Power producing buoy for strategic applications: Design Trade Study – Final Report

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Summary

The purpose of this project has been to perform the first steps of an investigation of concepts and prototypes for extracting wave energy on an autonomous platform that remains on station in the ocean without being moored. The approach taken has been to develop a numerical model based upon rational mechanics of wave-body interactions for various candidate concepts. The effort undertaken in this project is meant to enable a larger companion project and thus is limited to the development and validation of the numerical model. The use of this model as a design tool is performed in the companion project. The numerical model solves the equations of motion of one or more connected rigid bodies floating in the ocean. The solution is performed in the time-domain and the result of the model is time histories of quantities of interest such as forces, motions and power converted by generators of different types. Because of the complexity of the problem a number of assumptions about the behavior of the system and the ocean waves are required to make the problem tractable. Because of this it is important to validate the results of the numerical tool against experiments before using the model as a design tool. Such an experimental validation has been performed as part of this project and the final results are presented in this report.

In addition to the technical work performed in this project, a number of other meetings have taken place that also contribute to the companion project, these include a technical and programmatic meeting at MBARI with the technical contributors and larger team. Additionally, two visits to other institutions have been made under this project to investigate the suitability of available technologies to this project.

Activities

1. Held a technical meeting at MBARI with subcontractors Airflow Sciences, Marine Innovation and Technology, and consultant William Webster: March 11, 2009.
2. Held a project kick-off meeting with DARPA personnel: April 16, 2009.
3. Completed a global environmental-condition analysis.
4. Visited Roy Kornbluh at Stanford Research Institute (SRI) to discuss the applicability of their “artificial muscle” technology to this application.
5. Visited Sid Chao at CIIIS to evaluate the applicability of the “ferro-fluid” linear generator system to this project.
6. Completed the development of a general purpose computer code for modeling wave-body interaction problems.
7. Designed and built a test buoy system for validating the computer model.
8. Performed a “step-response” test with test buoy in the MBARI test tank.

Technical Results

Numerical Model Development

A significant results of this project is the development of the computational framework needed to perform time-domain simulations of the various concepts under consideration for a station-keeping wave-energy conversion device. These concepts all require very similar modeling capabilities to analyze; all devices involve a floating body in waves and a device to harness energy from the relative motion of two or more bodies. The framework developed effectively solves for the motion of one or more bodies that are acted on by outside forces such as the wave field, currents wind, and any wave-energy extraction devices included in the system. This computational toolbox that has been developed is modular enough to allow various elements such as floating buoys, submerged foils, linear power take-off generators, submerged turbines, and wind turbines to be combined in nearly any arrangement. Adding new elements to the system requires only defining the forces that act on that element as a function of the elements position history throughout the time-domain simulation.

The analysis of such systems is fundamentally straightforward and involves the solution of Newton’s equations of motion (force = mass times acceleration). Although the solution of this type of equation is not difficult, the evaluation of the forces acting on the various parts of the system can be complicated. For example, the forces acting on a body floating in waves depends on the hydrodynamic behavior of the particular shape and size of the body. Further complicating this is the fact that as existing waves cause a floating body to move, this motion then causes the body itself to generate waves which add an additional force that acts on the body, further modifying it's motion. This feedback causes a "memory effect" in which the forces acting on the body at the current time depend not only on the body's current velocity, but also on the velocity history of the body. Fortunately, this complicated problem has been solved by previous researchers. (at least for linearized systems, which is an assumption made throughout this projects wave-body interaction numerical analysis and is one reason that subsequent validation of the simulation results via prototype or model testing is important).

The computer code to perform this analysis has been implemented in the Matlab programming language. The required wave-body hydrodynamic characterization of the floating body elements is computed using the WAMIT code. This code computes the linearized wave-body behavior in the frequency-domain, subsequent conversion to an impulse response function in the time-domain via Fourier transform is performed to include the WAMIT results in the time-domain code. This technique is fairly common for this type of problem and reduces the computational requirements significantly compared to solving the fully non-linear wave-body interaction problem. The result is a code that can simulate the wave induced motion of the prototype concepts in approximately real time, that is a 10 minutes simulation requires about 10 minutes of computer time on a typical desktop workstation. This relatively modest computational requirement is important for the current application which requires the simulation of many cases while varying parameters such as buoy size, wave size, power take off characteristics, etc. The computer code that has resulted from this project is called TD_xxx (this is a working name, and should probably be replaced with something more descriptive).

