SurfPower Computer Modeling Phase III

Part C: Energy Capture

Executive Summary

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DSA
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1 Introduction

Seawood Designs, Inc. (SDI) is developing an ocean wave energy capture device called SurfPower. The device consists of a large buoyant wing which is actuated by passing ocean waves. The device pumps seawater into a high pressure hydraulic system that drives a turbine to generate electricity and fresh water through reverse osmosis.

Each buoyant wing has a nominal rated capacity of 300 kW in 9 second 4 meter waves. Any number of buoyant wings can be deployed in an array to deliver the desired system rated capacity. Fifteen or more buoyant wings are required to deliver steady flow to the pelton turbine without the use of a hydraulic accumulator. A schematic of an array of 50 buoyant wings with a total wave to wire nominal rated capacity of 15MW can be seen in Figure 1 and Figure 2, respectively (courtesy of SDI).

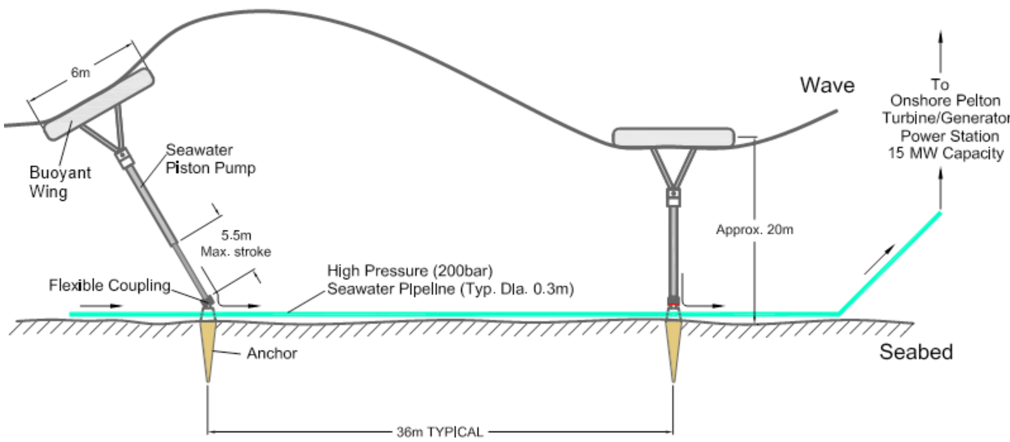

Figure 1: Buoyant wing operation

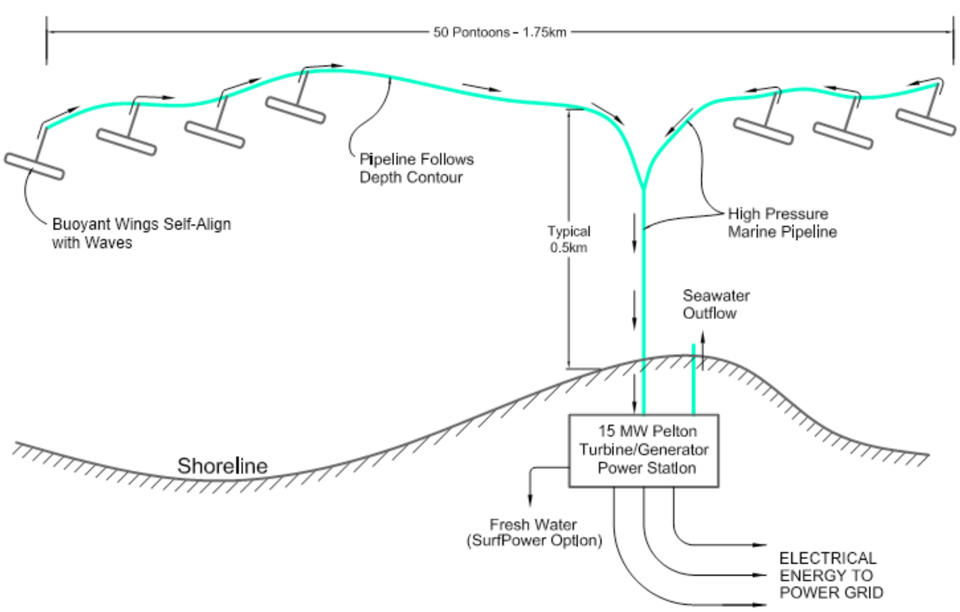

Figure 2: System layout

Dynamic Systems Analysis, Ltd. (DSA) has extensive experience with high-fidelity time domain simulation of mechanical systems in marine environments. DSA was charged with two tasks by SDI. The first task was to validate DSA's engineering software, ProteusDS, by comparing simulated results with those obtained through physical experiment testing in the wave basin at the National Research Council's Institute for Ocean Technology in St. John's, Newfoundland. The second task was to investigate a number of ways that energy yield could be improved. This work resulted in a number of significant breakthroughs that greatly enhances the economic viability of SurfPower.

