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Creating a Dynamometer for Experimental Validation of Power Take-Off Forces on a Wave Energy Converter

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Abstract — **Simulation tools are designed to represent subsets of the real world. To be effective, these tools must be experimentally validated with real world measurements. Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) have been tasked by the U.S. Department of Energy (USDOE) with the creation of a time-domain equation-of-motion simulator for the evaluation of wave energy converters called WEC-Sim. A project for the experimental validation of WEC-Sim features has resulted in the development of custom instrumentation designed to characterize the forces affecting the power take-off (PTO) of the model wave energy converter (WEC). This paper describes the development of this instrument, a dynamometer, including the original project requirements, model specification, component choice, and capabilities. The inclusion of the dynamometer in the experimental model has a disruptive influence on the hydrodynamic operation. Prior to the laboratory experiments, the instrument is simulated using WEC-Sim output as a driving force to verify the dynamometer design in a virtual environment. The results of these simulations are reported here, demonstrating the process used to validate the design prior to physical implementation.**

Keywords—wave energy; dynamometer; power take-off; scale model; WEC-Sim; PTO-Sim; simulation; experimental validation

I. Introduction

The Wave Energy Converter SIMulator (WEC-Sim) is a time-domain hydrodynamic code jointly developed by researchers at Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL) at the direction of the U. S. Department of Energy (USDOE) [1]. To be an effective development tool, WEC-Sim features must be experimentally validated through scale-model testing in a directional wave basin setting.

The experimental validation of WEC-Sim features is occurring in two phases over the next calendar year, with the first phase happening this summer and the second phase happening the following winter. The data used to validate WEC-Sim will be collected from instruments placed on and around the scale model during calibration and experimentation. The experiments will be performed in the Directional Wave Basin (DWB) at the Oregon State University's Hinsdale Wave Research Laboratory. A comprehensive series of tests for model characterization and WEC-Sim feature validation will be performed. The testing will include regular and irregular waves along with normal and directional waves. The surface elevation leading and following the model will be captured using wave gauges. A load cell built into the motion constraint system will record the forces and moments that impact the whole platform. The remainder of the instrumentation will be on-board the model and will record forces at joints and flaps, pressure distributions on the flaps, and motions of the model.

The goal of wave energy converters (WECs) is the generation of electricity from ocean waves. In many WECs, the energy source is the relative motion between two bodies, each moving in response to incident waves. The mechanical system used to convert the energy in the relative motion to hydraulic or electric energy is commonly referred to as the Power Take Off (PTO). Hence, records of the forces and motions of the model are primary data sets being extracted from the experiments. Measuring these variables required the development of a custom dynamometer.

Section II describes the project constraints that bound the experimental work. The model choice is explained with a focus on the data associated with the PTO. The section concludes with an introduction to the dynamometer concept. Section III provides details regarding the dynamometer design, including the instrument concepts, the specifications and their sources, and the capabilities enabled by the design. Section IV presents a brief description of the experimental operational modes. Section V presents the simulation results of the dynamometer design. Finally, Section VI contains conclusions from the simulation results and their projection into the future experimental testing efforts.