Although the techniques used in this code are well known, there are very few tools available that combine the techniques in the extensible nature of this code. In that regard the code itself appears to be fairly unique, in many discussions with other workers in the wave energy field it is clear that most don't have a tool such as this one at their disposal and that their efforts are hampered by the lack of an ability to predict the motions that their devices will undergo in the ocean environment. The TD_xxx code encapsulates most of the mathematics involved in the wave-body interaction problem and would allow non-experts to study their wave-energy concepts without a detailed knowledge of the wave-body interaction hydrodynamics. We have ideas of making this code available to a wider audience, but no such work has yet been undertaken.

Validation Tests

Because of the simplifying assumptions that are necessary, it is critical to validate the accuracy of the model against experimental results before using the model for design purposes. This has been done and the resulting comparison makes up the second major result of this project. To perform the validation a test buoy was designed and built that is similar in size to the expected concept designs. The response of the test buoy was measured over two days of testing in Monterey Bay, the tests where performed near an existing wave-measurement buoy that recorded the spectrum of wave heights present during the tests. Subsequently the numerical model was run with the measured characteristics of the test system (mass, dimensions, etc) and the wave input matching that which existed during the tests. The results from this comparison indicated that the numerical model faithfully replicates the important physics of the system and is useful for investigating the wave-energy concepts in mind.

The validation test buoy is shown in Figure 1 and consists of a surface buoy that is 96 inches in diameter and weighs 2600lbs. Submerged below this buoy is a flat, circular steel plate that is 48 inches in diameter and weighs 1300lbs. These two elements are connected by a 20 meter long tether and a 6 foot long hydraulic ram that operates as a spring/damper. One side of the hydraulic ram is plumbed to a system of accumulators that compress a gas as the ram is extended by the tension of the tether. These accumulators approximate a linear spring. The flow of hydraulic oil through the hoses and fittings introduces some damping also. These spring and damping characteristics have been estimated and are incorporated into the numerical model of the system. With this information, all important characteristics of the system are modeled, the buoy and plate mass, the buoy and plate hydrodynamic behavior, and the spring/damper characteristics.

A step-response test has been performed in which the buoy was lifted 12 inches above its static waterline and dropped. Because the buoy drops faster than the submerged plate, the ram is initially drawn in by the spring force provided by the accumulators. However, when the buoy reaches the bottom of its travel and starts back upward due to its buoyancy, the plate is still moving downward and the ram extends. The elongation and force history on the ram is the primary measurement made during the experiment and by comparing these to the motions predicted by the model, a validation of the model is accomplished. Figure 2 shows a photograph of the buoy in the MBARI test tank, the submerged steel disk is shown in the background of Figure 2 before deployment and submerged below the buoy in Figure 3. The top of figure 3 also shows the hydraulic cylinder between the buoy and the submerged plate in its static condition, extended about half-way due to the weight of the submerged plate.

