WAVE ENERGY SYSTEMS – FINAL REPORT

AS A PART OF FIELD WORK FOR
SPECIAL TOPICS IN OCEAN
ENGINEERING: MARINE FIELD PROJECT
15 JANUARY – 18 JULY, 2012

SUBMITTED BY: BILLY WELLS (BWELLS@my.fit.edu)
DATE: 20 JULY, 2012
SUBMITTED TO: DR. STEPHEN WOOD, P.E.
PROGRAM CHAIR, OCEAN ENGINEERING
DEPARTMENT OF MARINE AND
ENVIRONMENTAL SYSTEMS
FLORIDA INSTITUTE OF TECHNOLOGY

FLORIDA INSTITUTE OF TECHNOLOGY
150 WEST UNIVERSITY BOULEVARD
MELBOURNE, FL 32901
WWW.FIT.EDU/DMES

PROJECT MEMBERS:
BILLY WELLS
ISMAIL SULTAN
ALEX WIEST
PATRICK MALONEY
SITARA BABOOLAL
CHAD GESTEWITZ
MARIO SUAREZ

Abstract

The Wave Energy Team at Florida Institute of Technology aims to create an interchangeable, environmentally friendly power take off unit which can perform efficiently in a variety of wave energy harvesting devices. Secondary objectives include testing and proving of existing structural and mechanical components previously developed by ocean engineering and mechanical engineering students. The following report discusses a variety of limiting and parametrical issues, to include but not limited to:

- Motivations
- Background and Theory of Ocean Energy
- Design Parameters and Decisions
- Test Plans
- Deployment and Results
- Data Anaylsis
- Discussion, Recommendations, and Conclusion

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1.0 Introduction

Although still in its infancy, ocean energy technologies have already gained recognition as a viable and economical supplement to America's energy demands. In 2005, The U.S. Department of the Interior's Mineral Management Service began oversight of the Renewable Energy and Alternate Use Program projects, many of which are aimed at harvesting energy from the ocean along our coasts. The creation of such a service lends credence to the viability and potential of renewable energy as the United States begins to seek out alternate sources of energy besides petroleum based fossil fuels. In comparison to other forms of alternative energy from the ocean, wave energy is continuous, but also highly variable [1].

Through complex meteorological relationships, the uneven heating of the earth's surface produces large scale wind systems throughout the world. There are three main meteorological phenomena present in the formation of waves. Initially, wind from large scale weather systems blows across the surface of the ocean. This in turn creates a tangential stress on the water surface, resulting in the initial formation of waves. The second system to assist in building of waves is the pressure and shear stress variations at the surface of the water. When these fluctuations are in phase with the existing wave oscillations, further wave propagation occurs. Thirdly and finally, when the waves reach a particular size, the wind forces are greater on the windward side of the wave, which also increases the wave size. Throughout each step of the wave generation process, energy from the wind is transferred to the waves, which carry this energy away from their point of origin [1]. This energy eventually reaches the shore and interacts with the coastline. For this particular work, it is at this stage of the life of a wave when energy is being harvested. The estimated amount of energy contained within these waves is on the average of approximately 1000kW/m of wave crest length [3].

The importance of this unharnessed energy is being realized. Two existing prototypes at Florida Tech have been designed and manufactured, but lack power take off units (PTOs). The three main goals of this work are:

- Improve upon two existing wave energy conversion devices
- Proof of concept for these two devices

- Incorporate both devices into a shared, universal power take off unit in order to create an electrical output and test the efficiencies of the two devices against each other

Although the two types of wave energy converters are different with respect to their method of harvesting energy, a single interchangeable PTO will be used to generate electricity from both components. In theory, the commissioning of the overall system will prove the design concepts

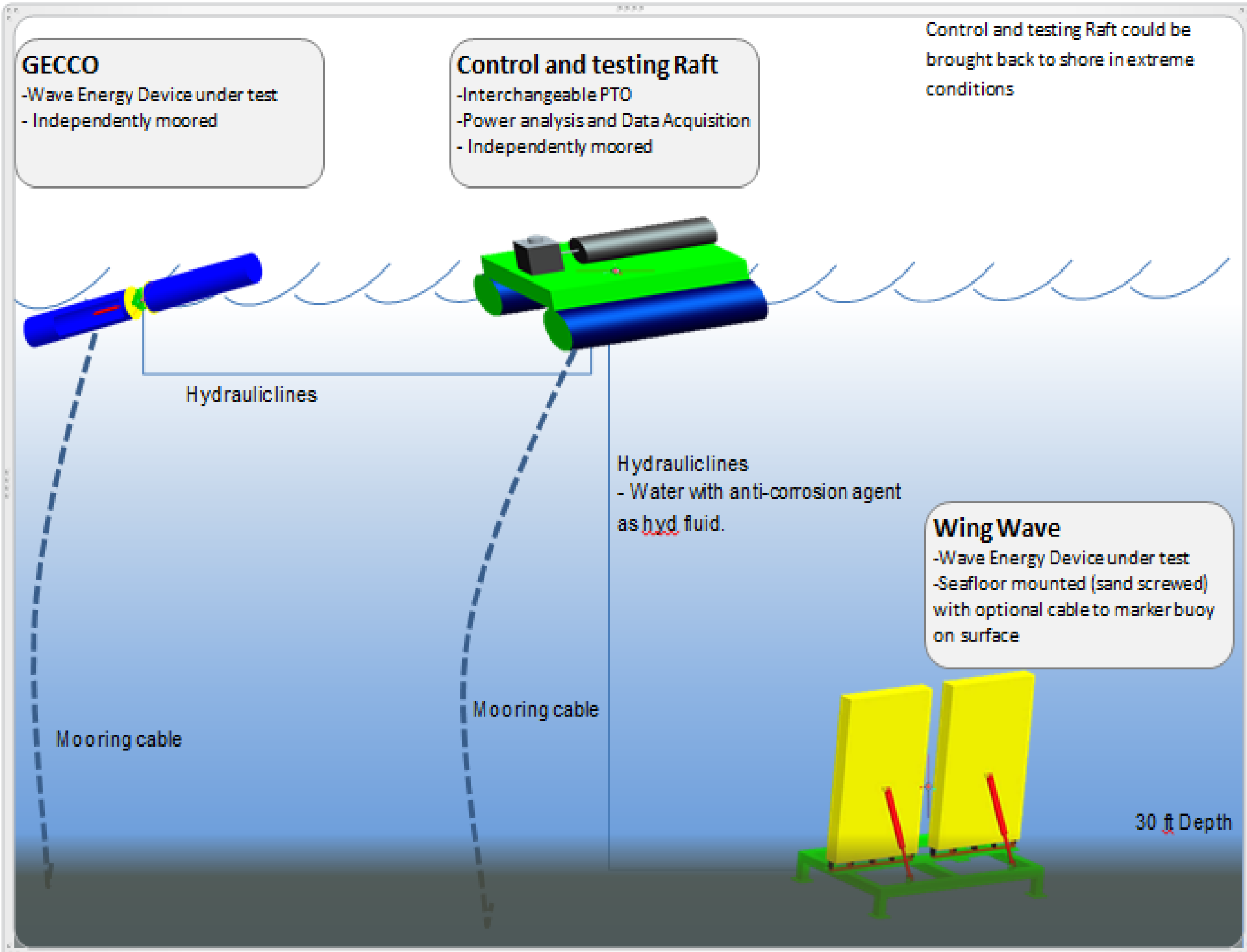

Figure 1: General Project Overview

of the individual components and will hopefully give a solid foundation for improving the efficiencies of each individual component in the future.

1.1 Background

Existing Technologies: There are many variations in the types and effectiveness of wave energy converters (WEC). Usually, WECs are grouped by the location of the wave in which energy is extracted. The most common types of WECs include terminators, attenuators, point absorbers, and overtopping devices.

Terminator WECs - Terminators are WECs which gather a wave's energy and stop the forward propagationof the wave. These types of WECs usually exist on the shoreline, since the wave terminates there anyway.

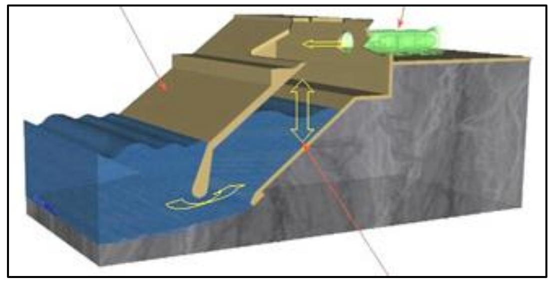

Figure 2: Terminator WEC [4].

Figure 4: Attenuator WEC [4].

Attenuator WECs - Attenuators can either float on the ocean surface or be partially submerged. They usually contain some sort of hinge mechanism and body section which move independently from one another about the hinge. As the wave passes the attenuator, energy is harvested, and the wave continues propagation further along the surface of the ocean.

Point Absorbers - Point absorbers are usually stationary and work on differences in pressure and/or elevation in the surface of the ocean. Again, after the energy is absorbed from a wave, the wave itself continues on its journey across the ocean.

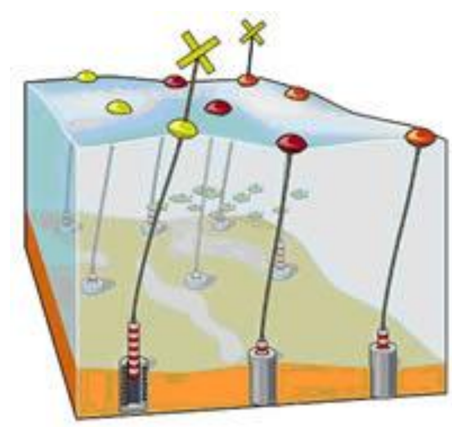

Figure 3: Point Absorber WEC [5].

Overtopping Devices - Overtopping devices collect water as it passes over some sort of boundary, essentially filling with water and using the pressure created by the collected water to create energy.

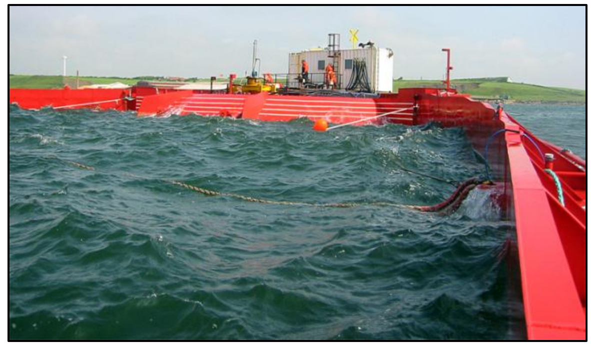

Figure 5: Overtopping WEC [5].

The two existing WECs at Florida Tech which required a Power Take Off (PTO) system are the Green Energy Coastal Collection Operation (GECCO), which is a floating heave/surge type of attenuator WEC, and the Wing Wave, which is also an attenuator. The GECCO floats atop the ocean surface and articulates about a fixed hinge and is freely moored to the ocean floor using mooring lines. The Wing Wave is moored directly to the ocean floor and is moved by underlying wave orbitals from waves passing overhead. Because these two systems are oriented differently spatially, and operate significantly different with respect to their mechanics, a PTO being shared would need to combine these energies. The most simplistic way to do this was via a high pressure hydraulic system. The PTO that was built for these two systems floats atop the surface of the ocean and is moored near the two systems.

1.1.1 Wing Wave

The goal of the Wing Wave project was to construct a sub-surface energy pump system to collect and analyze its power output. In recent years there have been several studies done about the validity of use of the waves as an energy source. Although most of these studies have been on the power output of the surface action of the waves the Wing Wave takes it deeper. It works with the concept that particles orbiting under a shallow water wave follow an elliptical path. As depth increases the horizontal movement of the particles' rotation remains the same while the vertical movement decreases. This causes the motion of the ocean floor to oscillate in an almost exclusively horizontal direction. The Wing Wave System was designed to capture this horizontal motion to pump the wings of the system, ultimately pumping a working fluid to a generator via a hydraulic ram.

The Wing Wave WEC is based on several private commercial designs. One in particular is the AW-Energy Wave Roller. Original concepts for the Wave Roller date back to 1999, when the first prototypes were designed and the first patents were applied for. The Wave Roller is fixed to the sea floor, and as waves pass overhead, the particle velocities impart a force over the presented surface area normal to the wave propagation.

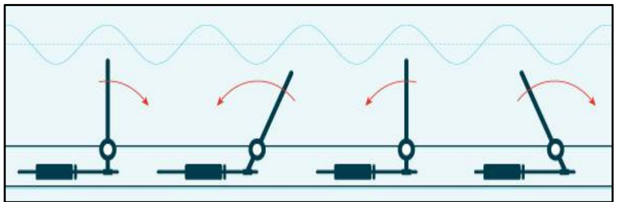

Figure 6: Wave Roller WEC [6].

Another private design is the Oyster Wave Energy Converter. Mechanically, this WEC works in the same fashion as the Wave Roller. The main difference is that the fluid in the hydraulic system is transferred onshore to a hydroelectric power plant. Current and plausible testing sites for the Oyster include Scotland, Ireland, and the west coast of the United States.

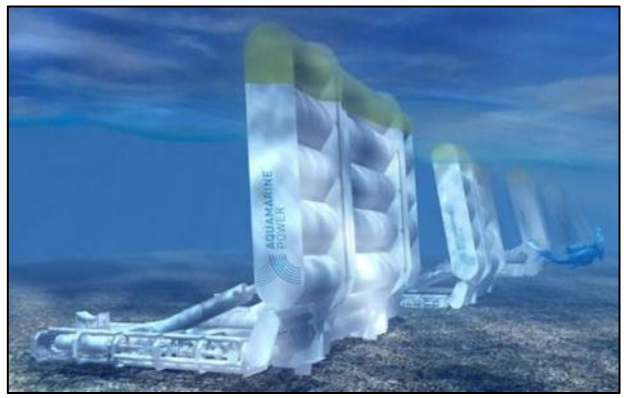

Figure 7: Oyster WEC [6].

The Water Wave Technology group for their senior design project started the Wing Wave System project in 2008. In order to figure out the best design for the wing, four models were built and their efficiencies compared by observing their range of motion when placed in a wave tank. They compared the range of motion on a flat wing, a flat wing with a top panel (T-shaped), a triangular wing and the flat panel with top and side panels. The least effective model was the T-shaped wing where as the most effective was the wing with top and side panels. This model testing finalized the design for the prototype wing.

