Copyright Warning & Restrictions

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a, user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use" that user may be liable for copyright infringement,

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Please Note: The author retains the copyright while the New Jersey Institute of Technology reserves the right to distribute this thesis or dissertation

Printing note: If you do not wish to print this page, then select "Pages from: first page # to: last page #" on the print dialog screen



The Van Houten library has removed some of the personal information and all signatures from the approval page and biographical sketches of theses and dissertations in order to protect the identity of NJIT graduates and faculty.

ABSTRACT

AIR PISTON APPROACH TO WAVE POWER GENERATION

by Arun Ramadass

Scientists have calculated that, by tapping just 0.2% of the energy produced by the world's oceans we can provide for all the worlds current energy needs. It is generally accepted that a combination of traditional energy production methods, (oil, coal, gas, nuclear) mixed with a combination of renewable energy production approaches is the future in providing for an increasingly energy hungry world. Wind, solar and biomass have moved into the public arena only in the last few years.

The proposed patented device (US Patent No.: 7,468,563) Ocean Wave Energy Converter harnesses the energy of ocean waves by continually raising and lowering a float, which in turn raises or lowers one side of a lever arm about a stationary pivot point. This, thereby, raises or lowers a piston, which is attached to the opposite side of the lever arm, through a cylinder, which causes large volumes of air to move. This air is funneled through drive turbines, which produce electric power.

This thesis focuses on analyzing the piston and the lever arm mechanism in order to determine the overall output of the system. A 2-D, 3-D model of the piston and lever arm mechanism along with the simulation of the air flow through the piston was done using ANSYS 11.0, the results and the source codes are discussed in the following chapters. Also discussed are the mathematical equations, which help us determine the ratio of the lever arm and hence the output force transferred to the piston.

AIR PISTON APPROACH TO WAVE POWER GENERATION

by Arun Ramadass

A Thesis Submitted to the Faculty of New Jersey Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Power and Energy Systems

Department of Electrical and Computer Engineering

May 2010

 \bigcirc \langle

APPROVAL PAGE

AIR PISTON APPROACH TO WAVE POWER GENERATION

Arun Ramadass

Dr. N.M. Ravindra, Thesis Co-Advisor Date Chairman, Department of Physics, NJIT. Dr Mengchu Zhou, Thesis Co-Advisor Date Professor, Department of Electrical Engineering, NJIT Dr. Walid Hubbi, Committee Member Date Associate Professor, Department of Electrical Engineering, NJIT. Dr. Max Roman, Committee Member 7 Date Assistant Research Professor, Department of Biomedical Engineering, NJIT. Joseph Forch, Committee Member Dáte President, Green Ocean Wave Energy LLC, Newark, NJ

BIOGRAPHICAL SKETCH

Author: Ar	run Ramadass
------------	--------------

Degree: Master of Science

Date: May 2010

Undergraduate and Graduate Education:

- Master of Science in Power and Energy Systems, New Jersey Institute of Technology, Newark, NJ, 2010
- Bachelor of Science in Electrical and Electronics Engineering, Visvesvaraya Technological University, Belgaum, India, 2007

Major: Power and Energy Systems

Presentations and Publications:

- Arun Ramadass, Tony Chow and N.M. Ravindra, *Magnetic Augmented Rotational System- Applications to Windmills*, Cairo International Conference on Energy and Environment, March 2009. (Published in Journal)
- Arun Ramadass, Srinivasamurthy Devayajanam and Nuggehalli Ravindra, A Novel Approach to Turbine Design, MS&T, October 2009 (Pages 186-198).
- Arun Ramadass, Joseph Torch, N.M. Ravindra, Vijay Kasisomayajula and Bilal Qazi, *Air-Piston Approach to Wave Power Generation*, Marine Renewable Energy Centre (MREC), October 2009 (<u>http://www.mrec.umassd.edu/past_events2.cfm</u>).
- Arun Ramadass, Joseph Torch, N.M. Ravindra, Air Piston Approach to Wave Power Generation, International Journal of Energy Research. (To be published)
- Arun Ramadass, Tony Chow and N.M. Ravindra Magnetic Augmented Rotational System Application to Wind Mills, TMS Annual Meeting & Exhibition, San Francisco, California, March 2009.
- Arun Ramadass, Tony Chow and N.M. Ravindra Magnetic Augmented Rotational System Application to Wind Mills, Dana Knox Research Showcase, NJIT, April 2009.

- Arun Ramadass, Joseph Torch, N.M. Ravindra Air Piston Approach to Wave Power Generation, Graduate Student Research Day, NJIT, November 2009.
- Arun Ramadass, Joseph Torch, N.M. Ravindra Air Piston Approach to Wave Power Generation, NJEC Showcase, Rutgers University, November 2009.

To four of the most important people in my life: God, my mother (Shyamala), my father (Ramadass), and my sister (Ajitha). Without you, my life would be incomplete.

Every step that I take is a new challenge, but walking along with you, God, through this journey has given me strength.

Mom, you were my rock I could lean on, Without your love and support none of this would be possible.

Dad, you always told me to "reach for the stars" and to "never give up", Thank you for inspiring in me the confidence to do so.

Sister, you have always been there when I needed you the most, Thank you for always guiding me towards the right path.

ACKNOWLEDGMENT

I would like to take this opportunity to express my gratitude towards Dr. N.M. Ravindra, for providing me with an opportunity to work with him. Being a part of his group that has pioneered in Alternative Energy research provided me with an ideal platform to pursue my interest in this field. I would like to thank him for his guidance and valuable advice throughout the course of this study.

