MODULAR, PROTECTIVE WAVE POWER GENERATION SYSTEM

Shift Power Solutions Inc.

EXECUTIVE SUMMARY

The concept of small wave energy conversion modules that can be built into large, scalable arrays, in the same vein as solar panels, has been developed. This innovation lends itself to an organic business and development model, and enables the use of large-run manufacturing technology to reduce system costs. The first prototype module has been built to full-scale, and tested in a laboratory wave channel.

The device has been shown to generate electricity and dissipate wave energy. Improvements need to be made to the electrical generator and a demonstration of an array of modules should be made in natural conditions.

TABLE OF CONTENTS

INTRODUCTION

The power available in coastal ocean waves is substantial. On the coast Oregon, the wave energy density averages about 30kW/m of wave front. While this makes ocean waves good candidates for electrical energy conversion, their energy often acts destructively on natural and manmade coastal structures. Transferring the destructive energy into a functional resource, such as electricity, and mitigating its destructive outcomes is an appealing proposition.

The high energy density is a challenge for wave energy converters of any design. These devices need to be robust enough to withstand the impact of the waves and the corrosive and erosive environment of the ocean. The challenge is to achieve this survivability while consistently producing inexpensive electricity.

Manufacturing location-specific components is expensive. Therefore, we are using a modular system to allow installations to be tailored for specific locations without the cost of bespoke manufacturing. The benefit of a modular system is that it is readily scalable. Unlike the development of large, single units, the business growth can be organic. This is due to the fact that the size and scope of an installation is not limited to only large grid-tied projects but can service small individual clients as well. Our system can be brought to market quickly because the units are already full size at the first prototype, small to begin with, simple to operate, and able to utilize commercially-available power management components. The cost of electricity can also be offset by defending coastal structures, reducing their operating and maintenance costs. Permitting is less onerous for smaller devices, and the development times are short. The first prototype module has been built in full-scale, and tested in laboratory waves.

1.0 MODULE DESIGN

1.1 DESIGN EVALUATION

We analyzed the overall system - including a review of potential sites, markets and stakeholder interests - to develop a list of factors that influence our system. From this work, we distilled the functional requirements and created a system specification.

In the course of this work, we made contact with several local sites that would be interested in having us install a test system at their facilities, including a breakwater that defends a small harbor and a city pier. Our review also showed how important the US Corps of Engineers is as a potential customer.

On the technical side, our review of possible sites showed us that for many locations, our devices would be operating in water 15-30’ deep, and would need to be fixed on framing to the seabed.

The intensity of the wave power was driven home to us when our research showed that waves of 16m are occasionally seen near shore. A pressure of 845kPa was recorded at Alderney Breakwater – the world maximum recorded to date. While designing for such an extreme is unwarranted, we did design our system to be robust enough to withstand the 8m waves occasionally seen during storms on the West Coast. This optimizes the cost of the unit, and allows for the possibility that installations may need to be replaced in the unusual event that they experience more severe wave conditions.

We found that the most desirable feature of our technology is its modularity. Small modules have been developed and tested at full scale, thus significantly shortening the development times. Modular systems have the flexibility to be installed in many locations, in natural or developed settings, close to the shore or further out as required. The small size in combination with its modularity provide the opportunity for organic growth from small, high-value, off-grid installations to large, utility-scale generation farms. Finally, the reliability of modular systems is higher. Since electricity production is based on a single module, failure of one module does not disrupt the production of the entire array.

A modular system is attractive from an environmental perspective. A limited number of modules can be installed in a candidate site to evaluate their impact on the environment, then the array expanded in stages, to ensure that no unexpected impacts arise during the scale-up. The permitting process is easier for smaller devices that can be readily removed or changed as experience is gained in a specific setting, and our design requirements include a provision that units should be easily removed from or installed in the array. Using our system alongside existing man-made structures is more eco-sensitive than installing devices in virgin settings.

1.2 STAKEHOLDER REQUIREMENTS & LOCATIONS

Our stakeholders include coastal property owners and users including ports, local marinas, island communities, private resorts, homes and settlements in remote locations, the Army Corps of Engineers, coastal commissions, recreational areas, fishing industries and residents and tourists of coastal towns and villages. In addition, stakeholders include the utilities, corporations with coastal operations (such as desalination plants, and oil rigs), electricity users, governmental branches dealing with energy, the environment and national security, coastal states and nations, equipment manufacturers – including power and distribution equipment developers currently addressing solar and other renewables – and producers of copper and magnetic materials.

To assess stakeholder requirements, we undertook a Feasibility Study that examined the requirements and potential solutions for a modular approach to wave power generation. This entailed desk research and one-on-one communications with others in the industry as well as representatives of coastal communities and users. We shortlisted potential sites through a detailed study of the American coastlines using Google Earth, then visited specific sites in California, Oregon and Hawaii. We reviewed maintenance budgets provided by the US Army

Corps of Engineers, and spoke with parties with coastal facilities who might be early adopters of the technology.

The need for renewable energy is a key interest for most of our stakeholders. In addition, there is substantial interest in controlling the impact of the waves on structures and shorelines, and managing sediment transport.

The ocean ravages its coastlines – and has the capacity to remove enormous granite slabs, weighing many tons, from breakwaters. The cost of repair is so high that repair has been delayed on several important breakwaters along the Oregon and Washington coastlines, which suffer from severe wave action during winter storms. Even though our system will need annual or semi-annual maintenance, this will be less expensive than rebuilding the breakwater. A positive business case exists for using our system to increase the longevity of the existing breakwaters, and using the proceeds from the energy produced to support their ongoing operation and maintenance.

Looking across the potential sites along the East and West coasts of the US, the need for our devices extends into deeper water than we first thought. This means that there would be additional markets for our module if it could handle wave action that has circular momentum in addition to translational movement. In other words, the waves will have both heave and surge components rather than purely surge. The implication of this is that a tilting motion may be more optimal than the horizontal movement of the panels in our initial design. To have maximum benefit, the system should accommodate waves found in shallow, transitional and deep waters.