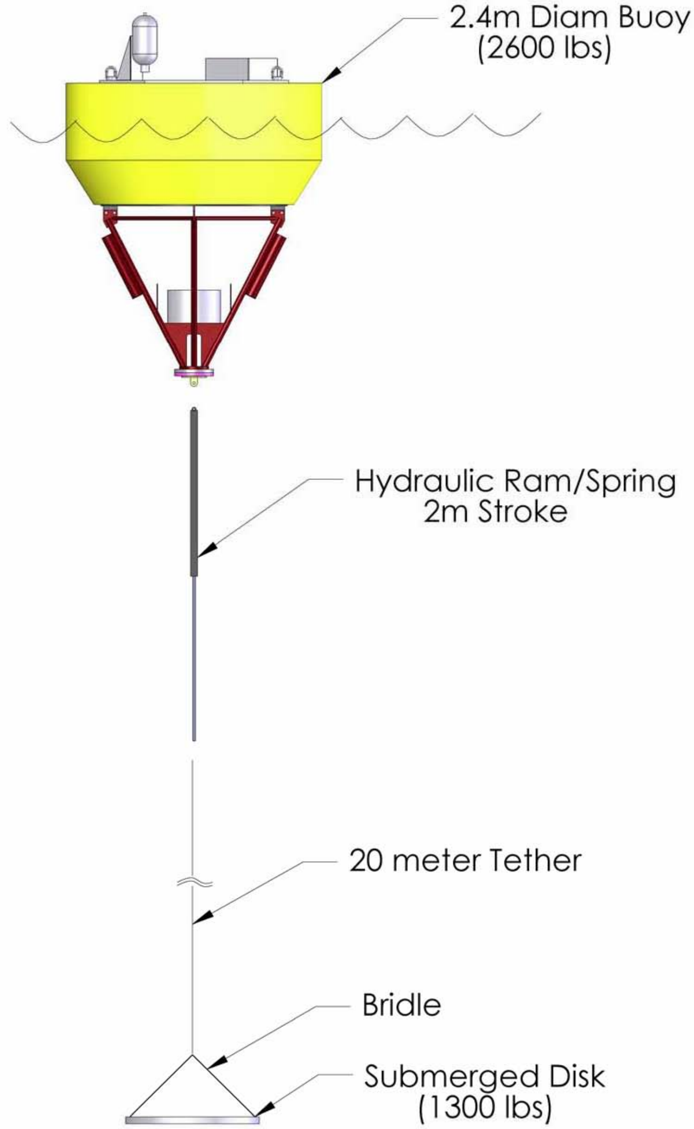

Figure 1: Diagram of test buoy system.

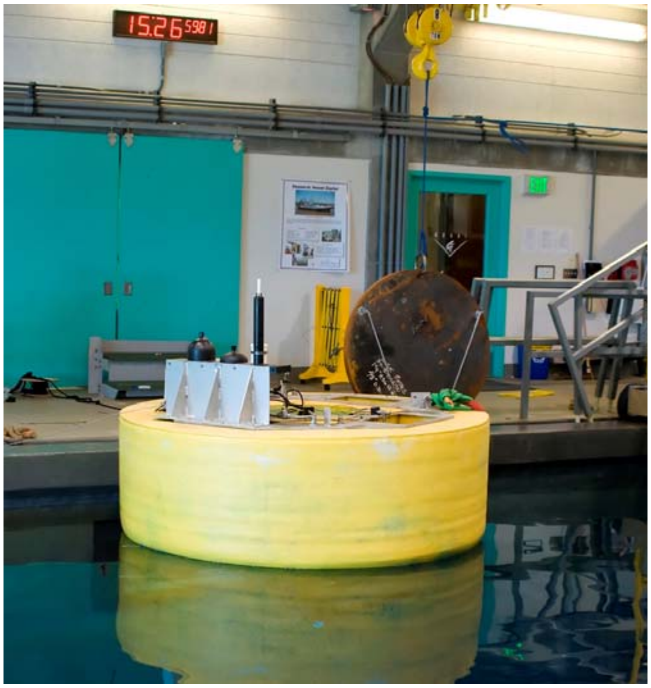

Figure 2: Test buoy in MBARI test tank.

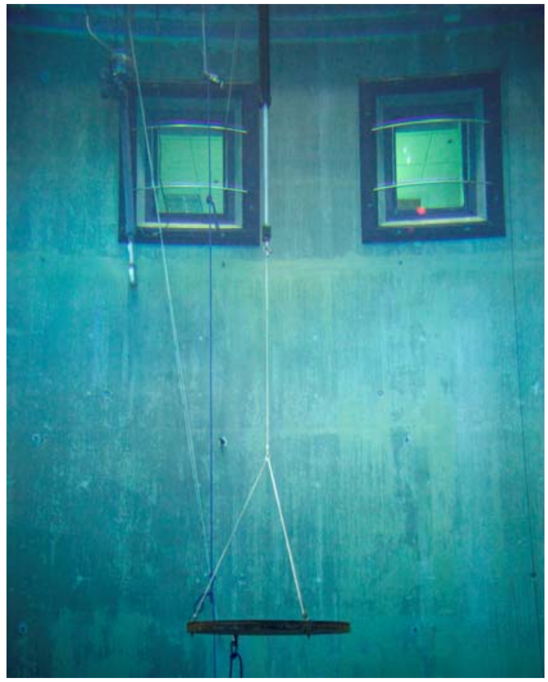

Figure 3: Plate submerged below buoy in test tank, supported by hydraulic ram visible in the top of the photo.

Two tests were performed with this system, the first was a “step-response” test in the MBARI test tank that involved measuring the oscillations of the system that resulted from an initial disturbance. The second set of tests were performed at sea in actual wave conditions. The step-response test is a simplified test of the model in that it does not include any wave exciting forces, that is, the buoy and plate motion is entirely a result of its initial displacement as there are no incoming waves to cause the system to move. This is in contrast to the at-sea tests in which all the motion of the system is due to the incoming waves. The two tests are complementary in that the step-response test includes all frequencies of motion (in theory), but doesn’t exercise the models ability to represent forces on the system due to incoming waves. The at-sea test includes the wave-exciting forces, but only subjects the model to frequencies that are present in the incoming wave-field. The results from these tests are included in the attached technical report.

Attachments

1. MBARI Final Grant Status Report
2. Technical Report: *Time Domain Model Validation Results*