I am also thankful to the committee members Dr. Mengchu Zhou, Dr. Walid Hubbi, and Dr. Max Roman, for their timely advice and valuable inputs.

I would also like to extend a special thanks to Joseph Torch, President, Green Ocean Wave Energy, Newark, NJ for his continual research support and assistance in problem solving, without which this thesis would not be possible.

Finally, I would like to thank my parents and friends for their love and constant support without whom this thesis would be incomplete.

TABLE OF CONTENTS

Cha	apter			Page
1.	INT	RODUC	CTION	1
	1.1	Ocean	Wave Energy	1
	1.2	Ocean	Currents	3
	1.3	Ocean	Waves	4
2.	FUN	JDAME	NTAL WAVE ENERGY CONVERTERS	5
	2.1	Introdu	action	5
	2.2	Turbin	e Type Wave Energy Converters	6
		2.2.1	Oscillating Wave Energy Converter	6
		2.2.2	Overtopping Wave Energy Converter	10
	2.3	Buoy 7	Type Wave Energy Converters	10
		2.3.1	Tube Type	11
		2.3.2	Float Type	12
3.	COMMERCIALLY DEPLOYED WAVE ENERGY CONVERTERS			
	3.1	Oyster	Aquamarine Power	15
	3.2	Ocean	Treader	17
	3.3	Wave '	Treader	18
	3.4	Pelami	s Wave Energy Converter	19

.

TABLE OF CONTENTS Continued

Ch	apter		Page
4.	WA	VE ENERGY OUTPUT PARAMETERS	21
	4.1	Introduction	21
	4.2	Wave Energy and Power Output	22
		4.2.1 Power Per Meter of Wave Front	23
		4.2.2 Variation of Energy With Respect to Depth	24
	4.3	Point Absorbers and Energy Calculations	25
		4.3.1 Float Type	25
		4.3.2 Tube Type	26
		4.3.3 Oscillating Water Column	28
5.	OCI	EAN WAVE AIR PISTON	30
	5.1	Ocean Wave Air Piston (US Patent No: 7,468,563)	30
	5.2	Survivability	35
	5.3	Adaptability and Achieving Low Cost Electricity	36
	5.5	Environmental Impact	37
6.	RES	SULTS AND DISCUSSIONS	38
	6.1	Initial Experiment	38
	6.2	Ansys Simulation Result	40
		6.2.1 2-D Model of OWAP	40
		6.2.2 3-D Model of OWAP	44

TABLE OF CONTENTS Continued

-

Cha	pter			Page
		6.2.3	3-D Model of OWAP Lever Arm Mechanism	48
	6.3	Mather	matical Analysis of Lever Arm	49
7.	CON	ICLUSI	[ON	55
	7.1	Ocean	Wave Air Piston	55
	7.2	Future	Work	56
API	PENE	DIX A A	NSYS SOURCE CODE	57
	A.1	Ansys	Source Code for a 2-D Model of Air Piston	57
	A.2	Ansys	Source Code for a 3-D Model of Air Piston	59
	A.3	Ansys	Source Code for 3-D Model of Air Piston with 8 and 16 inch	61
	A.4	Ansys	Source Code for 3-D Model of Lever Arm Mechanism	64
RE	FERE	ENCES.		68

LIST OF TABLES

Tabl	Table		
2.1	Classifications of Ocean Wave Energy Converter	5	
4.1	Shows the Maximum Power, Average Power and Full Load Output for Different Renewable Energy Sources	21	
4.2	List of Variables Used for Wave Power Calculations	22	
6.1	Average Power Reading with Weighted Float	38	
6.2	Average Power Readings with 2-stroke Piston Attached to Float	39	

LIST OF FIGURES

Figu	re	Page
1.1	Approximate global distribution of wave power levels (kW/m of wave front)	4
2.1	Oscillating water column device	7
2.2	Wells Turbine	8
2.3	Overtopping wave energy converter	10
2.4	Surface point absorber	13
2.5	Hose pump	14
3.1	Oyster	16
3.2	Ocean Treader	18
3.3	Wave Treader	18
3.4	Pelamis wave energy converter	20
4.1	Wave power density	23
4.2	Power per meter of wave front	24
4.3	Float type point absorber	25
4.4	Tube type point absorber	27
4.5	Oscillating water column (OWC)	28
5.1	Shows a platform in the ocean that is attached to the seabed with legs	30
5.2	Shows the main working parts of the device. A lever arm is attached to the platform at a pivot point	31

LIST OF FIGURES Continued

	Figu	re	Page
	5.3	Shows the working mode of the device	32
	5.4	Shows the piston and the piston head moving up through the cylinder	33
	6.1	Velocity vector of airflow through the piston	40
	6.2	Stagnation pressure inside piston	41
	6.3	Velocity of airflow through the piston with a 16-inch outlet	41
	6.4	Velocity vector of airflow through the piston with 16-inch outlet	42
	6.5	Air pressure inside the piston with 16-inch outlet	43
	6.6	Stagnation pressure inside piston with 16-inch outlet	43
	6.7	3-D Model of piston with 16-inch outlet	44
	6.8	Velocity vector of airflow through OWAP piston with 8-inch outlet	45
	6.9	Pressure within OWAP piston with 8-inch outlet	45
	6.10	Velocity vector of airflow through OWAP Piston with 16-inch outlet	46
	6.11	Pressure within OWAP with 16-inch outlet	47
	6.12	3-D Model of lever arm	48
	6.13	Lever arm with forces	49
	6.14	Lever arm shown as a beam	50
	6.15	Forces acting on lever arm when $\theta = 0$ degrees	51
	6.16	Forces acting on lever arm when $\theta < 0$ degrees	52
•	6.17	Forces acting on lever arm when $\theta > 0$ degrees	53
	6.18	Input to the piston	54