SDI retained the services of AXYS Technologies Inc. (ATI) to compute the expected annual energy recovery for a typical site off the west coast of Vancouver Island using real-time sea surface data. SDI provided ATI with three different performance curves developed by DSA representing three different system configurations and control strategies. The basic rectangular buoyant wing is the same in all cases but different control methods and control surfaces are employed in each case to improve energy yield. By comparing results for each case, SDI will be able to configure the system to optimize economic viability. Use of the control surfaces in each of the three cases gives the system the ability to assume a “storm mode” operating condition that greatly reduces energy production in extremely high seas and most importantly limits structural loading to less than a 20% increase over normal operating conditions.

The three control strategies are identified as follows:

- Configuration A: passive control except for activation of storm control operating mode
- Configuration B: full active control
- Configuration C: full active control with addition of energy recovery module

2 System parameters

This section presents the physical and environmental parameters used.

2.1 Environment conditions

All systems were tested in 9 second Airy waves. The wave height varied from 1m to 4m (trough-to-crest) height. Airy waves were used as they reduce the simulation execution time when compared to short-crested sea states with many frequency components. This facilitates converging to a dynamic steady state more rapidly and facilitates clear comparisons between systems with different configurations. The water depth used was 20m. No additional wind or water currents were tested.

2.2 SurfPower parameters

Mass and geometry values were provided by SDI for various components. No physical mass moment of inertia values were provided and so calculations were completed to assess the wing, cylinder, and piston inertia given the bulk masses, basic shapes, additional point load information provided by SDI. The resulting inertia of the main system components are summarized in Table 1. Key wing dimensions are 6.7m width, 24m length, and 0.9m height. The mass reflects the robust design of the buoyant wing that can withstand submergence to a depth of 10 m.

Component	Mass (kg)	Roll inertia (kg*m^2)	Pitch inertia (kg*m^2)	Yaw inertia (kg*m^2)
Piston rod	907	3.60E+004	3.60E+004	1.11E+002
Cylinder	4082	2.90E+004	2.90E+004	2.58E+002
Buoyant wing	17700	9.90E+005	8.20E+004	1.10E+006

Table 1: SurfPower full scale model component mass and inertia

A short sensitivity study was completed to ensure a reasonably optimal hydraulic system pressure level was used to provide adequate energy capture. With the 6.7m width SurfPower wing and the piston diameter selected by SDI, this resulted in a reaction force of 1.1e6 N during the power stroke. It was assumed that the piston seal would perform without significant leakage though a conservative resistive load of 8.8kN (2000 lbf) was included to account for piston seal and cylinder rod end seal friction losses.

2.3 Performance metrics

The key performance metrics that were measured in all runs were:

- Average power capture
- Energy recovery per wave period
- Buoyant wing surge

Note that average power capture was computed by establishing the captured energy averaged over several wave periods and then dividing by the total elapsed time.

2.4 Simulation model versus baseline design

The results of simulation studies were used in the development of detailed CAD models and drawings to facilitate manufacture of a prototype baseline system. A comparison of key inertial and geometric parameters can be seen in Tables 2 and 3. Sensitivity studies indicate that the inertia and hydrodynamic forces on the buoyant wing dominate the motion of the system, therefore the mass differences between the piston and cylinder components are unlikely to influence dynamic behavior. Further, the piston/rod assembly is attached to the seabed and therefore does not participate in any vertical motion. The taper in the baseline design wing thickness increases structural integrity but should not significantly affect the response of the system.

