LiftWEC

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

Deliverable D5.3

Performance function parameterisation

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EXECUTIVE SUMMARY

This document constitutes Deliverable "D5.3 Performance function parameterisation" of the LiftWEC project. LiftWEC is a collaborative research project funded by the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 851885. It is the intention of the project consortium that the LiftWEC project culminates in the development of one or more promising configurations of a Wave Energy Converter operating through the use of one or more rotating hydrofoils that generate lift as the primary interaction with the incident waves.

The report consists of the description of the performance function (PF) and its parametric structure. The presented PF can be used for development of the control methods for the cyclorotor based wave energy converter and its performance assessment in terms of Levelised Cost of Energy (LCoE) [1]. The document is based on the previous deliverable "D5.1 Determination of performance function parametric structure" [2], which was submitted during the early stages of the LiftWEC project and inherits some of its elements and structure. The research of the LiftWEC technology in collaboration with work packages WP6 Structural Design and WP8 Cost of Energy allows us to further clarify and determine elements of capital and operational costs of the device [3,4,5] as well as ~~a~~ structural fatigue which can be caused by ~~a~~ real time control [6].

Ideally, the performance structure should be based on a bulk economic performance indicator, such as LCoE and 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. It has been emphasised in the deliverables of our colleagues, the uncertainty level of the LCoE at this stage of development (Stage 1, TRL 3) is in the order of -30% to 80% [4].

The deliverable summarises the performance assessment results which were obtained in the set of authors' open access publications [7,8,9], where the optimal control strategy has been obtained for a cyclorotor based WEC in terms of mechanical power optimisation. It illustrates the range of cyclorotors' control effectors and their influence on device mechanical performance. The authors also show how the generated mechanical power is connected with electrical energy production. At the end of the document, the authors present the selected current technology state of LiftWEC performance function $\boldsymbol{E_{Total}}$. The PF consists of a combination of the generated electrical power $\boldsymbol{E_{Electrical}}$ (articulated in Section 4) and fatigue damage $\boldsymbol{D}$ (Section 3).

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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) [1].

The LCoE is a measure of a power source that allows comparison of different methods of electricity generation on a consistent basis. The significant analysis of the most advanced methods of the LCoE calculation has been presented in the deliverable of work package WP8: “D8.2 Parametric Cost Model” [3]. WP8 performed a review to compile the different cost models found in the literature. They introduced the software code where the parametric cost model has been implemented, including a description of the main features of the LCoE Calculation Tool (the selected software).

Basically, it can be presented in the form of the ratio:

$$\mathrm{LCoE} = \frac{\text{Sum of Costs Over Lifetime}}{\text{Electrical Energy Produced Over Lifetime}} \tag{1}$$

where:

$$\text{Sum of Costs Over Lifetime} = \text{Initial capital expenditures (CapEx)} + \text{Annual operating expenditures (OpEx)} \tag{2}$$

The LCoE could satisfy the main conditions, however, it cannot be fully 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.

Nevertheless, significant work has been conducted by WP8 who developed the “D8.3 LiftWEC LCOE Calculation Tool” [4]. The authors acknowledge that there is a large uncertainty in absolute terms and it is very challenging to provide a single unit cost as default value representative to all LiftWEC concepts. For example, a single value of 240,000 EUR for the installation of a floating configuration including mooring, umbilical cable and WEC deployment might be 50% inaccurate in some deployments. The authors of Deliverable 8.3 also assessed the performance assuming always optimal control, and maximal possible wave energy extraction evaluated in the work of Atargis Energy Corporation [10].

The developed tool has been also applied to four different baseline LiftWEC configurations selected by the LiftWEC consortium [5]. It was shown how significant LCoE depends on the design of the device, and how different prices of energy could be. It was also acknowledged that at this stage of development (Stage 1, TRL 3), the uncertainty in the LCoE is in the order of -30% to 80%.

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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 [3,4,5]. These financial assessments have different values for variable LiftWEC prototypes, and they will change with the future development of the technology. 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, such as actuators for hydrofoils and pith angles, as well as sensors of tangential and radial forces, and rotational rate or velocity. The estimation of the cyclorotor state and forecast of relative to hydrofoils fluid velocity will require the stable position of the central shaft. It will require a more rigid mooring system which will increase the capital costs. These requirements 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 and actuators, within which the control system must operate. In this respect, it gives an upper limit on the achievable performance of the control system.