In 2010 the project was taken on by another group using the wing design proven the most effective by the previous group to build a prototype. The large-scale prototype sat on a 20’ x 15’ based constructed using 6061 Aluminum. Four 2’ triangular extensions were added to the base to enhance the stability of the structure when fastened to the sea floor. The base of the prototype held two 15’ x 8’ tall aluminum wings placed one in front the other connected to the frame via

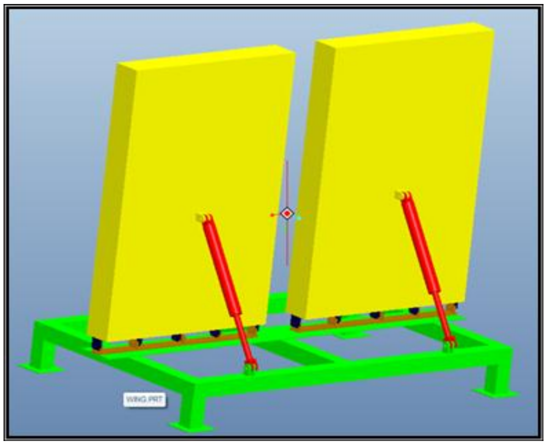

Figure 9: Wing Wave prototype design.

stainless steel hinges. A piston system was attached to the wings to transfer the pumping motion caused by the horizontal movement of the wave (wave energy) to a generator to produce power. This system was however not connected to a viable data recorder and its energy output was not recorded while at sea.

In 2011 Clean and Green Enterprise built and deployed a single flat composite wing 6’ x 4’, connected to a smaller aluminum frame via a large stainless steel hinge. It was equipped with accelerometers and its movement was recorded. This showed that the wing wave was a viable means of producing ocean energy.

The Wing Wave design for the 2012 project is based on two 6’ tall x 4’ wide wings, made of composite panel approximately ½” thick resin with alternating prism support beams, 8” wide base and 6" wide top. The approximate weight of each panel is 150 lbs. The wings are attached to metal frame which is bolted directly to the sea floor via sand screws. Attached to both the wings and the metal frame is a hydraulic ram which will provide mechanical energy to drive the hydraulic system.

1.1.2 Green Energy Coastal Collection Operation (GECCO)

The GECCO is a floating heave/surge attenuator which works with a combination of a mechanical and a hydraulic system in unison. In 2004 the Pelamis Wave Energy Company developed a attenuator which was successfully evaluated and currently has orders to produce energy with their second generation units. The G.E.C.C.O has been heavily influenced by the group of people who made the Pelamis a working WEC. Florida Techs students have design a system that will harvest not only the energy of the big swells of the ocean, but as well those small capillary waves by adding to the design Stephen Salters’ invention, the Salters Ducks. Currently the design has been limited to harvest energy from the big swells due to the vast amount of elements which require time to be perfected to

Figure 8: Pelamis Wave Energy Converter [7].

reach the designs primary purpose.

From 2009 to 2010, Florida Tech's Blue/Green Energy System group started research on methods to harvest energy via ocean waves. The Pelamis (shown in Figure 8) and the Salter's Ducks are existing systems that were identified as the best method to harvest wave energy. The new system that Blue/Green Energy Systems looked at was the combination of the two existing systems. The manufacturing process to create the new system was aided by computer software. This new system consists of two cylindrical sections with four
Salter's ducks which will be working in unison with a pulley and hydraulic system and a pump respectively that will push the hydraulic fluid into an expansion tank creating pressure. The pressure then will be released into an electric generator to generate electricity.

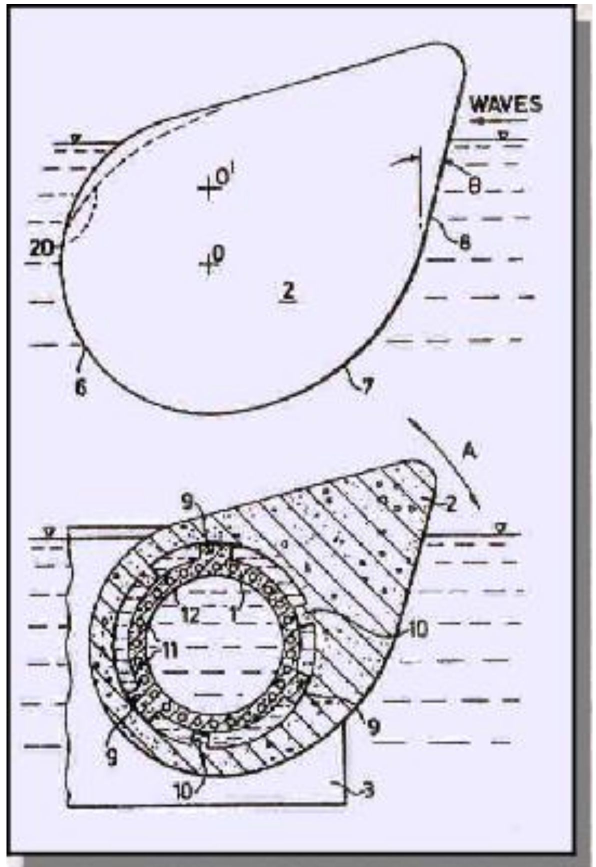

Figure 10: Salter's Duck Concept [8].

After the design was completed, the system was not running perfectly. The joints were being subjected to high amounts of stress due to the restricted motion it provided to the two cylindrical sections it was holding together. The cables that drove the hydraulic rams were subject to failure if they were subjected to a rapid load. The entire systems buoyancy depended on the Salter's ducks which can result in a complete failure if one duck is not completely waterproof. If there would be a hydraulic fluid leak then the system will lose the ability to generate power. The loss will depend on the amount of fluid lost.

The following year, the Green Energy Coastal Collection Operation group designed a completely new system that is basically the same as the Blue/Green Energy System but bigger. There were several significant changes done to the old design. One pair of the Salter's Ducks

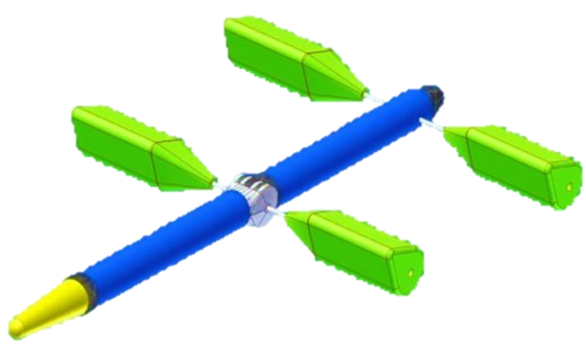
Figure 11: Blue/Green Energy Conceptual Design [9].

was moved away from the joint, which will reduce the amount of stress on the joint. Inside one cylindrical section, aluminum scaffolding was designed to create more strength of the system once all of the hydraulic equipment was installed. This hydraulic system operates on a set of pulleys to move hydraulic fluid via a ram mounted inside the body section. For this prototype version, the Salter's Ducks only act as stabilizers and will are not used for harvesting energy.

The main goal for the group was to prove the concept of their system, rather than generating energy. Significant lessons learned from the initial deployment of the GECCO were

Figure 12: GECCO Initial Deployment [14].

mainly water intrusion and the effect it can have on a surface mounted system. The main points of ingress were the large aluminum end caps as well as the maneuver points for the rods which hold the Salter's Ducks. The joint did not suffer any noticeable damages.

In spring and summer of 2012, work was done to improve upon the existing GECCO and to generate electricity. This mainly deals with the mounting of the hydraulic system and pulley system within the body of the GECCO.

The hydraulic accumulator and generator are not installed inside any section of the GECCO; instead a floating vessel containing the power take off components moored nearby is fed hydraulic fluid near the GECCO to facilitate data acquisition for further analysis.

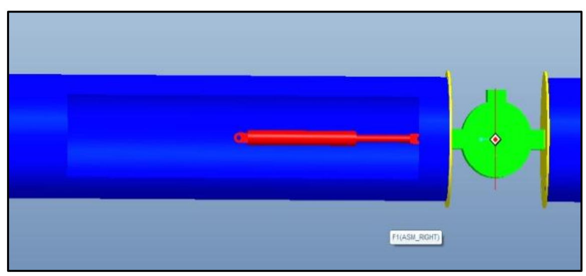

Figure 13: GECCO Hydraulic Assembly.

1.1.3 Power Take Off System

To ensure successful and smooth integration of the oceanic renewable energy generation into electrical power systems, it is necessary to develop methods and tools for faster, reliable, low cost and effective evaluation of *the ocean energy conversion technologies*. Such tools can be indispensable for concept verifications on a small-scale (for example, research and development at the academic level) and can help for fast and successful transformation of ocean renewable energy technologies from prototype to full-scale matured system.

This work describes the background, design, construction and results for such tool, ‘PTO (Power Take-off) Control and Data Acquisition System’ designed for performance evaluation of wave energy converters (WECs) under-testing i.e. Wing Wave and GECCO.

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Main goals for the PTO Control and Data Acquisition System were:

a. Design of a Control System for PTO, capable of controlling hardware, monitoring instruments and sending data to remote station for user viewing
b. Design of a web based interface for user to view the results in real-time.
c. Design of a Power System to regulate the electrical output of PTO as per load requirements

2.0 Theory

As our ability to forecast weather patterns becomes more advanced, so does our forecast of incoming energy from waves. Wave characteristics can be estimated as a function of the weather patterns which generate the waves. Speaking specifically about the United States; in order to fully assess the energy potential, an investigation of the amount of energy flux must be introduced. The summation of energies per unit volume can be given by the basic Bernoulli's equation (assuming irrotational flow of propagating waves):

Equation 1: Wave Energy Per Unit Volume

$$\frac{\partial \phi}{\partial t} + \frac{1}{2}V^2 + gz + \int \frac{dp}{\rho} = f(t)$$

ϕ= Velocity potential

V = water particle velocity

g = acceleration of gravity = 9.81 m/s^2

p= pressure

ρ = density of fluid

The local energy per meter length of wave crest transmitted can be calculated and estimated using the wave energy equation:

Equation 2: Wave Energy Equation

$$\mathrm{p} = \frac{\rho \mathrm{g}^2 \mathrm{T} \mathrm{H}^2}{32\pi}\ \mathrm{W/m}$$

ρ = density of seawater = 1025 kg/m^3

g = acceleration of gravity = 9.81 m/s^2

T = wave period in seconds

H = wave height in meters

When considering a wave propagating toward shore with respect to harvesting its energy, we can focus mainly on the horizontal presentation of the wave energy as it arrives normal to the affected shoreline. We can call this the energy flux, which in general terms is the time rate of change of energy per unit area normal to the flow direction. In mathematical terms, the energy flux can be determined by multiplying the energy per unit volume by the individual particle velocities:

Equation 3: Wave Energy Flux

$$\Delta\dot{E} = \rho\frac{\partial\phi}{\partial t}V = \rho\frac{\partial\phi}{\partial t}\nabla\phi$$

By describing the velocity potential in terms of wave height, water depth, horizontal distance over a given period, and wave length, and by integrating this over the wave period and the water depth, the average energy flux can be described as:

Equation 4: Average Wave Energy Flux.

$$\dot{\mathbf{E}} \simeq -\frac{\rho a^2 g^2}{Tc\cosh^2(kh)}\int_{-h}^{0}\int_{0}^{T}[\cosh(kx+kh)\cos(kx-\omega t) \cdot \cosh(kx+kh)\cos(kx-\omega t)\,\mathbf{i} + \sinh(kz+kh)\cdot\sin(kx-\omega t)\,\mathbf{k}]dt\,dz = \frac{\boldsymbol{\rho g a^2 c_g}}{\mathbf{2}}\mathbf{i}$$

Upon investigation of a wave entering shallow water, it must be noted that the motion of the wave orbitals (which transmit the energy of the wave), cease their vertical movement and are restricted to a near horizontal motion. Speaking specifically of the Wing Wave WEC, these horizontal velocities are what will provide the energy to be harvested. Because the velocity component ω is parallel to the vertical plane, the integral of the k term is equal to zero[5]. Theses energy calculations provide a reasonable estimate as to what sort of energy is available along our coastal zones, where these specific WECs are placed for deployment testing.

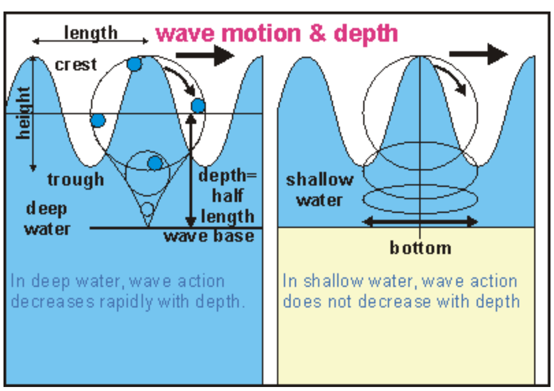

Figure 14: Wave Orbital Motions [15].

The basis for design parameters are the wave characteristics which the WECs will encounter during testing. The National Wave Buoy Data Center collects wave spectral analysis from various buoys moored throughout the world. Historical wave data for specific locations is available online at the National Wave Buoy Data homepage. Types of data available are wave heights, periods, and direction of swell:

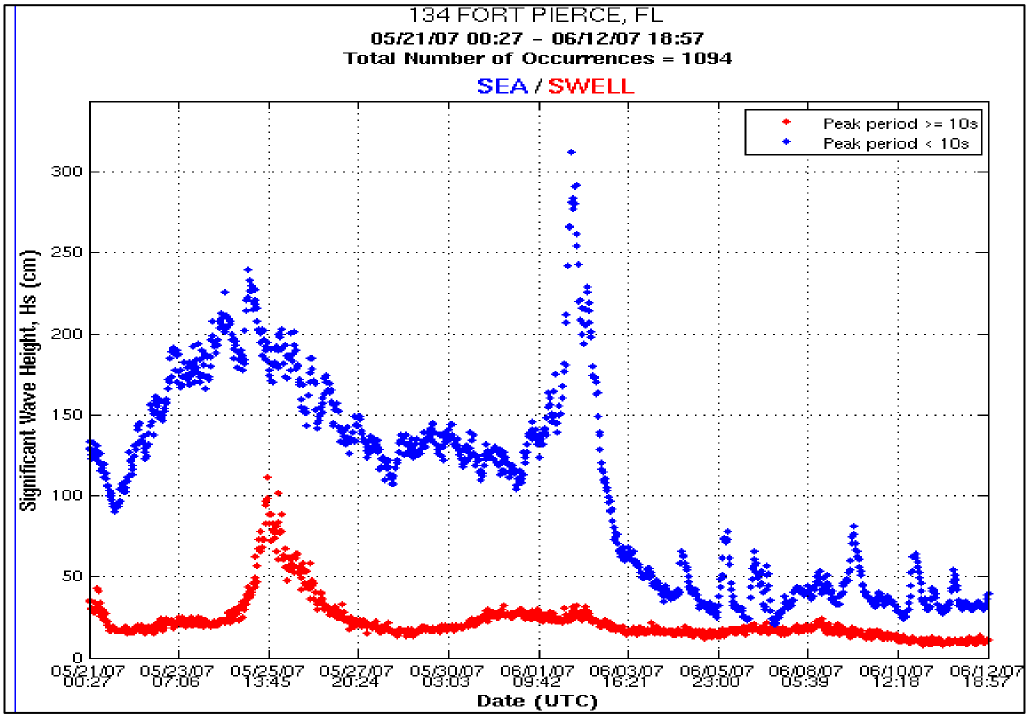

Figure 15: Wave Buoy Data, Ft. Pierce FL [17].