Component	Baseline design mass (kg)	Model mass (kg)
Piston/rod assembly	3605	907
Cylinder assembly	4051	4082
Buoyant wing	17168	17700

Table 2: SurfPower baseline design and model component mass comparison

Component	Baseline design (m)	Model (m)
Piston rod diameter	0.28	0.35
Cylinder diameter	0.6	0.55
Buoyant wing length	24	24
Buoyant wing width	6.7	6.7
Buoyant wing height	0.74 (ends) – 0.97 (center)	0.9

Table 3: SurfPower baseline design and model component dimension comparison

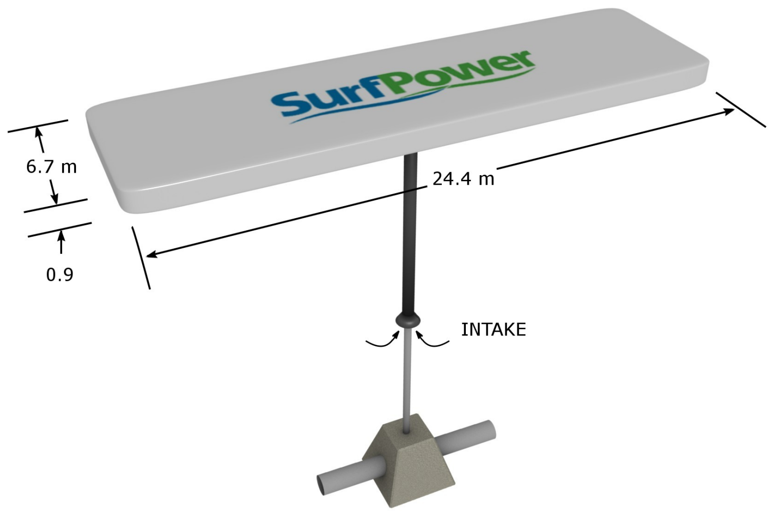

Figure 3: Simulation model system details

Figure 4: SurfPower baseline design CAD assembly

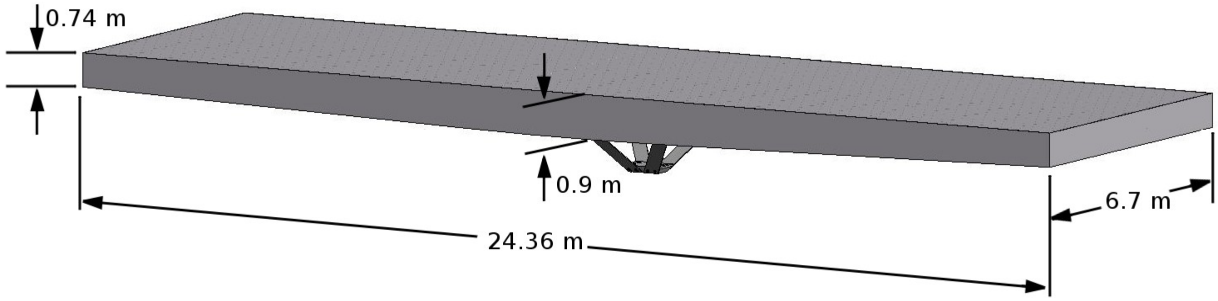

Figure 5: Buoyant wing baseline design

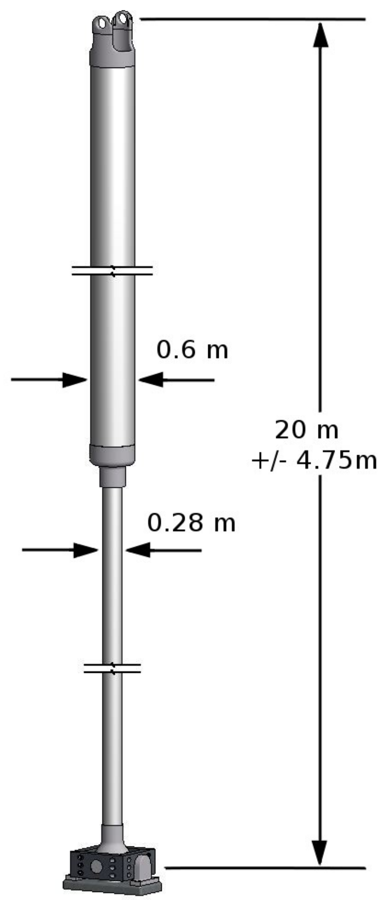

Figure 6: Pump assembly

3 Control system strategies

A number of approaches were considered such as adding counterbalance weights, restricting motion of the pump cylinder on the return stroke, and operating with a low and high system pressure. These were all found to be impractical and delivered only a marginal improvement in energy yield. This investigative work lead to uncovering some new approaches that had never been previously entertained. They proved to be significant breakthroughs. These new concepts were simulated and found to be very productive. They have been identified as follows:

- System configuration A: passive control with active storm control
- System configuration B: full active control
- System configuration C: full active control with an energy recovery module

These different system configurations are only described in detail in the foregoing confidential Report B. SDI plans to give this Report C wide circulation as it may be of interest to many working in the marine wave energy field. It has therefore limited description of the configurations to protect its intellectual property until patents have been applied for.

