LiftWEC

DEVELOPMENT OF A NEW CLASS OF WAVE ENERGY CONVERTER BASED ON HYDRODYNAMIC LIFT FORCES

Deliverable D5.1

Determination of performance function parametric structure

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Primary Author(s)	A. Ermakov (MU)
Co-Author(s)	J. Ringwood (MU)
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EXECUTIVE SUMMARY

Wave energy converters should be actively controlled to ensure maximum energy extraction from waves. However, it is important that the control objective is correctly posed, so that the control effort is directed towards economically advantageous actions.

The objective of this document is to set the context for the parametric structure of the performance function (PF) which will be used within WP5 of the LiftWEC project. Ideally, the performance structure will be based on a bulk economic performance indicator, such as Levelised Cost of Energy (LCoE) and that that performance indicator be expressible as a function of the control actions, so that the control actions can be optimised, maximising the economic performance of the LiftWEC. This ideal presents two difficulties: LCoE is very difficult to enumerate, especially with regard to operational costs, and it is virtually impossible to propagate the effect of control actions all the way through to LCoE. Therefore, this document will articulate the components which make up an idealised PF and examine the extent to which such components can be represented as functions of the control inputs.

In addition, the extent to which disparate performance function components (e.g. cost, power production) can be combined into a single monolithic PF is examined, opening the possibility for multi-criteria optimisation techniques in the determination of the optimal control signals.

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ABBREVIATIONS & DEFINITIONS

WEC – Wave Energy Converter

LiftWEC – a new class of Wave Energy Converter based on hydrodynamic Lift Forces

PF – Performance Function

CoE – Cost of Energy

LCoE – Levelised Cost of Energy

NPV – Net Present Value

IRR – Internal Rate of Return

CapEx – Capital Expenditures

OpEx – Operating Expenditure

FMEA – Failure Model~~s~~ and Effect Analysis

PTO – Power Take Off

WP – Work Package

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1 IDEALISED ECONOMIC PERFORMANCE METRICS

The following metrics are usually used for the financial assessment of WEC projects: LCoE (Levelised Cost of Energy), NPV (Net Present Value) and IRR (Internal Rate of Return) [2].

The LCoE is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis and it can be presented in the form of the ratio:

$$\mathrm{LCoE} = \frac{\text{Sum of Costs Over Lifetime}}{\text{Electrical Energy Produced Over Lifetime}}$$

where:

$$\begin{aligned}&\text{Sum of Costs Over Lifetime} = \\ &\qquad = \text{Initial capital expenditures (CapEx)} + \text{Annual operating expenditures (OpEx)}\end{aligned}$$

The LCoE could satisfy the main conditions, however, it cannot be achieved within the scope of this project due to the current level of uncertainty. Some elements of its parametric structure could be considered as the starting point for the performance assessment for our case. It is also possible to conduct a separate general review of control and optimisation problems for the members of CapEx, OpEx and Power Production for LiftWEC.

Other high-level economic metrics can also be employed, such as Internal Rate of Return (IRR), Net Present Value (NPV), etc.

2 CAPITAL EXPENDITURE

2.1 OVERALL REVIEW FOR CAPEX CALCULATION

CapEx for the WECs includes: development, infrastructure, mooring/foundation, device structural components, subsystem integration and profit margin, installation, contingency, decommissioning, etc. These financial assessments will have different values for variable LiftWEC prototypes, and they will change with the development of the project and its work packages. However, it is important to note that, in general, capital costs are not a function of the control variables and do not therefore need to be enumerated in the control performance function.

A related issue is the capital cost of control hardware. This will vary for different control effector configurations, which will evolve with the LiftWEC design and will determine, to some extent, achievable performance of the LiftWEC system. Such decisions will depend on the evolution of the LiftWEC system throughout the project but will not impact the control-related performance function required to optimise real-time control actions.