Swell and sea height data are extremely important for determining the amount of movement expected from each WEC. In conjunction with the National Data Buoy Center, Scripps Institute hosts the Wave Rider Buoy [Station ID: 41114, Location: 27.551°N, 80.225°W]. Through the use of Fast Fourier Transforms, spectral analysis of the raw data collected from the buoy is made into a useable form for predicting significant wave heights. By analyzing historical data, a legitimate estimation of wave heights during the proposed deployment window can be determined. Through the use of buoyancy calculations for the GECCO, angle of movement about the hinge can be calculated. For the Wing Wave, orbital velocities at various depths can be calculated, which can then be calculated into a force acting on the

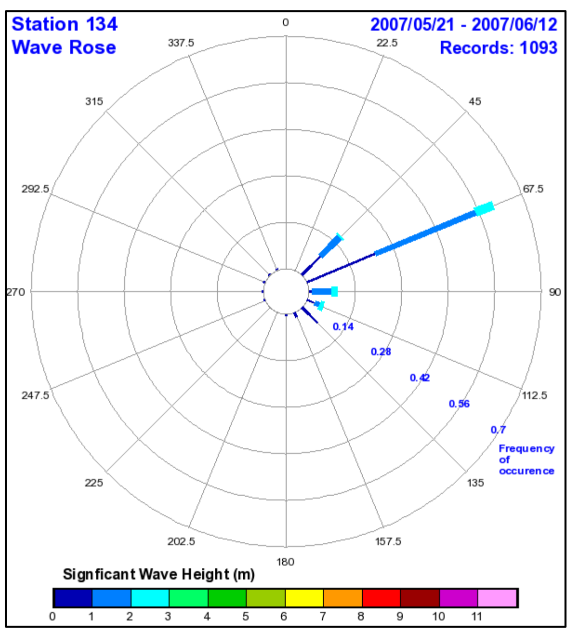

Figure 16: Wave Rose, Ft Pierce FL [17].

surface of the wave. The efficiency of both designs relies on the spatial orientation with respect to incoming ground swells. By knowing the direction of average swell, the GECCO and the Wing Wave can both be oriented for maximum energy conversion. This wave data is the beginning of the power output calculations, due mostly in part to the fact that these criteria cannot be changed.

2.1 Design Decisions

The most important criteria for design consideration were twofold; simplicity and efficiency. The research conducted to find a way to generate electricity brought two main types of systems; a mechanical system and a hydraulic system. With only one generator on hand and two types of different wave energy converters, the choice was made to run a closed hydraulic system in order to test both WECs on the same generator. The generator needed the capability to work with two different systems without compromising its original function which is to generate electricity. The two WECs are connected to the power take off unit via hydraulic lines.

2.2 Structural Designs

As stated, the Wing Wave design was a previous project. Various parts of previous projects were re-used, to include the hinges and one of the fiberglass wings. The base is made of Aluminum 6061 C beam 6’ long and 4 ½’ wide. The fiberglass wing consists of six separate fiberglass pieces attached together. A second wing was replicated from the existing wing. Some minor modifications were made to the structure of both wings, such as making the top of the wing wider than the bottom to form a triangular cross section and attaching both wings using a stainless steel plate. The triangular cross section allows the wing to catch most of the force from the wave orbitals. Attaching the wings together ensures they move in unison.

A critical portion in determining the forces acting on the Wing Wave energy system is the horizontal velocity of the waves. Using the dispersion relationship and historical wave data, we can calculate the velocities in the horizontal directions given a depth of 10 meters, a wave period of 7.92 seconds, a wavelength of 76.8 meters, and a wave height of 0.304 meters:

Equation 5: Horizontal Wave Velocities.

$$u = \frac{gHk}{2\sigma}\frac{\cosh\big(k(h+z)\big)}{\cosh(kh)} = \frac{(9.81)(0.304)\left(\frac{2\pi}{76.8}\right)}{2\left(\frac{2\pi}{7.92}\right)}\ \frac{\cosh\left[\left(\frac{2\pi}{76.8}\right)(1.524)\right]}{\cosh\left[\left(\frac{2\pi}{76.8}\right)(10)\right]} = .\mathbf{19}\,\frac{\boldsymbol{m}}{\boldsymbol{s}}$$

Because the horizontal component of the wave velocities changes as the water depth changes, the overall forces must be integrated over the water depth. At the same time, the surface area is going to change as the depth increases. We can combine the two variables (water depth and surface area) as a single integral. For density of seawater, an average salinity can be assumed, giving a density of 1,025 kg/m^3. The drag coefficient for a rectangular body can be given as a dimensionless 3.0. The breadth of the wing is 1.37m, and the height varies with water depth (-z-8.1712)m. This variation will account for changes in forces due to the change of surface area as the water depth (and consequently wave orbital velocities) change. The parameters for the horizontal velocity shown above are used for the horizontal velocities below:

Equation 6: Horizontal Velocities on Wing Wave.

$$\boldsymbol{F_D = \frac{1}{2}\rho C_D A\tilde{u}|u|}$$

$$F_D = \int_{-9.6952\,m}^{-8.1712\,m} \frac{1}{2}\left(1025\,\frac{kg}{m^3}\right)(3.0)(1.37\,m\,)(-z-8.1712)(2)\left[\frac{gHk}{2\sigma}\frac{\cosh(k(h+z))}{\cosh(kh)}\right]^2 dz$$

$$\boldsymbol{= 673{,}798\,lbs = 2997.2\,N}$$

The movement of the wing pumps a hydraulic ram, pushing fluid into a hydraulic accumulator thru commercial grade flexible lines. A total of five hinges are used on the wings. One of the hinges is a four-foot stainless steel hinge, placed at the middle of the base holding both wings. This helps reduce the stress on the beam connected to the wings. The other four hinges are smaller aluminum hinges, two of which are placed on the outer sides of each wing. The hinges are bolted onto the frame.

The GECCO system is a surface wave energy system based of the Pelamis project developed in 2004 by Pelamis Wave Power (PWP). The GECCO consist of two ten-foot long fiberglass cylindrical sections connected by aluminum joint, built by a previous design team. The same outer shell created by the previous GECCO team was used, with minor changes. The joint was built out of 6061 aluminum, it comprises of

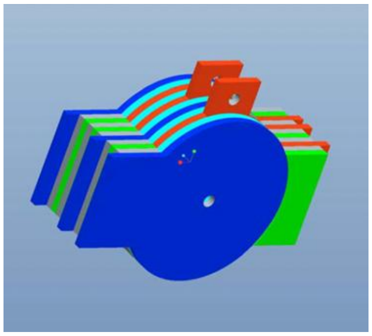

Figure 17: GECCO Hinge Design [14].

overlapping plates held together by a stainless steel shaft. Within the body of the GECCO is a pulley system connecting the joint to the hydraulic ram. The movement of the joint as a wave passes under it pumps a hydraulic ram, allowing it to push fluid into the accumulator thru hydraulic lines. The ram is connected to the joint by two steel cables which run thru a pulley system. In order for this system to work correctly, it must maintain positive buoyancy. A watertight seal around the end caps of the GECCO main body as well as adequate seals around the Salter's Ducks ensure the system maintains its positive flotation and operates as designed.

Equation 7: Forces on GECCO.

Forces on the GECCO:

$$Force\ Moment = w\ x\ d = 670.21lb * 6.75\ ft = 4523.9175\ lb - ft$$

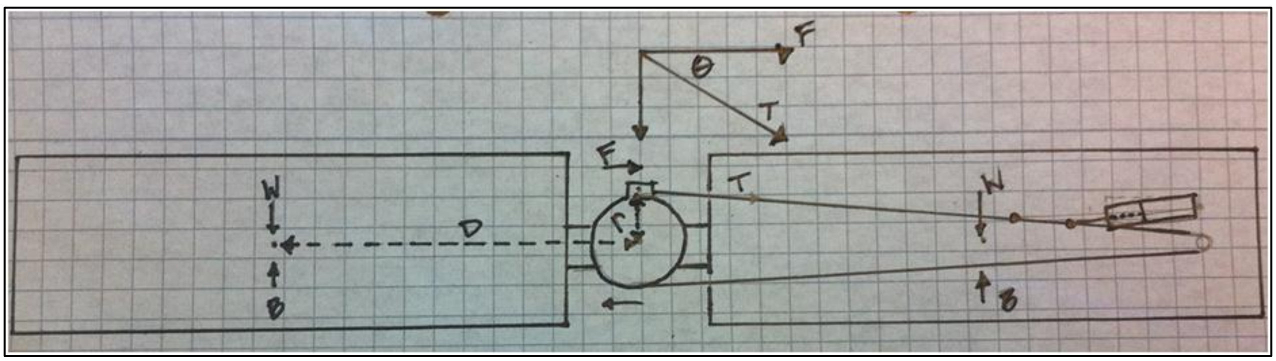

Figure 18: Forces on GECCO Hinge.

This force is the resisting force of the cylindrical body sections about the hinge's pin. These forces are what will drive the hydraulic ram. Using these forces, we can calculate a moment arm which acts upon the hinge. This is then seen to be the driving force acting upon the hinge:

Equation 8: Forces on GECCO Hydraulic Ram.

Forces on hydraulic ram:

$$Force = \frac{Force\ Moment}{Distance} = \frac{4523.9175\ lb - ft}{1.6667\ ft} = 3877\ lbs$$

The conversion of captured hydro-mechanical energy to electrical energy, or 'Power Take-off' (PTO) mechanisms, depends on the working principle of the energy device and typically could be mechanical, hydraulic or a direct driven system (Mueller and Baker, 2005). Following figure compares different PTO schemes generally applied for ocean energy devices. (In this project, hydraulic based PTO mechanism was used.)

The power take-off (PTO) is the greatest innovation of this project as a whole. Both the GECCO and The Wing Wave are connected and work synergistically to a power a universal PTO. The PTO provides an easy way to test the two prototypes together or separate, it also acts as a data center to collect all the data about the internal pressures and electricity generated from the waves, and it will houses and protects the sensitive electrical components from the harsh marine environment in which they operate. The components inside the PTO consist of two accumulators, one generator (Harris Hydroelectric Pelton wheel style, received through donation to the university), and a reservoir to collect the hydraulic fluid after it turns the turbine. The PTO is housed on a floating vessel, shaped like a simple box, constructed of ¼" plywood with a fiberglass coating. The finishing process was similar to a wood boat hull, in order to prevent water ingress into the vessel body. Angle 6061 aluminum was used along the edges of the housing to add structural strength. This allows two full grown adults to stand on or in the vessel while still maintain a minimal draft of about 4". A system of valves and fitting was also implemented into the system. Using these valves, flow could be diverted away from the generator in a separate closed loop to provide a means for testing the WECs individually.

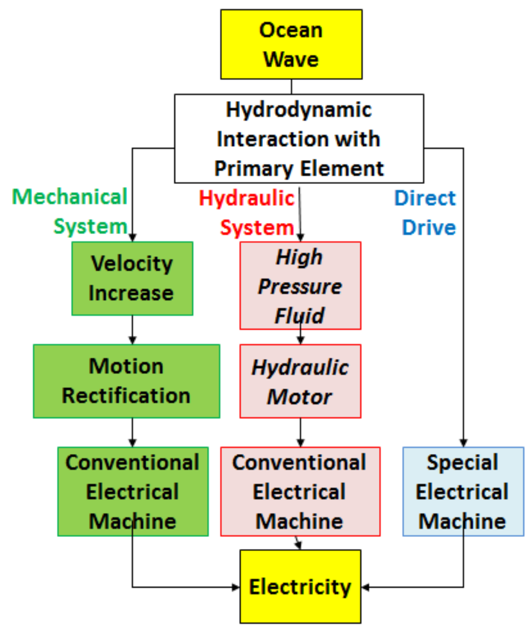

Figure 19: Basic Power Take Off Concepts

The diaphragm style accumulators are used for motion rectification. If the hydraulic rams would be connected directly to the generator, the pressure that they will be exerting might be so low that the small turbine will not spin. The motion of the waves will not force the wing to oscillate in a simple, harmonic motion. The wing wave might move fast for a period of time and then slow. The transition from fast to slow motion will also affect the flow of the fluid into the generator; the accumulator solves both problems. They allow the erratic motion of the waves to be stored as energy and released in a more controlled manner through the use of electronic solenoids. Once the internal pressure of the diaphragm tanks reaches a preset value, the solenoids are opened and the working fluid under pressure is released against the Pelton wheel and the generator is spun, creating an electrical output

The generator is also one of the most important components. Having four inlet tubes to allow the flow of fluid into its turbine, only two are currently in use for the prototype testing. One inlet will is connected to the accumulator of the Wing Wave and the other inlet is be connected

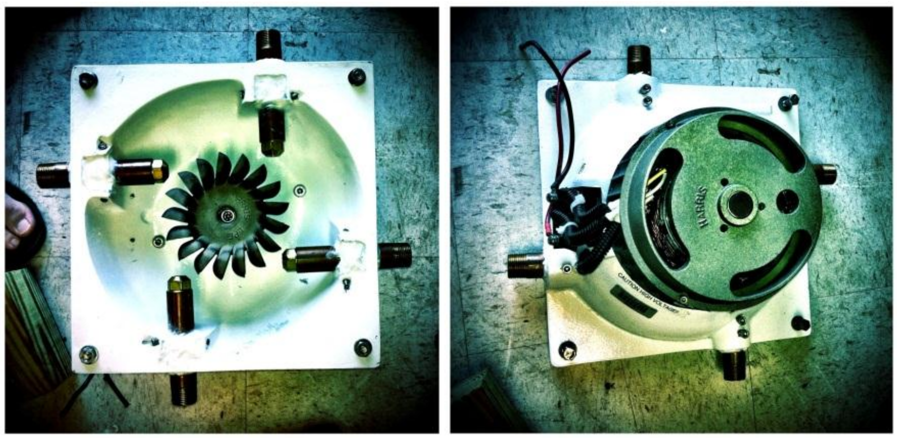

Figure 20: Harris Pelton Generator.

to the accumulator attached to the GECCO. If the accumulation of the pressure is high enough then the two additional ports can be used to ease the pressure of the flow into the turbine. The bottom of the generator is mounted to the top opening of a 125 gallon reservoir. This provides enough volume so that if both diaphragm tanks are full at the same time, there will still be enough fluid in the reservoir to account for free surface effects of the waves on the remaining fluid in the reservoir and no air will be introduced to the closed system through the low pressure return lines.