CHAPTER 1

INTRODUCTION

1.1 Ocean Wave Energy

Ocean wave energy is harnessed directly from surface waves or from pressure fluctuations below the surface. Waves are caused by the wind blowing over the surface of the ocean. In many areas of the world, the wind blows with enough consistency and force to provide continuous waves. There is tremendous energy in the ocean waves.

Wave power devices extract energy directly from the surface motion of ocean waves or from pressure fluctuations below the surface. Wave power varies considerably in different parts of the world, and wave energy cannot be harnessed effectively everywhere. Wave-power rich areas of the world include the western coasts of Scotland, northern Canada, southern Africa, Australia, and the northwestern coasts of the United States.

The ocean contains a vast amount of mechanical energy in the form of ocean waves and tides. The high density of oscillating water results in high energy densities, making it a favorable form of hydropower. The total U.S. available incident wave energy flux is about 2,300 TWh/yr¹. The DOE Energy Information Administration (EIA) estimates that, in the Pacific Northwest alone, wave energy can produce 40–70 kilowatts (kW) per meter (3.3 feet) of western coastline¹. The west coast of the United States is more than a 1,000 miles long. The concept of getting energy from the ocean is not new, patents for wave energy converters (WEC) go back a hundred years or more but only recently have companies started to explore the possibility of obtaining large amounts of

electricity from the ocean. A few ocean wave energy conversion systems have made it to full-scale prototype stage allowing experience to be gained from operational aspects, which is a critical aspect to develop economic models. However, despite enormous progress over the past five years, wave energy conversion technologies are at an initial stage of development. A lack of accepted standards, a wide range of technical approaches and large uncertainties on performance and cost of these systems reflect this fact.

Wave energy conversion devices are installed either on-shore embedded in a cliff or an existing harbor wall, or offshore in deep waters. Similar to offshore wind, a wider applicability and more consistent and concentrated resource of energy can be found offshore and is more suitable for large-scale deployments. Installing such devices away from the coastline solves many issues such as visual, permitting and environmental impact. Most designs have two major difficulties to overcome. First, even in areas where waves are consistent throughout the day and throughout the seasons, the device must be able to handle a wide range of incident wave power levels, from near flat seas to the most extreme storm conditions (which produce wave power levels that are more than an order of magnitude above the average). Second, waves typically have a low frequency of the order of 0.1 Hz, while power generation equipment runs at hundreds of rpm. The device must be able to change the slow-acting, multi-directional wave force into a high speed, unidirectional force capable of powering a generator.

1.2 Ocean Currents

There are two main types of ocean currents marine currents and tidal currents. Both of them are influenced by the rotation of the Earth and are highly predictable. Marine currents such as the Gulf Stream in the Atlantic originate from differences in water temperature within the ocean. When water at the Equator warms up, it moves towards the poles then cools, sinks, and flows back towards the Equator. The speed with which this water conveyor belt moves is cyclic such that it speeds up and slows down over about a ten year period².

Tidal currents are produced in a different manner than marine currents. Tides are produced as a result of the Moon's gravitational pull on the ocean. Depending on location and geography, tidal currents come in half-day (semi-diurnal), daily (diurnal), and 14-day cycles³. Tidal currents do not behave similar to marine currents, tidal currents flow in one direction at the beginning of the cycle and reverse directions at the end of the cycle unlike marine currents, which flow in only one direction.

Estimates conclude that marine and tidal currents combined contain about 5 TW^1 of energy, which is equivalent to the world's total power consumption. Prototypes of marine current generators have been deployed at various locations. The technology used to harness this type of energy is similar to hydroelectric, and some models may even be described as looking like underwater wind turbines⁴.

1.3 Ocean Waves

Ocean waves are produced by the combined effect of transfer of energy from the sun to wind then water. Solar energy creates wind, which then blows over the ocean, converting wind energy to wave energy. Once converted, this wave energy can travel thousands of miles with little energy loss. Most importantly, waves are a regular source of power with an intensity that can be accurately predicted several days before their arrival⁵. Furthermore, wave energy is more predictable than wind or solar energy. Figure 1.1 depicts wave power levels in kW/m of wave crest, the typical units for measuring wave energy.



Figure 1.1 Global distributions of wave power levels (kW/m of wave front)⁶.

There is approximately 8,000 - 80,000 TWh/yr or 1 - 10 TW of wave energy in the entire ocean³, and on average, each wave crest transmits 10 - 50 kW per meter. The energy levels depicted in Figure 1.1 is an important factor when designing any sort of wave power take-off device, it should also be noted that wave power decreases closer to the shore because of frictional losses with the coastline.

