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Conference Paper · April 2015

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SAND2015-8089C

Proceedings of the 3rd Marine Energy Technology Symposium
METS2015
April 27-29, 2015, Washington, DC

INSTRUMENTATION OF A WEC DEVICE FOR CONTROLS TESTING

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ABSTRACT

A set of tests have been planned to determine the extent to which various control strategies can increase the power produced by resonant wave energy conversion (WEC) devices. This paper describes the instrumentation and sensor suite developed for use in these tests. The instrumentation package was selected to simultaneously sample all the signals with high resolution at a frequency up to 1 kHz. The sensor suite for measuring parameters used in real-time control strategies will be recorded at a sampling frequency of 100 Hz. A set of sensors targeted at validating theoretical and numerical models of the device and will also be sampled at 100 Hz. A sensor suite comprised of slam panels and high-impact pressure transducers will measure the slam forces on the device. The slam sensors must be sampled at a higher rate of 1 kHz to capture any slam events.

INTRODUCTION

With advances in the technology of wave energy conversion (WEC) devices, a number of control schemes have been developed to maximize the amount of energy captured through control of the power conversion chain (PCC) (see, e.g., [1, 2, 3]). Theoretical studies performed with these control measures have shown promising results, but have done so using varying levels of idealization. A WEC device, referred to as the T3R2 (three-translations, two-rotations), has been designed to be tested in the Maneuvering and Seakeeping (MASK) Basin at the Naval Surface Warfare Center's David Taylor Model Basin. This WEC device has been designed to undergo testing using a Froude-scale factor of 17 and its motion has 5 degrees of freedom (all the modes are allowed except for yaw).

WEC control strategies attempt to alter the dynamic of the device to make it resonate under the excitation of incoming waves. The control signal is calculated by using information on the state of the system, which is measured or estimated by using the signals provided by a number of sensors (e.g. position, velocity, force). The T3R2 has been specifically instrumented in order to test WEC control measures.

First, this paper presents the rationale behind the overall instrumentation setup for the T3R2. Next, the sensor suite needed to implement real-time control will be discussed. The design and arrangement of any sensors targeted at model validation will then be detailed, including housing design for all the sensors. Any sensor to be used in order to monitor the test for errors (temperature and humidity sensors) will be listed.

EXPERIMENTAL SETUP

Magnitude, fidelity, and response rate requirements for sensors utilized in the tests of the T3R2 were informed by frequency and time-domain models of the system. A diagram of all the selected sensors, instrumentation, and connections for testing of the T3R2 is shown in Figure 1. Signal types and connections are indicated using the scheme detailed at the bottom of the figure. To allow for all measurement signals to be read simultaneously, the experiments will be monitored with a National Instruments (NI) CompactRIO (cRIO) capable of synchronously sampling all of the experiment's sensors.