Along with the electrical generator, this system needed an electrical set-up that could easily provide user interface to control the system without a physical hardwire. Another helpful feature that is built in to this system is data acquisition. There are several key components that make up the electrical portion of this project.

The Programmable Logic Controller (PLC) is a microprocessor-controlled electronic device that interfaces objects in the physical world to a distributed control system, or supervisory control and data acquisition system (SCADA), by transmitting telemetry data to the system, and by using messages from the supervisory system to control connected objects. It is also termed Remote Terminal Unit (RTU) in automation industry.

A general packet radio service (GPRS) is a packet oriented mobile data service on the 2G and 3G cellular communication system for GSM (global system for mobile communications). The GPRS core network allows 2G, 3G and WCDMA mobile networks to transmit IP packets to external networks such as the Internet. The GPRS system is an integrated part of the GSM network switching subsystem.

A charge controller limits the rate at which electric current is added to or drawn from electric batteries thus preventing overcharging. It helps to prevent overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk. Charge controllers can also divert excess electricity to a "diversion load" that can consume the excess power.

3.0 Engineering and Construction of Wave Energy System

3.1 Wing Wave Construction

The current Wing Wave design is centered around two 4’ wide x 6’ tall fiberglass wings placed side by side on a stainless steel base. Previous design teams built one fiberglass wing in 2011, however the design of the wing is a flat plate. In order to get the most out of the wing movement the wing was modified by adding panels down the side and at the top, perpendicular to the wing body. The panels on the sides were tapered from top to bottom, and the panel on top of the wing was rectangular. The second wing was built using the same paneled design as the first. The first wing was attached to the frame using the existing stainless steel hinge that was previously constructed. For the second wing is integrated into the wing by wrapping the hinge during the laying of fiberglass. This helps reduce shear stresses on the wing as it oscillates about the frame. This also helps reduce the risk of corrosion on some parts of the hinge that may occur during testing.

With the use of a hydraulic ram, the pivoting motion of the wing can be converted into hydro mechanical energy. When mounted on the wing and frame, the pivoting motion will cause the ram to expand and contract. The movement of the wing pumps the hydraulic ram, pushing fluid into the accumulator via hydraulic lines.

To begin constructing the wing, it was agreed to construct two halves and join them together. Each half was formed using the same mold. The mold was constructed of laminated particle board and mold release wax was applied to assist in separation once the fiberglass cured. Each half had minimum two layers of fiberglass and when placed back to back shaped the final geometry. After curing layers were added to wrap the outside edge. This would ensure that the top and sides would not break under stress. While the outside layers were curing the hinge was being fiberglassed into the main structure to disperse any stress through the wing. The final step in construction was to add structural foam members into the corners and up the center evenly spaced.

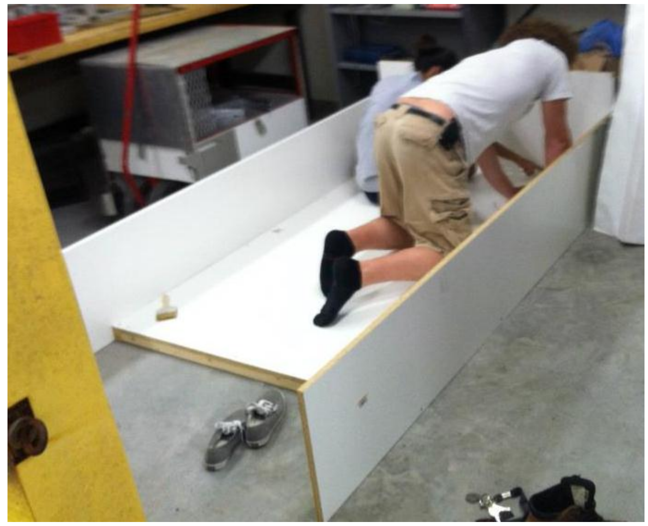

Figure 21: Making Mold for Wing Wave.

3.1.1 Wing Modification

A previously constructed wing was donated for this project, which measured 4’ x 6’ with a depth of 8” at the bottom and 6” at the top. This was the starting point in designing the second wing. To save time, money, and material, fiberglass was only added to this wing with metal structure at the top to help it keep shape when curing and to provide extra structural support. This wing also received tapered panels on the sides and a third, rectangle panel on the top.

Figure 22: Modification to Existing Wing.

3.1.2 Hinge

The existing wing already had a stainless steel hinge that had proven its worth during previous testing in 2011 so no modifications were made in that hinge. To construct the second hinge it was necessary to ensure it was the same height off of the base plate as the original stainless hinge so that no shearing would occur between the wings. The new hinge was a stainless steel tube cut into three 12” and two 6” sections so that they divided up a stainless steel rod into five sections with the shorter two sections on the end. The two 6” pieces as well as the middle 12” piece were fiberglassed into the main structure of the wing. The foam beams are on top of the center hinge to incorporate the hinge into the stronger reinforced section of the wing. The stainless steel rod acted as the pin of the hinge and the remaining two sections of tube were bolted to aluminum rectangular tube, the hinge base plate, with aluminum brackets. The rectangular tubing was previously bolted to the frame the aluminum brackets were “T” shaped aluminum beam cut into sections with a hole cut for the tubing, at the same centerline as the existing hinge to ensure they were the same height. Four aluminum brackets were used to hold each section of tubing; this dispersed the stress over many brackets and many bolts; 2 sections, 4 brackets per section, 2 bolts per bracket.

3.1.3 Piston

The hydraulic ram previously donated by Tractor Supply Company in Melbourne, FL. This ram has a stroke length of 24”. This number was used to initially determine the placement on the wings and the frame. In order to gain maximum output, the wing should pump the entire piston length while not bottoming out and causing additional stress on the structure. From previous experimentation it was observed that a four foot by six foot wing moved ±35° with no resistance. With the modified geometry and the hydraulic ram dampening the motion it was decided that the range of motion should be considered as ±40° movement. To calculate how high up the wing the ram should be it was necessary to calculate the distance the wing would move at a certain height

Figure 23: Close Up of Hinge Mount.

Equation 9: Placement of Ram.

$$\left(\frac{Degree\ movement}{360}\right) 2\pi R = Stroke\ Length$$

Solving for Radius

$$R = \frac{360 * Stroke\ length}{2\pi * Degree\ Movement} = \frac{360 * 24}{2\pi * 80} = 17.1887 = 17\frac{3}{16}"$$

This means the ram should be 17 $^{3}/_{16}$” above the hinge and should allow for 40° of motion in each direction without exceeding stroke travel length of the piston. To attach the ram to the wing it was necessary to take precautions so that the ram did not create concentrated stress points; this meant using an aluminum sheet between the two wings as well as a sheet on either side and bolting them together. Ten bolts were used to bolt it together; this decreased the stress tenfold on each bolt. This would also disperse the stress throughout the height of the wing instead on a single point. The aluminum sheet was only 1/8” thick, so it was also necessary to stack more where the ram come into contact with the sheet to ensured that the forces of motion would not tear the sheet joining the two wings. After the position for the ram was set on the wing the ram was set to half stroke while the wings were vertical to place the bottom of the ram. With some fine tuning, and trial and error, the ram was placed on the adjacent cross member; a section of the frame had a hinge that held the base of the ram was cut out and bolted with $^{5}/_{8}$ inch threaded rod.

When tested it allowed for approximately 45° of motion in each direction and when bottomed out the cross member swayed but held under additional weight.

3.2 GECCO Construction Methods:

The First team that has introduced a wave energy converter to work as an attenuator was from 2009 to 2010 called the Blue/Green group. This group has identified two major WEC mechanisms that if combined, they would harvest a large amount of the wave energy that is available in the ocean. The inspiration of their design was the Pelamis Wave Energy and Salters Duck . This new system consists of two cylindrical sections with four Salter's ducks which will be working in unison with a pulley and hydraulic system and a pump respectively that will push the hydraulic fluid into an expansion tank creating pressure. The pressure then will be released into an electric generator to generate electricity. Even though this mechanism was working, there were many aspects which were not so promising for a long term deployment.

The joint was being subjected to high amounts of stress due to the restricted motion it provided the two cylindrical sections it was holding together. The cables that drove the hydraulic rams were subject to failure if the load they were under was suddenly large. The entire systems buoyancy depended on the Salter's ducks which can result in a complete failure if one duck is not water proof or damaged during handling or while it was deployed. If there would be a hydraulic fluid leak then the system will lose the ability to generate power. The loss in its efficiency will depend on the amount of fluid lost. The joint was highly congested with many elements and a pair of Salters Ducks which made it very complex to maintain if some element in it was malfunctioning.

The Green Energy Coastal Collection Operation group in 2011 to 2012 designed a complete new system that has the same concept as the Blue/Green Energy System but bigger. A pair of the Salter's Ducks was relocated away from the joint to reduce the amount of stress and congestion in that area. Now the two pairs of Salter's Ducks are located on the main section of

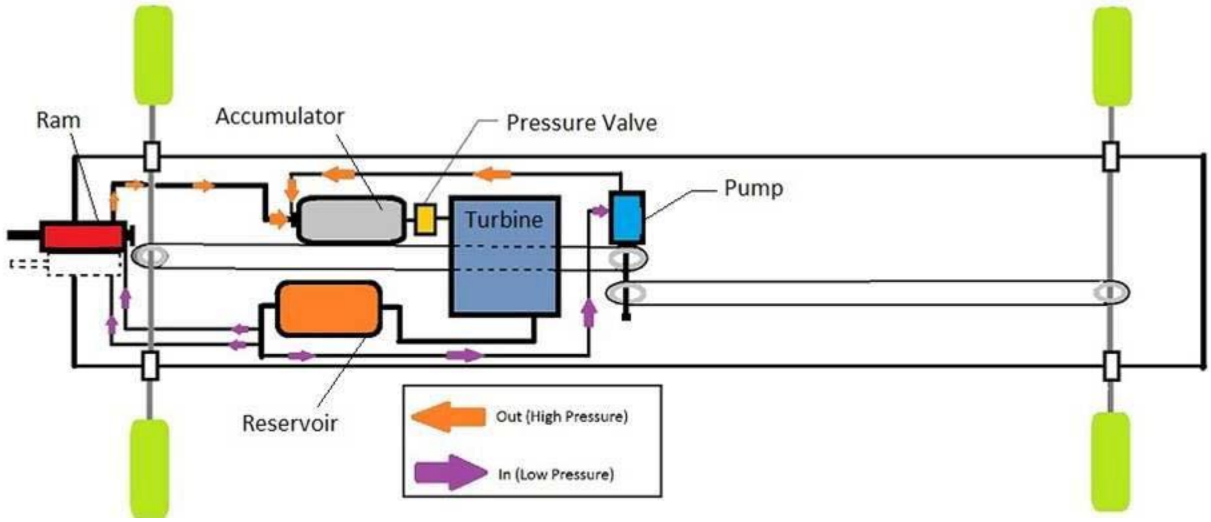

Figure 24: Original Hydraulic System Design [14].

the prototype. Inside the main cylindrical section, aluminum ribbing was designed to increase the strength of the section once all of the hydraulic equipment is installed. The G.E.C.C.O had a hydraulic design that worked with salters ducks but there were some aspects that were not taken in consideration when the tab on the joint was manufactured.

The tab that was designed to drive the hydraulic ram was attached at the wrong side of the joint. The joint consists of different plates that slip between each other and are secured with a pin to prevent it from separating. Depending on the section the aluminum plates will move accordingly. The problem that the GECCO team did not catch is that the tab is moving with the main section thus preventing the displacement of the hydraulic ram. This problem did not affect this group due to the lack of time they had to manufacture the prototype. The main focus for this group was to make a strong structure that will move in unison with the ducks without falling apart. There were no noticeable failures in the prototype built. The only aspect that might cause a failure was the intrusion of water that was caused by the orifices drilled on the section to allow the shafts that were holding the Salters Ducks. To prevent a lot of water to be stored inside the section a bilge pump was installed as well as additional hole to let the water back out into the ocean to prevent the GECCO to sink.

Figure 25: GECCO Deployment [14].

Early design considerations for the internal pump system of GECCO consisted of a spring mechanical spring system, a hydraulic gear system, and a hydraulic pulley system. With the time and funding limitations a hydraulic pulley system was most feasible. This internal pulley system is comprised of six smaller pulleys with a seventh larger pulley. These pulleys were mounted on the inside of the aluminum ribbing located inside one of GECCO's ten foot sections. The pulleys were placed strategically to allow a 3/16'' steel cable to attach to a hydraulic cylinder with a twelve foot stroke length while avoiding slack in the cable. The steel cable would connect to top and bottom of the opposing ten foot section of GECCO thus providing the rocking motion for the cable to pump the hydraulic cylinder forcing pressurized

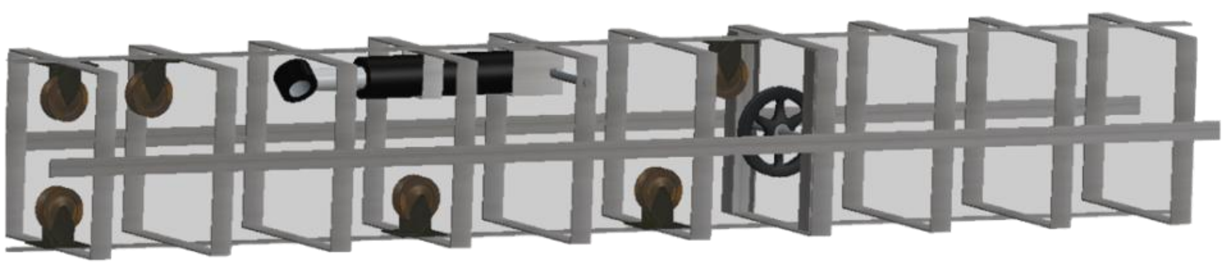

Figure 26: GECCO Internal Components.

fresh water to the accumulator on the PTO raft. Stainless steel hardware in addition to rubber washers were used in the mounting of the pulleys. Each pulleys ball bearing was serviced with marine grade grease to ensure smooth rotation during testing. The rubber washers served as separation from aluminum and stainless steel material within the assembly.

