Optimal Control of Wave Energy Device

Importance of Optimal Control

The energy flux across a vertical plane in the ocean is very large but there is a (much smaller) fundamental limit to how much of that energy can be absorbed by a point absorber device. This fundamental limit is a function of the volume of the device as well as the wave height and period. This limit exists because the amount of energy absorbed by the device is exactly equal to the interference between the incoming wave field and the outgoing waves generated by the motion of the device. If the two wave fields interfere destructively, there is less energy in the wave field due to the presence of the device and therefore the energy must have made it into the device where it is hopefully converted to electricity as efficiently as possible. The solid lines in figure 1 illustrate these two limits, P_A is the power in the waves of period T, and P_B is the power that can be absorbed by a device of volume V.

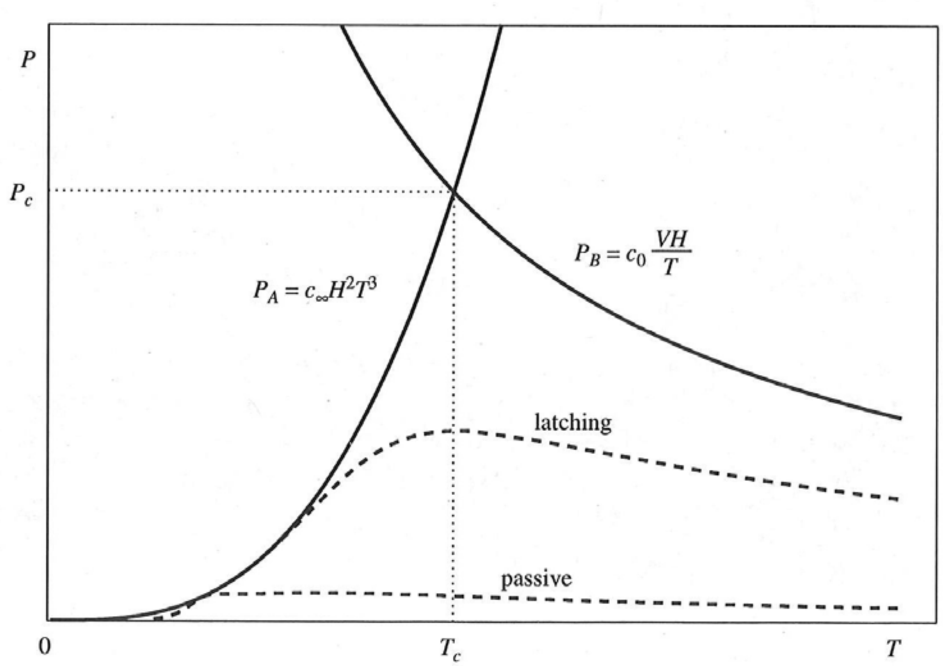


Figure 1: Illustration of relative levels of power absorbed versus that which is theoretically possible for a given wave height (H) and device volume (V). Representative lines for a passive and latching control scheme are shown. Reproduced from Hals [2011] without permission.

In order to maximize the amount of energy captured by a particular device, it is necessary for the power take-off device to resist motion optimally such that the system motion creates an outgoing wave that interferes most destructively with the incoming waves. Unfortunately, a power take-off device that behaves as a linear damper does not come close to producing this maximum energy absorption. Figure 1 also shows the expected energy absorbed for two control schemes, one that uses a passive linear damper for the power take-off device and one that implements a ”latching” scheme in which the power take-off device exerts more (or less) resistance to motion at different parts of the wave cycle. This variation in resistive force is done to force the body motions phase to change relative to the incoming waves and cause a more destructive interference pattern between the incoming and outgoing waves. As can be seen by the representative lines in the figure, there is the potential to capture many times more energy with a power take-off algorithm that includes some phase control.

A variety of algorithms are possible, each with pros and cons. Hals et al [2011] compare numerical models of a variety of these and representative results are shown in figure 2 here. There are two types of algorithms, reactive and non-reactive. Reactive schemes require that energy is put back into the system at some points during the wave cycle. Although this is theoretically possible, the implementation details of the required power electronics are not simple. Fortunately, some of the non-reactive schemes still perform very well.