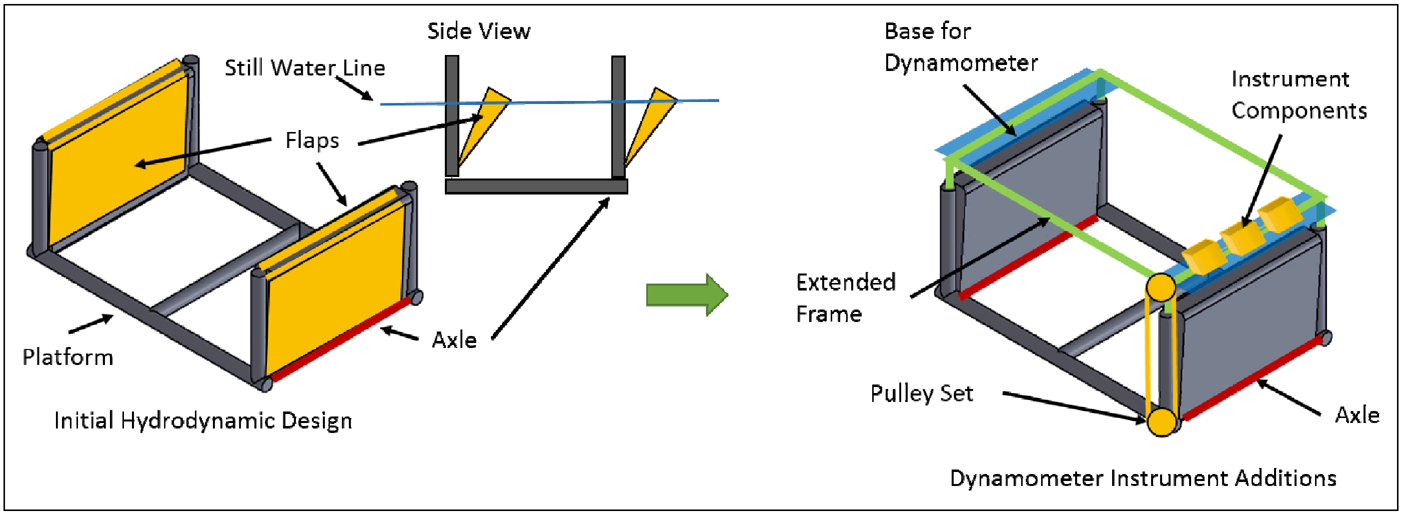

Figure 1 Experimental model illustration

II. Experimental Model

A. Project Constraints

The first project constraint is that the model used in the experimental testing is sufficiently complex to enable high-quality validation of all the WEC-Sim features. The second constraint is the desire to increase the complexity of the model in a piece-wise manner, through independently controlling the motion of various model components. Not only does this expand the matrix of possible experiments, it also facilitates the comparison of results and allows for the model to be reverted to a simpler state for the investigation of unforeseen issues. The final constraint is the desire to maximize the useful tank time and minimize the data manipulation required by minimizing the model configuration procedures.

B. Model Choice

The complexity of the model was addressed in the model selection process. Several different WEC architectures were ranked with respect to the WEC-Sim features to be validated and the ease of instrumenting the device. This process resulted in the choice of the floating oscillating-surge WEC (FOSWEC) architecture shown in the left of **Error! Reference source not found.**. There is a flap at each end of the platform frame. The flaps are connected to the bottom of the platform through a hinge, which allows them to move in response to the incident wave field. Each flap can be independently locked in place, free to move, or allowed to move with controlled damping. This hinge is the location of the PTO, and hence, the connection to the dynamometer. The top of the platform adds stability to the frame and provides a foundation for on-board instrumentation.

C. Project Optimization Constraints

The final driver for the model implementation is the optimal use of laboratory time for testing purposes. One factor affecting this is the testing plan, which is structured so that any test not requiring the wave facility is performed either before or after the scheduled laboratory time. The factor with the largest impact on laboratory time is model re-configuration. This has been minimized by requiring that configuration changes are simple to implement with the model installed in the basin. This leads to the requirement that all possible configurations affecting the model center of gravity are physically available at all times. With this arrangement, the number of laboratory tests needed to determine the center of gravity and the associated data manipulations are minimized.

D. Resulting Hydrodynamic Model Changes

As illustrated in **Error! Reference source not found.**, the basic model design shown on the left of does not support the dynamometer design without some changes. These changes are illustrated in the right side of Figure 1, which shows the conceptual placement of the instrument components and extension to the model platform. In addition, the instrument components need to be carefully placed as to maintain the model stability in the water. Each flap will be instrumented, so the front/back balancing of the model is simplified. However, the left/right balancing may require adding mass to the platform to ensure the model is not top heavy.

The second hydrodynamic change is a shield that protects the pulley sets from the oncoming waves and encourages the smooth flow of water past the platform uprights and the flaps. The pulley is required to transfer power from the flap axle to the dynamometer, which is largely placed out of the water due to technical issues with obtaining waterproof components. This shield is open to the water at the bottom, maintaining the overall model hydrodynamic performance. The shield itself isolates the flaps from the disturbances caused by pulley motion, ensuring the hydrodynamic interaction is as simple as possible. This arrangement results in the axle pulleys and a portion of the pulley belt being submerged.

III. DYNAMOMETER DESIGN

A. Dynamometer Concept

A dynamometer is defined in [2] as “a device for measuring mechanical power, especially one that measures the output or driving torque of a rotating machine.” Since rotational mechanical power is the product of torque and angular velocity, the base dynamometer components are a torque sensor and a tachometer. The addition of a motor component enhances the dynamometer capability by enabling it to drive and control the mechanical motion, either as a dynamic load or as a prime mover. It also provides an experimental means of correlating mechanical power with electrical power for any given equipment set.