Figure 27: Construction of GECCO Internal Components

The hydraulic cylinder was fixed to the internal aluminum ribbing with a cradle assembly made from spare aluminum. In addition to the aluminum fixture a steel rod was passed horizontally through the ribbing to the fix the motionless end of the cylinder. This same method, the use of a steel rod, was used to fix the seventh larger pulley in the center of the ribbing which acted as the axel for the ball bearing inside the pulley.

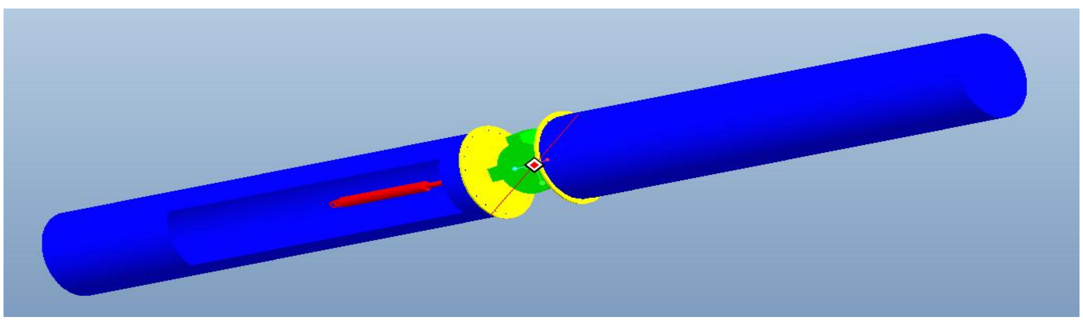

Figure 28: GECCO rendering with hydraulic ram.

The hydraulic system is comprised of brass barbed fittings for standard hydraulic line with four one-way valves in-line with the hydraulic cylinder. The hydraulic lines were run towards the hinge of GECCO and connected to pressure fittings on the top of GECCO. This design allowed for easy access to the hydraulic lines and a safe way to run the lines from GECCO to the PTO raft. In addition to the hydraulic pulley system was an integrated bilge pump system assisted by a

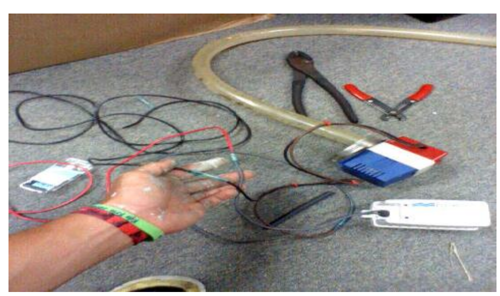

Figure 29: GECCO Bilge Pump.

14 V marine battery. The bilge pump was tested successfully and was re-wired to reach the battery which was located in the rear of the pulley system.

3.3 Power Take Off Construction:

Pressuized fluid from the Wing Wave and GECCO is fed into respective diaphragm tanks which act as hydraulic accumulators. The size for the accumulators was chosen based off of the estimated flow rates for the individual WECs due to the size of the hydraulic rams in each system. The diaphragm tanks are 36 gallons, with a 125 gallon reservoir. The tanks are originally designed for commercial water systems but their mechanics suited this project as a motion rectification device.

Once the pressures inside the diaphragm tank reached a preselected limit, an electronically controlled automated solenoid released the pressure from the tank, turning the Pelton wheel of the hydrokinetic generator. The details of the electrical system are now explained.

Figure 30: Power Take Off Diaphragm Tank [21].

The PTO Control and Data Acquisition Unit is installed with PTO to regulate the electrical output of the Power take-off device and to log all the system parameters (electrical and process) in real-time for analysis. The standalone PTO Control unit, housed in a weather-proof (IP67) panel to protect against the harsh marine environment, resides on a Power Take-off (PTO) raft anchored near wave energy converters during testing. Following figure shows overall block diagram of the unit:

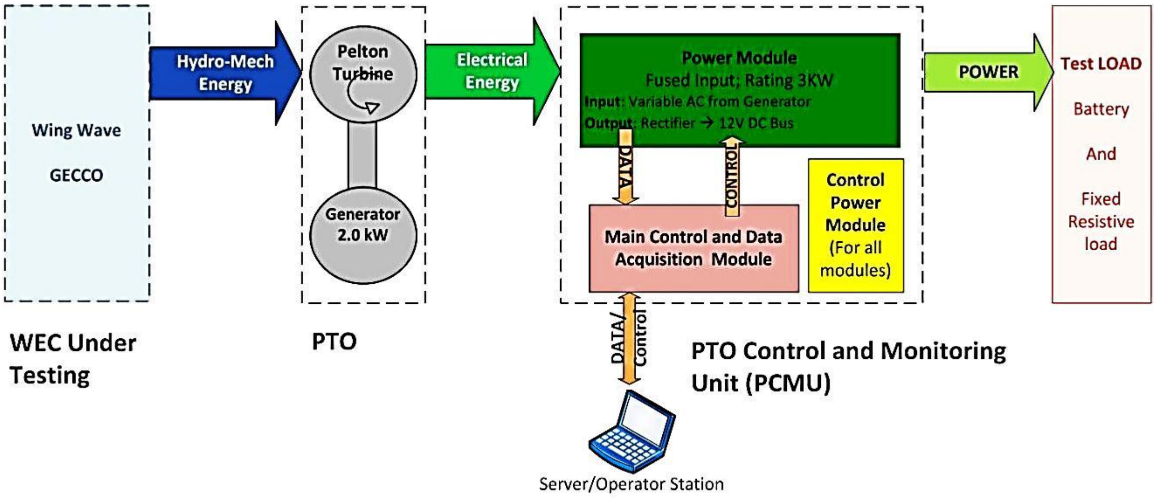

Figure 31: PTO System Block Diagram.

The 'PTO Control and Data Acquisition Unit' has two main parts:

1. *Control System* for controlling, monitoring and sending data to remote system.
2. *Power System* for regulating the electrical output of PTO as per load requirements.

In the following sections, these will be described in detail.

3.3.1 Control System

Control system is based on Industrial controller ioLogik W5340i by Moxa® with GPRS (Cellular network) support. All the data from instruments is logged in the system memory card as well as sent via cellular network/internet to the main server computer (land based). The data on the main server computer is accessible via internet to be viewed in real time by user end.

The unit records internal hydraulic pressure for Wing wave and GECCO, generator output voltage/current and panel's internal battery voltage. It also controls solenoid valves installed at the inlet of the generator from Wing Wave and GECCO.

A 16 GB memory card was used with the system. AT&T's cellular network of was used for GPRS communication. Following figure shows the network topology between PTO control system components.

3.3.2 Cellular Micro RTU Controller

Core of the control system is ioLogik W5340 by Moxa®. The ioLogik W5340 is designed for cellular remote monitoring and alarm systems, such as automated river monitoring and pipeline monitoring etc. The ioLogik W5000 series uses GPRS technology to maximize the coverage of remote monitoring applications.

This cellular Micro RTU Controller is highly integrated, stand-alone solution that combines cellular communications, front-end intelligence, a front-end data logging and serial tunnel function for data acquisition, information analysis, and prediction.

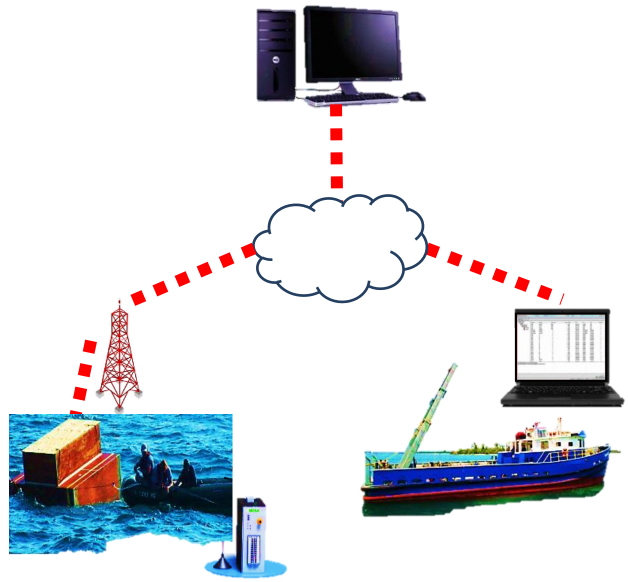

Figure 32: Control System Topology.

Figure 33: MOXA® ioLogik GPRS Controller W5340i [22].

Main features are as follow:

- GPRS, Ethernet LAN, RS-232/422/485 supported
- 4 Analog Inputs, 8 Digital Inputs/Outputs, and 2 relay outputs
- Smart Active GPRS connection
- Low power consumption
- Active messaging with real-time stamp
- Data logging with SD card

- Unicode Active Messaging with real-time stamp, including SMS, SNMP Trap with I/O status, TCP, email
- ioAdmin and Active OPC Server supported
- Windows/WinCE VB/VC.NET and Linux C APIs

For configuration, programming and settings of the Moxa W5340 controller, ioAdmin™ software was used.

Figure 34: Screenshots for ioAdmin software

For additional analog inputs, ioLogik E1240 (Ethernet Remote I/O with 2-port Ethernet switch and 8 AIs) was used. This unit also provides built-in 2-port Ethernet switch for daisy-chain topologies.

Figure 35: MOXA® ioLogik Ethernet IO device E1240 [23].

Moxa's RTU Controllers log I/O and serial device data to a single, expandable SD card slot that supports up to 32 GB of storage space and provide multiple methods to remotely retrieve data logs, whether through FTP, e-mail or *OPC* based softwares.

OPC (OLE for Process Control) is an open software interface standard that allows Microsoft Windows programs to communicate with industrial hardware devices. OPC is implemented in server/client pairs. The OPC server is a software program that converts the hardware communication protocol used by a PLC (Programmable Industrial Controller) or RTU into the OPC protocol. The OPC client software is any program that needs to connect to the hardware, such as an HMI. The OPC client uses the OPC server to get data from or send commands to the hardware. Following figure shows this link:

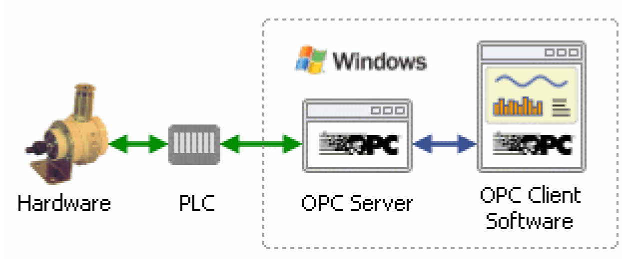

Figure 36: Link between OPC software and automation hardware [24].

For Moxa's Controller, 'Active OPC Server ™ software was used as OPC Server software and 'DA-Center™' was used as OPC Client software. Following figure shows the software hierarchy.

Figure 37: Hierarchy Diagram for MOXA® Automation Softwares ioAdmin and ActiveOPC [23].

Active OPC Server ™ receives and registers the ioLogik W5340's IP address and receive tag updates. Application programs can poll the data via Active OPC Server without expending any effort on managing IP addresses. The Moxa's DA-Center™ provides a standard OPC interface that interacts with Active OPC Server™, so that when users want to retrieve logs associated with the RTU, DA-Center™ will automatically compare historical data stored on the SD cards in the individual device with locally stored datasets and then retrieve the missing data by requesting re-transmission from the RTU.

Both of these softwares were installed in the Main Server Computer (land based) which was receiving data from the Moxa Controller and then updating it on internet for user viewing.

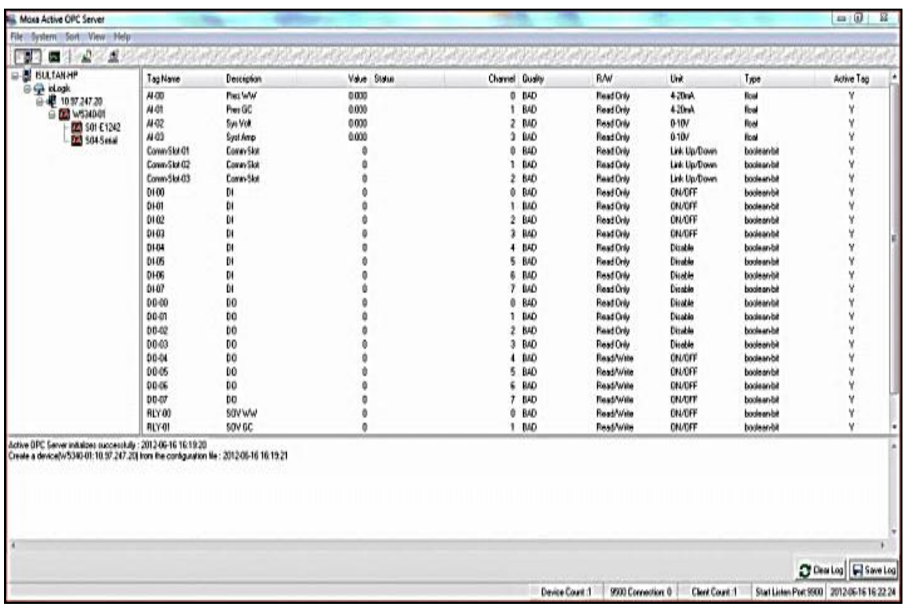

Figure 38: ActiveOPC Server software

3.3.3 Instrumentation

For Pressure measurement, WIKA® industrial grade general-purpose Pressure Transmitters were used in the system. Specs are as follow:

- Model 50398083 General Purpose Pressure Transmitter,
- 4-20mA 2-Wire Signal Output,
- Stainless Steel 316L Wetted Parts,

- 0-200 psi Range, +/-0.5% Accuracy
- By WIKA

For inlet controlling at generator, 12VDC Solenoid Valves were used. Specs are as follow:

- 12V DC
- Normally Closed 2-way
- Stainless Steel Viton
- Semi-Direct Lift, 16mm Orifice
- 3/8" 16mm NPT Threaded Connection
- Working Pressure: 0-147 psi
- Working Temperature: -50-266 F
- Water, Gas, Air, Oils, Freon
- By: Biodiesel Supply Store & Chemicals

Figure 39: WIKA Pressure Transmitter Model 50398083; Solenoid Valves [25].