3 OPERATIONAL EXPENDITURE

3.1 OVERALL REVIEW OF OPEX

The OpEx for the WEC includes: maintenance, marine operations, shore-side operations, replacement parts, etc [3,4,5].

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:

$$\mathrm{J_{OpEx}} = \sum_{\mathrm{i}} \mathrm{OpEx_i} + \sum_{\mathrm{j}} \mathrm{OpEx_j(u)} \tag{3}$$

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

$$\frac{\partial \mathrm{J_{OPEX}(u)}}{\partial \mathrm{u}} = 0 \quad \rightarrow \quad \mathrm{u} \tag{4}$$

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.

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- The configuration of the LiftWEC device will limit the control input "**u**" from actuators, for example, a PTO/Motor torque on the main shaft, changes of the rotational velocity and pitch angles.
- Some intensive work regimes can improve energy production, but they may lead to fatigue of structures, actuators and materials [6]. This may, in turn, increase operational expenditure and as a result increase the Cost of Energy:
$$\mathbf{u} \rightarrow \text{Fatigue}(\mathbf{u}) \rightarrow \text{OpEx} \rightarrow \text{CoE} \tag{5}$$
- An alternative would be to devise a controller which reduces fatigue by avoiding large torques, speeds, tangential and radial forces.

3.3 FATIGUE ANALYSIS

When developing a control strategy, it is important to remember that each movement of the actuators increases the fatigue experienced. 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. As an example, we present a Palmgren-Miner [11,12] linear damage hypothesis which assumes that the fatigue damage in a loaded component can be expressed as the sum of damages contributed by each stress cycle:

$$\mathrm{D} = \sum_{\mathrm{i}=1}^{\mathrm{k}} \frac{\mathrm{n_i}}{\mathrm{N_i}} \tag{6}$$

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.

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.

The analysis conducted by WP06 in the deliverable "D6.4 Fatigue assessment" [6] illustrate the damage computation methodology in one hot-spot (Critical areas of stress concentration). The hotspot is the fixed end of the foil for a rotor with the foil supported at both ends. It demonstrates the effect of passive structural dynamics in the damage that occurs in this hot spot. This is with the aim to develop methods that retard or avoid complete structural failure. In terms of structural dynamics and their impact in the damage of the hot spot, it is found that passive compliance of the support structure and passive radial motion of a single foil do not alter significantly the power and damage footprints of the hot spot when the device is operated with constant speed in irregular seas. In contrast, it is found that a passively pitching foil can help in reducing the damage on the hot spot, although incurred at a penalty in power production.

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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 opportunity for maintenance arrives.

4 CALCULATION OF ELECTRICAL ENERGY PRODUCTION

The control methods for electrical energy production must ensure a optimal variable operational rotation rate and hydrofoil pitch angles for a LiftWEC's turbine/electricity generator wheel for different waves input. Basically, it requires the maximisation of the generation of rotational mechanical power from the wave/foil integration and conversion of it into the electrical power. Requirements should be expanded to include minimisation of the operational expenditures, loads on actuators, fatigue analysis etc.

The interaction between cyclorotor's hydrofoil and waves case the generation of **F_L** lift and **F_D** drag forces which act on a particular hydrofoil depend on the angle of attack α, lift and drag coefficients $C_L(\alpha)$ and $C_D(\alpha)$, hydrofoil chord length S, fluid density ρ and overall relative velocity $\boldsymbol{\hat{V}}$ at a hydrofoil position:

$$F_L = \frac{1}{2}\,\rho\, C_L(\alpha)\left|\hat{V}\right|^2 S, \tag{7}$$

$$F_D = \frac{1}{2}\,\rho\, C_D(\alpha)\left|\hat{V}\right|^2 S \tag{8}$$

The resulting tangential force **F_T** are directly responsible for mechanical power generation can now be presented as their combination based on hydrofoil pitch angle γ:

$$F_T = F_L(\alpha)\sin(\alpha-\gamma) - F_D(\alpha)\cos(\alpha-\gamma) \tag{9}$$

The radial forces **F_R** are directly responsible for structural loads and fatigue of the structure can be evaluated as:

$$F_R = F_L(\alpha)\cos(\alpha-\gamma) + F_D(\alpha)\sin(\alpha-\gamma) \tag{10}$$