It is important to note that previous work on the SurfPower system showed the buoyancy pendulum formula for natural period in surge/sway as a function of constant mooring tension can be a useful guideline to indicate when sway instability and hence energy loss will be a problem. The reference equation presented in previous reports is repeated for convenience in equation (1).

$$T_n = 2\pi\sqrt{\frac{(m + a\,p_w V)\,l}{T}} \quad (1)$$

where T is mooring tension, m is buoy mass, l is the mooring line length, a is the added mass coefficient, and V is displaced water volume. Note that this equation does not consider the influence of ocean waves or variations in submerged volume or tension and is only intended to be used as an approximation to indicate the natural period. Using the SurfPower wing mass of 17.7e3 kg, 1.1e6 N as the mooring tension, 20m for equivalent mooring length, and assuming 100% submergence, the resulting surge/sway natural period from equation (1) is 4.9 seconds, which is far from the wave period studied at 9 seconds.

In an earlier phase of work, comparison with data from wave tank experiments indicated that both steep waves and proximity to the surge natural frequency seem to produce conditions that reduce the energy capture accuracy due to viscous fluid dynamic model limitations. Note that while the simulation model takes in to account variation in submerged volume and area used for hydrodynamics calculations, the assumption of constant hydrodynamic coefficients was made. Knowledge of the true variation of hydrodynamic coefficients in different conditions (frequency of loading and different submerged volumes) is a complex problem to solve. It was found, however, that large changes in the coefficients do not significantly impact the energy capture predictions.

A single set of drag and added mass coefficients was used for the SurfPower wing and are compiled in Table 4. These were based on the values produced by IOT wave tank experiments with some refinement based on full-scale system modeling.

Hydrodynamic coefficient	Value
Surge drag (CDx)	1
Sway drag (CDy)	1
Heave drag (CDz)	2
Surge added mass (CAx)	0.2
Sway added mass (CAy)	0.2
Heave added mass (CAz)	2

Table 4: SurfPower wing hydrodynamic coefficients

4 Results

This section presents information on the validation efforts as well as energy recovery prediction based on the engineering software analysis.

4.1 Software validation

A 1:10 scale model was constructed and tested in the wave basin at the National Research Council of Canada's Institute of Ocean Technology. A wide range of wave conditions and hydraulic operating system pressures were used to investigate performance ranging from normal to extreme storm conditions. The scale model was recreated in simulation in order to assess the applicability of the modeling capability of ProteusDS with the experimental results. The greatest error in energy capture occurred with very steep storm waves when white water was overtopping the device. Energy recovery was over-predicted by as much as 38% in these conditions. Short period waves, which were also at the natural surge period of the system, resulted in over-prediction as high as 29%. Fortunately, results were much better in normal operating conditions. Predicted energy capture in moderate waves was only 5.8% high that increased to 7.6% in higher waves. In very low wave heights close to the height of the buoyant wing, the error approached 23%. In any case, a conservative de-rating factor of 14% has been applied to all full scale system results to account for the apparent simulation error. This de-rating factor is considered conservative because the error is much smaller in that portion of the typical wave regime that accounts for most of the energy production.

4.2 Energy recovery

The power capture results for system configuration A and B are compiled in Table 5 and 6, respectively. Note that these results are an optimum combination of individual control options that depend on the wave height conditions. Some of these control options were simulated individually. System configuration C power capture results can be seen in Table 7. These results include the expected performance of the energy recovery module, which was not modeled by DSA as this was beyond the scope of the tasks assigned. The additional power capture yield is based on an internal preliminary analysis completed by SDI.

Wave height (m)	1	2	3	4
Average power capture (kW)	15	154	287	444
Upstream surge (m)	3.6	4	3.7	3.1

Table 5: Performance values for configuration A

Wave height (m)	1	2	3	4
Average power capture (kW)	55	195	326	460
Upstream surge (m)	1.7	1.6	1.1	0.4

Table 6: Performance values for configuration B

Wave height (m)	1	2	3	4
Average power capture (kW)	75	215	340	480

Table 7: Performance values for configuration C

The power capture values recorded in Tables 5-7 are reproduced in Figures 8-10. It should be noted that the power capture is tapered off after 4m wave height by enabling the storm control mode. Each power curve also indicates the power captured by the device as well as a wave-to-wire power curve value. The wave-to-wire power curve incorporates a loss factor that incorporates simulation error as well as pumping losses, flow losses, turbine efficiency, and generator efficiency.