Fluctuations in water levels due to tides, etc. will change the nature of the waves that will impact our devices. Ideally, the height of the devices will be adjusted for optimal performance when the water level changes. We envisage using a support system that floats the array so that it takes the appropriate position relative to the water line, accommodating tidal and other changes in water level.

Particularly with breakwaters, we are more likely to mount our devices on their own pilings driven into the seafloor rather than being mounted on the breakwater itself. This is because breakwaters are usually designed with sloping sides and are not designed for additional structures. Positioning an array of devices forward of the breakwater position does not interfere with the function of the armor but enhances its functionality.

Our feasibility study, and subsequent prototype testing, shows that our concept is appropriate for sites with a wide range of potential wave conditions. These go from the frequent, shallow waves found in places like river deltas, large inland lakes, ocean gulfs and seas, to the long period, deep water waves that occur along the ocean coastline.

To address the needs of the various stakeholders, we find that our modular system can be brought to the market through a sensible roadmap, allowing us to move from sheltered to exposed locations, and from small, low power installations to large arrays with high power output.

1.3 MODELING OF WAVE ACTION

AQWA

AQWA was used to model the action of the waves on arrays of flat panels being moved by the surge component of the waves. The flat panels were arranged in a pyramid formation, mounted against a perpendicular wall. The model used Pierson-Moskowitz wave spectra for fully developed seas in the Gulf of Mexico, and took Fourde-Krylove+Diffraction effects of the wall and panels into account. The model was evaluated for significant wave heights of 1, 2, 2.5 and 5 meters. The mean water depth at the top of the pyramid was 10m.

The model showed that the power exerted by the waves is enormous – and seems to be concentrated by a pyramid array formation, particularly if waves are reflected off of a back wall. Mounting the devices some distance in front of the breakwaters will allow the reflected waves to interfere with oncoming waves that have passed through the array.

Simulink

Once the design was finalized, the dynamics of a single module was analyzed using Matlab's Simulink modeling tool.

The model uses a Taylor expansion to integrate the torque resulting from the force of the fluid elements acting on the panel as the wave sweeps forward and back across it. Sinusoidal waves are used to approximate our waves. The wave torque is offset by buoyancy and the weight of the generator, and the resulting torque acts upon the inertial, elastic and dissipative features of the module, represented by an inertial element, an ideal rotating spring and an ideal rotating damper. Possible improvements to the model include replacing the ideal damper with the actual characteristics we found for the linear generator, and improving the modeled behavior of the water as it flows around the module.

The model solves the resulting equations of motion to determine the angular displacement and velocity of the panel – and to determine the amount of power that would be dissipated by the unit.

Since the waves do not always completely immerse the panel, a calculation is made of the depth of the panel in the water. For this purpose, a triangular saw-tooth approximation is used for the wave height, which avoids the need for an iterative solution.

Results of the model and comparison with experimental data are presented later in this report.

1.4 DESIGN

In addition to the modeling work described above, the initial design was analyzed using finite element analysis (FEA) and small scale physical models. An analysis was made of the electrical take-off, anchoring, manufacture and maintenance.

We elected to use a 3-bar linkage to avoid placing shear forces on the generators. The design, shown in the adjacent figure (Figure 1.4.a), has a flat panel that rotates about a pivot when pushed by the wave action. This, in turn, drives the magnet rod of a linear generator in the same manner as a piston. A simple frame connects the panel and generator, providing a reactive force to between the panel and the stator. It provides a fixed route for signal and generated power cables, and has flanges which allow the modules to be connected together into an array. A spring can be added to the pivot structure to ensure that the panel returns to its original position after the wave passes over it – reducing or eliminating the need to motor the generators back.

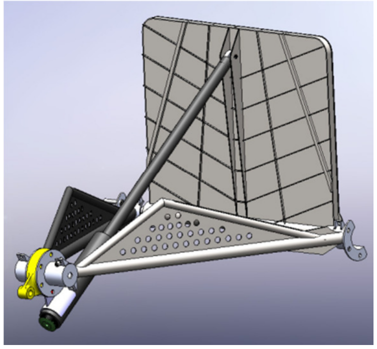


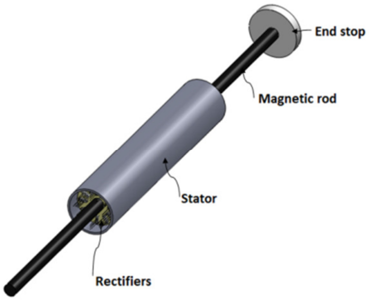
Figure 1.4.a. 3-Bar Linkage Design

Tilting the panels reduces their profile in heavy waves, improving their survivability. In an array configured of rows of modules, each row tucks down parallel to the flow once it has taken as much of the power as it can – allowing the next row of panels to extract more energy as the wave moves forward through the array.

2.0 PROTOTYPE MANUFACTURE

2.1 GENERATOR

The overall concept behind the generator is to convert translational mechanical energy into electricity. Its components are the magnet rod, stator and power takeoff system.



Magnet Rod and Stator

Neodymium magnets have the highest known magnetic strength. The magnet rod was assembled using a proprietary method to control the attraction between the opposite poles of adjacent magnets. The Neodymium magnets, which are axially magnetized, were stacked using this method to create a column of magnetic fields in series.

Care was taken while building and installing these strong magnetic units to avoid adverse magnetic effects and the acceleration of magnets or ferritic objects due to the strong forces.

The stator was built in-house.

Take-off system

The output of each individual coil was fed into its own rectifier. The rectifier outputs were then connected in parallel to the output cables. We did not use protective diodes since our wave heights are controlled.

Fig 2.1.a is the equivalent circuit for a single stator coil. V_{coil} represents the voltage generated by motion across magnetic flux. R_s is the coil series resistance. D1 through D4 represent the diode bridge rectifier, and out1 and out2 are the parallel output terminals.

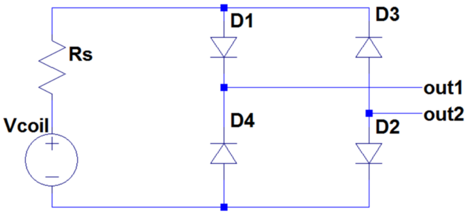


Figure 2.1.a: Stator coil equivalent circuit.

