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Preliminary Experimental Results for a Novel Wave Energy Converter

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Abstract: This research proposal is concerned with the design and analysis of an ocean wave energy converter (WEC) which uses a novel water intake system to vary the mass of the converter. With the help of a simple model for a hybrid system, the variation of mass is shown to increase the energy harvesting capabilities of the converter. The present paper presents a summary of the analysis of the hybrid system along with preliminary experimental results.

1. Introduction: Ocean waves contain the highest energy density among renewable energy sources. The resource concentration is also very predictable and virtually inexhaustible. Thus, they present a great opportunity as we search for cleaner sources of energy. However, harvesting wave energy is not a trivial task. The earliest recorded attempts to do so date as far back as early 19th century. But it is in the last four decades that we have seen a major resurgence in academic and industrial research on the subject, as well as the greatest amount of experimental work. While there are currently no full-scale converters in operation, a number of scale prototypes have been deployed off the coasts of Portugal, Ireland, and Scotland that are functioning and are supplying power to the grid.

There are three primary types of ocean wave energy converters – oscillating water columns, overtopping devices, and wave actuated bodies. In our work we are concerned with the latter type of converters. Specifically of interest are heaving buoys that are set into motion by the incoming waves. Because their radial dimensions are much smaller than the wavelength, they are also known as point absorbers, meaning that they can absorb waves incoming from every radial direction. This makes such devices versatile in changing wave climates and easier to arrange several units into arrays, making connections to the grid more cost effective. The reader wishing to learn more about wave energy conversion should refer to [1].

2. Summary of the Novel Excitation Scheme: The most advanced current buoy prototype is manufactured by Wavebob, Inc. in Ireland. Wavebob is comprised of two concentric floats – an inner and an outer one. A hydraulic power takeoff (PTO) system is connected between the two and utilizes the relative motion of the floats to drive an electric generator (see Figure 1).

To generate power heaving buoys rely on being in resonance with the waves, which amplifies the buoy's vertical excursions. The effect is achieved when the buoy's natural frequency matches that of the waves' dominant harmonic. Because the wave climate changes over time, the natural frequency of the buoy must be periodically (on the order of hours) adjusted. To that end, the Wavebob incorporates a mass modulation system, comprised of hollow underwater tanks connected to each float. These tanks can be fully or partially filled with water, which changes the system's mass and thus its natural frequency [2].

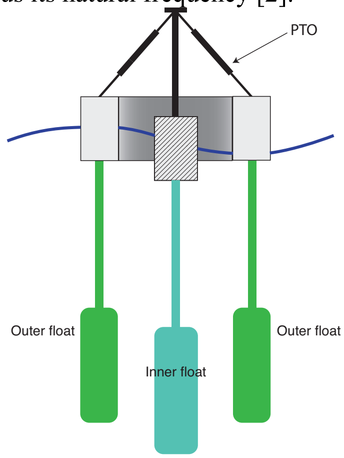

Figure 1. *Schematic of the Wavebob buoy WEC.*

For our proposed excitation scheme, we significantly modify the idea of mass modulation. In addition to infrequent mass adjustments, we aim to vary the mass of the system twice during its motion period. The goal of such variation is to induce additional resonance in the system, thus amplifying its motion even further. Effectively, the system belongs to a class of hybrid systems where the parameter variation is state dependent. The reader is referred to [3, 4] for further information on hybrid systems.

We have designed a passive water intake system that uses the incident waves to trap and release water twice every cycle, thus achieving the desired mass modulation. The system is comprised of a hollow open-ended cylinder, submerged at all times and rigidly connected to the inner float. At the midpoint of the cylinder are two sets of centrally hinged butterfly flaps. When a set of flaps is closed, the water flow through the cylinder is blocked off, thus trapping water inside the cylinder. The flaps move in such a way as to trap water in the first and third quarter cycles, while allowing the water to flow through the cylinder in the second and fourth quarter cycles. Thereby, the desired mass modulation is achieved. Further details about the water intake mechanism can be found in [5,6], and its operation is animated at [7].

3. Summary of the Numerical Model and Results: To model the wave energy converter, we start with a simple mass-spring-dashpot system that features a variable mass. The model is illustrated in Figure 2.

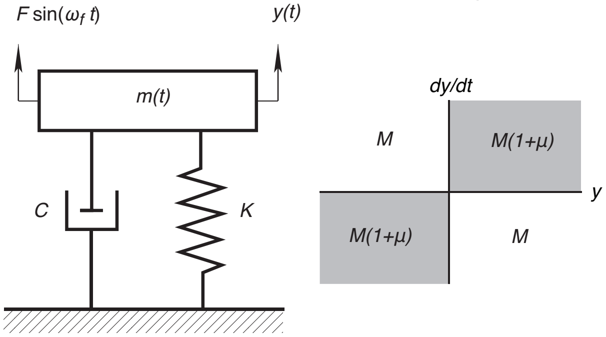

Figure 2. *A simple model of the wave energy converter. The mass changes as shown in the phase diagram on the right. μM is the amount of mass added when* y *changes sign and subsequently released when* dy/dt *changes sign.*

The relevant analysis and equations of motion can be found in [5,6]. The numerical results show a dramatic improvement in harnessed power, compared to a non-mass modulated system when the motion amplitude is unlimited, as shown in Figure 3, and a 25-60% improvement when the amplitude is severely limited.