Annual energy yield was computed by AXYS Technologies, Inc. (ATI) using these power curves in conjunction with real-time data recorded by a buoy located 2.3 km off Long Beach, Vancouver Island. This real-time data provides a valid estimation of the annual energy accumulation by a single SurfPower buoyant wing. The resulting annual energy production estimated by ATI using high resolution time domain wave data was 368, 455, and 552 MWhrs, respectively, for the three control strategies. The monthly breakdown of energy capture by each configuration can be seen in Figure 7. It is worthwhile to note that during October through March (winter period), 75% of the annual energy is delivered that is an ideal load match for most power grids in northern latitudes. The average power delivered by the buoyant wing over the winter period was 95 kW. A typical SurfPower array would employ 50 wings that could deliver 25 GWhrs annually.

The annual energy flux for the site in the year under study was calculated to be 27 kW/m. SDI chose this site for analysis simply because it was in relatively shallow water (35m) and a full year of data was available. SurfPower is configured to operate just outside of the surf zone where it can benefit from shoaling effects that are not accounted for in the foregoing energy yields.

The active control systems clearly increase the energy capture of the device. However, it is still early in the investigation in these control methodologies and further optimization of both control and buoyant wing parameters is warranted to optimize performance. This could result in lower structural requirements and greater energy yield to reduce the cost of electricity and fresh water produced. The current buoyant wing is configured for sites with an annual energy flux in the range of 20 – 25 kW/m with a much lower level of variability than the site studied. A larger wing height will significantly improve energy yield to take best advantage of higher waves in the winter period.

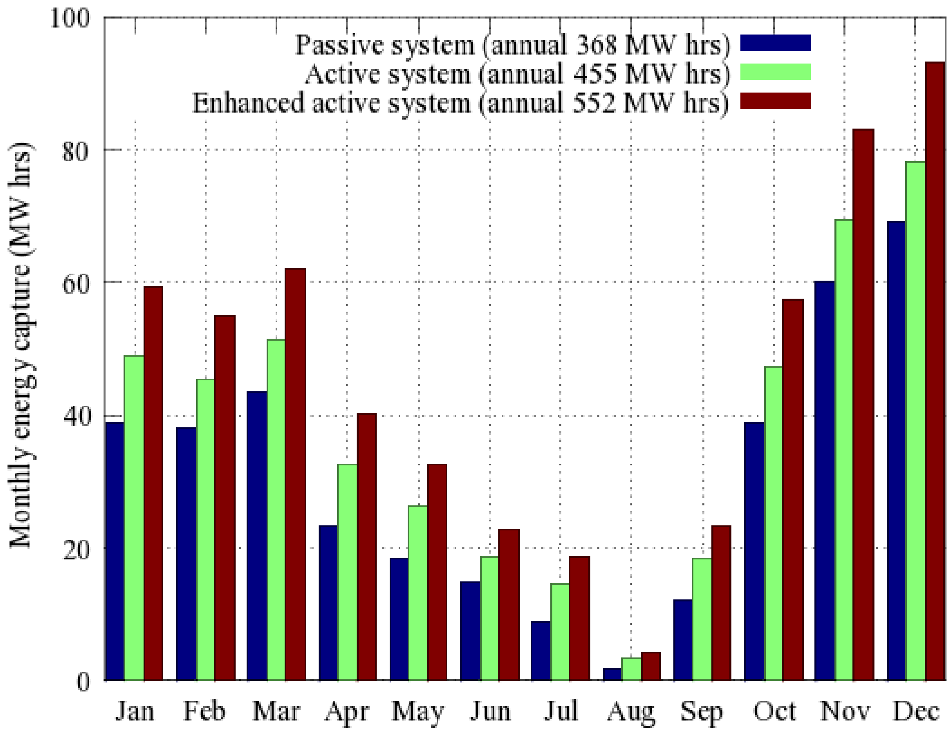

Figure 7: Annual energy capture by month estimate produced by AXYS. Site average annual resource is 27 kW/m