2.2 PANEL

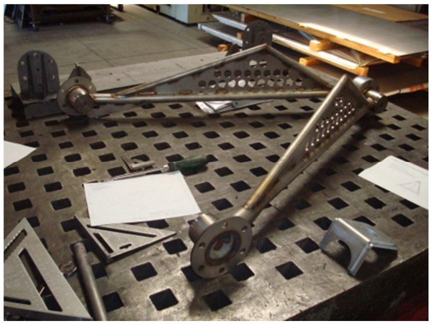
The panel was designed for open water and high wave forces, and utilized stainless steel skinned honeycomb. This original model was not used for the prototype due to the testing conditions. Instead, we used a foam-cored fiberglass unit.

2.3 RETURN SYSTEM

The return system for the panel was designed to be internal to the pivot tube of the panel itself. This was done intentionally to reduce the number of components exposed to the environment. A return mechanism was deemed necessary for those wave conditions unable to bring the panel back to the upright starting position.

Because we needed to access and adjust the return system during the wave flume tests, the prototype return system consisted of external elastic bands which could be changed or tightened while the device was in the water.

2.4 STRUTS & FLANGES



The intent of our design was to have modules that could be readily manufactured with commonly available equipment and materials. The struts are tubular structures with welded joints. The circular connecting flanges are of a uniform design and are welded to the struts. The struts and mounting flanges were built from 304 stainless for this prototype.

3.0 TESTING & RESULTS

3.1 DRY TESTS OF GENERATOR

Two versions of the linear generator were tested by operating the device in the OSU Linear Test Bed (LTB). The first device was a small device, initially without back iron, which was added on the outside of the stator in the lab to get a second set of results. The second device used back iron, more windings and other improvements indicated by testing the first generator.

The linear test bed drives the device mounted in it (in this case, our generator) up and down with a fixed speed. We attached the generator to known loads and measured the voltage it produced. This allowed us to find out how much power it produced at specific speeds. The graph on the next page (Fig 3.1.a) shows how the LTB ramps up to speed, holds it, then de-accelerates to end its stroke. All measurements are taken at full speed.

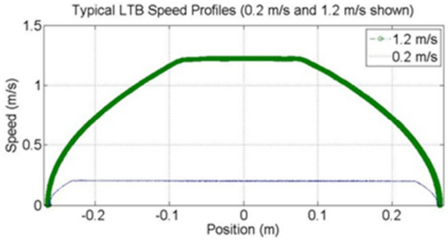


Figure 3.1.a. Typical LTB Speed Profile

3.1.1 Results

The open circuit voltage increases linearly as a function of speed for each of the LTB speed profiles. The data shown in Fig. 3.1.b is for the second generator.

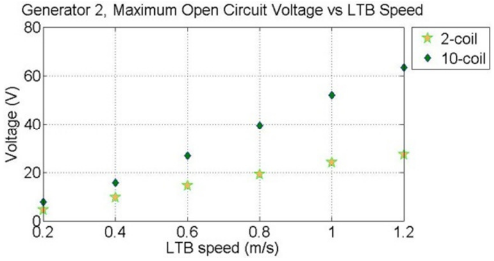


Figure 3.1.b. Maximum open circuit voltage at output of parallel bridge rectifiers

Electrical power generation was evaluated by running the generator with a range of resistive loads. Results for the 10-coil output of the second generator are shown in Figures 3.1.c.

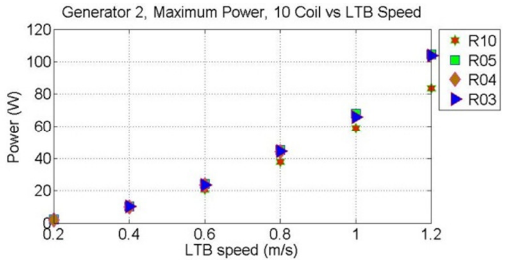


Figure 3.1.c: Maximum power output for 10 coil output.

The maximum speed of the LTB was 1.2 m/s so extrapolation was used to predict power output at higher speeds, shown in Figure 3.1.d. The output power for both generators is shown for comparison.

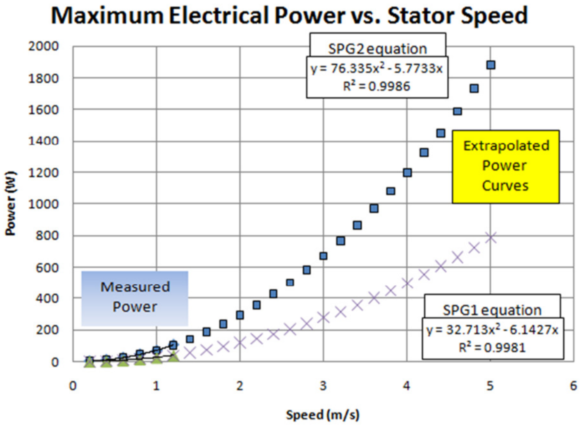


Figure 3.1.d: Extrapolated power curve with 2nd order polynomial regression equation.

The maximum power transfer resistance is approximately 5 ohms as shown in Figure 3.1.e.

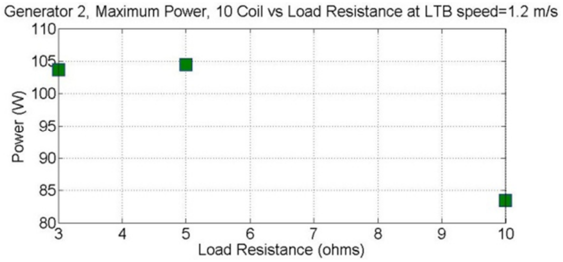


Figure 3.1.e: Maximum power transfer curve.

The addition of back iron, maximizing the number of turns and reducing the spacer thickness were important improvements to the generator. The results demonstrate the importance of speed in producing power – which should be taken into account in device design.

3.2 WAVE FLUME TEST OF MODULE

The purpose of our in-water testing was to determine how our module interacted with the waves and to characterize the electrical generation profiles for different wave parameters.

