must be solved while preserving the modes of motion that are important for power production in this type of device (heave & pitch).

To represent the hinges between the barges a constraint elimination approach, similar to [9] is taken. For an N body device the vector of velocity is $u \in \mathbb{R}^{2N}$, whose elements represent heave and pitch of the N bodies. In the presence of the hinges only $N + 1$ of these $2N$ velocities are independent, therefore we define the independent velocity vector, $\bar{u} \in \mathbb{R}^{N+1}$. In the analysis presented here the elements of $\bar{u}$ are the heave and pitch velocities of the first body and the pitch velocities of the remaining $N - 1$ bodies. A transformation matrix $P \in \mathbb{R}^{N+1 \times 2N}$ allows the definition of u in terms of $\bar{u}$, P is the partial derivative of the elements of u with respect to $\bar{u}$:

$$P_{ij} = \frac{\partial u_j}{\partial \bar{u}_i} \tag{1}$$

so that $u = P^{\mathrm{T}}\bar{u}$.

An example P for our hinged barge with $N = 5$ and distance L between hinges is:

$$P = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & \frac{L}{2} & 0 & \frac{L}{2} & 0 & \frac{L}{2} & 0 & \frac{L}{2} & 0 \\ 0 & 0 & \frac{L}{2} & 1 & L & 0 & L & 0 & L & 0 \\ 0 & 0 & 0 & 0 & \frac{L}{2} & 1 & L & 0 & L & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{L}{2} & 1 & L & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{L}{2} & 1 \end{bmatrix} \tag{2}$$

The power absorbtion calculation is done in the frequency domain. The steady state frequency dependant velocity phasor, $\hat{u}$, is calculated from:

$$\hat{u} = \frac{\hat{F}}{Z_m} \tag{3}$$

$$\hat{F} = X_\omega a \tag{4}$$

$$Z_m = i\omega(M + A_\omega) + \left(B_\omega + B_{pto} + B_v\right) + \frac{(C + C_{pto})}{i\omega} \tag{5}$$

where $\hat{F}$ is the excitation force, Z_m is the mechanical impedance of the system as a whole, X_ω is the transfer function from wave amplitude to excitation force, a is the wave amplitude, M is the inertia matrix for the system, A_ω is the added mass, B_ω is the radiation damping, B_{pto} is the PTO damping coefficient B_v is a viscous loss coefficient, C is the hydrostatic stiffness matrix and C_{pto} is the PTO stiffness term.

The linear hydrodynamic coefficients for each device, (X_ω, A_ω & B_ω) were assessed using Wamit™, the radiation and diffraction solutions for the same sample geometry presented in section 2 are presented in figures 2 to 5. The radiation solution is almost identical for each body in the device while the diffraction solution is more diverse, particularly in pitch excitation.

For simplicity the PTO stiffness, C_{pto}, is assumed to be zero and the PTO damping coefficient is assumed to be equal at each hinge. An example B_{pto} matrix, which achieves this for a 5 body hinged barge, with damping coefficient *b* at each hinge is:

$$B_{PTO} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b & 0 & -b & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -b & 0 & 2b & 0 & -b & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -b & 0 & 2b & 0 & -b & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -b & 0 & 2b & 0 & -b \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -b & 0 & b \end{bmatrix} \quad (6)$$
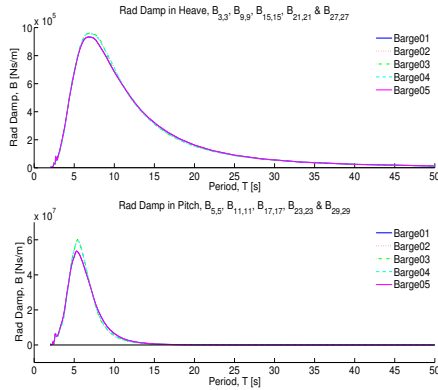

Figure 2: Radiation Damping for Sample Device.
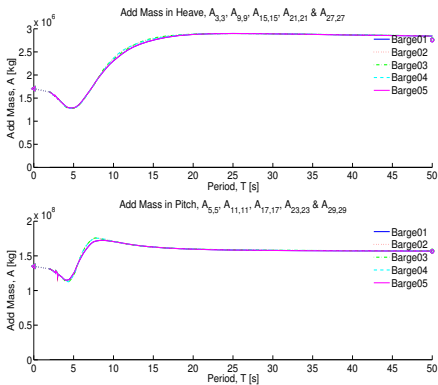
Figure 3: Added Mass for Sample Device.