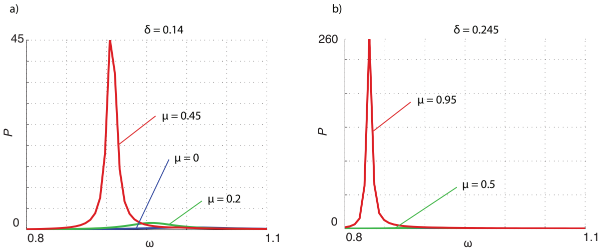

Figure 3. *Numerical simulations showing the improvements in power harnessing potential when the novel excitation scheme is used. (a) Nondimensional damping $\delta = 0.14$, and the results show average nondimensional power per cycle P of 0.56, 1.6, and 45 for when 0, 20%, and 45% mass is added. (b) $\delta = 0.245$, and the results show P of 0.32, 1.55, and 260 for when 0, 50%, and 95% mass is added.*

An important part of the conducted numerical analysis is the analysis of the stability of the system, and its sensitivity to changes in damping and the amount of mass modulation. This work can be found in [6]. The basis of this work can also be extended to systems with noise and delay [8].

4. Summary of Experimental Results: To verify the efficiency of the proposed excitation scheme, a scale prototype of the system has been constructed for testing in the tow tank facility at UC Berkeley's Richmond Field Station. The tow tank houses a 68m long water tank with a wavemaker that can generate harmonic waves of desired frequency and amplitude. The scale prototype is shown in Figure 4.

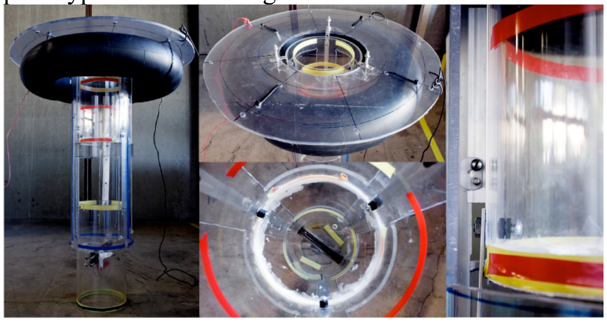

Figure 4. *Photos of the scaled prototype WEC in October 2010. The height of the prototype is 1.02 meters.*

The prototype currently does not feature a power takeoff system. To measure its performance, a 3-axis accelerometer has been mounted on each float. The acceleration data is then integrated during post processing to obtain velocity data for the individual floats. Since harnessed power is proportional to the square of the velocity difference between the floats, we believe this metric serves as a fair way to assess system performance.

Testing has been conducted in several configurations: 1) with both sets of flaps in place, allowing full motion range of the flaps, 2) with one sets of flaps permanently locked in a closed position, blocking off water flow through the cylinder, and 3) with all flaps removed. The last configuration mimics a "standard" system without the excitation scheme. The results of the tests are shown in Figure 5.

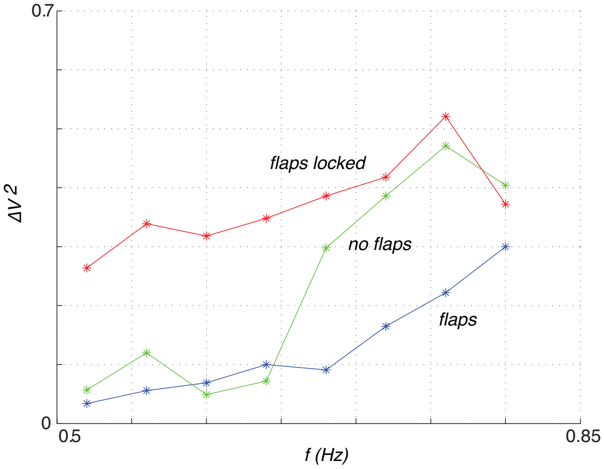

Figure 5. *Experimental results showing the square of velocity difference between the inner and outer floats as a function of wave frequency. Frequencies beyond 0.8Hz have been determined to produce excessive super-harmonics and were therefore omitted from the test. The tested cases were (1) flaps - both sets of flaps in place, allowing full motion range of the flaps, (2) flaps locked - one sets of flaps permanently locked in a closed position, blocking off water flow through the cylinder, and (3) no flaps - all flaps removed.*

As can be seen, currently the performance of the system with the flaps installed is lagging behind that of the no-flaps case. We believe that the performance deficit is caused by the prototype not being hydrodynamically optimized, thereby creating more drag in the mechanism. Detailed hydrodynamic modeling, analysis, and optimization of the prototype are being carried out. Subsequent redesign should address the performance issues experienced.

At the same time, we have discovered that locking flaps in position effectively stalls the inner float, especially at higher excitation frequencies. This stalling creates a favorable velocity differential between the floats, and is another avenue worth exploring in the design of the WEC.

5. Conclusions: We have currently completed preliminary modeling and testing of a prototype. However, the expected improvement in energy harvesting – which is proportional to the velocity difference between the floats – has not materialized. As mentioned, we are currently working on optimizing the design of the novel excitation system. In addition, improved models for the WEC are being developed and analyzed.

10. References:

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