The second generator was mounted in the completed module for in-water testing in the Wind-Wave Channel (WWC) at the Hydraulics Laboratory at Scripps Institute, La Jolla, California. The wave channel, also known as a wave flume, is 44.5 m long, 2.39 m wide, and 2.44 m deep, and able to accommodate one of our modules, but not suitable for testing an array of modules. It has transparent windows along the side that allowed us to video the movement of our device. It is equipped with an electro-hydraulic wave generator at one end of the channel, and a fixed 1:10 slope beach at the other end.

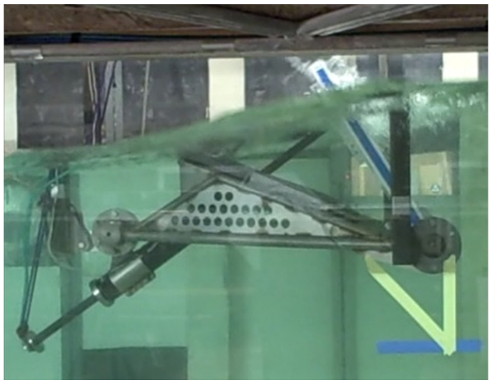
Further description of this flume and the Hydraulics Lab can be found at http://hydraulicslab.ucsd.edu/Facilities.html[1]

There were four parameters that we could change:

- The module position in the water
- The period of the waves
- The height of the waves
- The amount of force exerted by external springs that acted to return the panel to the pre-wave position

The module position setting describes the amount of the panel that is submerged in the water. The three height settings used were: one-half submerged, three-quarters submerged and fully submerged. Note that in the fully submerged position, the top of the panel was just at the neutral water line, so that it would experience the maximum fluid momentum.

The period settings were 2 sec, 4 sec and 8 sec. The nominal wave amplitude settings were 8”, 12” and 15”. These were set by measuring the wave height 3’ in front of the module, and setting the wave channel’s wavemaker rheostat to achieve the desired height. All data were taken in a still water depth of 54.5”.



3.2.1 Results

The module performed well in all wave heights, and we would be confident of exposing it to much higher wave conditions. It produced power and removed energy from the wave.

Electrical power production

The electrical power generated increased with wave height, and with wave frequency. Maximum power production was achieved when the device was positioned with three quarters of the panel was submerged below the water line. This appears to be the optimal combination of panel buoyancy and the momentum of the fluid across the front and back of the panel for this design.

The highest electricity production achieved was 2.9 watts - when the device was three quarters submerged in 15” high waves with a 2 second period.

The primary reason that power generated decreases with increasing wave period is that the generator is inactive for longer portions of the wave. Electricity is generated as the crest pushes the panel down, but then the panel stays down while the rest of the wave washes over it. The panel rights again when either its buoyancy or the momentum of the wave pushes it back. Figures 3.2.a and 3.2.b show the electrical power generated as a function of height and frequency.

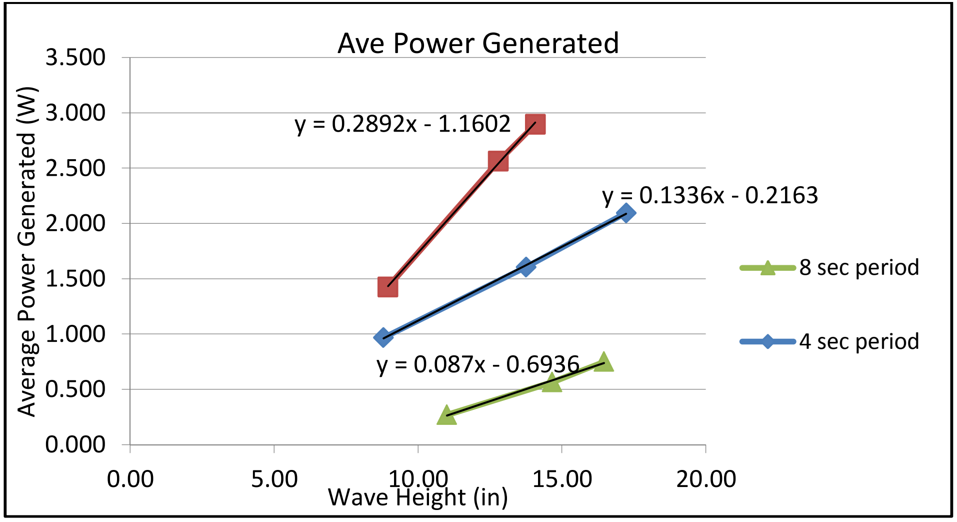


Figure 3.2.a. Average power generated versus wave height at the forward staff ¾ submerged.

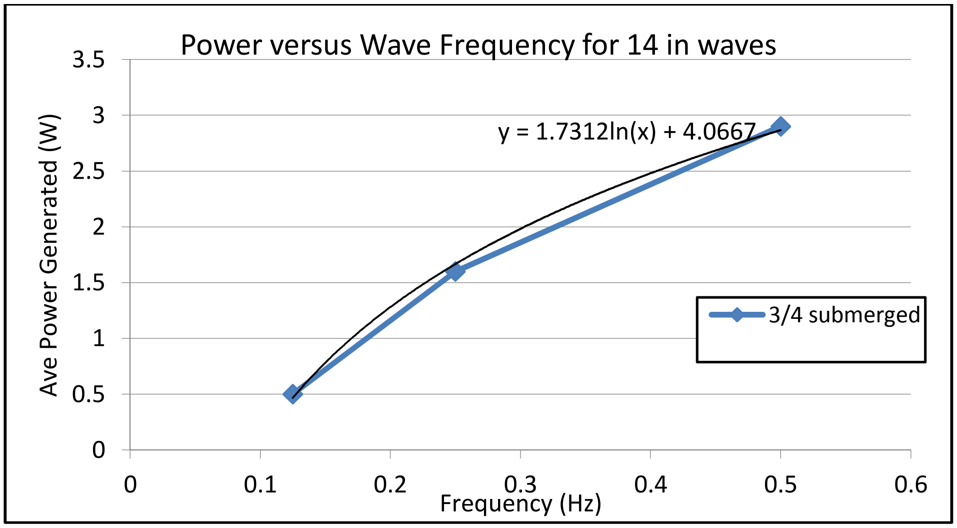


Figure 3.2.b. Average power generated versus wave frequency. ¾ submerged in 14” waves

An additional reason that less electricity was generated from 8 second waves is that the velocity of the generator was lowest for these waves. So, not only did the waves generate power less frequently, but when they did generate it, they produced lower voltages. The power produced by the generator is similar to what we found in the dry tests for a given velocity.