B. Drivers

There are three additional requirements driving the dynamometer design, two of which are used in operational wave conditions as described in [3]. The first is the ability to hold the flaps in position regardless of the incident wave while measuring the forces on the fixed bodies. This situation creates the largest torque on the flap joint for operational conditions, estimated via simulations to be a maximum of 85 Nm. This measurement provides the upper boundary of the forces stressing the axle and the platform joint, giving developers guidance for their joint designs.

The second operational wave constraint is that the dynamometer must react to the incident forces with a programmable damping on the PTO, resulting in a measurable and controlled motion resistance. This feature enables friction compensation and damping optimization. It also enables optimization of the PTO and development of appropriate control schemes.

The final requirement is created by the need to measure the radiation forces caused by the flap motion. This is accomplished through a forced oscillation test, which is detailed in [3]. The flaps are driven by the dynamometer, creating waves in a still basin. This situation creates the maximum torque at the flap axle, and is estimated via wave maker theory to be a maximum of 225 Nm.

C. Resulting Specifications

The dynamometer design, housed on the model itself, is implemented with considerations for weight and friction as to minimize the instrumentation impact on the model operation. The design must be capable of driving 225 Nm at about six rpm, which was calculated from the periodic motion of the fastest planned wave case. The accuracy of the torque and speed measurements require the instruments are calibrated according to the National Institute of Standards and Technology (NIST) guidelines for standards and tracking. Components not pre-calibrated in NIST-qualified laboratories must be calibrated prior to the experimental testing. The material choices should be corrosion resistant, as some of the components are submerged, as seen in Figure 2.

D. Design

The combined requirements resulted in a dynamometer design that consists of a DC motor and driver, a rotational encoder, gearing, and a torque transducer. The conceptual implementation of the instrumentation is shown in Figure 2. The motor and gearing provide the reactionary or driving power to the system, as appropriate for the particular experiment set. The encoder provides a time-series of position data which is used to determine the velocity of the flap. The control of the motor operation is provided by a feedback controller that uses position, velocity, and shaft torque as control input variables. All of the instrument components are placed on top of the model, avoiding the need to have them waterproofed. They will be shielded from splashing by a plastic enclosure.

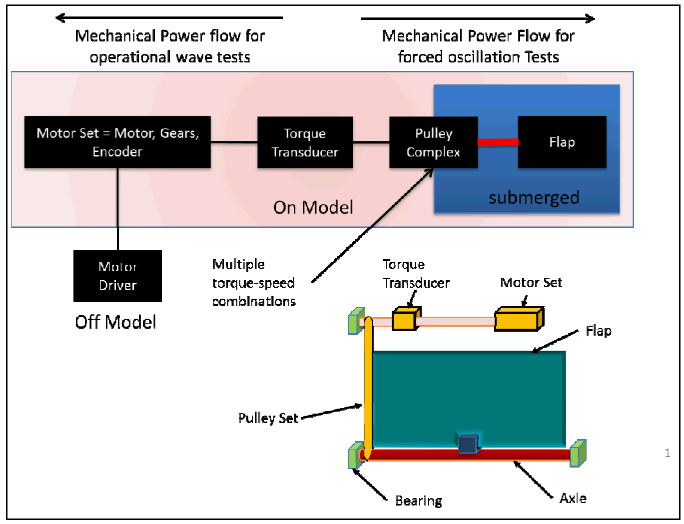

Figure 2: Dynamometer Conceptual Implementation

The motor set consists of a DC motor, a rotational encoder, and a planetary gearbox, all from Maxon Motors. This integrated component is used to provide linear damping during operational waves. It is also used to hold the flaps in place allowing for the examination of joint stresses. Finally, it drives the flap for the forced oscillation tests.

The motor is a 200 W, 36 V brushed DC machine with a nominal torque of 0.418 Nm and a nominal speed of 5420 rpm. It has a stall torque of 8.92 Nm at 148 A. Finally, it weighs 1.1 kg and is 157 mm long with a 50 mm diameter [4].

The planetary gearbox is integrated with the motor at the factory site, and provides a gear ratio of 71. This results in an output speed of 59 Nm and 76 rpm. The gear is rated for 75 Nm intermittent torque, with a maximum intermittent transmittable power of 330 W and a 70% efficiency. The gear is 62 mm in diameter, 104.2 mm long, and weighs 1.5 kg [5].