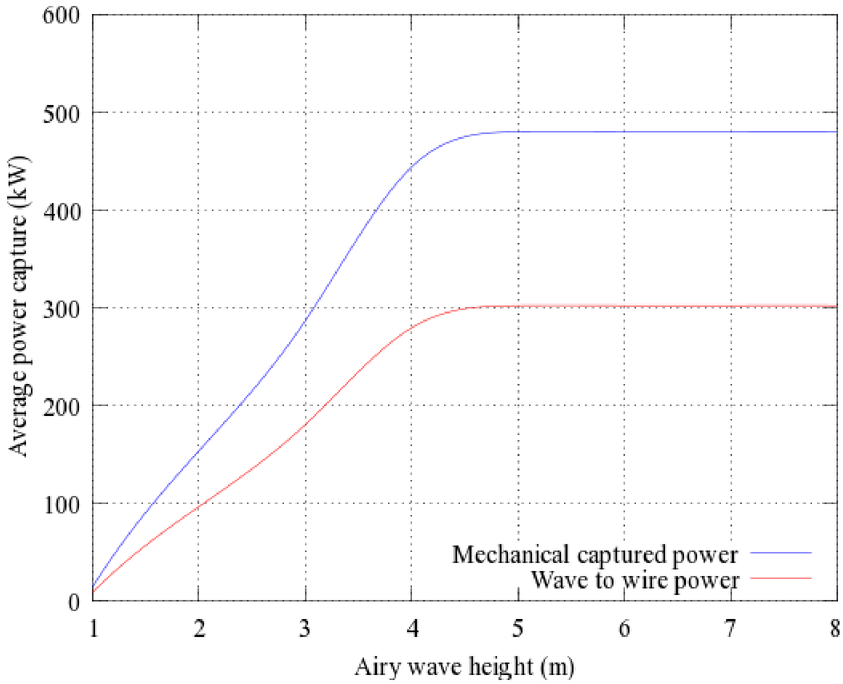

Figure 8: Configuration A average power capture

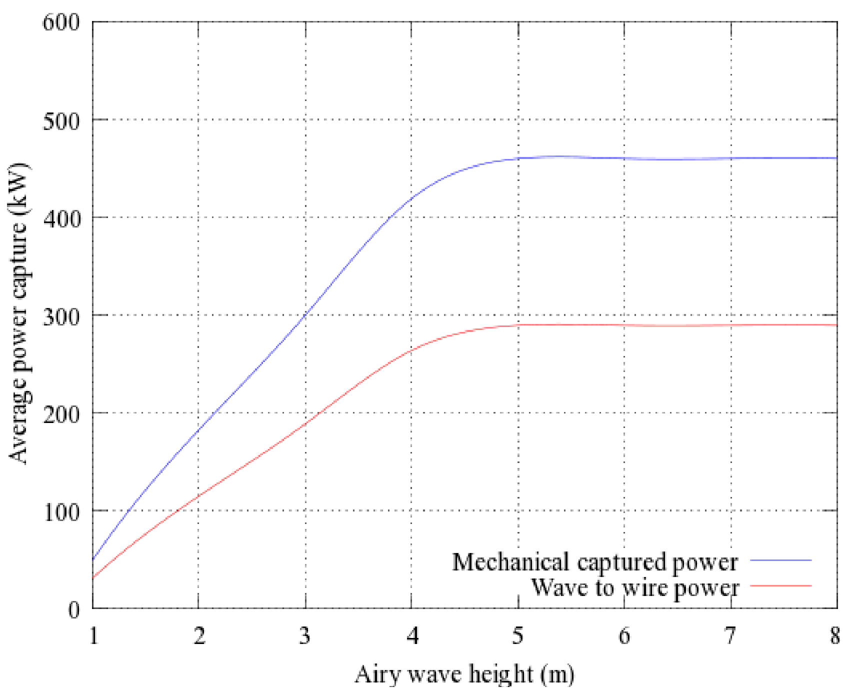

Figure 9: Configuration B average power capture

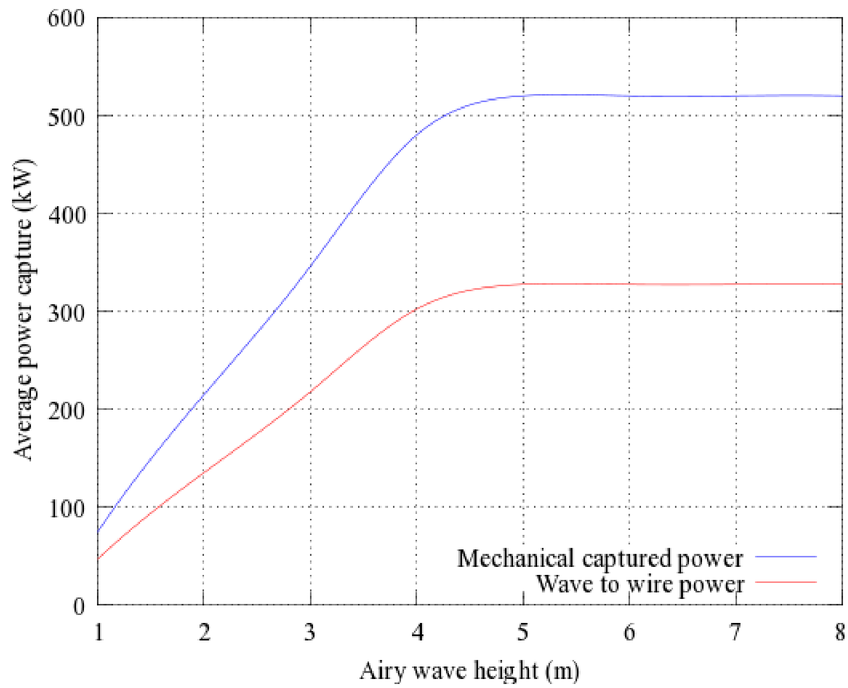

Figure 10: Configuration C average power capture

4.3 Storm operation mode

As indicated in Figures 8-10, power capture is limited in seas greater than 4m wave height through storm mode operation. This special operating mode is comprised of a combination of settings that facilitate reduced loading on the system. Simulation results indicate the expected pressure increase is approximately 20% higher than normal operating pressure that directly relates to structural loading of system components.

5 Conclusions

Validation of the simulations with scale model experimental data yielded important results on the accuracy of the model predictions. In extreme conditions in very steep waves and in smaller period waves close to the natural surge period of the system, the power capture results were over-predicted by as much as 38%. This is not a concern as extreme conditions are rare and do not contribute significantly to annual energy capture. In longer period waves that scale to the range of the power curves presented, the error in energy capture was as low as 5.8% in moderate waves and up to 7.6% in higher waves.

Previously, SurfPower relied on the use of a trapezoidal buoyant wing. The tapered edges provide yaw stability in all seas above 1m. However, some yaw instability was identified in 1m waves. Yaw instability greatly diminishes energy recovery. SDI has opted to resolve this by employing rectangular buoyant wings with unique control surfaces from this point onward.

The three system configurations A, B, and C studied each have a different capital cost and maintenance expense associated with them. Configuration A is the least expensive and configuration C is the most expensive in terms of both capital cost and maintenance expense. SDI is currently establishing the cost of the system components by acquiring vendor quotations. It will only be able to identify the most cost effective configuration when all quotations have been received and evaluated.