CapEx also has a bearing on the physical constraints of the power take-off (PTO) system, within which the control system must operate. In this respect, it gives an upper limit on the achievable performance of the control system and may, for example prohibit complex conjugate control

3 OPERATIONAL EXPENDITURE

3.1 OVERALL REVIEW OF OPEX

The OpEx for the WEC includes: maintenance, marine operations, shore-side operations, replacement parts, etc. The operational expenditure $\boldsymbol{J_{OpEx}}$ can be presented as two sums of members, where one is independent of the control input $\boldsymbol{u}$ and the other is dependent:

$$J_{OpEx} = \sum_i OpEx_i + \sum_j OpEx_j(u)$$

Then, the control related OpEx minimisation problem can be presented in the following form:

$$\frac{\partial J_{OPEX}(u)}{\partial u} = 0 \quad \rightarrow \quad u$$

3.2 OPERATIONAL LIMITATIONS AND CONSTRAINTS

The main goal of the control is the maximisation of electrical energy production, but we have to consider the following constraints:

- Using the more intensive control we can obtain significantly more energy, but at the same time a great deal more generated energy will be expended for actuator/control purposes.
- Some intensive work regimes can improve energy production, but they lead to fatigue of structures, actuators and materials. This will, in turn, increase operational expenditure and as a result the Cost of Energy:

  u → Fatigue(u) → OpEx → CoE
- An alternative would be to devise a controller which reduces fatigue by avoiding large torques.

3.3 FATIGUE ANALYSIS

When developing a control strategy, it is important to remember that each variation of the actuators increases their fatigue level. Therefore, fatigue analysis for all actuators, hydrofoils, indeed the whole structure should be included in the control development.

Fatigue is the damage accumulation process on a component produced by cyclic loading. The Palmgren-Miner [3] linear damage hypothesis assumes that the fatigue damage in a loaded component can be expressed as the sum of damages contributed by each stress cycle:

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i}$$

where D is fatigue damage fraction, and n_i/N_i is the ratio of operational cycles to the maximum allowable number of cycles at each stress range. However, in reality amplitudes of cyclic loading are rarely constant.

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The inclusion of the fatigue analysis into the control model allows us to solve the following problems:

- Extend the lifetime of the actuators
- Extend the time period between maintenance tasks
- Limit the control strategy methods area with constraints from the fatigue and lifetime analysis.

3.4 FAILURE MODELS AND EFFECT ANALYSIS (FMEA)

FMEA is a structured approach to discovering potential failures that may exist within the design of a product or process. Failure modes are the ways in which a process can fail. Effects are the ways that these failures can lead to waste, defects or harmful outcomes. Failure Models and Effects Analysis is designed to identify, prioritise and limit these failure models. The developed PF should be suitable for FMEA.

This analysis also will help to determine the WECs actuators, their lifetime and the possible control strategies. The comparison of CapEx to OpEx can be conducted within the FMEA. Some actuators can survive harder loads and produce more energy, but they will be much more expensive. The others typically require more frequent maintenance but are less costly. The assessment of this combination through different control strategies can help to find the optimal LiftWEC design.

There is also the possibility to develop new control strategies for the case of failure of some of LiftWECs actuators. The WEC should be able to continue its work within new limits until the next maintenance.

4 CALCULATION OF ELECTRICAL ENERGY PRODUCTION

The control methods for electrical energy production must ensure a consistent operational rotation speed for a LiftWEC's turbine/electricity generator wheel for different waves input. Requirements should be expanded to include minimisation of the operational expenditures, loads on actuators, fatigue analysis etc.

The electrical energy produced during the time t, can be determined using the following formula:

$$\boldsymbol{E_{Electrical}} = (\boldsymbol{T} \times \boldsymbol{\omega}) \times \boldsymbol{\eta_{Gen}} \times \boldsymbol{t} - \boldsymbol{E_{Control}}$$

where:

$\boldsymbol{E_{Electrical}}$ – is the produced electrical energy, $\boldsymbol{T}$ – is the instantaneous hydrodynamic torque, $\boldsymbol{\omega}$ – is the angular velocity, $\boldsymbol{E_{Control}}$ – is the electrical energy spent for control purposes/actuators, $\boldsymbol{\eta_{Gen}}$ – is the overall efficiency of electrical generator.

If we consider the LiftWEC's inertia $\boldsymbol{I}$ as a constant or using its average value we are left with the $\boldsymbol{E_{Rotational}}$ function which is based solely on maintaining an operational rotation speed for a turbine/electricity generator wheel.