Thus, ideally, the control algorithm must maximise tangential **F_T** and minimise radial forces **F_R**

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The average mechanical power $\boldsymbol{E_{Mechanical}}$ generated by cyclorotor with two hydrofoils during the time interval [0,T] can be presented in the following form:

$$\boldsymbol{E_{Mechanical}} = \frac{1}{T}\int_0^T \left(\left(F_{T_1} + F_{T_2}\right)R - I\ddot{\theta}(t)\right)\dot{\theta}(t)dt \tag{11}$$

where $\boldsymbol{I}$ - the inertia of the rotor, **R** – operational radius, $\dot{\boldsymbol{\theta}}$ – the rotational rate and $\ddot{\boldsymbol{\theta}}$ – the rotational acceleration of the device.

The produced electrical energy $\boldsymbol{E_{Electrical}}$ can be determined using the following formula:

$$\boldsymbol{E_{Electrical}} = \boldsymbol{E_{Mechanical}} \times \boldsymbol{\eta_{Gen}} - \boldsymbol{E_{Control}} \tag{12}$$

where $\boldsymbol{E_{Control}}$ – is the electrical energy spent for control purposes/actuators, $\boldsymbol{\eta_{Gen}}$ – is the overall efficiency of electrical generator.

Some optimal control solutions for the mechanical power $\boldsymbol{E_{Mechanical}}$ maximisation using PTO torque and pitch control in both monochromatic and panchromatic waves were obtained by authors and published in open access in [7,8]. The results have shown significant up to 600% mechanical power increase after the real time control implementation. However, it was achieved by significant and frequent changes of the rotational velocity and pitch angles, that will also cause significant cyclical loads on actuators and structure, decreasing their lifetime. The additional energy which can be spent on real time control $\boldsymbol{E_{Control}}$ as well as optimal generator and its efficiency $\boldsymbol{\eta_{Gen}}$ also require additional study and can be determined by a capital and operational cost of the corresponding parts of the final LiftWEC configuration [3-5]. We can also adapt the theoretical approximate assumptions from [10], where for example the generator efficiency is assumed to be $\boldsymbol{\eta_{Gen}}$=0.95.

5 PERFORMANCE FUNCTION, ITS VARIABLES AND OPTIMISATION METHODS

5.1 CONTROL EFFECTORS

The control effectors form the set of variables with respect to which the PF should be optimised. The selected baseline configuration of LiftWEC enables the advanced adaption of the hydrodynamic gain. One benefit of a controller adapting to 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.

In order to implement control strategies, the following control inputs were identified as real time control inputs for wave-by-wave control algorithm:

- Hydrofoil pitch angles – $\boldsymbol{\gamma}$
- The PTO/Motor torque on the shaft – $\boldsymbol{T}$**,** which can be used to achieve the optimal rotational rate – $\dot{\boldsymbol{\theta}}$

and the following structural parameters can be considered as slow, sea state-based control inputs

- The distance between the rotation centre and free surface – $\boldsymbol{Z}$
- Operational radius - **R**

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- The yaw control which allow us to align the blade of foils with the front of incoming waves – $\boldsymbol{\varphi}$

Therefore, the control input can be implemented by variation of the four members $\boldsymbol{u} = \{\boldsymbol{\gamma}, \boldsymbol{T}, \boldsymbol{Z}, \boldsymbol{\varphi}\}$.

The influences of the real time pitch and torque control methods on the adaption of the hydrodynamic gain and the mechanical energy production has been studied in authors' articles [7,8]. The research conducted in the articles has clearly shown the benefits of the optimal pitch and rotational rate control application, in both monochromatic and panchromatic waves. It was shown that, while rotational rate control looks more compelling than pitch control, in terms of shaft power increase in monochromatic waves, this observation is reversed in the case of panchromatic waves. The implementation of the joint pitch and rotational rate control strategy in panchromatic waves shows a significant increase over the fixed or single input of rotational rate/pitch cases. The main conclusion from the presented results, therefore, is that cyclorotors must be controlled in real time using both actuators, in order to reach their full potential. It has been shown that real time control strategy can potentially increase the energy production in panchromatic waves by 600%.