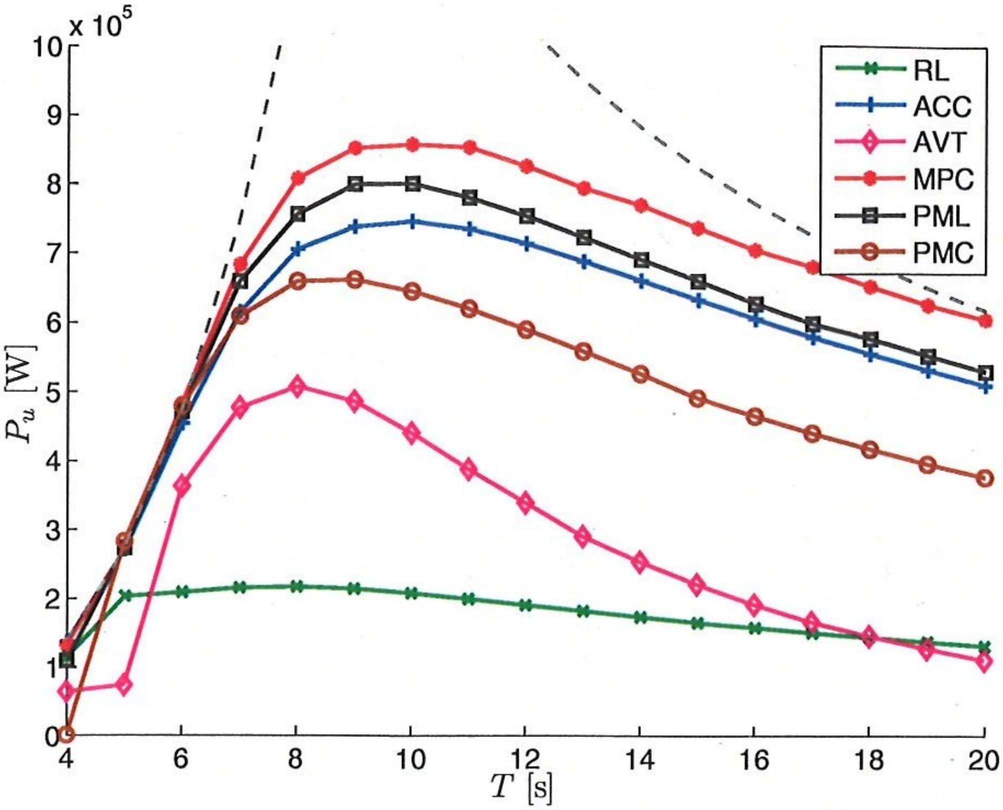


Figure 2: Average absorbed wave power for different control strategies. “RL” is a simple linear damper model for the power takeoff. “ACC”, “AVT”, and “MPC” are reactive schemes, the rest are non-reactive. Reproduced from Hals [2011] without permission.

These computer simulations have perfect knowledge of all states of the system and this sometimes leads to predictions that can’t be achieved. A particular example is the distinction between regular waves (shown in the figures here) and irregular sea states. For irregular seas it is very difficult to know what wave is coming next and this can limit the control algorithm. Some schemes are more sensitive to this than others, but real systems will rely on at least some on-board instrumentation of the systems state to achieve improved results.

Another key parameter to consider in selecting a control scheme is the resulting range of peak to average powers the system will produce. It is desirable to have a low ratio so that power electronics can be optimized around a narrower operating region.

