WAVE ENERGY PRIZE TESTING AND DATA ANALYSIS OVERVIEW

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INTRODUCTION

The United States' Department of Energy's Wave Energy Prize contest encouraged the development of innovative deep-water wave energy technologies that at least double device performance above the state-of-the-art.

The Prize was comprised of three phases that progressively evaluated each team's technology [1]. The first phase evaluated the wave energy converter (WEC) concepts using the technology performance level (TPL) methodology and 20 teams qualified to proceed to phase II. In Phase II, each team used numerical simulations to estimate their WEC performance. Each team then developed 1:50 scale physical prototypes that were tested at various smaller wave tank facilities. The nine teams that had the best combination of the criteria in Table 1 proceeded to phase III. The nine finalists each built and tested a 1:20 scale physical prototype at the NSWC-CD's Maneuvering and Seakeeping Basin (MASK). Data from the 1:20 scale testing, in combination with a first-order capital expenditure estimate for the WECs, were used to determine the winners. This paper discusses the testing and analysis methods for the 1:50 and the 1:20 testing.

1:50TH SMALL SCALE TESTING

The 20 semi-finalists were notified by mid-August 2015 of being selected to participate in Phase II. The teams had a three month window, until November 23rd, to design, build and deliver their model to the small scale test facilities. In parallel, each team developed numerical models of their concepts and simulated their WEC operation. Scoring of the WECs for Phase II was based on four criteria (Table 1) of which, testing results are used to calculate the first two criteria.

TABLE 1. PHASE II JUDGING CRITERIA.

Criteria		Weighting
1	Measured net capture width for each wave set	15%
2	Correlation of numerical results with test results	25%
3	Re-evaluation of the TPL	30%
4	Predictions of ACE [1] expected in Phase III.	30%

A total of 31 waves were specified for simulation and testing. The waves are divided in five sets: three sets of seven monochromatic waves with a steepness of 1/80 (Table 2); one set of five monochromatic waves with a steepness of 1/40 (Table 3); and one set of five irregular polychromatic waves, Table 3. Each of the three sets of monochromatic waves with a 1/80 steepness have the same height and period, but each have a different direction of propagation relative to the WEC. The small scale testing was performed at five different tanks that had different depths that ranged from 1.3 to 5 m (Table 4). To account for the changes in depth, the 26 monochromatic waves were adjusted for each tank by changing the wave height and holding the wave energy fluxes and wave periods constant. The dispersion relation was used to ensured that each team experienced the same wave for the different water depths

TABLE 2. FULL SCALE (1:1) PARAMETERS FOR WAVE SETS 1 – 3, THE THREE SETS OF WAVES WITH A STEEPNESS OF 1/80.

Wave Set			T (s)	H (m)
1	2	3		
Direction relative to the forward facing direction of the WEC [deg]				
0	20	50	6	0.7
0	20	50	7.5	1.1
0	20	50	9	1.58
0	20	50	10.5	2.15
0	20	50	12	2.79
0	20	50	13.5	3.48
0	20	50	15	4.19

TABLE 3. FULL SCALE (1:1) PARAMETERS FOR WAVE SET 4, THE WAVES WITH A STEEPNESS OF 1/40 AND WAVE SET 5, THE IRREGULAR POLYCHROMATIC WAVES.

Set 4		Set 5	
T (s)	H (m)	T_P (s)	H_S (m)
6	1.41	5.8	1.75
7.5	2.20	8.95	2.5
9	3.16	15.5	5.2
10.5	4.30	12.5	2.7
12	5.58	11.4	1.35

TABLE 4. WATER DEPTH OF THE SMALL SCALE TEST FACILITIES.

Facility	Water Depth (m)
University of Maine	5.0
Stevens Institute of Technology	1.97
University of Iowa	3.0
Oregon State University	1.3
University of Michigan	2.93

WEC power takeoff (PTO) design for the 1:50 scale models was limited to a linear response between the dynamic (force, torque, or pressure) and the kinematic (linear velocity, angular velocity, and volumetric flow rate) components of power. For testing, different PTO settings could be specified for each wave type but the settings could not change during a run – adaptive control was not allowed [1]. For criteria 1, the net capture width was calculated for each set of waves by summing the capture width for each wave in that set:

$$NCW_j = \sum_{i=1}^{n} \frac{\sum_{k=1}^{m} \bar{P}_k^i}{J_i} \qquad (1)$$

where NCW_j is the net capture width for wave set j, n is the number of waves in wave set j, m is the number of PTOs, $\bar{P}_k^i$ is the average absorbed power for PTO k during wave i, and J_i is the wave energy flux for wave i.