The rotational encoder is also assembled with the motor and gearbox at the factory. It has 3 channels, 500 counts per turn, and a maximum mechanical speed of 12,000 rpm [6].

The next component in the drive train is the torque transducer. It is a FUTEK TRS300 model shaft to shaft sensor. It has a 50 Nm limit with a 150% safe overload, which matches the torque and limits achieved with the motor set. The nonlinearity, hysteresis, and non-repeatability tolerances total ±0.5% of the rated output, for a total of 0.25 Nm. The sensor weighs 0.5 kg and is 108 mm long, 38 mm wide, and 58 mm high [7].

These components combine to create the base capability of the dynamometer. However, the 50 Nm torque limits are insufficient for the estimated loads. The final instrument component, the pulley complex, addresses this issue with different sized pulley wheels, which scale up the base torque to encompass the higher torque requirements. It also transfers the mechanical power from the top of the platform to the axle flap. This basic approach is the least expensive, most accurate and proven method for achieving the load requirements.

In order to meet the requirement of maintaining the mass throughout the testing, every pulley needed for all the options are included on the model at all times. And, to facilitate changing the model configuration in-situ, a pulley stack is created. Figure 3 illustrates the concept. This is a structure where all the pulleys on the top of the model are stacked to form a pyramid, while the axle pulley stack is an inverted pyramid. This approach was commonly used in machine or wood shop equipment prior to electronically controlled gearing. It provides a single belt size for controlling multiple pulley setting and is simple to design. The materials used for the belt and pulleys are easily selected from waterproof, minimal friction materials. It is likely that the structure will use some of the characteristics of a timing belt to reduce slipping. The belt will also have a quick-release tensioning element.

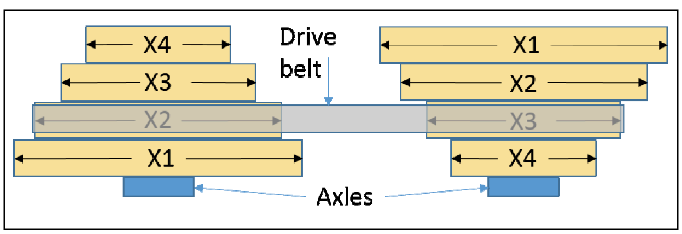

Figure 3: Drill Press Pulley Stack Concept

The final component of the dynamometer is the motor driver electronics. The driver board is a Maxon product, designed to support four-quadrant motor operation with current, speed, and position control capabilities. The motor power supply is driven by a 50 kHz pulse-width-modulated source. The current controller has a max sample rate of 10 kHz, while the speed and position controllers sample at 1 kHz [8]. The torque sensor, encoder, and motor cabling are routed out the top of the model and over to the driver board outside of the wave basin. All of the cables are bundled and provided with strain relief so as to not impact the free motion of the model. The output of the torque sensor and the encoder are also routed to the facility data acquisition instrumentation.

IV. Operational Modes

The first operational mode that utilizes the dynamometer is the regular and irregular wave excitation tests. The encoder output is used to calculate the angular velocity of the flap motion, which is used as the reference for the speed controller of the motor driver. The torque sensor output is used to create a constant speed-to-torque ratio, which results in a stable, programmable, linear damping on the flap axle. During this mode of operation, the dynamometer acts as a consistent load.

The forced oscillation tests form the second operational mode. During this test the dynamometer acts as a motor only. The encoder and torque sensor feedback is used to accurately create waves of a specific amplitude and frequency. The resulting wave field measurements will be used to validate the radiation hydrodynamics.

Prior to any testing, the entire instrument will be calibrated and characterized. Gear train and pulley losses and efficiencies, backlash and friction effects, will be determined at a lab bench setting. The tabulated results will be used to ensure that the measurement uncertainties are well understood.

V. Simulations

A regular WEC development program can be structured so that simulations of the instrumentation are not required. However, this development effort is specifically focused on understanding how laboratory experiments map correlate with simulation efforts. As such, simulating the dynamometer design in the equivalent of the experimental setup is a necessary step in identifying differences between the WEC-Sim model and the results obtained in the lab.

Many of the experiments planned for the wave basin testing are regular wave tests designed to understand the model response to wave excitation forces. Numerically, this was accomplished by taking an appropriately scaled output from a WEC-Sim regular wave simulation and using it as the forcing input on the dynamometer simulation. The dynamometer simulation is created in MATLAB SimScape, which allows the combination of physical and non-physical signals. The mechanical components contain inertia and friction models based on preliminary estimates of the drivetrain characterization. The top level schematic of the instrument is found in Figure 4.