In general, electricity production appears to be predicted by wave velocity times H/gT^2 (the dimensionless quantity that expresses the steepness of a wave) as shown in the graph below. The linear relationship is approximately y=101x, so roughly 1 watt was generated for each cm/sec of phase speed multiplied by the steepness factor.

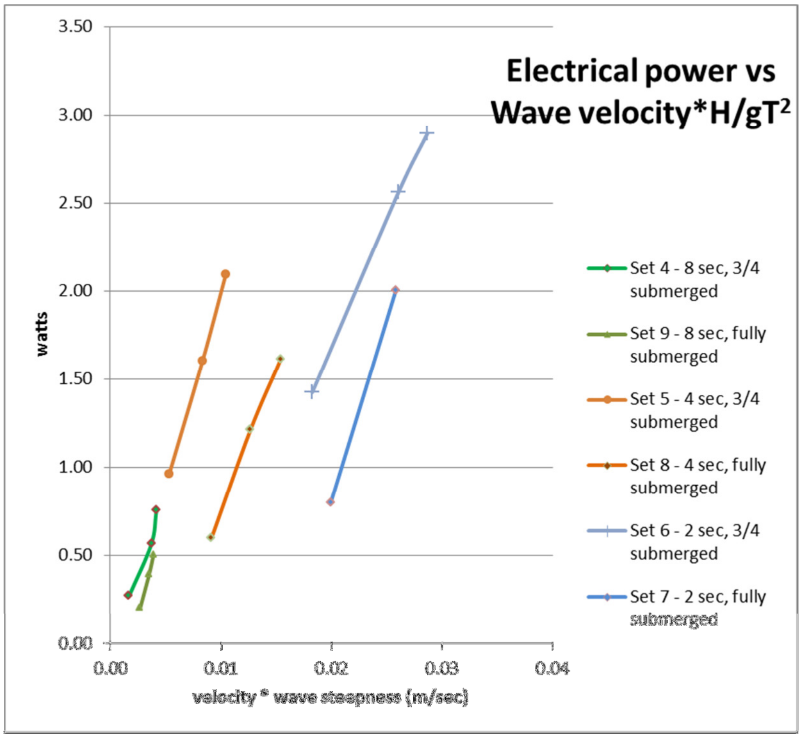


Figure 3.2.c. Electrical power vs Wave velocity factored by steepness

Wave energy dissipation

The device disturbs the fluid flow, making it successful in reducing the wave's energy. We found that energy dissipated from the wave increases as period increases for periods between 2 and 8 sec.

Interestingly, this trend is in direct contrast to electrical power production. In addition to providing power to the generator, the change in the energy flux is also due to perturbation of the wave as it passes over the device - including vortices and turbulence that occur as the fluid passes the support framework and flows around the panel, back pressure and wave reflection as the wave approaches the module, counter flows induced by the panel when its momentum is opposite that of the water, and drag against the device.

3.2.2 Comparison between model and experiment

Angular velocity and displacement

The model successfully predicts the angular velocity and displacement seen experimentally for different wave conditions. An example comparison is shown below for Test 8.2 in which the module was fully submerged in 4 second period waves with a 0.324m wave height.