The correlation, criteria 2, was estimated with the correlation coefficient calculated between the simulated and measured magnitude of the response amplitude operators (RAOs) for the six degrees of motion of each body (surge, sway, yaw, roll, pitch, and heave) and the kinematic and dynamic components of power. RAOs were calculated for each of the four sets of monochromatic waves and for each of the five polychromatic waves, yielding a total of nine RAOs for each of the eight response variables. Each set of monochromatic waves yielded one RAO for each response variable:

$$H_i(f_r) = \frac{S_i(f_r)}{\zeta_i(f_r)}. \qquad (2)$$

where f_r denotes the frequency of monochromatic wave r, $H_i(f_r)$ is the RAO for the monochromatic wave set i at a wave frequency f_r, $S_i(f_r)$ is the square root of the variance of response variable and $\zeta_i(f_r)$ is the square root of the variance of the wave height.

1:20^TH^ SCALE TESTING AT MASK

Nine finalists were notified on March 1, 2016 of being selected to participate in the Phase III testing at the MASK basin. The teams then had until July 18 to design, build, and deliver their 1:20 scale model to the MASK. Unlike the smaller scale tests, there was no limit placed on the WEC controller. All controller software was required to be submitted on August 1st to ensure equal development time for all teams.

The MASK is an indoor basin having an overall length of 360 feet, a width of 240 feet and a depth of 20 feet except for a 35-foot deep trench that is

50 feet wide and parallel to the long side of the basin. The basin is spanned by a 376-foot bridge supported on a rail system that permits the bridge to transverse to the center of the basin width as well as to rotate up to 45 degrees from the centerline (Figure 1). The wavemaker system consists of 216 paddles. There are 108 paddles along the North edge of the basin, 60 paddles in a ninety degree arc, and 48 paddles along the West edge of the basin.

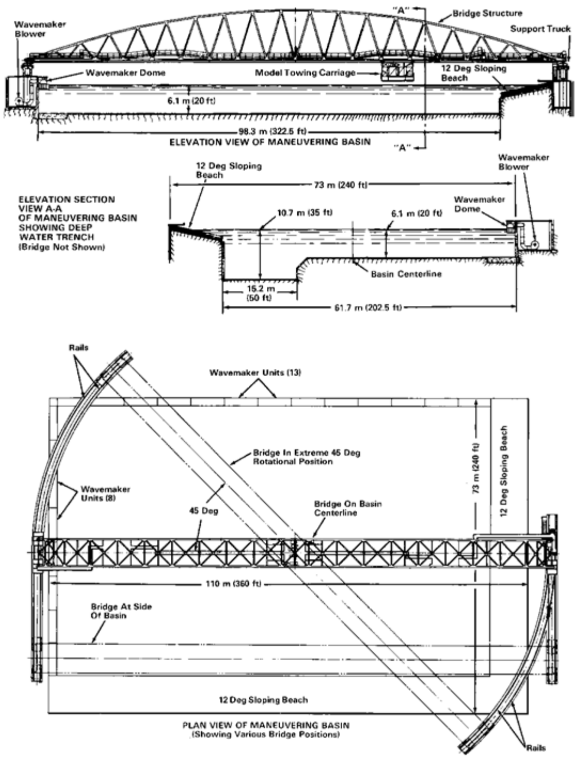

FIGURE 1: GENERAL SCHEMATIC OF BRIDGE AND MASK BASIN

Each team had two consecutive weeks at MASK. During the first week, each team assembled their WEC and the Prize Administration Team (PAT) and test lead verified dimensional compliance and sensor performance. During the second week, the WEC was deployed, tested and recovered. Tests were conducted sequentially leading to a 10 week test program.

Scoring for Phase III is solely based on the Hydrodynamic Performance Quality, HPQ, metric. Only teams that met or exceeded the ACE threshold of 3 m/$M had HPQ evaluated. HPQ can be visualized as the ACE score weighted by the device performance during testing in the following areas:

- station keeping,
- mooring loads,
- peak to average absorbed power,
- absorbed power in realistic (bimodal) seas
- PTO behavior, and
- control effort

The ACE metric is a reduced version of the LCOE specifically developed for the Prize. ACE provides an equitable comparison of low Technology Readiness Level (TRL) Wave Energy Converter, WEC, concepts. ACE is the ratio of the Average Climate Capture Width (ACCW) to the Characteristic Capital Expenditure (CCE). ACCW is the absorbed power of the device divided by the wave energy flux per meter crest width, and CCE is a first order estimate of the structural cost [1]. The HPQ weighting and the ACCW are solely dependent on the overall performance of the WEC model during the tank testing in the MASK Basin. Details of how the HPQ and ACCW were calculated can be found in [1] and [2], and details of the sea states tested in the MASK basin can be found in [3] and [4].