4

CHAPTER 2

FUNDAMENTAL WAVE ENERGY CONVERTERS- CLASSIFICATION

2.1 Introduction

Most of the patents relating to wave energy extraction date back to the 1920s. Those devices form the basis to the modern-day oscillating water column (OWC) as well as the float-type point absorber. Unlike today's wave energy converters, which focus on large-scale power production the first devices were meant to compress air or pump water. Recent improvements in design and technology have enabled engineers to use the compressed air in an OWC device to drive a turbine and the water pumped by a point absorber to run a generator. Table 2.1 shows the different ocean energy conversion devices, which is classified into two main categories.

Ocean Flow Energy Converter		Ocean Wave Ene	rgy Converter
Tidal Flow	Ocean Currents	Turbine Type	Buoy Type
Tidal Lagoon	Bi-directional	Oscillating Water	Tube Type
	Turbine	Column (OWC)	
Tidal Dam	Uni-directional	Over Topping Wave	Float Type
	Turbine	Energy Converter	

Table 2.1	Classifications of	Ocean	Wave	Energy	Converter
		O VV VIII		211016/	CONTRACTOR

As seen from Table 2.1 there are two fundamental types of Wave Energy Converters (WEC), ocean flow energy converters and ocean wave energy converters. The first type of WEC to get attention from the research community was the turbine-type while buoy-type converters are a newer idea. Both have operational prototypes, some of which have even been commercialized.

2.2 Turbine Type Wave Energy Converter

The turbine-type wave energy converter uses a turbine as an energy conversion device. There are various types of turbine wave energy converters, the most prominent being the oscillating water column. The other type of device is described as an overtopping WEC.

2.2.1 Oscillating Water Column (OWC)

The oscillating water column (OWC) as illustrated in Figure 2.1 operates much like a wind turbine via the principle of wave induced air pressurization. A closed containment housing (air chamber) is placed above the water and the passage of waves changes the water level within the housing. If the housing is completely sealed, the rising and falling water level will increase and decrease the air pressure respectively within the housing. With this concept in mind, we can place a turbine on top of the housing through which air may pass into and out of. Air will flow into the housing during a wave trough and will flow out of the housing during a wave crest. Because of this bidirectional airflow, the turbine must be designed to rotate in only one direction no matter the direction of airflow. The Wells Turbine was designed for this type of application and is used in most OWC devices today³.



Figure 2.1 Oscillating water column device³.

Oscillating Water Column Design. Some of the factors that need to be considered while designing an air chamber within the OWC housing are wave period, significant wave height, and wavelength characteristics of the local ocean climate. If the size of the housing is incorrect, waves could resonate within the air chamber, which then results air not passing through the turbine. Ideally, the air chamber dimensions will be designed to maximize energy capture in the local wave climate while research has shown that the generator design (generator size and generator coefficient) is almost completely independent of wave climate such that only areas of extreme wave energy benefit from larger generators⁷.

Apart from sizing the air chamber with respect to the wave climate, the air chamber must also be conducive to air flow through the turbine. Implementing a funnel shaped design where the chamber narrows from the water surface level to the turbine does this. This will concentrate the airflow through the turbine. For the last twenty years, most OWC research has focused on the Wells Turbine, shown in Figure 2.2, as the solution to bidirectional flow. Even though this turbine is not outdated, it may be advantageous to investigate new schemes. Energetech Australia Limited has taken the lead by exploring a new turbine design³. While the energy capture efficiency of a rotor cannot exceed the theoretical maximum Betz limit of 16/27 or roughly 52%⁸, there is room to improve a bidirectional turbine since studies have shown that rotor blade sections specially designed for a Wells Turbine increases the efficient operating range⁹. The procedures for wind turbine blade design in a variable speed environment may be cross-applied to this situation.



Figure 2.2 Wells turbine¹⁰.

Locations of Deployment. OWC devices are usually deployed on the shoreline or near the shore. The shoreline devices are placed where the waves break on the beach and tend to be noisy. The near shore devices are fixedly moored to the ocean bottom in that same manner as offshore wind turbines or slack moored so as to respond to changes in mean water level, i.e. tides. The housing is placed just above the water surface⁴.

Both these types of placements have their advantages and disadvantages. The main concern is that the wave energy is greater offshore than at the shoreline, so more energy is available for capture in a near shore OWC. The disadvantage of being offshore is that installation and maintenance costs are high. Both the near shore and shoreline OWC's are eyesores since they are visible over the ocean surface, hence both will experience public resistance to their installation.

The changing mean ocean surface level accompanying tides may pose problems for a fixed moored OWC. Nonetheless, this type of device maintains its position better than a slack moored device so as to provide more resistance to incoming waves and therefore produce more energy. Another tradeoff between the fixed and slack moored OWC is that while the fixed moored OWC collects more energy; the slack moored OWC provides some flexibility in rough seas, which might damage a fixedly moored device. Also, the installation costs of a slack moored device are less than a fixedly moored device because a rigid foundation does not need to be constructed⁴.

2.2.2 Overtopping Wave Energy Converters

The working of an overtopping wave energy converter is similar to the functioning of a hydroelectric dam. Here waves roll into a collector, which then funnels the water through a hydro turbine as shown in Figure 2.3. The turbines are then coupled to generators, which produce electricity. In order to protect the turbine from physical damage a mesh grid is provided which extracts trash and marine debris before the waves reach the turbine. The overtopping WEC can be placed both on the shoreline and near shore but are more usually placed at a near shore location. As with the OWC, the overtopping WEC may be slack moored or fixed moored to the ocean bottom.



Figure 2.3 Overtopping wave energy converter¹¹.