<u>Algorithm Development and Testing with RASP Hardware</u>
Currently the system implements a linear damper which is the “Resistive Loading” scheme shown on the graphs. It appears that a doubling or tripling of the captured power is not out of reach. The hardware and software products that have been developed for the RASP program provide an excellent test bed for exploring and demonstrating improved control as follows:

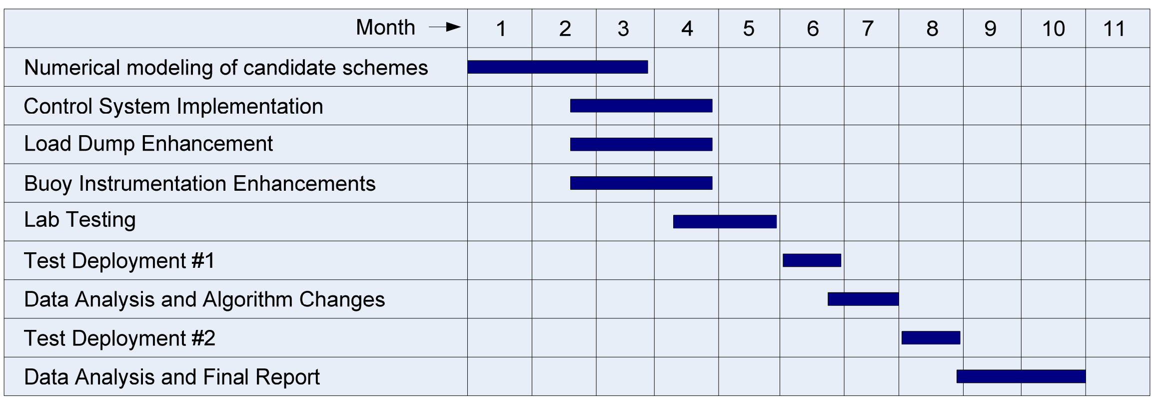
- **Numerical Modeling Tools**: The numerical modeling tools developed for the project are specific to wave-energy conversion devices and currently have all the capabilities needed to model various control schemes. This tool has been validated against data from the test deployments and has been shown to capture the main behaviors of the system. Currently the numerical models have used a resistive loading scheme that matches what has been implemented, but any control scheme can be readily programmed.
- **Wave-energy buoy hardware**. The buoy and power take-off system that has been fielded is well suited for these experiments. The load that is applied to the power take-off device is currently under computer control, which implements a linear damping scheme. Implementing different control schemes is almost entirely a matter of changing the software. The system also currently measures and records a lot of state information that could be used in the control scheme. In particular there is an inertial measurement unit that measures the buoy’s motions in six degrees of freedom, a load cell that monitors the tension in the system, and sensors that report the elongation and elongation rate of the power take-off system in real time. The computing infrastructure can accept additional sensors without modification if the application requires additional information about the state of the system. Of particular interest is the buoy’s depth of submergence relative to the local wave height. To determine this, the depth of the water in the buoys center well could be measured and logged. Depending on the success of the improvements, an expanded electrical load dump may be required to absorb higher power levels. This design is complete and it’s a relatively straightforward process to make a second one to put in parallel with the first.
- **Power Take-off device.** The mechanical to electrical efficiency of the power take-off device has been carefully measured at a range of operating points (speed and load). This is important; much of the work done to date on optimal control does not consider the efficiency curve of the power

take-off device. Ideally the efficiency of this key device would be included in the evaluation of one control scheme versus another.

- **Test-Machine.** The test set-up at MBARI has been invaluable to test and characterize the power-take off device. This system is capable of excercising the system at the same power levels experienced in the ocean. This capability would allow any control scheme to be executed in the lab in conjunction with the numerical modeling tools before the system is tested at sea (possibly in a “hardware in the loop” mode).
- **Deployment experience.** By the end of the current effort we will have experience with extended deployments that include continual radio contact with the system from shore. This will allow extensive modification of the control system parameters during test deployments that could last weeks or months.

Tasks, Schedule and Costs

Here is a rough outline of schedule and costs for a sub one-year effort. This is intended as a starting point and can be adjusted as needed.



References

The main reference that compares adaptive control strategies is by Hals, Falnes, and Moan in 2011. The other listed here is a good reference as well.

- Hals, Falnes, and Moan. “A Comparison of Selected Strategies for Adaptive Control of Wave Energy Converters”, Journal of Offshore Mechanics and Arctic Engineering, August 2011, Vol 133.
- Falnes. “A review of wave-energy extraction”. Marine Structures, 2007, Vol 30.