The motor control used in these simulations is a proportional integral (PI) controller, as shown in Figure 5. Prior to implementing the control, the system variables of flap axle velocity and measured torque are converted to the motor frame of reference, negating the effects of the gearing. The design method used for selecting the PI controller gains was taken from chapter 8 of [9]. The crossover frequency used in the design is the maximum sampling frequency of the current controller of the Maxon motor drive board, 10 kHz. This is less than the 50 kHz of the PWM rate, and three orders of magnitude greater than the expected operational speed. These choices allow for additional tuning and customization, without a controller redesign, once the drivetrain is characterized. A plot of the controller step response is shown in Figure 6.

The angular velocity of the axle taken from the WEC-Sim simulations is used to demonstrate the ability of the dynamometer to appropriately track the flap motion. A close view of representative data from WEC-Sim clearly showing the non-ideal periodic waveform, is shown in Figure 7. Figure 8 shows the results of the dynamometer simulation with WEC-Sim angular velocity as the forcing input. The first 100 seconds are constrained with a ramp function, leaving the last 20 seconds to show the steady-state operation.

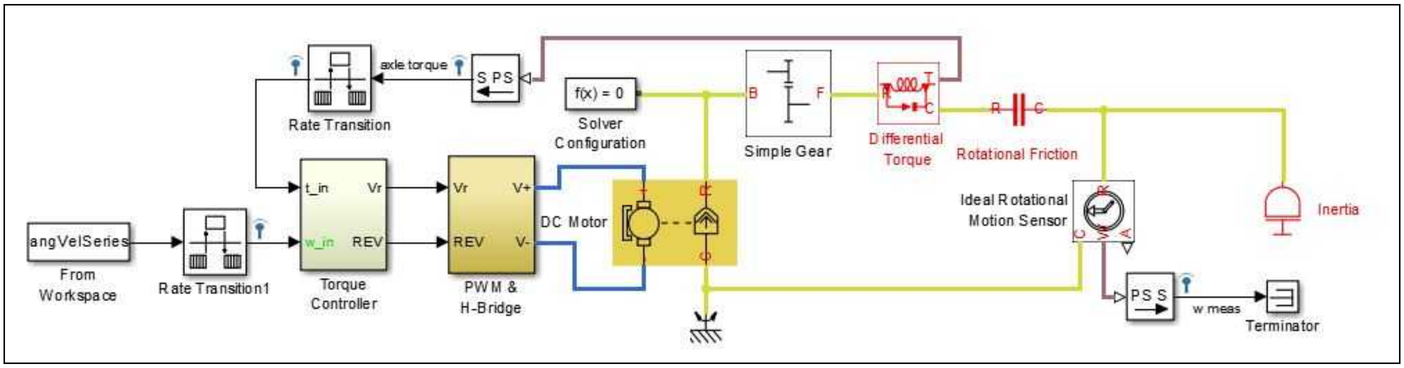

Figure 4: Schematic of dynamometer SimScape model

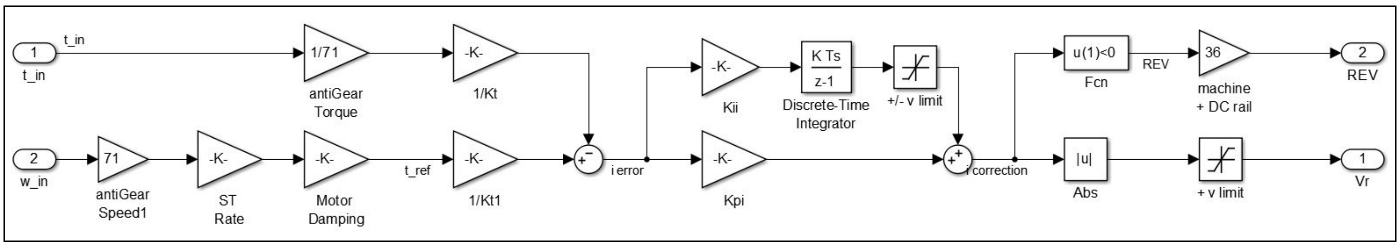

Figure 5: PI Controller schematic

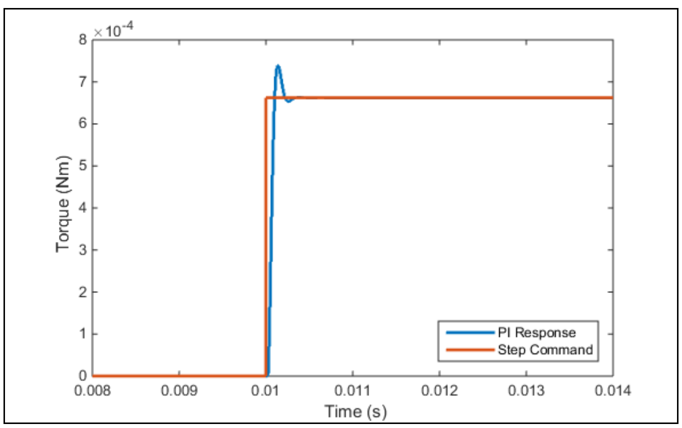

Figure 6: PI controller step response

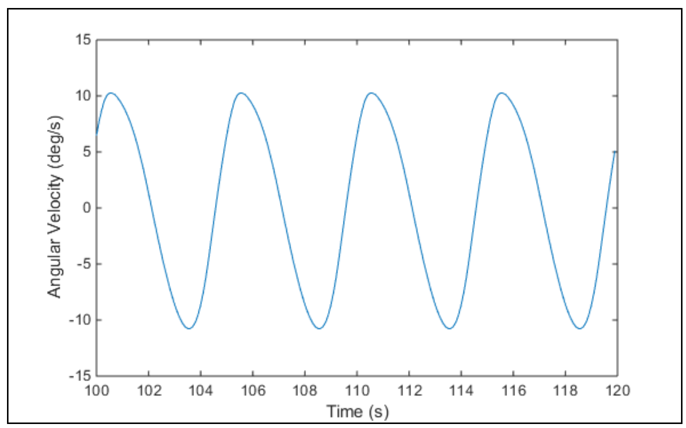

Figure 7: WEC-Sim flap angular velocity

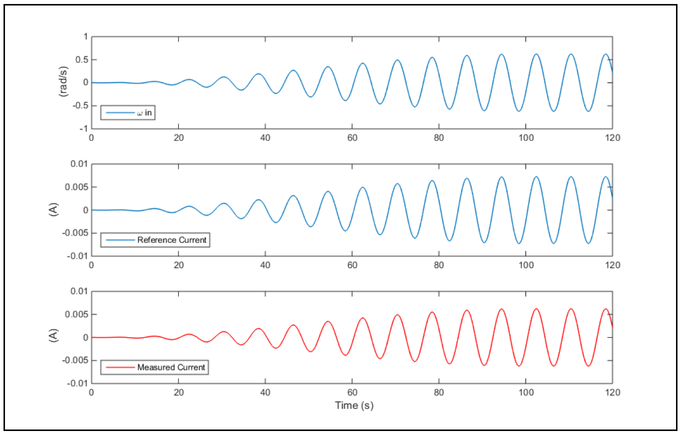

Figure 8: Dynamometer Response to WEC-Sim sourced input

VI. Conclusions and Future Work