It is anticipated that configurations B and C will accommodate tidal currents that are not aligned with the direction of wave propagation without incurring a significant impact on energy recovery. The influence of tidal currents have not yet been simulated but modeling experience to date strongly suggests that the system configurations currently in hand will perform well except configuration A that will be subject to some performance degradation when encountering unaligned tidal currents.

The baseline SurfPower design employs an aluminum buoyant wing that has a mass of 17168 kg and a steel/aluminum pump with mass of 7656 kg that connects the buoyant wing to a seabed anchor as shown in Figure 4.

This specific arrangement is configured for installation in 20-25 m deep water. The pump is sized to provide a working stroke length of 5.5 m and accommodate a tidal range of 4 m. SDI is very encouraged by the foregoing results that are in line with earlier energy recovery estimates used to predict economic viability. SurfPower's ability to weather extreme storms with only a slight increase in structural loading is one important key to its future success.

DSA suggests that additional modeling be undertaken when the optimum system configuration has been established based on vendor supplied component costs. Computer simulation would provide fine tuning of the system by evaluating how best to sequence a number of different control functions to establish the performance under various sea conditions. Most of the simulations developed in this program assumed Airy waves with a 9 second period. Simulations with wave periods ranging from 6 to 15 seconds need to be evaluated to give insight as to how best to control performance in normal wave heights and also storm seas when operating in “storm mode”. Similarly, work is needed to expand knowledge of the influence of tidal currents.