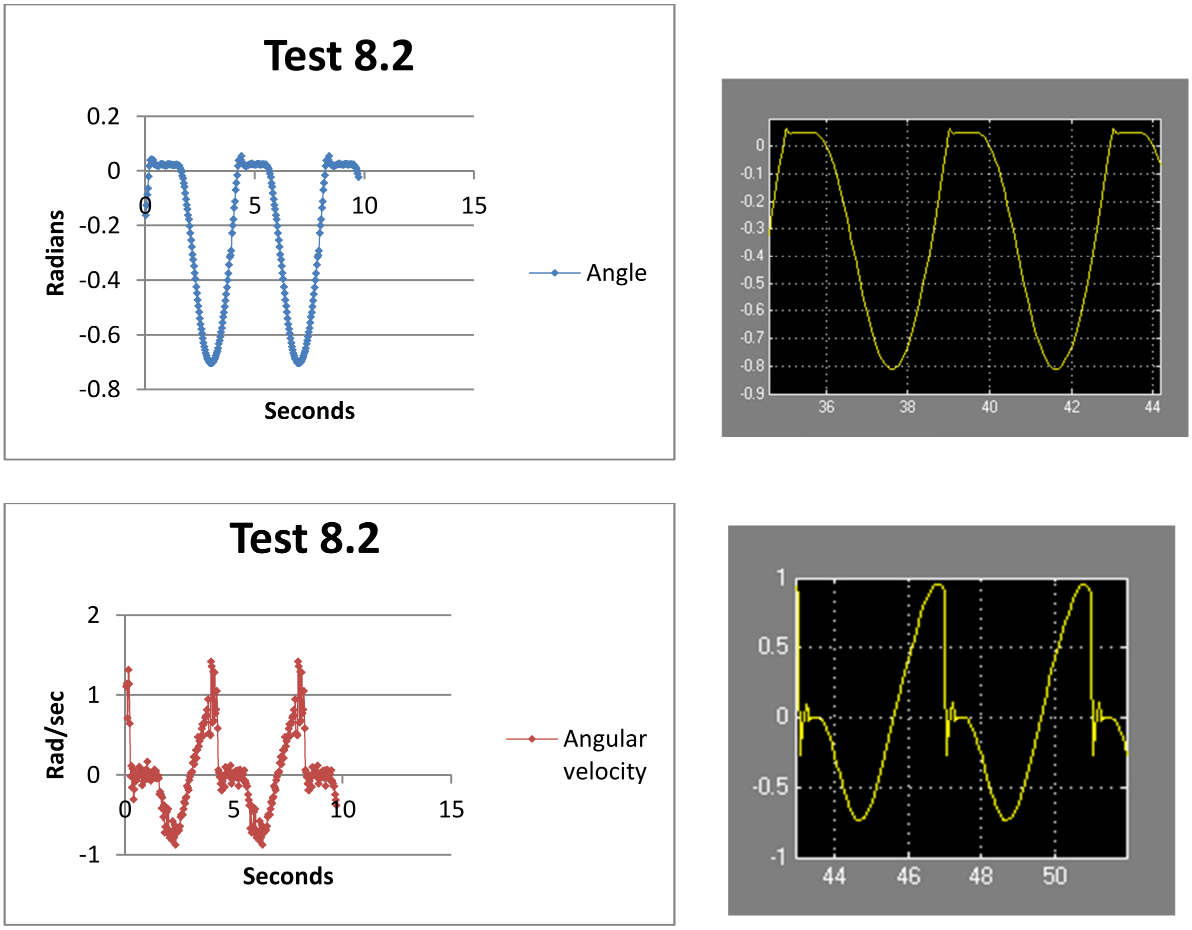


Figure 3.2.d. Comparison of model and experimental data for the module fully submerged in 4 sec period, 0.324m waves.

Note that the velocity test data shows the cogging of the linear generator, but that detail is not included in our model.

Position of the panel

For low wave power conditions and full submersion of the panel, the panel tends to remain vertical because of its buoyancy. However, with more energetic waves, the panel rotates fully down onto the stops. Whether the panel has time to return to the vertical position depends upon the wave frequency, the force of the returning wave, and how deeply the module is submerged with respect to the mean waterline. The model is able to predict this behavior. The chart below shows the maximum and minimum angles predicted by the model compared with that found in the lab.

Test	Bottom angle Lab test	Bottom angle Model	Top angle Lab test	Top angle Model
1.1	0.919	0.910	0.654	0.7800
1.2	1.133	1.035	0.732	0.6110
2.1	1.124	0.879	0.757	0.5635
2.2	1.188	1.208	0.807	0.6030
2.3	1.110	1.205	0.721	0.7695
3.1	0.969	0.989	0.722	0.7670
3.2	1.070	1.032	0.745	0.7830
4.1	0.943	0.848	0.000	0.0511
4.2	0.847	0.844	0.000	0.5060
4.3	1.000	0.932	0.000	0.0508
5.1	0.757	0.714	0.000	0.0528
5.2	0.830	0.819	0.000	0.0543
5.3	0.895	0.777	0.000	0.0554
6.1	0.737	0.716	0.258	0.2540
6.2	0.850	0.778	0.259	0.2560
6.3	0.970	0.948	0.288	0.3333
7.1	0.330	0.555	0.000	0.0533
7.2	0.590	0.674	0.000	0.0557
8.1	0.546	0.402	0.000	0.0567
8.2	0.700	0.707	0.000	0.0591
8.3	0.770	0.811	0.000	0.0614
9.1	0.640	0.633	0.000	0.0515
9.2	0.770	0.699	0.000	0.0522
9.3	0.800	0.753	0.000	0.0524

Figure 3.2.e. Panel angles predicted by model vs those found in lab tests

Electrical power and damping

From the experimental results, we saw that the electrical power increases linearly with wave velocity and steepness. The model shows that the power dissipated by the damping element also increases with wave velocity and steepness, but as a square of that term rather than linearly. This reflects the difference between an ideal damper, whose power output is proportional to its velocity, and our linear generator, whose power output was shown to be proportional to its velocity squared. We have not made this amendment to the model yet, since we intend to replace the linear generator with a piston-based system in our next prototype.

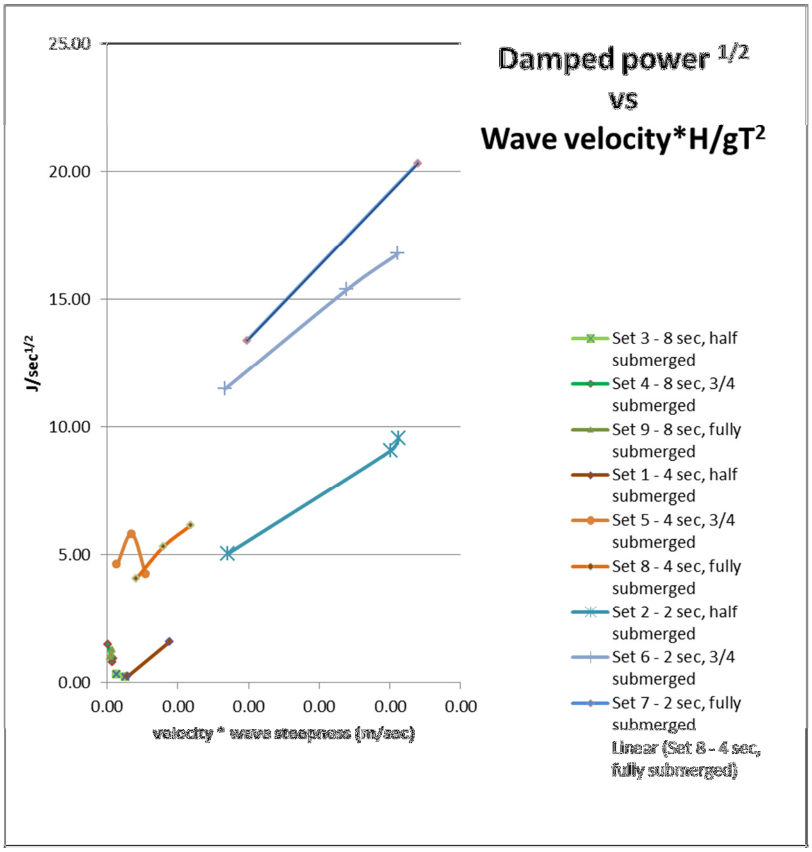


Figure 3.2.f. Relationship between damped power and steepness-adjusted wave velocity predicted by the model

Experimentally, we found that electricity generation is optimal when the module was submerged with three quarters of the length of the panel below the neutral water line. However, our model does not reflect this, presumably because of the difference in behavior between the linear generator and the damper.

