Department of Mechanical Engineering

UNIVERSITY OF BATH

Adaptive Control of the WaveSub WEC using a Romax electromechanical PTO

WES Control Systems Stage 1
Public Report

University of Bath

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1 Project Introduction

The project investigates the feasibility of applying an adaptive control methodology to the WaveSub Wave Energy Converter (WEC) in conjunction with the Romax electro-mechanical Power Take Off (PTO) system. The two systems are, in principle, compatible and well suited to provide an efficient and cost-effective overall solution. The purpose of the control system is to maximise energy capture within the physical constraints of the WEC and PTO across a wide range of sea states.

The project team consisted of members of the University of Bath Departments of Mechanical and Electrical Engineering, Marine Power Systems Ltd and Romax Technology Ltd. This report summarises the work performed by the consortium under a Stage 1 WES Controls project which ran from October 2nd 2017 to January 19th 2018.

2 Description of Project Technology

WaveSub, developed by Marine Power Systems Ltd, is a submersed point absorber with unique multi-tether configuration and variable geometry which can be tuned to the prevailing sea state. A float moves with the waves and reacts against a moored base. The tethers pull on rotational drums which are attached to a PTO. WaveSub has geometric controllability as the float-reactor separation is adjustable for mean sea state tuning and survivability.

Romax have proposed an electromechanical PTO system comprising a single stage planetary gear-set connected to a permanent magnet electrical generator. In principle, the system could be an efficient and cost-effective match to the WaveSub WEC. Control is effected through adjustment of the generator torque.

The proposed control methodology is computationally simple and can accommodate physical constraints such as position limits in a simple and robust manner. It also requires no *a priori* knowledge of plant dynamics. This offers several advantages over other strategies as:

- Implementation is very straightforward.
- It is insensitive to errors in estimates of the plant (sensors, PTO and WEC), which are not always easy or even possible to achieve.
- It is robust to parameter variation and nonlinearity (e.g. plant ageing or damage), and fault tolerant.
- It is applicable to any WEC/PTO system combination without the need for extensive retuning.

The Simple and Effective control strategy [Fusco 2013] is used here. An optimal velocity trajectory is evolved from the estimated wave excitation force and the WEC hydrodynamic response. The strategy is computationally simple so readily implemented in real time and is inherently robust to parameter variation, non-linearity and damage. It is also tuneable for different objectives – e.g. maximum efficiency, survivability, minimising LCOE. A variant of Model Reference Adaptive Controller known as Minimal Controller Synthesis (MCS) is used. This can achieve good tracking performance despite modelling uncertainty and nonlinearity. High control accuracy and robustness are simultaneously achieved. MCS has previously been applied to shaking table control and active engine mounts for road vehicles.

3 Scope of Work

The study aimed to demonstrate the feasibility of the proposed control system in terms of the following requirements:

- The control system is stable.
- A performance benefit is seen against target metrics compared to the optimally tuned passive system.
- Implementation is possible using only information that is physically measurable using standard sensors.
- The control system will execute in real time using available hardware.

Dynamic models of the WEC and PTO systems were developed and used to compare the performance of the adaptive control strategy to the optimally tuned passively damped benchmark system. A range of irregular sea states were used to excite the system representing realistic conditions for which the WEC is sized.

All required algorithms to calculate or estimate the quantities needed to implement the control were developed and deployed on standard real-time control hardware to demonstrate feasibility of implementation.

4 Project Achievements

The feasibility of the control system was demonstrated. The main achievements were:

- Development of a comprehensive simulation model of the WaveSub WEC
- All required algorithms to calculate or estimate the quantities needed to implement the control were developed and demonstrated to have sufficient accuracy to make implementation feasible
- Implementation of control including realistic restrictions such as torque limits and uni-directional power flow in the PTO
- >35% increase in captured power compared to the optimally tuned passive system
- Demonstration of real time deployability on standard hardware

It has not been assumed that all required parameters will be directly measurable. For example, it is not possible to measure the wave excitation force, and it may not be desirable to use certain sensors such a battery powered Inertial Measurement Unit (IMU) on the float. It has been demonstrated that all required information to achieve control is available from readily available encoders mounted at the PTO drums and from torque sensors at the PTO or current measurement within the generator. It has been demonstrated that this information which is measurable can be used to calculate or estimate with sufficient accuracy all information required to achieve control, assuming that hydrodynamic models have sufficient accuracy. This directly enhances the i**ntegratability** metric. Furthermore, the control strategy does not rely on forward prediction of the wave excitation which would increase uncertainty, reduce robustness and erode **performance, reliability and integratability** metrics.