In order to minimize disturbance in measurement signal pro-

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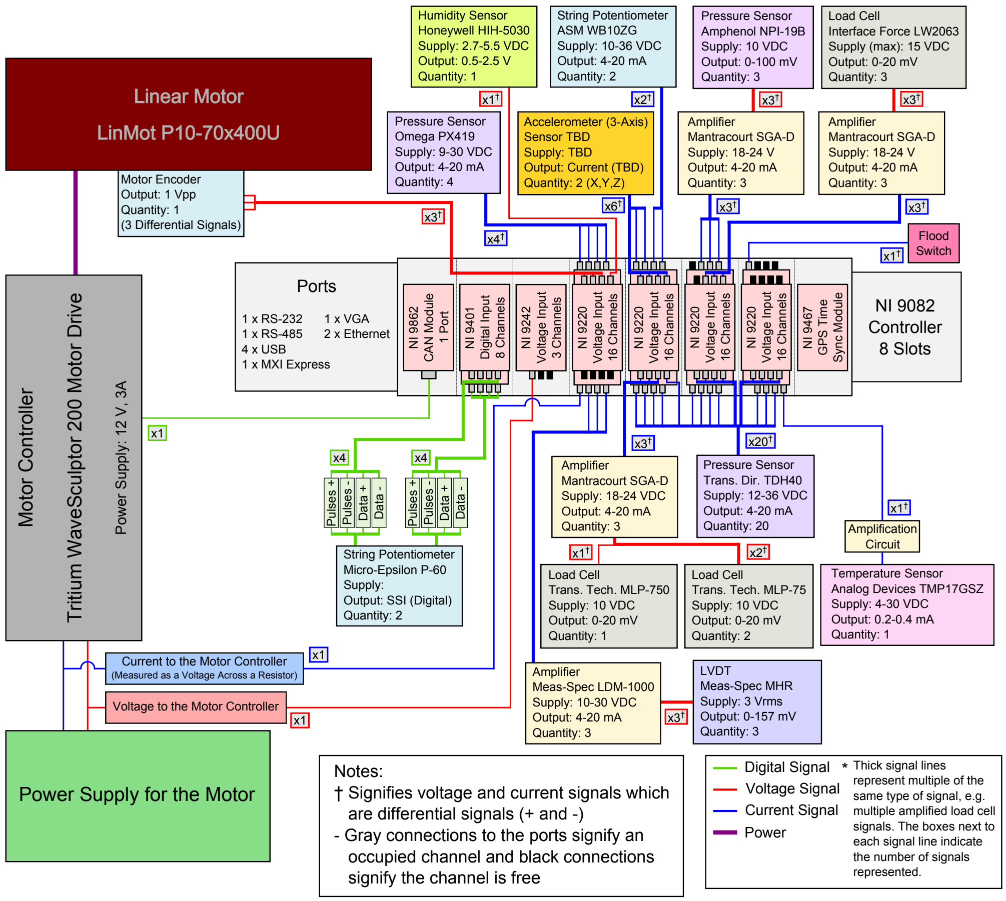

FIGURE 1. Diagram of the sensors system for T3R2 tests.

vided by analog sensors due to resistance in wires or the magnetic field of the rod, all the signals will be transmitted as analog current loops ($4-20$mA); voltage signals will be avoided when possible. Only synchronous digital interfaces will be used for communication between sensors and the acquisition system. Therefore, sensors will be purchased with current signals when available or converted to current when possible. Any amplifiers used to convert signals from voltage to current will be placed as close to the sensor as possible to minimize noise. Current amplifiers for pressure sensors will be located inside the buoy and the maximum cable length is ~10 meters. All current signals will be read as voltage across precision resistors. Any digital signals will be read through a bidirectional I/O module. GPS time-stamping and synchronization module will be used to sync T3R2 signals with signals from the MASK wave basin (e.g., wave gauges).

To implement the full range of control strategies currently being considered for WECs, a LinMot® P10-70x400U [4], which has the ability to accept and output energy (act as a generator and a motor), has been selected. The generator will be controlled by the Tritium WaveSculptor200 motor controller [5]. Commands to the generator and information from the generator's sensors will be read through the cRIO's CANbus interface.

Sensor for Real-Time Control

In general, real-time control requires a number of sensor readings for the correct calculation of the control signal. The measurements available to the control system are: forces and moments on the float, float velocity, and float position. Any sensor measuring a parameter used for real-time controls will be sampled at 100 Hz.

The locations for sensors that will be used to measure the system parameters for controls are shown in Figure 2. The motor encoder is housed within the LinMot PCC Motor. The planned locations for all the other sensors are displayed by locations A, B, and C (orange boxes). The planar motion table (PMT) load cell, PMT string pot, and T3R2 string potentiometer all have a similar sensor placed along the other axis not shown. The PMT load cell will be placed in line with a spring that is not shown.