The dynamometer design described here is only possible due to the current state of technology. Small, high-power, and accurate motor and gearing make it possible to instrument the model without additional basin support structures, like those described in [10]. The design facilitates the measurement and control of the PTO joint, providing data to researchers on the forces fundamental to energy harvesting.

The results shown in this publication clearly show that the design meets the project requirements. It is the least invasive design possible for a model-mounted instrument, and is structured with simple programmability and configuration options. Additional simulations mimicking the remaining experimental procedures will be performed so that every experiment type using the dynamometer is well understood. These simulations will be expanded with refined friction, inertia, backlash, and power transfer characteristics as the drivetrain design is completed.

The first set of future work regarding this dynamometer is to use the measurements to validate the WEC-Sim tool. Once that is complete, the design should be revised based on limitations and issues that arise during the wave basin testing. These modifications will ideally happen between the two rounds of testing, and will hopefully result in a tighter, more focused data set from the second set of laboratory experiments. Following the second round of testing, the full impact of the dynamometer instrumentation can be assessed, and recommendations regarding the use of a similar design in other WEC investigations can be made.

Although not currently planned or funded, a far future extension to this work could be made using a prototype-size version of the model, complete with up-scaled versions of the instrumentation. This model should be tested in an ocean test berth, and the results compared to the model data. These additional experiments will result in a more complete view of the factors that impact a WEC design, along with a better assessment of the new technology development costs.

Acknowledgment

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