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When the operational speed is small, the PTO is working in a partial regime that only captures a part of its nominal power, and the electricity production is considerably reduced. Here, we can control the operational speed by adjusting actuators to increase the torques from hydrodynamic forces created by waves, or we can apply the opposite torque using the PTO system. However, in the real case, we can also change the inertia $\boldsymbol{I}$ by increasing or decreasing the distances between hydrofoils and the rotation axis, making the control problem much more complicated. Generally speaking, we can consider $\boldsymbol{T}$, $\boldsymbol{\omega}$ and $\boldsymbol{E_{Control}}$ as functions of the control **u** (taking into account a high nonlinearity of these dependences)

5 SOLVING THE CONTROL PROBLEM

5.1 CONTROL EFFECTORS

The control effectors form the set of variables with respect to which the PF should be optimised. The reconfigurable LiftWEC enables the advanced adaption of the hydrodynamic gain. One benefit of a controller adapting the hydrodynamic gain is to modulate the wave load on the hydrofoils, in particular under high-power or extreme waves, yielding better survivability capacity of the WEC in extreme working environments.

The LiftWEC can be controlled via different proposed operating principles, some of them are:

- Phase-locked lift
- Moment of inertia control
- Hydrofoil radius control
- Hydrofoil pitch control

However, only some of these options will exist in each of LiftWECs configurations.

In order to implement control strategies, the following parameters can be manipulated in real time.

- Rotor radiuses – $\boldsymbol{R}$
- Hydrofoil~~s~~ pitch angles – $\boldsymbol{\phi}$
- The load torque on the WEC shaft – $\boldsymbol{T}$
- The distance between the rotation centre and free surface – $\boldsymbol{Z}$

Therefore, the control input can be implemented by variation of the four members $\boldsymbol{u} = \{\boldsymbol{R}, \boldsymbol{\phi}, \boldsymbol{T}, \boldsymbol{Z}\}$. The influences of the proposed operating principles of the adaption of the hydrodynamic gain on the energy production and the performance function will be studied on the next stages of the project. The comparison of the different control strategies using various actuators, or their combinations will also be conducted.

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A similar control strategy to that proposed for the LiftWEC has been widely investigated for wind turbines, and comparisons with wave energy are made in [4,5]. As shown in the 2D power curve scheme [Fig. 1] at high wind speeds between rated output wind speed and cut-out speed, output power of the wind energy converter is kept constant, i.e. the rated power, and this is typically approached by adjusting the pitch angle of wind turbine blades.

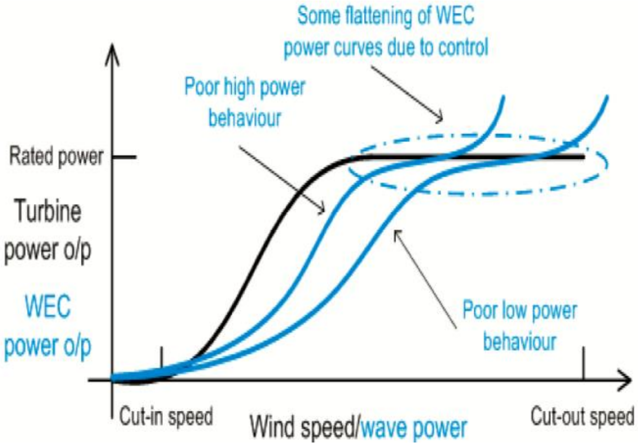

Figure 1: Scheme of a 2D flat power curve, for wind turbine power and wave energy converter power.

This principle can be applied to configurable WECs in order to improve their performance: the hydrodynamic gain is increased to improve the power production when the wave power drops into a range between cut-in value and rated value, and is reduced to approach the rated power when wave power is higher than the rated value and lower than the cut-out value.

5.2 SINGLE-OBJECTIVE OPTIMISATION

In single-objective optimisation, all performance and cost components are combined into a single objective, e.g.

$$J_{total} = \alpha_1 J_1 + \alpha_2 J_2 + \cdots + \alpha_n J_{1n}$$

Where the various J_i refer to the various cost/performance components, such as power production, CapEx, OpEx, etc. The main difficulty of trying to optimise a composite performance function, such as the one above, is the need to determine the coefficients α_1, α_2, etc. which determine how the individual cost/performance components relate to each other and contribute to overall performance. This is not a trivial exercise, since there is a need to find a common metric or set of units within which each of the cost/performance components can be expressed to allow them to be added together. In addition, combining cost and benefit components is particularly difficult, usually requiring reciprocation of one or other quantity (depending on whether the optimisation problem is cast as a maximisation, or minimisation problem), leading to a nonlinear contribution of that term.