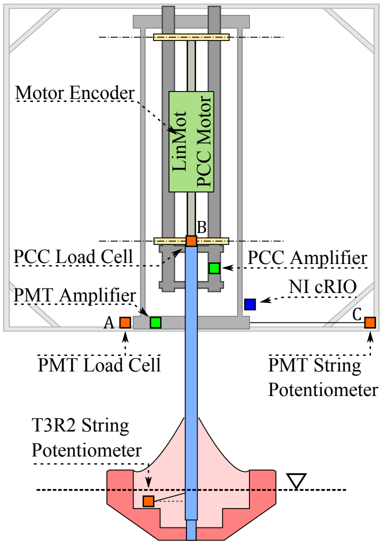

FIGURE 2. Layout for the instrumentation used by control schemes.

Translational Displacements. The LinMot® P10-70x400U has an encoder built into the system which can monitor the extension of the generator arm through two differential sinusoidal signals [4]. The PCC arm beneath the generator is rigid and the height of the stator will be fixed. Therefore, the measurement of extension from the encoder can be used to determine the vertical displacement of the buoy.

The buoy's position in the horizontal plane will be measured on the PMT, as shown in Figure 2. Sensors that give high-quality measurements of displacement often have slow response rates. On the other hand, signals with high response rates often have noisy signals. Since the testing planned for this system occurs from 0.25 to 2 Hz, it is safe to use a slower sensor to avoid noisy signals. Considering cost, accuracy, and effect on the system, string potentiometers were selected to measure both surge and sway. The force added into the system from the string potentiometers will be minimal compared to the hydrodynamic and mooring loads.

The velocity of the system will be determined by means of signal processing techniques.

Measuring Roll and Pitch. There are many ways to measure the angle of the buoy in pitch and roll, either directly or indirectly. One of the most common, methods of measuring rotation of a device is to use MEMS (micro-electro-mechanical) sensors, such as accelerometers and gyroscopes. However, due to the low frequency range associated with small scale testing (0.25-2 Hz) and the importance of bias and random walk effects in this frequency range, it was determined that these sensors were not suitable for real-time integration. Both liquid-capacitive and -conductive inclinometers can measure angular displacement accurately, but have too slow of a response for this application.

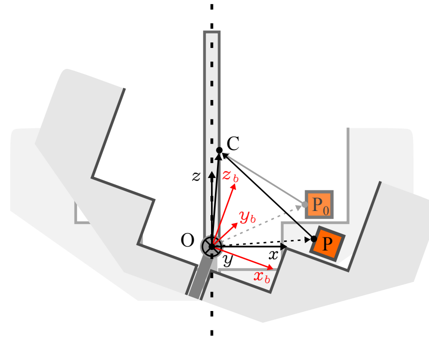

FIGURE 3. System for calculating pitch and roll, the black axes are the body-fixed frame and the red axes are the inertial frame.

String potentiometers can directly measure positions with high accuracy; relatively simple transformation calculations can convert the position measurement into an angle measurement. The roll and pitch angles are measures indirectly by measuring two distances between two fixed points on the buoy and two fixed points on the down tube. Figure 3 illustrates the principle, where point C is fixed on the down tube and point P is fixed on the buoy. The distance between point C and point P changes when the buoy rotates. The relation between the angles (roll and pitch) and the lengths can be obtained by considering the rotation of a vector between two reference frames, one attached to the buoy and one attached to the down tube, and both frames having the origin located on the joint. The distance between point C and point P ($\vec{PC}$) can then be related to the angles with the formula:

$$\vec{PC} = \vec{OC} - R_b^3(\theta, \phi) \cdot \vec{P}_C^b \tag{1}$$

where $\vec{P}_C^b$ is the vector between the origin and the location of the point P in body fixed coordinate, and $\vec{OC}$ is the vector between the origin and the position of the point C on the expressed in the frame attached to the down tube. Equation 1 describes the (variable) distance between points P and C in the coordinate system of the down tube as the difference between the vector $\vec{OC}$ and the position of the point P in the coordinate system of the down tube, obtained by rotating the vector $\vec{P}_C^b$ using the standard rotation matrix R for the transformation of vectors between two coordinate systems (eq. 2.18 from [6]). At least two independent length measurements are necessary to calculate the roll and pitch angles; for this reason two string potentiometers will be used to measure distances between the down tube and two points on the buoy. The potentiometers are located such that the distances they measure are approximately orthogonal, when projected onto the horizontal plane.