The magnitude of wave energy

Our model can predict the energy flux of the waves before they strike the module by integrating $\rho g H^2$ over time. This does not correlate perfectly with the values for the same quantity that we obtained experimentally because the real waves are not sinusoidal.

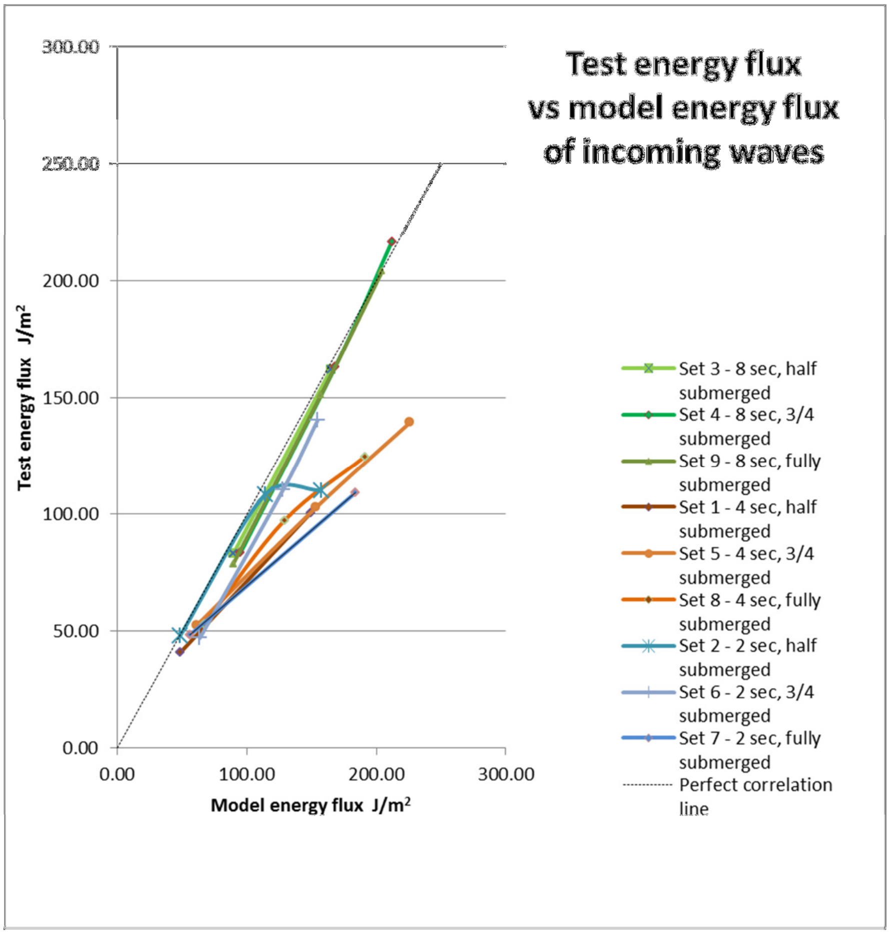


Figure 3.2.g. Comparison of energy flux found in lab tests with that predicted by model

Since our model does not calculate how the fluid flows around the device, we are not able to calculate the wave surface profile after the wave passes by the device. Until we incorporate these calculations, we will not be able to corroborate the decrease in wave energy flux we observed in the lab.

As we saw before, our calculation of the power dissipated by the module predicts the amount of electricity produced. Consistent with our experimental results, the power dissipated does not correlate with the reduction in wave energy flux that we found in the lab. Experimentally, we found that 8 second period waves experienced a marked decrease in their energy flux as they passed across the module, whereas 2 second period waves were relatively unaffected. However, the average electrical power produced by 2 second waves was far greater than that produced by 8 second waves – because the generator moves much more frequently. Until we model the fluid flows, our model can be used to understand power takeoff by the generator, but not the reduction in wave energy.

Extrapolation of the results

The production of both damping and electrical power depends upon the phase velocity and steepness of the wave. Using the relationships we found, we can project how much power can be produced with different wave conditions.

Experimentally, we found that the device generated power most successfully in waves with short periods. This is reflected by our model as well – as can be seen in the Figure 3.2.f. Since a single module is only able to take a limited amount of power out of long, high waves, it harvests more energy from lower waves at higher frequencies.

3.2.3 Discussion

The knowledge gained from the model and experiments leads us to certain design decisions.

While the generator produced low power levels, the module was quite successful in reducing the wave's energy. The device dissipated the most energy from waves with long periods. This is encouraging for its use to protect marine structures and shoreline.

In natural waters, higher waves tend to occur at lower frequencies. This means that the current design of our modules would be well suited to locations not usually addressed by wave devices, such as the Great Lakes or the Gulf of Mexico.

For higher waves, the modules would be built into arrays configured so that the waves pass over several rows of modules. Our laboratory tests showed that the waves keep their frequency as they pass across a module – although they may experience a phase shift. It might be possible in certain circumstances to encourage a component of the wave to be reflected by one of the back rows – and this could introduce another frequency component, which might increase the power harvest. These aspects provide interesting opportunities for future development.

References:

1. Alden, D., ed. *Hydraulics Laboratory*. Retrieved February 14, 2012, from Scripps Institution of Oceanography - UCSD website: http://hydraulicslab.ucsd.edu/Welcome.html
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4.0 EVALUATION

Our approach of building generating systems from small, repeating modules shows great promise. It allows an organic business model, in which experience and finance can be gained in niches where access to electricity is more important than its cost – then the finance and experience gained there can be used to expand into larger, more cost-sensitive installations. Our work is unique in that it can bring a solution to the market quickly, since our first prototype is already at full scale. We can address both large and small installations with a single device – giving us the ability to address a wide audience.

4.1 DESIGN ASSESSMENT

Our design in which a pivoting panel operated a power-capture module through a three-bar linkage worked well – and appears capable of handling a variety of wave conditions, especially if deployed with feedback control and/or adaptive arrays.

