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A summary of the Advanced WEC Dynamics and Control project

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ABSTRACT

This report serves as a comprehensive summary of the work completed by the “Advanced WEC Dynamics and Controls project” during the period of 2013-2019. This project was first envisioned to simply consider the question of designing a controller for wave energy converters (WECs), without a complete recognition of the broader considerations that such a task must necessarily examine. This document describes both the evolution of the project scope and the key findings produced. The basic goal of the project has been to deliver tractable methodologies and work flows that WEC designers can use to improve the performance of their machines. Engineering solutions, which may offer 80% of the impact, but require 20% of the effort compared to a perfect result (which may be many years of development down the road) were preferred. With this doctrine, the work of the project often involved translating existing methods that have been successfully developed and applied for other fields, into the application area of wave energy.

The Advanced WEC Dynamics and Control project

The potential for a more thoughtfully designed controller to improve the performance of a wave energy converter (WEC) has long been understood to be significant. In fact, the underlying principle needed to improve the power absorption of a WEC has been very well understood since the 1970s. Nonetheless, there have been relatively few model-scale experimental applications and even fewer large scale applications of controllers other than resistive dampers in WECs.

This lack of practical application has limited overall performance of WECs, including factors such as levelized cost of energy (LCOE). At first, this problem looks as if a better controller were some sort of amplifier that, once "plugged in" to an existing design, would create the needed increases in energy to drive down LCOE. However, the issue is more complex than that–in fact, the impact of improved WEC control design is much more fundamental. Because designing such a controller to increase energy absorption requires an understanding of the fundamental principles at play in the operation of a WEC, the process of designing a better WEC controller can and should lead to important insights on the larger problem of WEC design. Additionally, the practical implementation of real-time controllers on WECs is a nontrivial task on both large and small scale models, even for a simple resistive controller. This is due mostly to the fact that hardware design always defines the limits within which the controller can operate. This principle, that control design both draws on and influences all other aspects of WEC design, is at the core of Sandia's "Advanced WEC Dynamics and Controls" project. This brief report summarizes work completed under the Advanced WEC Dynamics and Controls project.

The Advanced WEC Dynamics and Controls project originally started with the goal to design a "plug-and-play" controller to realize the benefits in terms of performance that researchers had shown could be attributed to control systems, such as the great improvement in power absorption. According to the original approach, most of the effort would have been spent on bringing to bare nonlinear modeling/control and other highly-focused efforts on the problem. After the initial simulation work conducted to provide a comparison of control systems for WECs, and during the design stages of the "WaveBot" device that was tested at the Navy's Maneuvering and Sea Keeping (MASK) basin [8, 7, 10], it became evident that a more fundamental understanding of the problem was necessary.

It is well known that the control system is a critical element of the device, as it plays a central role in the regulation of the power flow and on the motion of the device. The implications of having a controller on board, however, were not completely fully appreciated: on one hand, the controller can improve power absorption within the physical limits of the device; on the other hand, a poorly designed controller (e.g., unstable, not sufficiently robust) can lead to delays in the development of the project, such as failure on bench testing and wave tank testing, or more dramatically, to catastrophically damage the device once deployed in open sea [12]. While the concept of optimal WEC control and dynamics existed, there was a lack of understanding about the implications of control concepts for overall device design.

The interaction between control design and overall device design can be brought to light by comparison with other engineering fields, such as wind energy technology and naval architecture. Traditional design methods for ships and wind turbines are directed towards shaping the dynamics of the device to be affected as little as possible by the external disturbance (e.g., quick variations of wind conditions, such as gusts, for wind turbines and waves for ships). In this case, the control system can be designed separately, once the design of the device has been finalized, because the controller is only concerned with the quasi-steady state conditions of the device (mean rotor speed and pitch angle for wind turbines, orientation of a ship), that is the slow dynamics, and it does not have to interact or compensate with the disturbance.

With this realization, the much of the project's work became integration of knowledge from disparate sources. The scope was effectively broadened to become understanding the overall dynamics, and the product became a tractable workflow for designing, modeling, and testing WEC controllers with readily available components and methods, with particular regard to the immense literature and tools available from classical control theory and practice. This has been done by shifting the point of view when looking at WECs from a mainly hydrodynamic focused approach to a more dynamics and control oriented framework, by starting to use classical control tools, such as block diagrams and Bode plots. Additionally, we have studied and documented in depth the practical aspects of implementing a control system on a real device, such as closed loop stability analysis; a fundamental requirement that had been previously overlooked. As a consequence of this work, we have developed an initial framework that will enable control co-design of WECs (power take-off systems, hulls, mooring systems, power electronics, etc.). At this stage, the focus of this project team has further pivoted to transferring knowledge to developers and academia through direct and indirect collaborations and dissemination of data, reports, and peer-reviewed scientific publication.

A comprehensive listing of publications is available at `advweccntrls.sandia.gov`. Based on the preceding conceptualization the project's findings can be summarized as follows:

- **System identification (SID) [1, 3, 8]:** To perform experimental tests of a WEC and obtain empirical models, the methods that are preferred in fields such as aerospace, automotive, and electronic engineering are equally powerful for testing WECs. Based on the wealth of knowledge on the topic of SID, wave tank tests should be using multi-sine signals that repeat to provide noise cancellation. Model fitting and data processing techniques utilizing the frequency domain are both powerful and well-suited to WECs.

- **PTO design and bench testing [4, 5]:** Given the critical role played by the PTO, the design and testing of these systems must be given focused attention. The principles practiced in robotics design, where closed-loop performance must also be considered, offer a wealth of guidance for WEC PTO design. Additionally, testing PTO hardware, using hardware-in-the-loop (HIL) and rapid prototyping experiments, is essential to understanding the dynamics and efficiency of such systems.

- **Local linear models [6]:** While the physics of a WEC system are indeed nonlinear, the nature of operation and the slowly changing nature of the ocean sea states enables the usage of local linear models. This approach is both simpler and also enables the usage of a large suite of tools and methods. The drawback of this approach is the neglect of what turns out to be a very small amount of power.

- **Band-limited controller design [11, 9, 2]:** By acknowledging the band-limited nature of real ocean waves, the maximum power transfer problem for WEC control can be simplified greatly. For the WaveBot device studied in this project, a simple PI controller can achieve roughly 80% of the optimal power absorption. A higher-order feedback controller can achieve 93% of the optimal.
- **Integrated WEC impedance model [2, 10]:** By utilizing a multiport framework, the dynamics of various WEC subsystems (hydrodynamics, drivetrain, generator, transmission system) can be integrated into a single impedance model, allowing both for control design that considers the entire WEC system as well as control co-design of the entire WEC system.

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