For measurement of generator output voltage, Battery Voltage and load current, a simple voltage divider based Signal Conditioning Card was used as input for the controller.

3.3.4 Power System

Power system of the PTO is based on Harris hydrokinetic Pelton wheel style impulse turbine with 2kW rated PM brushless alternator. Hydro-Mechanical energy from WECs is converted to electrical energy by Pelton turbine and coupled alternator. The alternator electrical output is then regulated by a charge controller (at 12Vdc) and is then directed to charge battery, which is primary load and then to secondary diversion load (in case battery is fully charged). Following figure shows the working of power system.

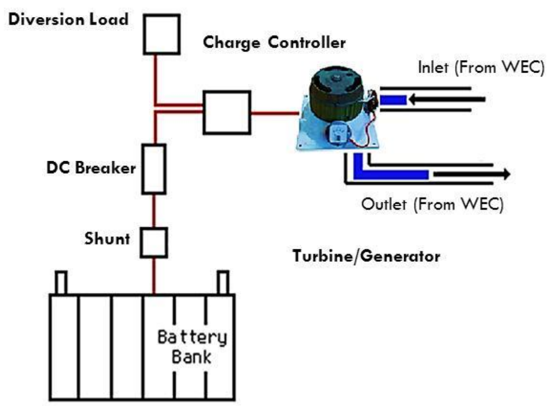

Figure 40: Schematic diagram for Power system

Generator

Specs for Pelton Turbine based Harris Hydroelectric generator are as following:

- Permanent magnet (PM) brushless alternator
- Output: power 725W (with 12V) to 2500W (48V)
- Output: DC Voltage, uses six pulse diode rectifier
- Efficiency: from 25% to 50%,

Harris generator was selected for its ease of use and ability to generate power in the low flow environment.

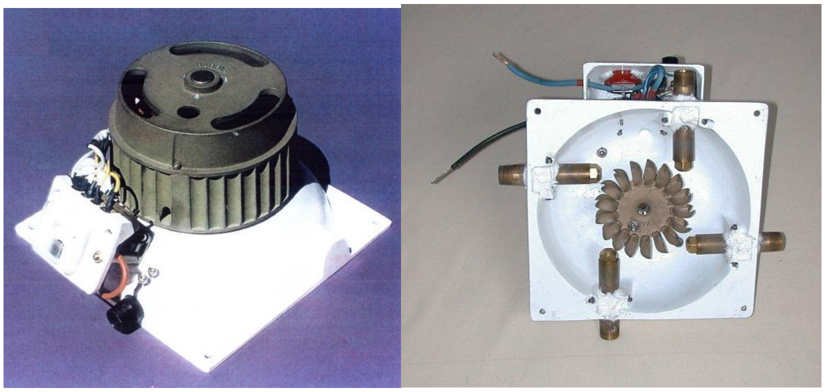

Figure 41: Harris Hydroelectric generator [26].

Charge Controller

NC25A (High Efficiency 25 Ampere Solar and Wind System Charging System Controller) by FlexCharge is used as the charge controller in the power system design.

It is series regulator designed for alternative energy charging systems ranging in size from 0.1A to 25A. The NC25A also includes the "charge divert" feature which allows using the excess charging source energy for other tasks, or for placing a load on permanent magnet charging sources such as wind generators to prevent over speed conditions. The divert connection is only activated after the charging source is making energy and the batteries are not using the energy. This controller can easily and inexpensively be expanded to handle one or more banks of 100A charging sources.

Figure 42: NC25A Charge Controller by FlexCharge® [27].

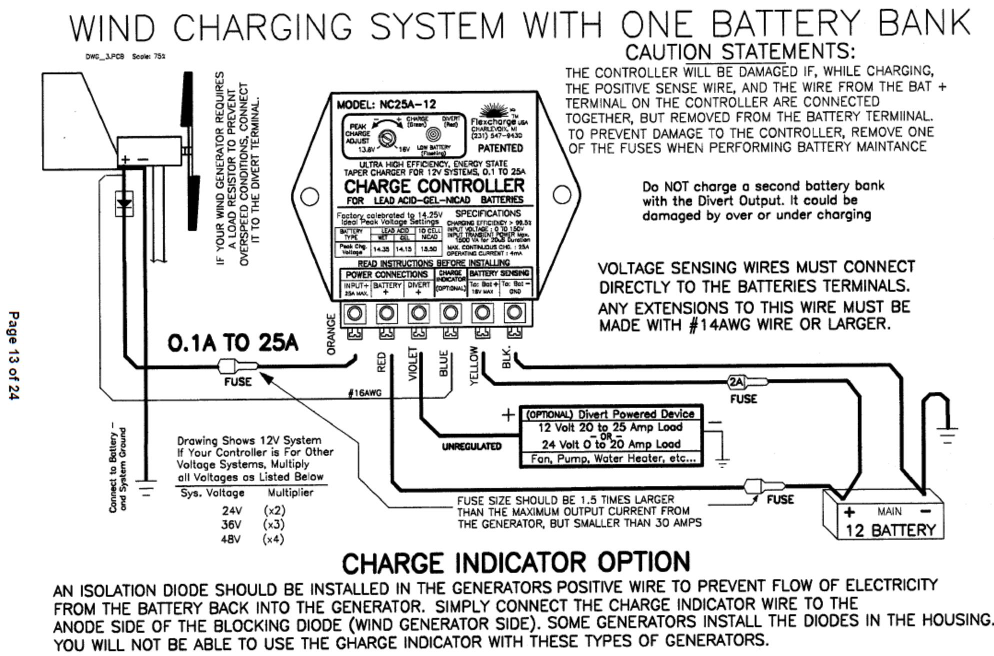

Figure 43: Configuration used for NC25A Charge Controller[27].

4.0 Lab Testing

Every prototype need to go through many types of tastings that allow the engineer to improve or change different parts of their prototype Because the Wing Wave and GECCO were preexisting projects which had already been tested in the ocean, lab testing was mostly centered around the PTO. However, the Wing Wave and GECCO received structural testing by manual methods on land, and were found to function as intended with the addition of the hydraulic systems and mechanical modifications.

The main land test for the Wing Wave was to find a range of motion due to the geometry of the hydraulic ram placement. Initially, the range of motion was approximately ±30°, but it was decided the ram should be moved in order to provide a range of motion of ±30°, based on historical wave data and previous prototype testing.

The testing for the GECCO was slightly more in depth, due to the fact that the internal workings were slightly more involved. Time limitations ultimately controlled testing methods. After all of the components were installed and set up in the main section of the GECCO, the hydraulic ram was displaced manually. The ram was not filled up with any type of working fluid, since the hydraulic lines were still being designed. The main purpose of displacing the ram manually was to determine if all of the cable clamps were holding correctly and if the hydraulic ram was moving without any problem.

Once the hydraulic lines were completed and ready to be installed, a secondary hydraulic ram was used to check if the flow of the working fluid was correct once the lines were connected to it. The secondary hydraulic ram had the same characteristics as the one inside the GECCO

Testing for the PTO was much more in depth, due to the sophisticated electronics and instrumentation that went into the system. The Harris Pelton turbine was designed for residential use with low flows. For this reason, no data sheet existed for this specific application. One had to be made through lab testing. Due to missing data for the generator (Nameplate Data, Datasheets, Max current / speed limitations), lab testing was conducted to establish relationship between rpm (revolutions per minute), inlet pressure and electrical output as following.

4.1 Mechanical Testing:

Generator was coupled with a mechanical rotational source (max speed 1500 rpm) using tachometer and voltmeter to determine rpm and Voltage relationship.

Figure 44: Setup for mechanical testing of Generator

Following are the results recorded:

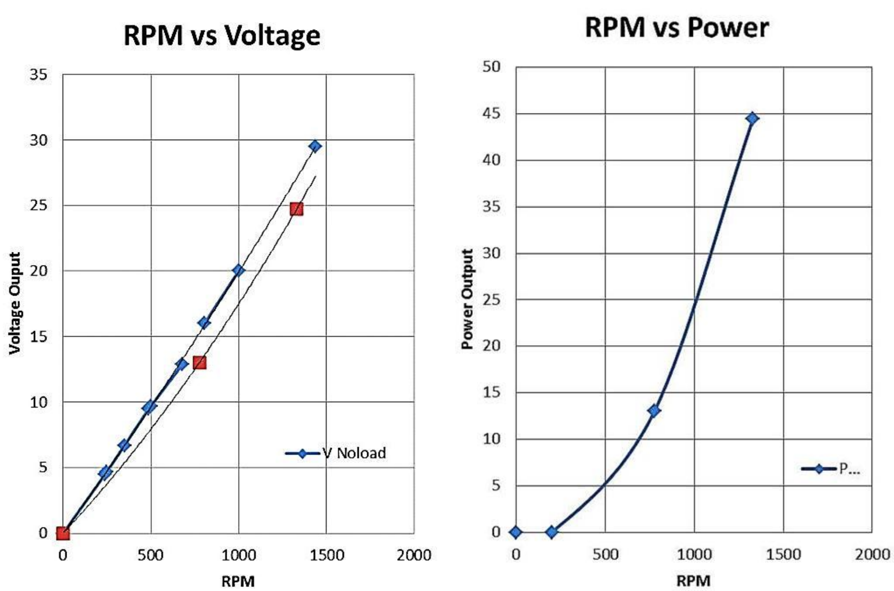

Figure 45: Results for the mechanical testing of Generator

4.2 Process Testing:

For process related parameters, generator setup was done in wave tank and a centrifugal pump 1.5 HP (Specs: Dayton LR22132 capacitor start motor 1.5 HP; 3450 rpm; 115/230 FLA 15.6/738A; 60 Hz) was used as input source. Following lineup was used during testing:

Pump → 1.5" Pipe → 0.5" pipe –- T –- PT –- Manual Inlet Valve –- Generator

|

Regulation Valve

Figure 46: Setup for Process testing of Generator (in Wave Tank)

Following are the results recorded. As can be seen here, around 13 PSI inlet pressure, generator started to operate with output approximately 22V (no load).

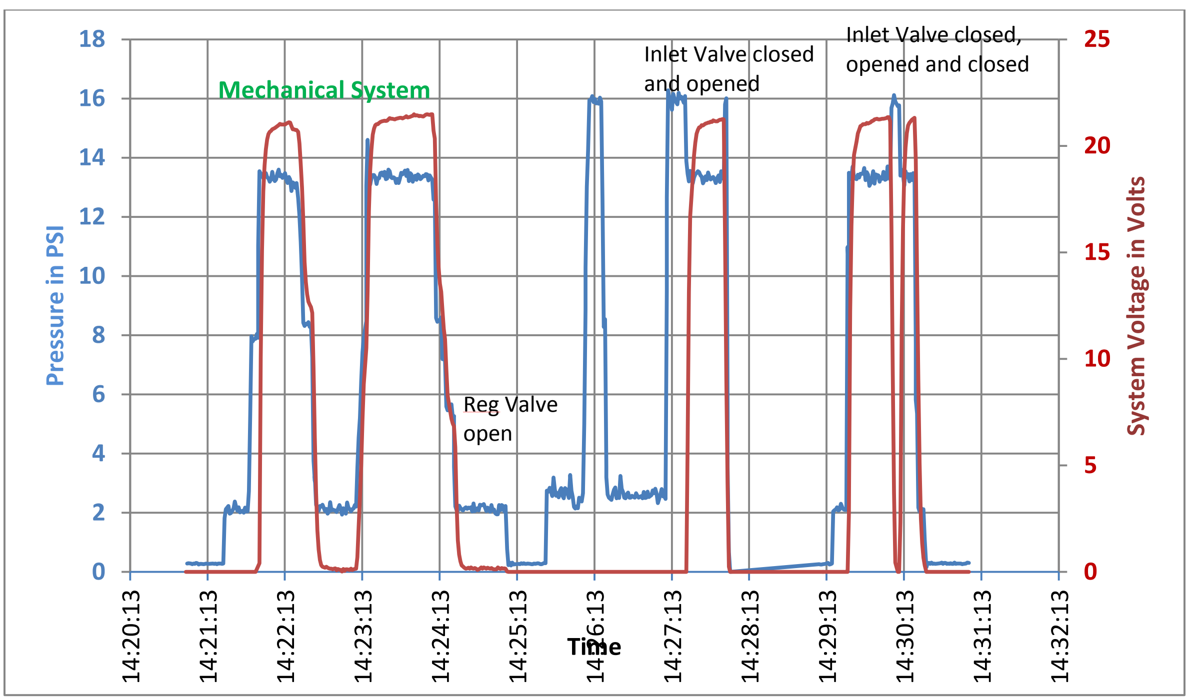

Figure 47: Results for the process testing of Generator Hydraulic System

This lab testing proved to be crucial in the analysis of data gathered during the commissioning of this energy system. The important lesson learned from the lab testing was that test results provided a method for correlation of power outputs based on parameters other than electrical output. For example, by analyzing pressure readings, a power output could be calculated without collecting data from the generator output specifically.

5.0 Deployment

The entire wave energy system, to include Wing Wave, GECCO, and universal PTO were deployed off the central east coast of Florida, approximately 1.5 miles east of Ft Pierce Inlet from June 8-10, 2012. The main research vessel for this deployment was the M/V Thunderforce, owned by American Vibracore Services. Each section of the wave energy system had significant results and many lessons were learned by the design team over the course of the deployment.

5.1 Wing Wave Results

After initial deployment and securing of the frame to the ocean floor, the wing started moving with full force. With calm sea conditions, 1-2 foot with a 9 second period, the wing was observed to move +/- 42 degrees on a 8-10 second period with ease. The hydraulic lines were set to loop within a separate closed system until it could be hooked into the Power Take-off. Initially it worked without difficulty, although upon returning the next day one of the lines had blown off the ram and another was under vacuum. After replacing a faulty one way check valve, inevitably allowing sea water into the ram along with any floating particles, the system seemed to work again. It was connected to the PTO raft and was successful in pumping water through the check valve. After the sea conditions had increased to 3-4 foot waves cracks begun to show on the cross member that the hydraulic ram was mounted to; after recovery these cracks became more apparent.