The device behaves differently in different wave conditions. So far, we have tested it in low waves with periods from 2 to 8 seconds. To summarize the findings:

- Electrical production increases as wave frequency increases
- More electricity would be produced if the panel was allowed to pivot forward as well as back
- The device dissipates wave energy successfully, and is more effective in this regard for long period waves.

Without substantial design changes, the application for the system appears to be in two distinct wave regimes. For energy production, the system is possibly best sited in seas, gulfs and similar size water bodies, where the waves typically have periods under 8 seconds. These locations have the advantage of being more benign – and therefore the device would not need to be designed to withstand the huge impacts of large ocean waves.

For locales that experience higher waves, the modules would be deployed in multi-row arrays. Because of the complexity of interaction between the waves and modules, our results cannot be reliably extrapolated to estimate the power which would be produced by large ocean waves across an array of modules. This merits further investigation in a much larger wave flume or a natural setting.

4.2 DEFENSIVE USES

For deep water waves, three dimensional arrays (ie, rows of multiple sets of modules mounted one above the other) might be more effective than arrays of surface-only modules.

By reducing the wave energy, the modules will decrease the velocity of the flow within the waves. We believe that, if correctly positioned, the modules will be able to reduce the scour which undermines breakwaters and other structures. This remains to be demonstrated in-situ.

4.3 POWER PRODUCTION

Unfortunately, the amount of electrical power the module produced was disappointing, especially compared to the cost of the raw materials required to produce it.

This is an inherent problem for small units. Substantially larger generators are more efficient. We believe that this issue needs a new solution to enable the small modular approach to succeed for electricity production.

We have designed two novel technologies that address this issue. For both of these, the linear generator in our current design would be replaced by a pressure piston – which would feed a generating system. This has the advantages that

- Pressure can be accumulated across a number of devices, and regulated to give steady flows to the generator.
- The generating technology used is independent of the module itself, so it can be chosen to suit the locale and community requirements.
- The pressure can be used for other purposes than electrical generation – such as pumping, mechanical drives or chemical processes.

5.0 FUTURE WORK

GENERATION TECHNOLOGY

The major design issue we encountered was the low level of electrical power produced. Therefore, we will pursue generator innovation in parallel to the work described below to complete the module development. We plan to replace the linear generator with a piston, and use the pressured fluid to drive generating equipment. This allows flexibility, so that the nature of the generator can be chosen to suit the site conditions and user demands. Options include using the hydraulic pressure directly, direct electricity production, and combined fresh water/electricity generation units.

NEXT STEPS TO DEVELOP MODULE

In the wave channel, we were only able to test a single module in waves up to 15” high in wave channel. In light of this, we believe that ideally we should test an array of modules in natural waves along the coast. Our plan is to try to use semi-sheltered waters where the waves are not too high, in preparation for a full ocean deployment. This will not only give us the chance to observe the performance of multiple units, it will allow us to investigate the system’s behavior in a variety of wave conditions, observe the resilience of the system in the natural environment and demonstrate its ability to generate electricity over a longer period.

Because our system can be deployed with a small footprint close to the shore in areas where there are already manmade structures, we believe the permitting process, installation and maintenance will be easier than for larger installations further from shore.

The in-situ tests will also help us some insight into whether our system can be used to control wave impact on coastal structures, or whether it could be used to manage sediment transport.

6.0 LESSONS LEARNED

6.1 Design lessons

- Locales with the largest waves may not be the most optimal place to harvest energy – especially for our system.
- From an environmental and financial point of view, survivability is not simply a matter of keeping the device in the water for long periods. It is a balance between the initial costs and impacts with those required to keep it operational. Being able to swap out modules for on-land maintenance has great advantages.
- We were able to find alternatives to welded structures that will reduce costs and improve survivability.
- Linear generators are not well-suited to this application, because they are not efficient at small sizes, and because they need to move faster and at higher frequencies to offset their high cost of material.

6.2 Prototyping lessons

- Our model illustrates the importance of the relative sizes of the panel and the waves. We benefitted from being able to test our first prototype at full scale, since we are now ready to put our device in natural waters.
- The position of the stops is an important design consideration that affects the efficiency of the device. It would have been helpful to be able to adjust the stops in the laboratory setting.
- Use of a buoyant panel provided a simple return system, which we found successful enough to incorporate in the final design. The motion of the returning wave is also an important factor in returning the panel to its original position.
- Replacement of metallic with non-metallic parts reduced costs, improved functionality, and minimized corrosion.
- Mounting the module on the supporting structure was straightforward. Last minute changes to a smaller wave flume were easily accommodated.
- Construction of the linear generator was time and material intensive, reflecting the cost-ineffectiveness of this technology.

6.3 Testing lessons

The next time we undertake in-water tests, we will ensure that we:

- Use pairs of wave staffs in front and in back of the device to obtain more accurate wave speeds.
- Measure wave heights for the various wave types before modules are installed.
- Record video of the upper and lower portions of the flume so we can see if phase changes are occurring.

- Calibrate the pressure & strain gages, and test their water resistance before coming to the flume.
- Improve the coordination markers between the data feeds and video footage.
- Record narrative over video as testing is being conducted and observations are seen in real time.

7.0 CONCLUSION

The concept of small modular units that can extract and dissipate energy from ocean waves has been validated, and warrants investigation in natural conditions. The units can be used individually or in an array to generate electricity and preserve shoreline and other marine structures. The modular design is exceptionally flexible and will aid in the development and commercialization of ocean wave energy. Unlike large single generating units, it enables organic development and business growth. The flexibility and adaptable design of the modular system is conclusively a winner.

When subjected to laboratory waves, a single module demonstrated excellent survivability. It was very effective in dissipating the energy contained in the wave. Electrical energy generation was achieved, although at low levels. Other methods of generation are easily incorporated and will be explored. We believe that a different generating technology could greatly improve the electrical output.

The financial viability of utilizing wave energy can be enhanced by providing other benefits in addition to generating electrical power. We have shown that it is feasible to create usable power and reduce the energy carried by the waves. Therefore, its operational costs can be offset by protecting shoreline and manmade structures.

We conclude that the concept has clear potential for harnessing and controlling the power of coastal waves.

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