2.3 Buoy Type Wave Energy Converter

The buoy type wave energy converter is also known as a "point absorber" because it harvests energy from all directions at one point in the ocean. These devices are placed at or near the ocean surface away from the shoreline. They may occupy a variety of ocean depths ranging from shallow to very deep water depending on the WEC design and the type of mooring used. There are several types of point absorbers with the most common being the hollow tube type and the float type, although there are other forms⁴.

2.3.1 Tube Type

This type of WEC consists of a vertically submerged, buoyant hollow tube the tube allows water to pass through it, driving either a piston or a hydro turbine. The piston power take-off method is better suited for this application because the rate of water flowing through the tube is not rapid¹². There are two tube arrangements such that one end may be closed and the other open or both open. With both ends closed, no water flows and the device becomes the float type.

The hollow tube type WEC works on the principle that waves tend to cause pressure variations at the surface of the ocean. The long, cylindrical tube experiences a pressure difference between its top and bottom, causing water to flow into and out of the open end(s) of the tube. When a wave crest passes above a tube, water will flow down the tube, and when a wave trough passes above the tube, water will flow up the tube. This flow will push a piston, which may either power a drive belt, a hydraulic system, or a linear generator.

In the case of the drive belt, the piston is connected to a belt, which turns at least one gear. The gear may be connected to a gearbox to increase the speed of rotation of the shaft, which turns the rotor of an electric generator. With a hydraulic system, the piston pumps hydraulic fluid through a hydraulic motor, which is coupled to an electric generator. The hydraulic system is preferred over the drive belt due to maintenance issues¹². Also, multiple WECs may be connected to one electric generator through a hydraulic system. When the piston is connected to a linear generator, it bypasses the hydraulics process and the gearbox of a drive belt. Power take-off with this method is a result of the up and down movement of the linear generator's translator (in the case of linear generators, the rotor is referred to as a translator), which is directly coupled to the piston.

2.3.2 Float Type

As mentioned above, the float-type WEC is some sort of sealed tube or other type of cavity. It will most likely be filled with air or water or a mix of the two. In order to make the sealed cavity positively buoyant so that it floats on top of the ocean surface, it should contain some air. If the cavity is to be just below the surface, it should contain water at the pressure of the depth it is placed thus making it neutrally buoyant with respect to its depth. Varying the pressure within the cavity may alter the behavior of the float.

The float type WEC in Figure 2.4 operates with several different power take-off methods. The floater will move in different directions relative to wave motion depending on its location above or below the water. If the floater is on the surface, it will move up and down with the wave. This poses control problems because the wave height may exceed the WEC's stroke length (how far up and down the floater is permitted to move by design). The worst possible outcome could be damage to the WEC during a storm when wave heights are extreme. The solution to this problem of limited stroke length is to place the tube under water as described above.



Figure 2.4 Surface point absorber¹³.

Figure 2.4 illustrates the motion of a below surface point absorber relative to wave motion. When a wave crest passes overhead, the extra water mass pushes the float down, and when a wave trough passes, the absence of water mass pulls the float up since it becomes lighter than the water overhead. A control system can pump water and/or air into the float to vary buoyancy and thus restrain the float if large wave heights are experienced. Moreover, if a rough storm occurs, the entire system will be underwater and out of harm's way.

As with the tube type point absorber, the up and down motion of the floater relative to some stationary foundation will act on a piston. This piston can be connected to a generator using any of the methods described earlier. With a float instead of a tube, other conversion mechanisms may be utilized.

Rather than a piston, the float may act on what is called a "hose pump" as seen in the Figure 2.5 It is similar to a hydraulic system in that the hose pressurizes seawater, which drives a generator. The difference with the hose pump system is the method of pressurization. A long flexible hose is attached to a float and a stationary reaction plate. The float moves relative to the reaction plate, stretching and constricting the hose. When the hose is stretched, it pulls in seawater, and when the hose is constricted, pressurized water is pushed out to a generator.



Figure 2.5 Hose pump¹⁴.

CHAPTER 3

COMMERCIAL WAVE ENERGY CONVERTERS

3.1 Oyster – Aquamarine Power

Aquamarine Power is the owner and developer of Oyster, the world's largest working hydroelectric wave energy converter. Oyster has been designed to harness the abundant natural energy found in near shore waves and convert it into sustainable zero-emission electricity¹⁵.

Oyster is a simple mechanical hinged flap connected to the seabed at around 10m depths. Each passing wave moves the flap, driving hydraulic pistons to deliver high pressure water via a pipeline to an onshore electrical turbine. Multiple Oyster devices can be deployed to serve as utility-scale wave farms typically of 100MW or more¹⁵.

As this device can be deployed in near shore depths, it benefits from the more consistent seas and narrower directional spread of waves found near shore. Reduced wave height and load enhance Oyster's natural survivability. Any excess energy is spilled over the top of Oyster's flap; its rotational capacity allowing it to literally duck under the waves.



Figure 3.1 Oyster¹⁵

Oyster has been designed to have high capture efficiency in the most common wave patterns. Its lightweight structure will reduce capital costs and gives an excellent power-to-weight ratio; Oyster's annual average power output is competitive with devices weighing up to five times more. With multiple pumps feeding a single onshore generator, Oyster offers good economies of scale. Modular mass production will also minimize capital costs, while ease of installation, accessibility and routine maintenance will offer highly competitive operating costs¹⁵.