5.1.1 Wing Wave Structural Analysis

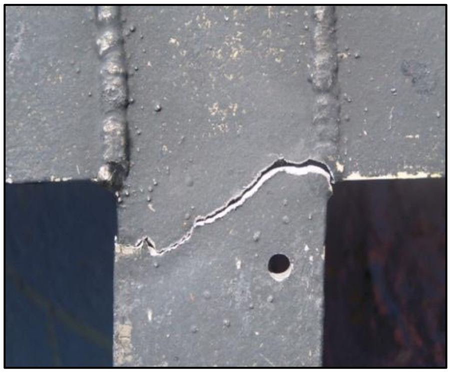

Figure 48: Stresses on the Wing Wave Frame.

The only structure to begin to show signs of failure on the Wave Wing was the cross member that the base of the hydraulic ram was mounted to. This was a ten foot section of aluminum “C” channel with the ram mounted in the center and the only points of failure were stress cracks at the ends and near the mounting point. The aluminum has a tensile strength of 30,000 psi (asm.matweb.com), if the physics are broken down, the force to cause such a failure can be estimated.To exceed the tensile strength the moments need to balance each other.

Equation 10: Force of Hydraulic Ram.

$$(2")(30{,}000\ \text{psi}) = (60")(Ram\ Force)$$

$$Ram\ Force = \frac{60{,}000}{60} = 1000\ psi$$

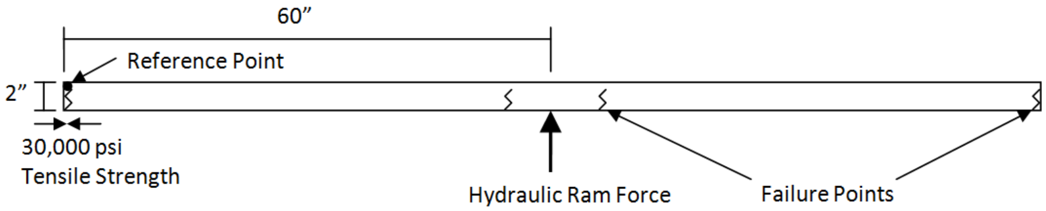

Figure 49: Shear Stress FBD.

For the beam to have failed, the hydraulic ram must have exerted forces exceeding this value. A ram with longer stroke length would have alleviated this problem. However, the ram on hand was donated and was used due to monetary constraints.

There were two other areas of high stress, the connecting plate between the two wings and the aluminum brackets holding the stainless steel tube. The center plate was the center of the stress, it held the wings and the ram withstanding the stress and dispersing the stress throughout the fiberglass to prevent failure. Twelve bolts dispersed stress throughout the fiberglass, this allowed for approximately 6,000 lbs, 500 lbs per bolt. The ram was connected to five sheets of aluminum, one of which was the center plate between the wings. These were bolted together with eight bolts but the stress was distributed throughout the one inch aluminum pin.

5.2 GECCO Results

When the assembly process was completed, the preparation for the deployment was based on possible foreseen implications. Monetary constraints were a main issue of consideration. Many of the parts inside the main section of the GECCO were donated and are relatively unique due to their previous use and age. The only spare parts that could be purchased were cotter pins, bolts, nuts, and washers. Additionally to the spare parts purchased for this prototype, there were additional hoses and connections purchased for the Power Takeoff Unit (PTO) which could be adapted to the GECCO.

Figure 50: GECCO Deployment.

The deployment method that was chosen for the cruise was to hook up the G.E.C.C.O by hooks that were fixed at the external side of each section of the prototype with a lift strap onto the A frame of the ship. To prevent the prototype from bending a special stopper was manufactured from wood, steel, and fiberglass to fit around the joint between the sections. Once the prototype was on the water a small boat would be there holding one line to it like that it would not float away while the divers prepare the mooring lines.

Figure 51: Towing GECCO.

The GECCO had an unseen implication that ended the possibility to gather numerical information of the energy being extracted from the ocean. After the prototype was deployed, divers prepared the mooring lines. While the divers were in the water, the current was pushing the GECCO towards shore with a small boat that was trying to prevent it from drifting away. An additional rescue boat that was attached to the main research vessel was sent to bring the prototype and the small boat back in. The shaft that holds the ducks together has a delicate ring which holds it on the section. The ring was fastened and sealed with marine sealant 5200 on the main section to prevent it from letting large amounts of water to intrude. Due to the additional load that was applied to these rings while being towed, a great quantity of water poured into the main section thus increasing the weight that the ducks were holding up with the shaft. After a couple of hours nobody noticed that the draft of the prototype is very high (Figure 2 and 3). The intrusion of water in the section was so much that the shaft sheared a couple of

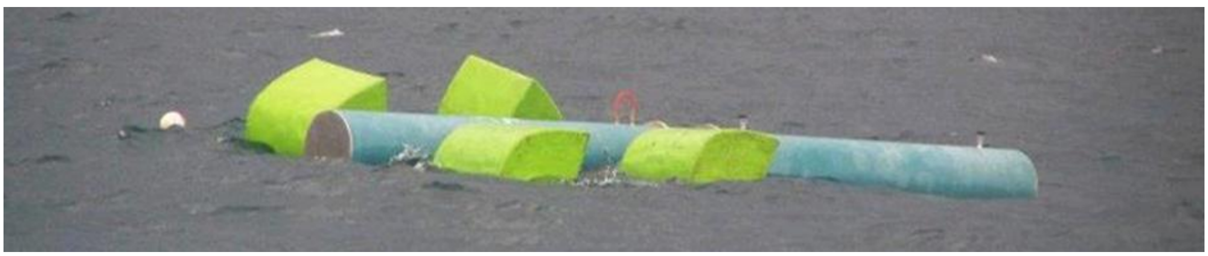

Figure 52: GECCO with increased draft.

millimeters towards the ducks from the section. The bilge pump was not sufficient to pump water out of the GECCO once the first pair of ducks broke, and the second pair were not strong enough sheering them after a while. A couple of hours the prototype was almost submerged completely underwater, but never touched the bottom of the sea.

5.3 Power Take Off Deployment Results

The PTO control and data acquisition unit was deployed with the main project in ocean from 9th to 11th June 2012. Unit was successfully able to measure instruments, log data and establish remote connectivity. However there were some malfunctions in the power system (failure of solenoid valves/check valves).

Due to failure of GECCO, there was no data recorded from GECCO. Hydraulic Pressure data from Wing Wave was recorded and monitored successfully through the PTO control Unit. A summary of collected two sample datasets and their time-series plots are shown as following:

Table 1: PTO Deployment Results.

	Dataset 1	**Data Set 2**	**Overall**
Start Time	16:04:42	16:22:02	
End Time	16:14:06	16:36:44	
Total Time (mm:ss)	00:09:24	00:14:42	
Total Time (seconds)	564	882	
Total number of Samples	52	274	
Avg time for a sample (seconds)	10.846	3.219	
Average PSI	11.802	21.524	
Maximum Value PSI	38.879	33.261	59.678
Minimum Value PSI	0	2.990	0
Std Dev PSI	9.261	7.104	
Max Frequency (cyc/min)	6.000	9.000	
Min Frequency (cyc/min)	0.500	6.000	
Avg Frequency (cyc/min)	2.316	7.055	

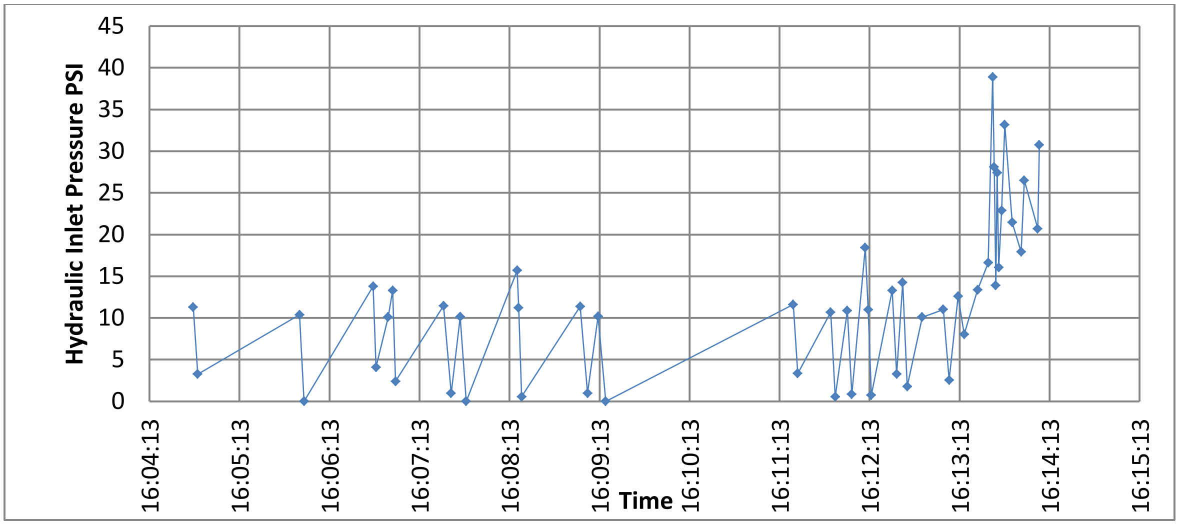

Figure 53:Time Series Plot for Dataset 1 (Start-up)

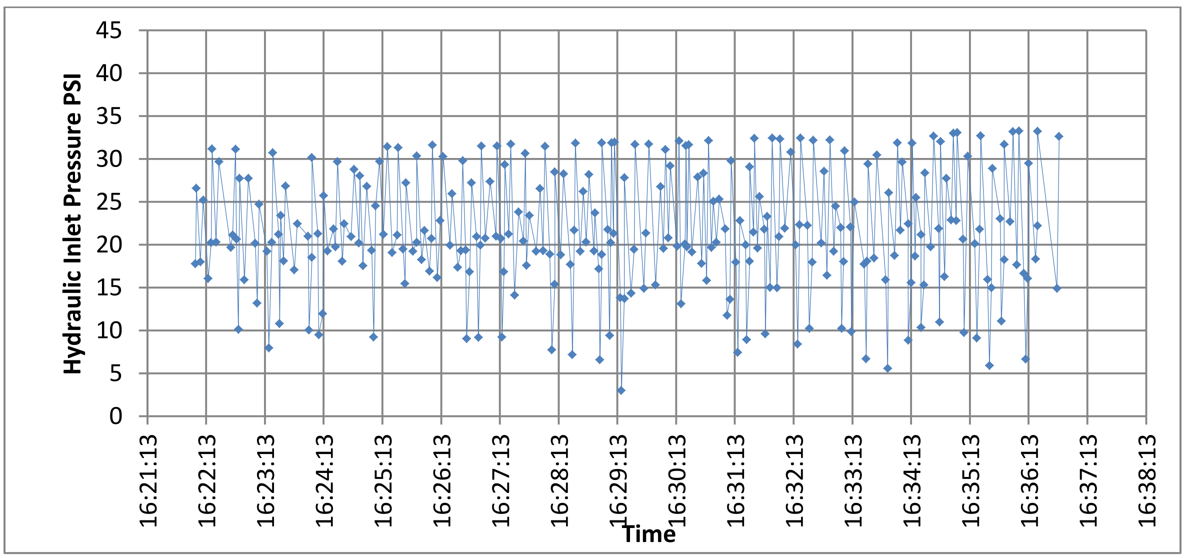

Figure 54:Time Series Plot for Dataset 2 (During continuous operation)

6.0 Discussion

6.1 Wing Wave Discussion

Learning the techniques of laying fiberglass was one of the major struggles encountered. It was found that the best material to spread the resin with was paint brushed but despite all efforts none were able to be reused with any quality results. Larger areas posed the most difficulty because of the size and set time of the resin although smaller areas used more supplies and had to cure for minimum of 8 hours before another layer could be added. Through perseverance and patients laying fiberglass became smoother and more efficient. During this process ventilation masks were needed as well as large fans and shade to prevent heat exhaustion, intoxicating fumes and fast curing cracks.

The new hinge design held firmly, cost less, and was easier to construct than the existing hinge appeared to be. The new wing design also showed greater motion even while dampened by the hydraulic ram. This shows that the design captures more energy than the previous and could ultimately provide greater pressure or higher volume.

Since the ram was bottoming out it created concentrated stress on the cross member it was mounted to thus causing stress cracks in the frame. This could have been avoided two ways, either have a longer ram so that it could handle the longer stroke length or move the mount on the wing lower so that there wouldn't be as much motion. The frame structure could have also been reinforced but that would not have solved the issue of the ram bottoming out.

While the hydraulic lines were disconnected and the ram was pumping sea water in and out of each port, the velocity and force the water exiting was tremendous; so much that a hand could only be held approximately six inches away from the port before it was blown back. This proved the wing could pump the working fluid to high pressure.

6.2 GECCO Discusion

The early hours of deployment went exceptionally well, despite the towing of GECCO. The failure of the ducks shafts proved to be a surprise at first until it was seen that the ducks were damaged and experienced severe water intrusion. This flooding of the ducks in addition to the lateral forces on the ducks during towing exerted maximum allowable stress on the stainless steel shaft connecting the ducks. The stress point that experienced this maximum load can be clearly seen in the figure below. A hole that was drilled in the shaft just outside of the GECCO shell by a previous team was meant for a pin that would prevent lateral shifting of the ducks. This point was where the shearing moment occurred during deployment.

Figure 55: Corrosion on GECCO.

Using the free body diagram shown below a force analysis was performed on the sheared stainless steel shafts. The shafts had cross sectional areas of 0.785 in^2. The yield strength for steel is roughly 22,000 psi. The total amount of stress applied due to water intrusion on the entire GECCO system was calculated to be 16,904.5275 lb. The GECCO system thought could not hold this water therefore the wear and tear from previous deployment and long-term weathering of the material assisted in the shearing of the stainless steel.