The simultaneous optimisation of the slow, structural control inputs **{R,Z}** for the cyclorotor with real time pitch and torque control has been conducted by authors in [9]. It was shown that there is significant interaction between the two (fast and slow) control hierarchies, particularly for the monochromatic case. The results show a significant sensitivity in $\boldsymbol{E_{Mechanical}}$ to variations in $\boldsymbol{Z}$ and $\boldsymbol{R}$, suggesting that the optimum $\boldsymbol{Z}$ and $\boldsymbol{R}$ calculated for the optimal constant $\dot{\theta}$ and optimal constant $\boldsymbol{\gamma}$ may not be optimal for the case where a variable $\dot{\boldsymbol{\theta}}$ and $\boldsymbol{\gamma}$ are employed. The results of more realistic panchromatic waves show a broad monotonic increase in $\boldsymbol{E_{Mechanical}}$ with increasing R and decreasing **Z**. Therefore, the choice of the ideal **Z** and **R** parameters for a particular wave site are likely to be determined by economic issues which balance the capital, and potential operational, cost of a large rotor against the energy receipts which incremental changes in R bring. We note that, in general, given a particular optimal radius R, maximum power is captured by placing the cyclorotor as close to the surface as possible, subject to avoidance of harsh surface effects. Significant issues relating to structural loading on larger devices must also be considered.

The impact of misalignment between incoming waves and WEC span was investigated in [Siegel2019]. According to the estimation presented by Atargis [10] the 20° angle between WEC and wave crest for LiftWEC parameters can potentially cause of 20% of the generated energy losses. Such problem can be solved by implementation of the yaw control – $\boldsymbol{\varphi}$**,** but it may also increase the capital cost of the device.

5.2 SINGLE-OBJECTIVE OPTIMISATION

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

$$J_{total} = \alpha_1 J_1 + \alpha_2 J_2 + \cdots + \alpha_n J_{1n} \tag{13}$$

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.

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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. The example of the single objective optimisation can be found in authors articles [7,8], where all control strategies have only one goal, - maximisation of the generated mechanical power.

5.3 MULTI-OBJECTIVE OPTIMISATION

Multi-objective optimisation or Pareto optimisation [14-17] 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 **R** or submergence depth control **Z**, in response to sea state variations. The example of simultaneous optimisation of the cyclorotor design (submergence depth **Z** and operational radius **R**) for the real time control of hydrofoil pitch $\boldsymbol{\gamma}$ and shafts torque $\boldsymbol{T}$ /rotational rate $\dot{\boldsymbol{\theta}}$ was presented in the authors publication [9]. One of the goals was to minimise the size of the device (in particular its operational radius R), while increase its performance in terms of generated mechanical power.

5.4 THE OPTIMAL PERFORMANCE FUNCTION FOR THE CURRENT TECHNOLOGY STATE

Though the ultimate goal of LCoE reduction as a performance objective (for control) is 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 3 and 4 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. extremal loads on the hydrofoils, support structures and main shaft, displacements of the various control actuators, position and stability of the rotor in the open ocean.
2. The limitation of control torques for PTO/motor on the main shaft and pitches actuators. It will determine how fast can we change rotational velocity and foils position.

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 3 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 known publication dealing with the effect of control actions on OpEx for WECs, [12] examines a performance function relating control action to structural fatigue.

Therefore, the selected performance function $\boldsymbol{E_{Total}}$ consists of a combination of the generated electrical power $\boldsymbol{E_{Electrical}}$ (eq. 12) and fatigue damage $\boldsymbol{D}$ (eq. 6).

$$\boldsymbol{E_{Total}} = \alpha_1 \boldsymbol{E_{Electrical}} - \alpha_2 \boldsymbol{D} \tag{14}$$

Generally, $\alpha_1$corresponds to the desired electricity prices and converts electrical kW to Euro, while α_2 corresponds to the price of the hot-spots elements of cyclorotor actuators and supporting structure [3-5]. The coefficients values will be determined for the final LiftWEC configuration in discussion with WP6 and WP8. The results of the application of the developed performance function will be published in Abel Arredondo-Galeana, Andrei Emarkov, Weichao Shi, John V. Ringwood and Feargal Brennan "Control strategies for power enhancement and fatigue damage mitigation of wave cycloidal rotors".

The similar approach to a performance is used in wind energy (for example [13]), where the optimal controller performance is evaluated with respect to the power production maximisation and structural loads minimisation goals that are joined together in a single performance function expressing the profit of the wind turbine control system operation.

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