In order to go from the length of the potentiometer cable to the angles of the buoy, Equation 1 must be inverted. The length of each cable creates a set of possible orientations for the buoy. In

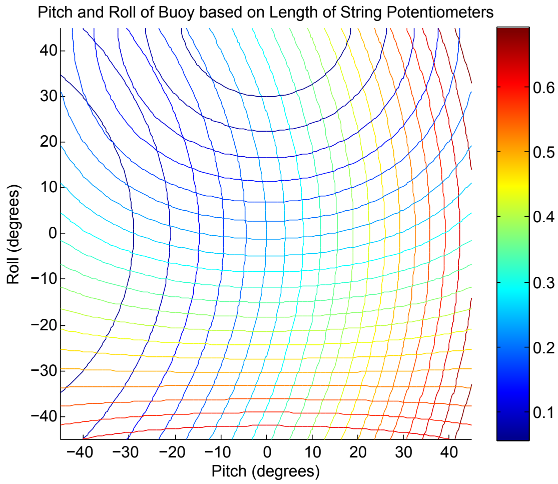

FIGURE 4. The contour circles in this plot represent various extensions of the string potentiometer cables represented by color. Angles of the buoy are determined by the intersections of the contour circles.

order to determine both angles, the intersection of possible angles as shown in Figure 4 must be determined. Adding a third string potentiometer inside the buoy is one way to eliminate ambiguity of the orientation, that may occur for large positive roll angles and for large negative pitch angles (top left of Figure 4).

Measuring Forces in the System. The forces being applied into the system will be measured in surge, sway, and heave with load cells. While S-beam load cells are often the most accurate style of load cell, they have a slower response rate due to high deflection. A low profile tension/compression load cell with a maximum deflection of 0.0762 mm was selected to have both high accuracy and fast response.

The total heave forces input to the buoy, both from waves and from the motor, will be measured in-line with the PCC at the bottom of the LinMot slider but above the down-tube (see Figure 2. The Tritium motor controller allows to specify the force exerted by the linear motor/generator; therefore, by combining this value with the force measured by the load cell, it could be possible to estimate the contribute on the heave force due to the fluid-body interactions.

The total surge and sway forces will only be measured when the system is unlocked. The load cells for these forces will be placed in line with the springs used for mooring. Since the forces are so much larger when the system is locked, these load cells would get damaged if used in all cases.

Sensors for Modeling

While the main aim of these tests is to determine the effectiveness of various WEC control strategies, a secondary aim is to measure effects on the buoy to enhance numerical modeling of WEC devices. The pressure distribution over the buoy will be recorded to help development of modeling for WEC devices in operational conditions. Additionally, slam loading on the device at three different locations will be measured in order to increase the knowledge of WEC devices in extreme conditions.

In the future, a subset of these sensors may be used in the control algorithms.

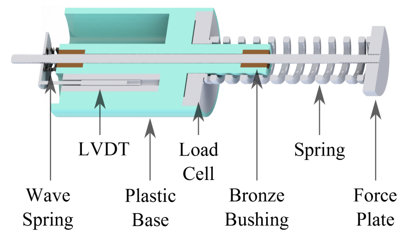

FIGURE 5. Section view of the slam panel design.

Design of the Slam Panel. The phenomena of slam is very complicated and requires special attention for both numerical and physical modeling [7]; wave breaking on the side of a structure or a structure leaving and then re-entering the free surface are highly nonlinear events. Slam events are tightly-coupled structural-hydrodynamic systems, which are governed by both inertial and elastic forces (Cauchy's number). Hence, in order to reproduce a structure's response to external loads, structural similitude must be achieved in which the stiffnesses and stresses of the full-scale design are matched.