Test Waves

Each WEC was subjected to ten different irregular wave states that commonly occur on the west coast of the United States, including Alaska and Hawaii (Table 5) [3]. The ACCW was calculated from the six unidirectional long crested irregular wave states (IWS). The HPQ was calculated from all 10 sea states, including two bi-modal and multi-directional "realistic wave states" (RWS) and two storm "large irregular wave states" (LIWS).

TABLE 5. PARAMETERS FOR THE SIX 1:20TH SCALE SEA STATES. DIRECTION IS SPECIFIED RELATIVE TO THE FORWARD FACING DIRECTION OF THE WEC [DEG] AND SPREADING IS BASED ON $\cos^{2s}$

Wave Designation	T_P (s)	H_S (m)	Dir (deg)	s
IWS 1	7.3	2.34	10.00	none
IWS 2	9.9	2.64	0.00	none
IWS 3	11.5	5.36	-70	none
IWS 4	12.7	2.06	-10.00	none
IWS 5	15.2	5.84	0.00	none
IWS 6	16.5	3.26	0.00	none
LIWS 1	13.9	7.90	-30.00	3.00
LIWS 2	11.2	9.20	-70	7.00
RWS 1	14.4	1.52	-70.00	7
	7.2	2.16	0.00	10
RWS 2	14.8	1.58	-70.00	7
	8.6	1.3	-10.00	10

Testing

Each test run was about 50 minutes with 10 - 20 minutes allocated between runs for basin settling and to allow configuration changes. The schedule of events is given in Table 6. The tuning stage allowed teams to adjust their control settings or allow their adaptive controller to self-tune. Thereafter, teams could not interact with their WEC. Teams could also elect to skip this step. The 25 minute interval for testing provided a sufficient window to ensure stationarity.

TABLE 6. BREADKOWN AND DURATION OF EACH WAVE TEST

Event	time from t = 0 (start of test)
Startup (time for waves to fully develop)	0 – 5 min
Optional Tuning (teams tune their controller and PTO settings for the waves)	5 - 15 min
Testing (data to be used for analysis)	15 – 40 min
Basin Settling, Re-Configuration as needed, Data Checks	40 – 60 min

Basin Setup

All WECs were moored so that they had the same undisturbed location, centered underneath the carriage. Prior to testing, the wave maker was tuned so that the spectrum of each wave time series measured at the WEC test station closely matched the spectrum of the specified wave.

Data Acquisition and Sensors

Prize measurements consisted of wave height, mooring loads, PTO variables and device motion. The wave measurements were provided by sets of acoustic and capacitive wave sensors located upstream of the WEC test station at 0 deg and -70 deg. A National Instruments Compact RIO (primary cRIO) data acquisition system was used to sample the PTO and mooring load sensor at 100 Hz. A natural point tracking system (NPTS) was used to track the motion of each body in the WECs at 100 Hz. The wave probes were on separate cRIO systems. The primary cRIO interfaced with the NPTS and the wave DAQs to ensure tight data synchronization (Figure 2). Data streams were fed from the primary cRIO to the team if they needed the data to support their control. The Prize recommended that each team have sensors with a NIST (or equivalent) traceable calibration.

Given that each team had only one week to deploy, test, and recover, and that the test schedule was tight, it was critical to ensure that all sensors were performing properly and to identify any issues as they occured. Thus, after each test, the data were processed and a first-order data quality assurance was performed.

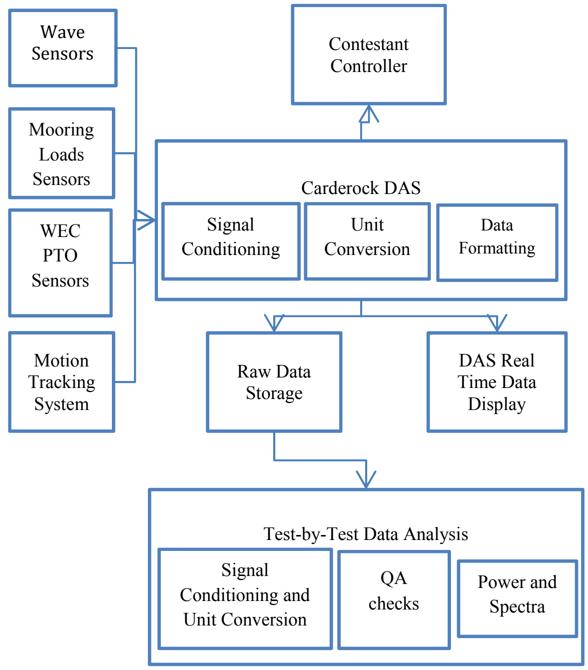

FIGURE 2: SCHEMATIC OF THE DATA FLOW AND PROCESSING

CONCLUSIONS

The Wave Energy Prize program successfully tested twenty 1:50 scale WECs and nine 1:20 scale WECs. Data collected during these tests provided quantitative performance information that was used to evaluate each WEC and determine the winners.

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