3.2 Ocean Treader

Ocean Treader is simple in concept, efficient in operation and robustly designed to withstand the aggressive environment of the ocean. It uniquely harnesses the different responses of horizontally and vertically floating bodies to passing waves¹⁶.

Ocean Treader comprises of a Sponson at the front, a Spar Buoy in the centre and a second Sponson at the back end. As the wave passes along the device first the forward Sponson lifts and falls, then the Spar Buoy lifts and falls slightly less and finally the back Sponson lifts and falls. Hydraulic cylinders mounted between the tops of the arms and the Spar Buoy harvest the relative motion between these three floating bodies. The cylinders pressurize hydraulic fluid, which, after smoothing by accumulators, spins hydraulic motors and then electric generators. The electricity is exported via a cable piggy-backed to the anchor cable. Ocean Treader is directional and has been proven to passively weather vane to face the wave train, and it also has active onboard adjustment to allow for offset due to the effects of current¹⁶.

The structure comprises of steel load bearing members with the buoyant bodies molded from GRP (Glass Reinforced Plastic), and also modular, which allows for great flexibility in the manufacturing process¹⁶.



Figure 3.2 Ocean Treader¹⁶.

3.3 Wave Treader

Wave Treader was developed using the same aspects of Ocean Treader and mounting them on the foundation of an offshore wind turbine¹⁷.



Figure 3.3 Wave Treader¹⁷.

The Wave Treader concept utilizes the arms and sponsons from Ocean Treader and instead of reacting against a floating Spar Buoy, will react through an interface structure onto the foundation of an offshore wind turbine. Between the Arms and the interface structure hydraulic cylinders are mounted and as the wave passes the machine first the forward sponson will lift and fall and then the aft sponson will lift and fall each stroking their hydraulic cylinder in turn. This pressurizes hydraulic fluid, which is then smoothed by hydraulic accumulators before driving a hydraulic motor, which in turn drives an electricity generator. The electricity is then exported through the cable shared with the wind turbine. Periodically the interface structure moves vertically to allow for the effects of tidal range, and it also can rotate to ensure that the sponsons are optimally aligned with the wave direction¹⁷.

3.4 Pelamis Wave Energy Converter

The Pelamis Wave Energy Converter is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure fluid through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. Power from all the joints is fed down a single umbilical cable to a junction on the seabed. Several devices can be connected together and linked to shore through a single seabed cable¹⁸.

Current production machines are 180m long and 4m in diameters with 4 power conversion modules per machine. Each machine is rated at 750kW. The energy produced

by Pelamis is dependent upon the conditions of the installation site. Depending on the wave resource, machines will on average produce 25-40% of the full rated output over the course of a year. Each machine can provide sufficient power to meet the annual electricity demand of approximately 500 homes¹⁸.



Figure 3.4 Pelamis wave energy converter¹⁸.
CHAPTER 4

WAVE ENERGY OUTPUT PARAMETERS

4.1 Introduction

Oceans cover about 70 % of the Earth's surface. The utilization factor for wave power, which is the ratio of average generated power to the installed power of the power plant, is expected to be as high as 50% (4,380 h/year). The ratio of the total energy produced from waves to wind is about two times for example a wind power plant only delivers energy corresponding to full power during 25% of the time (i.e., 2,190 h out of the 8,760 h per year) a wave power plant is expected to deliver 50% (4,380 h/year)¹⁹.

Table 4.1 Shows the Maximum Power, Average Power and Full Load Output for Different Renewable Energy Sources²⁰

Source	Pmax	Paverage	Full Load		
Sun	1 KW/m^2	100 W/m^2	1000 h		
Wind (11 m/sec)	1 KW/m^2	1 KW/m^2	2000 h		
Wave	$20-200 \text{ KW/m}^2$	5-40 KW/m ²	3000-4000 h		

It has been shown that wave power is more energy dense than wind power and can produces more power for a larger percentage of the year. Therefore, calculating the power available from a wave is an essential parameter. It is essential for the design process of a wave energy converter. In order to achieve this, the power and forces acting on the device should be assessed and then the device may be sized for the desired energy output. The following sections explain how to calculate the wave energy and power and how to size point absorbers and oscillating water columns for a given power level⁴.

E _{density}	Wave energy density [J/m ²]			
P _{density}	Wave power density [W/m ²]			
ρ_{water}	Sea water density [1000 kg/m ³]			
А	Wave amplitude [m]			
g	Gravitational constant [9.81 m/s ²]			
Н	Wave height [m]			
Т	Wave period [m]			
$E_{wavefront}$	Energy per meter wave front [J/m]			
С	Celerity (wave front velocity) [m/s]			
SWL	Mean sea water level (surface)			
$\mathbf{P}_{wavefront}$	Power per meter wave front [W/m]			
h	Depth below SWL [m]			
ω	Wave frequency [rad/sec]			
λ or L	Wavelength $[m] = gT^2/(2\Pi)$			

Table 4.2 List of Variables Used for Wave Power Calculations

4.2 Wave Energy and Power Output

The energy density of a wave, shown in Equation 4.1, is the mean energy flux crossing a vertical plane parallel to a wave's crest. The energy per wave period is the wave's power density. Equation 4.2 shows how this can be found by dividing the energy density by the wave period^{21, 22}. Figure 4.1 illustrates how wave period and amplitude affect the power density.