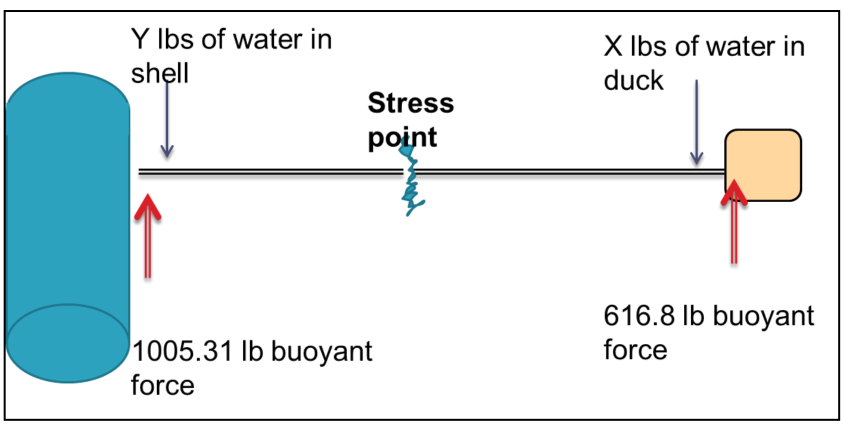

Figure 56: Stress FBD.

6.3 PTO Discussion

Data recorded from Wing Wave was very encouraging, showing a maximum record peak of 59 PSI and moving average between 20-25 PSI. As per earlier lab testing of Harris hydro-electric generator, the minimum pressure required for the electrical output generation is greater than 15 PSI, thus implying there was sufficient pressure available for generator operation. Though due to mechanical malfunctioning (SOV and/or check valve), electrical output could not be generated, the lab testing implies that there was sufficient pressure to generate output voltage around 30 Volts. Following is the time series plot for the wing wave pressure with the moving average.

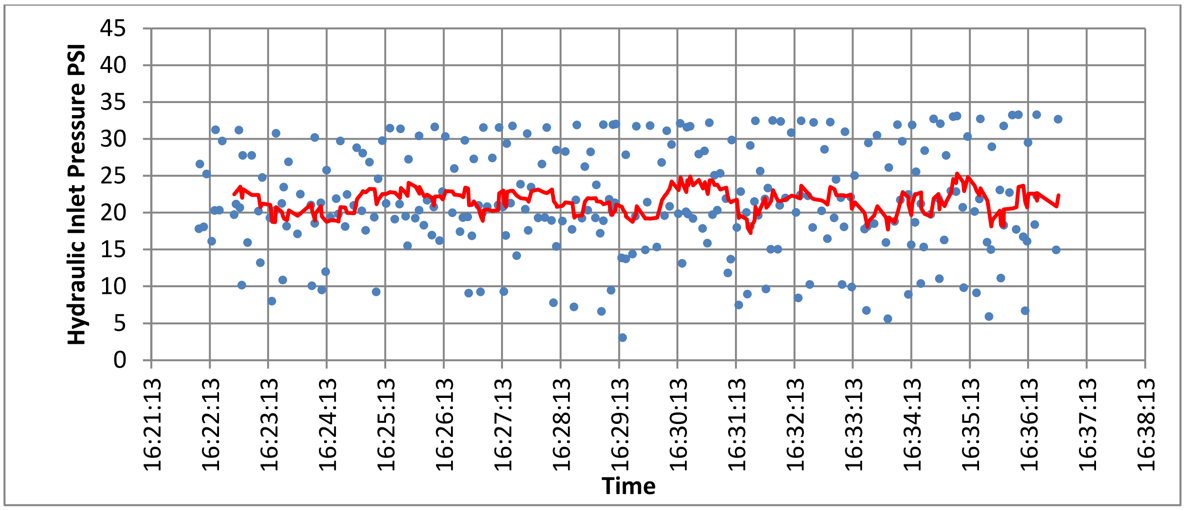

Figure 57: Hydraulic Inlet Pressures.

6.4 Project Administration Particulars

This project began mid-January, 2012 as part of the spring semester. From mid-January through mid-May, designs were considerations were finalized. The construction phase lasted from May 14th-June 8th. There was a 3 day deployment window, and a five week report and analysis phase.

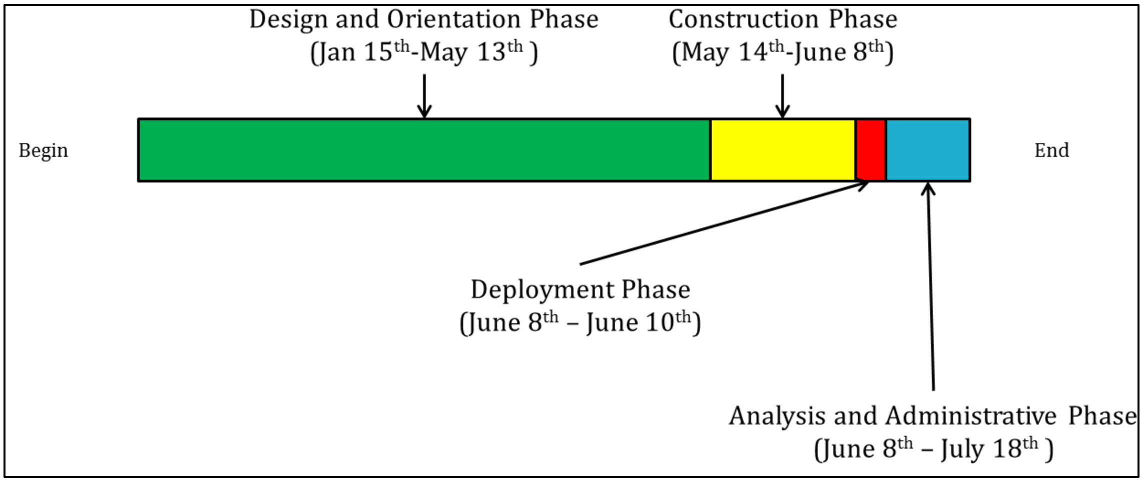

Figure 58: Project Timeline.

During the construction phase, an overall work estimation was 1,055 man hours. This figure does not take into account time spent during the design phase or the administration phase following deployment.

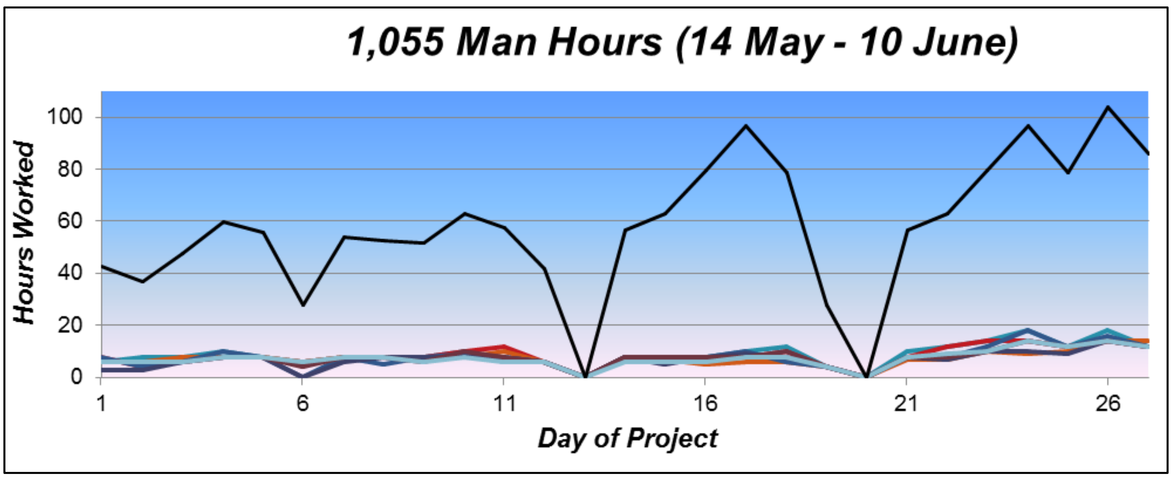

Figure 59: Project Man Hours.

The overall project budget began at $1,500. However, midway through the building phase, an additional $1,000 was supplemented to the project. The final budget was $3,356, not including over $2,500 in donation as well as existing project materials. The final estimation of this project is approximately $70,000. If the existing materials are taken into consideration, this figure goes well beyond $100,000.

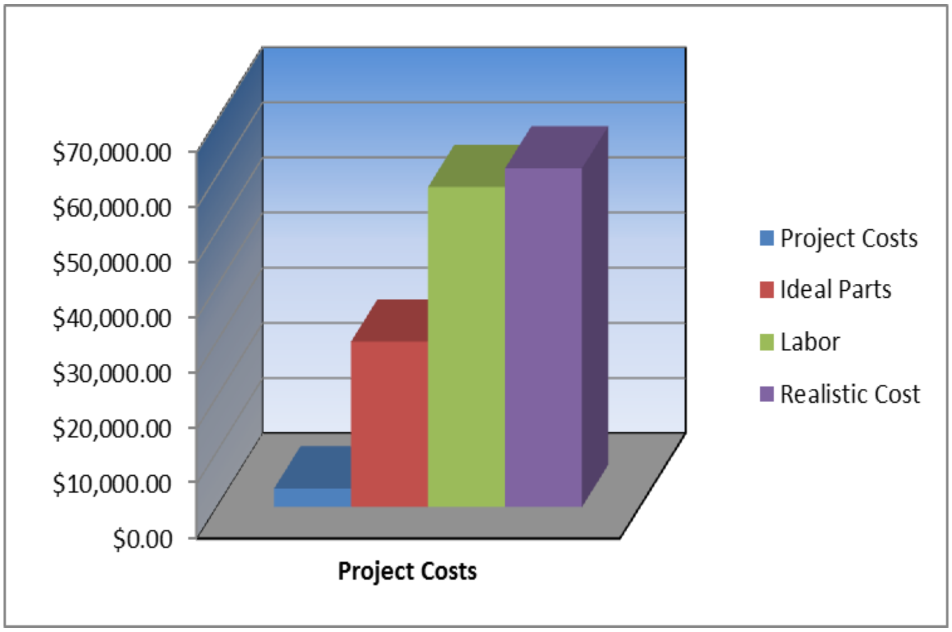

Figure 60: Project Budget.

These monetary restrictions definitely had an impact on the overall functionality and ultimate success of the project (discussed below).

7.0 Conclusions

7.1 Wing Wave Conclusions

The data collected during deployment show an obvious amount of energy in waves. The Wing Wave has again proven to be a sufficient method for harvesting these waves efficiently. Between the two WECs tested in this project, the wave wing has shown the most potential. The construction was a major success as well as the performance while testing; the only part that succeeded partially was the frame structure and the hydraulics which still performed just not as seamlessly as hoped. With more funding and time the wave wing could power our future.

7.2 GECCO Conclusions

To have prevented the intrusion of water into the GECCO, additional calculations on the shaft should have been done. The whole prototype has suffered some damages during handling from previous years in addition to this current year which was not known and therefore not taken in consideration. If there would have been a possibility to have fixed any damaged members of the prototype a good pre deployment test on water would have been essential to ensure that the system is waterproof.

Another aspect that was not foreseen before deployment was the ocean currents that took the GECCO away once it was deployed. The boat that had to prevent the prototype to float away did not have a good engine to stop it so it drifted away with it. The best method to deploy a prototype in the ocean is to have ready the mooring lines before the prototype is put on the water.

7.3 PTO Conclusions

As discussed above, data recorded from Wing Wave was very encouraging and showed that the Wing Wave performed as designed. Also there was sufficient output pressure generation from Wing Wave which would have converted to electrical output if there were no SOV and check valve malfunctioning.

Another big achievement was establishment and smooth operation of remote link between work station at research vessel and PTO control Unit. We were able to see and record real-time values from the PTO successfully. This was helpful in understanding the operational status of the Wing Wave and generator though it was identified that with additional/redundant instrumentation, the operational and maintenance working would have been enhanced.

The housing of the unit provided sea-worthy protection and there were no signs of water ingress in spite of rough weather and rains. Summarized list of major findings are as follow:

- Failure of Solenoid Valves/Check valves resulting in no electrical output (despite of sufficient pressure)
- Data Recording failures: One of three recording methods for controller didn’t work at all (Data transmittal through ‘File transfer Protocol’ FTP)
- Lack of additional/redundant instrumentation for root cause identification (Tachometer or flow meter etc.)
- Insufficient Battery Sizing and/or lack of independent charging system
- Maintenance provision: Difficulties faced for battery replacement and SOV control mode selection

8.0 Recommendations

8.1 Wing Wave Recommendations

Given a larger budget and more time, a more robust frame can be built to handle the large amounts of energy encountered during deployment. This would undoubtedly prevent the structural integrity of the frame being compromised. A larger budget would also have helped with material selection. A hydraulic ram with a larger stroke length would have also prevented cracking in the frame. However, when it comes to procurement of materials, the more specific an item is the more expensive it becomes. Corrosion resistant check valves and hydraulic fittings would have also benefitted this project.

8.2 GECCO Recommendations

If given an opportunity to expand on the GECCO project, a few considerations would be necessary with the assistance of additional funding. The ducks require refurbishing which includes fiberglass and resin. The stainless steel shafts would need replacing. Careful monitoring and analysis should be followed with the duck assembly. A sealed bearing mechanism would be desired for the duck assembly as well thus resulting in four total sealed bearings. These sealed bearings would allow for independent rotation of the ducks while preventing water intrusion into the GECCO shell.

8.3 PTO Recommendations

Overall performance of PTO Control and Data Acquisition System was satisfactory. The unit was able to log data and successfully transmit the data over cellular network smoothly without any failure which was very helpful in understanding the operation. However there were some operational failures including battery, SOV/Check valves and data logging through FTP. Also there are some modifications required to make the operational interface of the system (when accessed through internet) easier to understand.

The instrumentation design also needs to be reconsidered with additional redundancy. There should be also instrumentation to measure wave data so that a relationship can be understood easily between environmental data and energy data.

Also for long term, there should be an independent power source (vessel mounted solar panel or wind turbine) to ensure continuous control supply availability.

8.4 Overall Recommendation

A very important lesson to take away from this work is that although important, component level testing is not sufficient for a project of this size. Ideally, an entire manual test including all components fully integrated would have been beneficial to this project. The largest hindrance to this was time. The weather was also a factor in the building phase. Unrelenting rain during the last week of deployment prevented a large scale set up and testing of the entire project. Through a fully integrated test, failure points could have been realized and steps taken to mitigate them. Overall, the project was a huge success and much more was learned about the harvesting of ocean energy through wave energy converters.

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10.0 Appendixes

1. Datasheet for Harris generator
2. Datasheet for Moxa GPRS Controller
3. Datasheet for WIKA Pressure Transmitter
4. Datasheet for FlexCharge Charge Controller
5. Settings for Server with Active OPC
6. Project Bill of Materials