The average power produced by the device in a given sea state is:

$$\phi_{PTO} = \sum_{\omega} \frac{1}{2} B_{PTO} |\hat{u}||\hat{u}| \quad (7)$$

The assessment is based on evaluation of a full annual scatter diagram of panchromatic sea states, the scatter diagram for Belmullet by Mollison [10] is used. The annual average power production is:

$$\phi_{ann} = \sum_{i} \phi_{PTO} x_i \quad (8)$$

where x_i is the fraction of a year for which sea state i occurs.
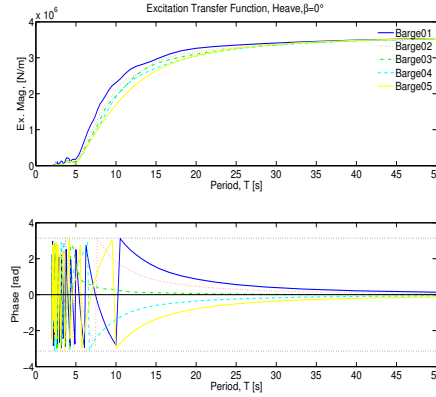

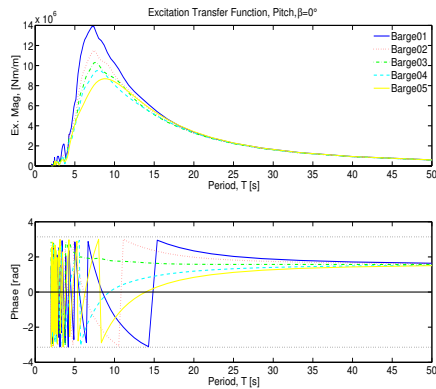**Figure 4:** Heave Excitation for Sample Device.

Figure 5: Pitch Excitation for Sample Device.

3.2 CapEx Drivers

An important link between the techno and economic evaluations is the CapEx drivers of the system, these are the aspects of the device specification that have a very strong influence on the capital cost of the device. In the optimisation reported in this paper the CapEx drivers considered are: Device surface area, device displacement, number of hinge/PTO units, maximum PTO effort, maximum PTO excursion, maximum device power. These quantities are calculated from the geometry and from the results of the energy absorption calculation.

4   Economic Calculation

The method used to assess the economic performance of each device is the same as that reported in [11]. Figure 6 gives the top level structure of the calculation. The outputs of the "techno" component are the inputs to the "economic" component of the techno-economic objective function. The productivity and costs assessment generates estimates of CapEx, OpEx and productivity and the economic value of the project is calculated.
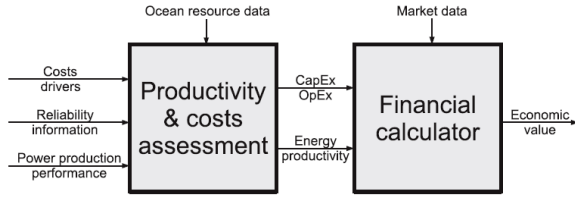
Figure 6: Top Level Structure of Economic Assessment

The method estimates the productivity, capital expenditure (CapEx) and operational expenditure (OpEx) over the lifetime of a large wave farm deployment.

The device CapEx is considered to be composed of the cost of the hull structure and the PTO-hinge system(s) moorings and anchors are neglected for this preliminary analysis.

$$CapEx_{device} = CapEx_{structure} + CapEx_{PTO} \quad (9)$$

$$CapEx_{structure} = AA_{skin} + BM_{ballast} \quad (10)$$

$$CapEx_{PTO} =$$
$$(N-1)(C4|F_{max}||\xi_{max}| + D(P_{max}) + E) \quad (11)$$

where A is the cost per unit surface area of the outer skin and B is the cost per unit mass of the ballast material. Assuming that $4|\xi_{max}|$ is the maximum total travel of the PTO in one cycle, the product $4|F_{max}||\xi_{max}|$ is equal to the maximum energy that the primary stage of the PTO can extract from the oscillating bodies in a single cycle, C is the cost per unit energy of providing this energy extraction capability in the PTO. D is the cost per unit installed power capacity of providing for the onward transmission of this absorbed energy. E is the fixed cost per hinge in the device.

The cost of the grid connection is calculated as:

$$CapEx_{grid} = P_{farm}L_{shore}F + N_{device}G \quad (12)$$

F is the cost of cable per km per MW. G is the cost of connecting additional devices.

The cost of wave farm installation is calculated as:

$$CapEx_{install} = N_{device}HI \quad (13)$$

H is the number of days per device install and I is the daily cost of the installation mobilisation.
The total CapEx is:

$$CapEx_{total} = N_{device}CapEx_{device} \\ + CapEx_{grid} \\ + CapEx_{install} \quad (14)$$

The operational expenditure, plant availability and energy productivity are estimated by an operational simulation as described by [11].

5 Optimisation Approach

Selected technical parameters of the generic hinged barge, introduced in Section 2, are optimised using firstly a physical or non-economic objective function and secondly using a techno-economic objective function. In both cases the selected technical parameters of the device to be optimised are the overall length of the device, the number of bodies composing the device and the damping values for each cell in the

scatter diagram. The optimisation of the damping values is nested within the optimisation of the geometric values.