The computational overhead of an algorithm limits the sampling rate which can be used. If the computational burden is too high to permit a sufficiently high sampling rate to achieve control then the algorithm cannot be said to be feasible in terms of real-time implementation. The algorithm was developed in the WEC-Sim environment and then extracted and flashed to standard real-time hardware. It was found that the computational overhead was very low as predicted, enabling sampling rates of up to 10kHz to be used. Therefore, the control system can be implemented using standard low-cost hardware **[affordability, reliability, integratability]**.

A control system may be feasible but not offer any significant performance benefit over a well-tuned passively damped system. It has been demonstrated that >35% more power can be captured in a range of sea states using the adaptive control system as a 4Q (bi-directional power flow) system. The adaptive strategy maximises power capture within the inherent physical constraints of the WEC and PTO. It has been demonstrated that constraints can be readily incorporated and adherence to them is achieved in a smooth manner, reducing structural loading **[performance, reliability, survivability]**.

It may not be possible to implement 4Q control, or it may not be desirable. Therefore, it has also been demonstrated that the control system can be implemented with a 2Q restriction (i.e. only generation is permitted, not motoring). This reduces performance compared to 4Q but still offers good improvements in power capture compared to the optimal passive system. Stability has not been an issue, even with the non-linearity of the 2Q restriction. This directly enhances the **integratability** metric.

The adaptive control strategy has now been successfully applied to two WEC types with radically different designs. Previous research by the investigators has applied the strategy to a nonlinear OSWEC. This demonstrates applicability to different WEC/PTO combinations **[integratability]**.

Overall the study has been successful and feasibility has been demonstrated. It has not been possible to investigate all aspects of the study due to time constraints and underestimation of the system complexity. However, the performance benefits of the control strategy provide a compelling case for further investigation.

5 Recommendations for Further Work

Within the time constraints of the project it has not been possible to explore the sensitivity of the control system to parameter uncertainty. While the hydrodynamic parameters of the WaveSub device should be accurately captured by BEM codes due to the simple symmetrical geometry of the float, there could be errors. Further errors could be introduced if fault conditions occur or if the plant changes due to ageing or biofouling. It is anticipated that this is one of the main benefits of the adaptive strategy over other control systems, as it can adapt to the changing conditions.

Under the current investigation, gain inflation of the adaptive gains has been observed. While this has not resulted in instability in the test cases run, the potential exists for this to occur over longer time periods. A practical reality of adaptive systems is that forgetting factors are often required to avoid this effect anyway due to the accumulation of numerical errors resulting from using fixed-point real-time hardware. The use of forgetting factors would eliminate gain inflation, but could also impact on system performance. The balance of these competing factors requires further investigation.

Under 2Q control, high frequency motion was observed in the float pitch velocity response. This is attributed to the discontinuous nature of the 2Q control signal. Further investigation is required to determine if this effect would be seen in reality, and to explore methods of alleviating the effect. It is anticipated that natural filtering effects in a realistic PTO, combined with adjustment of the adaptive effort coefficient acting on the pitch control loop would eliminate this effect.

Overall this approach shows promise to provide a substantial increase in power capture for a minimal additional device cost (addition of sensors) and therefore a significant improvement in cost of energy would likely result. Further work is recommended to refine the simulation and add detail to the power take-off system model. Hardware in the loop testing of the control approach should be developed alongside development of cost and power assessments. Application to stage 2 of the WES controls project will be made to allow this continuation.

6 Communications and Publicity Activity

Poster presentation at 2nd Annual Wave Energy Scotland Conference, 28th November 2017, Edinburgh, UK.

7 Useful References and Additional Data

[1] Marine Power Systems Ltd. Adaptive control of the WaveSub wec using a Romax electromechanicalPTO. R01 - wec-sim model setup. Wave Energy Scotland Controls 1, 2017. CONFIDENTIAL

[2] Romax Technology Ltd. Adaptive control of the WaveSub wec using a Romax electromechanicalPTO. R02 - WES PTO concept sizing report. Wave Energy Scotland Controls 1, 2017. CONFIDENTIAL

[3] University of Bath. Adaptive control of the WaveSub wec using a Romax electromechanicalPTO: D01 – Control system feasibility study. Wave Energy Scotland Controls 1, 2017. CONFIDENTIAL