$$E_{density} = \rho_{water} g H^2 / 8 = \rho_{water} g A^2 / 2$$
(4.1)

$$P_{\text{density}} = E_{\text{density}} / T = \rho_{\text{water}} g H^2 / 8(T) = \rho_{\text{water}} g A^2 / 2(T)$$
(4.2)





4.2.1 Power Per Meter of Wave Front

A wave resource is typically described in terms of power per meter of wave front (or wave crest). This can be calculated by multiplying the energy density by the wave celerity (wave front velocity) as Equation 4.3 demonstrates²². Figure 4.2 characterizes an increase in the amplitude and period of a wave increases the power per meter of wave front.

$$P_{\text{wavefront}} = C^* E_{\text{density}} = \rho_{\text{water}} g^2 H^2 / (16\omega) = \rho_{\text{water}} g^2 A^2 / (4\omega)$$
(4.3)



Figure 4.2. Power per meter of wavefront⁴.

4.2.2 Variation of Energy With Respect To Depth

To properly size an underwater wave energy converter, the wave power at the operating depth must be known. In general, the wave power below sea level decays exponentially by $-2\pi d/\lambda$ where d is the depth below sea level. This property is valid for waves in water with depths greater than $\lambda/2$. Equation 4.4 gives the relationship between depth and surface energy¹².

$$E(d) = E(d = SWL)^* e^{-2\Pi d/\lambda}$$
(4.4)

4.3 Point Absorbers and Energy Calculations

The two types of Point Absorbers will be discussed here the Tube type and the Float type. Both point absorbers have different energy conversion mechanisms but work on the same principle.

4.3.1 Float Type

The float on this point absorber moves up and down with the change in mass above it. As a wave crest approaches, the water mass increases above the float, thus pushing it down. The forces acting on the float may be modeled via Newton's equation, F=ma, which is shown in Equation 4.5. Figure 4.3 shows a Float type point absorber.



Figure 4.3 Float type point $absorber^{23}$.

The mass of water is taken to be $\rho_{water}HA_{float}$ and gravity is the accelerating force. To calculate the power transferred to the float in Equation 4.6, F_{water} is multiplied by the velocity of the float, where the velocity is the stroke length divided by half the wave period. These equations may be used for sizing the float and reactionary forces required in the generator.

$$F_{water} = (\rho_{water} HA_{float})g$$
(4.5)

$$P_{\text{generated}} = F_{\text{water}} (2L_{\text{stroke}}/T)$$
(4.6)

Where:

 F_{water} is the force of water mass on the float [N] A_{float} is the area of float [m²]

P_{generated} is the generated system power [W] and

L_{stroke} is the length of float stroke [m]

4.3.2 Tube Type

The tube type point absorber equations can be calculated using Bernoulli's theory for unsteady flow which is a more complicated method instead an easier method of evaluating the power for the tube type point absorber is found by calculating the force on the piston within the tube based on how much power is to be developed and how long the piston stroke is. By dividing the generated force from Equation 4.7 by the pressure difference across the tube, the area of the piston may be determined in Equation 4.8. Figure 4.4 shows a tube type point absorber²⁴.



Figure 4.4. Tube type point absorber²⁴.

$$F_{\text{generated}} = P_{\text{desired}} T / (2L_{\text{stroke}})$$
(4.7)

$$A_{piston} = F_{generated} / p_{diff}$$
(4.8)

Where:

F_{generated} is the force of water pressure on the piston [N]

P_{desired} is the desired system power [W]

 L_{stroke} is the length of piston stroke [m]

 A_{piston} is the area of piston $[m^2]$ and

 p_{def} is the pressure difference across tube [Pa = N/m²]

4.3.3 Oscillating Water Column (OWC)

The oscillating water column (OWC) energy equations are similar to those used for wind turbines. Equation 4.9^3 expresses the power available from the airflow in the OWC's chamber. The airflow kinetic energy term, $v_{arr}^3 A_{duel} \rho_{atr}/2$, is common to wind turbine analysis but the air pressure term, $p_{atr}v_{atr}A_{duet}$, is unique to this application. From Equation 4.9, it can be seen that the size of the duct and the airflow through the duct play a significant role in an OWC⁴. Figure 4.5 shows an OWC device.



Figure 4.5. Oscillating water column (OWC)²⁵.

$$P_{OWC} = (P_{air} + \rho_{air} v_{air}^2/2) v_{air} A_{duct}$$
(4.9)

Where:

P_{OWC} is the power available to turbine in OWC duct [W]

 v_{air} is the airflow speed at the turbine [m/s]

A_{duct} is the area of turbine duct [m2]

 p_{air} is the pressure at the turbine duct [Pa = N/m2] and

 ρ_{air} is the air density [kg/m3].

CHAPTER 5

OCEAN WAVE AIR PISTON

5.1 Ocean Wave Air Piston (US Patent No.: 7,468,563)

The Ocean Wave Air Piston (OWAP) utilizes the power of ocean waves to push large volumes of air and funnel that air to drive turbines that generate electrical power.





A float is attached to one end of the lever arm and a piston rod is attached to the other end. One end of the piston rod is attached to a piston head. The piston head moves into a cylinder through an air tight membrane inside the cylinder. The cylinder is attached to the platform, which in turn is at a fixed distance from pivot point²⁶. A lever arm is attached to the platform at a pivot point.



Figure 5.2 Shows the main working parts of the device.