Even if a reasonable set of coefficients α_1, α_2, etc. can be found, the optimiser returns a definitive solution for this particular set of coefficients, while a much better overall solution might be achievable with a slight adjustment in one, or a number of coefficients. Such sensitivities are not explicit in single-objective optimisation.

5.3 MULTI-OBJECTIVE OPTIMISATION

Multi-objective optimisation or Pareto optimisation [6-9] permits each cost/performance component to be kept separate, with a wide variety of combinations evaluated to give an overall picture of the best compromise which can be chosen by the designer, via a Pareto front.

However, one of the difficulties with this approach is the fact that multiple evaluations, for different combinations of the cost/performance components, are required, leading to real-time computational difficulties. As a result, multi-objective optimisation is probably restricted to slow-moving control actuators, such as, hydrofoil radius control, in response to sea state variations.

5.4 GENERAL RECOMMENDATIONS

Given the early stage of the project, it is not possible to specify a definitive performance function at this point in time. However, this deliverable is timely in that it articulates the important issues related to the control performance function, and how they might interact with other project workpackages.

Though the ultimate goal of LCoE reduction as a performance objective (for control) is well beyond the scope of this project (it has also never featured in any other WEC control scheme to date for the same reasons) it is still possible to form a performance function considering a number of more tangible measures, typically taken from Sections 4 and 5 of this report. Initially, it is worth separating the relationship between the control system and CapEx, since CapEx will only define the ultimate performance limit of the WEC, including the control system. Specifically, CapEx will determine:

1. The maximum physical limits of the system i.e. control force, and displacement of the various control actuators.
2. Whether regenerative power can be used as part of the control signal. This is related to the generator and control electronics, and also has implications for torque limits, since reactive control typically involves greater spikes in power and torque than for non-reactive control.

In terms of the control performance function itself, a sensible approach would be to include components related to produced energy (one of the 3 components which comprise LCoE), and at least one other component which relates the control actions (either directly or indirectly) to OpEx (another major component of LCoE). Produced energy is directly quantifiable, so the remaining challenge is to find a quantifiable measure which relates the control actions to OpEx. Section 4 of this document gives some clues in this regard. Specifically, a focus on structural measures gives a potentially enumerable quantity, which has direct implications for OpEx. Note that, in possibly the only publication dealing with the effect of control actions on OpEx, [10] examines a performance function relating control action to structural fatigue.

A significant strength of the consortium is that it has expertise in structural design and also in economic performance calculations (Universities of Strathclyde and Aalborg, respectively), which are articulated in Workpackages WP6 and WP8, respectively.

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Therefore, the performance function is likely to have the following 2 components:

J_e = total energy produced

J_{OpEx} = cost of structural damage due to control actions

As articulated in Section 6.2, it may be difficult to combine J_e and J_{OpEx} in a single cost function. However, it is equally unlikely that all control functions can rely on a real-time implementation of multi-objective optimisation.

To that end, it is proposed to employ a single performance function to determine the following control variables:

- Phase-locked lift, and
- Moment of inertia control,

while multi-objective optimisation may be viable for:

- Hydrofoil radius control
- Hydrofoil pitch control

5.5 LEVELS OF UNCERTAINTY

It is difficult to have a clear determination of the PF and its specific parameters at the earliest stages of the project. For example, at this moment OpEx has the highest level of uncertainty. In this document we have derived the first approximation of the control problem and identified the parametric structure of the performance function which can be used for the performance assessment on the early development stages.

5.6 EVOLUTION OF PF WITH FUTURE DEVELOPMENT OF THE PROJECT AND ITS WPS

The development of the project and its work packages will decrease levels of uncertainty but at the same time will significantly change the parametric structure of the performance function. It is clear that we will have to review our approaches during the next stages of the project. Numerical (WP03) and physical modelling (WP04) will affect control and power take off conceptions as well as the structural design (WP06) of the prototype. This will clarify the OpEx and CapEx and help us to understand possible value ranges. There is also the possibility of collaboration with WP02 in terms of actuator and sensor specification. The determination and discussion of LCoE parameters should be discussed with WP08 (cost of energy). This specified parametric structure may also require a new general review of the problem statement and its solution methods.

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