The T3R2's slam panels have been designed with a natural frequency to match outer panels of current designs of WEC devices. Based on frequency analysis tests in SolidWorks Simulation, a natural frequency of $\sim$150 Hz at model-scale was selected. This matches well with the natural frequency of some slam panels used in testing on ships [8]. The resulting design is shown in Figure 5. In order to make the design interchangeable if anything should fail, the design developed is a plate attached to a rod that applies force to a spring (with a spring constant chosen to match the model-scale natural frequency) which transfers the force to a load cell. The load cell is protected from off-axis loading with two bronze bushings placed along the rod. The design also ensures that the front spring will stay in contact with the load cell by adding a wave spring to the back of the design. The base is made of 3-D printed plastic, making it both inexpensive and highly customizable. Three slam panels, each at a different vertical position, will be placed on the T3R2 buoy (see Figure 6). Since slam events occur very quickly, all sensors for slam will be sampled at 1 kHz.

Slam Panel Validation. While seeking expert advice and examples in literature, the slam panel design shown in Figure 5 is completely novel. Since pressure transducers have been used heavily in the past when studying slam, each slam panel will be accompanied by a "slam" pressure transducer with a high

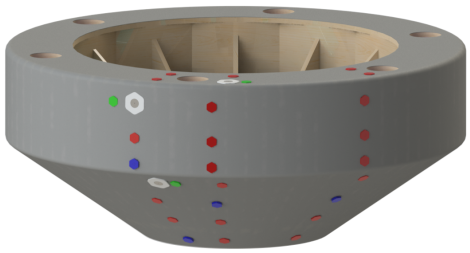

FIGURE 6. Small circles are locations of pressure/slam sensors on the buoy (red: low-fidelitey transducers, blue: high-fidelity transducers, green: "slam transducers," dark gray: slam panels). Large circles on top of the buoy are ballast ports.

response rate. The pressure sensors selected to validate slam measurements are encased in oil in order to negate the effects of temperature increases during an impact and have a very fast rise time.

Layout of the Pressure Sensor Array. In order to attain a high fidelity model of the pressure on the buoy as a wave passes over the surface, an array of 24 pressure transducers will be set into the buoy's hull. To save cost, 20 of the pressure transducers be lower quality pressure transducers and only 4 will be higher quality pressure transducers. There are also 3 sets of slam sensor units, each including a slam panel and high-impact pressure transducer as described above. The pressure/slam sensors will be aligned at angles 0°, 20°, and 60° (with 0° being aligned with the dominant wave propagation direction) as shown in Figure 6. In some cases, these sensors must be slightly offset from this layout due to physical constraints.

Sensor Housing. Since all pressure/slam sensors will be placed flush with the buoy hull, they must be sealed to prevent any water from getting inside the buoy. Each will be mounted inside of a PVC tube housing made of off-the-shelf parts. The slam panels will have a flexible silicon cover to water-proof the cover. Each pressure transducer will screw securely into an outer plug. Since all the sensors are gauge pressure transducers, pressure fluctuations on the backside of the sensor will cause errors in the sensor reading. Hence, the housing will be sealed on the backside to prevent any errors due to pressure fluctuations from inside of the T3R2 buoy.

Sensors for Monitoring Tests

When using sensors and sensor collection systems, such as the NI cRIO, there is always a possibility that something goes wrong during a test. Since there is no way to ensure a 0% chance of some error occurring, some sensors will be added in to monitor the system. These monitoring sensors include: a humidity sensor, a simple current-loop to determine if the buoy is flooding, a temperature sensor in the buoy, and accelerometers to monitor vibrations on the upper structures.

CONCLUSIONS

An instrumentation and sensor suite has been developed for a WEC device for use in testing advanced WEC control strategies. The justification for the sensors selected for this testing program has been discussed. A plan for how to measure parameters for use with controls was detailed. Additional sensors will provide measurements to validate numerical models for WECs and develop a better understanding of slam events. Sensors were added to monitor the system to ensure the tests run as planned. Individual sensors were then selected based on the predicted values of measurement. The first tests using the T3R2 will occur in the summer of 2015. All results will be made publicly available.

ACKNOWLEDGMENT

This work was funded by the U.S. Department of Energy's Wind and Water Power Technologies Office. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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