The optimisation method in the outer optimisation is a simple pattern search, as given by [12] and the optimisation of the damping value is a line search, also described by [12].
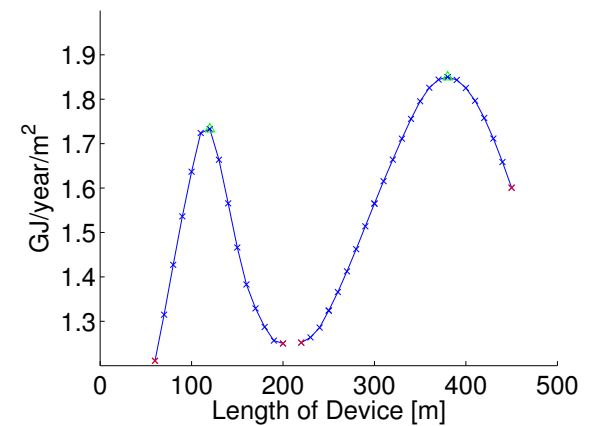
6 Results

6.1 Non-Economic Optimisation

Figure 7 and 8 show the results of the optimisation with the non-economic objective function. In both cases the red "x" points indicate the initial values for an optimisation and the green triangle points indicate a local maximum in the objective function.
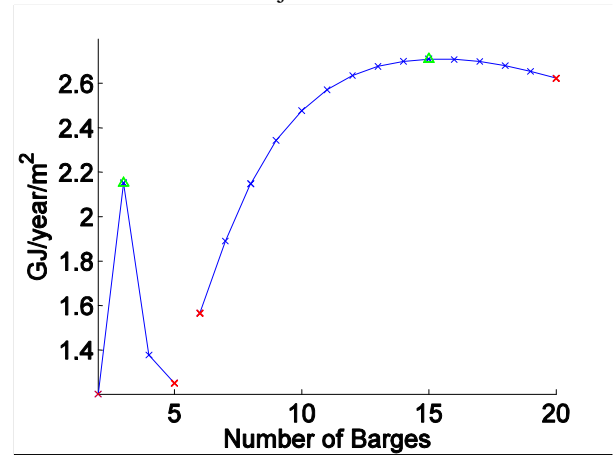
Figure 7: Results for Optimisation of Number of Barges with non-economic objective function.

Figure 8: Results for Optimisation of Length of Device with non-economic objective function.

The results show multiple local solutions in both variables, corresponding to candidate devices with favourable geometrical tuning to the predominant wavelengths in the scatter diagram.

6.2 Techno-Economic Optimisation Results

Figure 9 and 10 show the optimisation of the same variables as in the previous section but this time with the NPV of the wave farm project as the objective function.
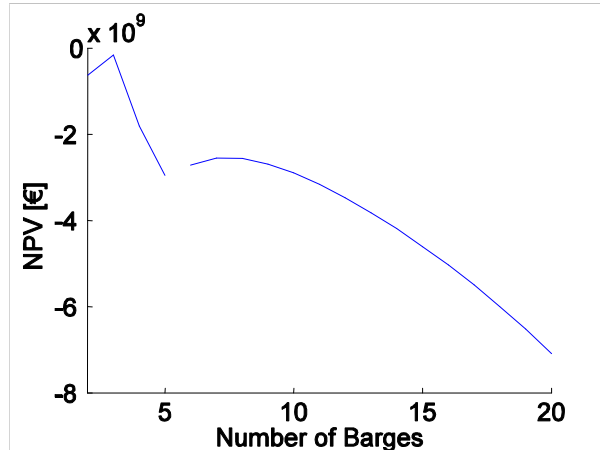

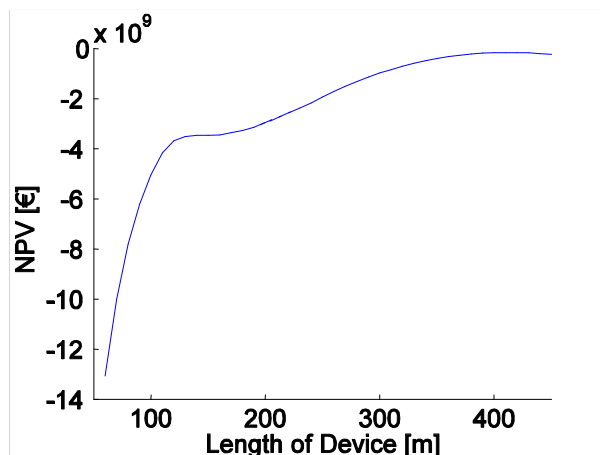**Figure 9:** Results for Optimisation of Number of Barges with techno-economic objective function.

Figure 10: Results for Optimisation of Length of Device with techno-economic objective function.

The optimal length of the device given by optimisation with each of the alternative objective functions is similar at around 400m. However, the optimal number of bodies in the device is very different, 15 when optimised with the non-economic and 3 with the economic objective function.

7 Conclusions

The device which gives the best NPV is significantly different from the device which gives the best energy production per unit surface area.

The device which is optimised for energy production per unit surface area gives a significantly lower NPV than the device which is optimised for NPV.

The number of bodies in the device optimised for maximum NPV is much less than that in the device optimised for maximum energy production per unit surface area. This is consistent with the practical experience of some WEC developers, for example [5].

The length of the optimised device, in the case of both objective functions, is long compared to devices that have been proposed for practical development.

For the generic device used, the parameters selected for optimisation and the assumed costings the NPV estimates produced for all devices were negative.

Acknowledgements

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