Two air ducts are attached to the cylinder outlets, which are both on the top and bottom of the cylinder. The top air duct is connected to top turbine with the help of an air release duct, which connects to the top air vent. Similarly, the bottom air duct is connected to bottom turbine through an air release duct, which connects to the bottom air vent. Generators are connected to both the top turbine and the bottom turbine to generate power.



Figure 5.3 Shows the working mode of the device.

The float is in direct contact with the ocean wave. As waves move into the float area, the wave crest pushes the float up which causes the lever arm that is connected to the float to move and the top of the lever arm which is connected to the piston goes down pushing the piston head down through the cylinder. Also, when the wave trough moves into the float area, the float drops vertically causing the end of the lever arm to move up which pulls the piston head up through the cylinder. As the piston head moves up and down in the cylinder, it is in direct contact with the cylinder walls. A steel or Teflon piston ring is attached to the piston head so that it forms an air tight seal between piston head and the walls of the cylinder. The air inside the cylinder is forced out through either the top or bottom outlet holes.



Figure 5.4 Shows the piston and the piston head moving up through the cylinder.

The direction of the air that is pushed in front of the piston head is indicated in Figure 5.4. The air is forced out through the bottom of the cylinder outlet through the bottom turbine. This action causes the bottom turbine to spin. As the falling piston head pushes the air down through the cylinder, a vacuum in created behind the piston head. Also as shown in Figure 5.4 air is pulled back into the vacuum that is created. From the outside, air goes through the top vent into the top turbine and then into the cylinder. This action causes the top turbine also to spin. When the piston head is being pulled up through the cylinder, the air is pushed up and is forced out through the top of the cylinder outlet into the turbine. This action causes the top turbine to spin. As the rising piston head pushes the air up through the cylinder, a vacuum is created behind the piston head. Air travels as it is pulled into the vacuum that is created by this rising piston head. From the outside, air travels through the bottom vent into the bottom turbine this action causes bottom turbine to spin.

In the described embodiment, air travels through both the top and bottom turbines in both directions, as it is either being pushed out or pulled in. The use of the Wells Turbine allows for the turbine to spin in only one direction irrespective of which direction the air flows. The top and bottom turbines are connected directly to the generators. As the turbines spin, it spins the generator and produces electricity. This electricity is then transmitted through a cable under water to the power grid. As the up and down motion of the ocean waves are continuous, so is the see-saw action of the lever arm and the up and down motion of the piston pushing and pulling the air through the Wells Turbines producing constant electrical power. The wave motion in this case was simulated with the help of a two-stroke air piston.

As more air flows through the turbine, larger turbines can be used resulting in the production of larger amounts of power. The amount of air flowing through the turbines of this device is in direct correlation to the diameter of the cylinder as well as the height of the cylinder, more specifically the distance the piston head travels through the cylinder. As more air is displaced on the down-stroke and the up-stroke, more air is directed through the turbines. The advantages of the proposed approach is an environmental friendly and benign to sea life device for producing electrical power from ocean waves. The device can be deployed both off shore on floating platforms or attached to the sea bed where many such devices can be grouped together. Also since the device minimizes direct contact with the ocean water, but rather uses a float to drive a piston that moves air

in large volumes to run turbines, most of these parts are not in contact with the corrosive nature of sea water which helps to reduce operational costs.

5.2 Survivability

One of the reasons for the wave energy sector to lag behind other renewable energy sources is because the systems and its components have to be designed to withstand the harsh ocean environment. This young industry has already had its share of promising projects derailed by the power of the ocean. The OWAP is a point absorber type of WEC but its power take off is more like that of an Oscillating Water Column (OWC). It is designed such that it can be manufactured in port side facilities and can be readily deployed with existing technology that is in use in the oil and natural gas industry. The main components of the OWAP are free from direct contact with the ocean water, which minimizes corrosion. Further, because of its simple design, the working parts are designed on existing mechanisms and parts that can be easily manufactured using standard materials.

Being put off-line or pulled on shore to dry dock is an additional expense. In keeping with consideration for survivability of the float, which is the only working part of the OWAP that is in direct contact with sea water, it has the ability to be pulled out of the water in times of extremely high seas.

5.3 Adaptability and Cost of Electricity

A very small number of ocean wave technologies use on-shore controls to monitor and control its systems. The OWAP unit will have the ability to adapt to changing ocean conditions.

While the U.S Department of Energy has shown that wave technology has cost curves similar to wind energy and better than solar energy at this point in its development, any discussion of wave energy production has to address the levelized cost of electricity (LCOE). Low cost to build units in multitude, deploy multiple units, maintain and continually produce power will have to be shown. Finally, connection of the devices to the mainland grid will have to be accomplished economically in order to achieve a low LCOE.

Worldwide, there are 60-100 companies at some stage in the ocean energy field. Most of these companies are in Europe with only a handful in the U.S. Only one of these companies, Ocean Power Technologies²³, has a device deployed in the water. Life expectancy of the various parts of the device will be better if the parts are not exposed directly to ocean water. As stated earlier, all the working parts of the OWAP, except the buoy, are not in direct contact with the water. Most of these parts are made of steel and coated with water resistant materials.

A low cost approach to routine maintenance will also have to be addressed. Floating systems such as the Pelamis¹³ or the Powerbuoy²⁴ have little means for regular maintenance. The fixed platform of the OWAP will be accessible by boat and will provide a comfortable working environment for maintenance and routine inspection.

5.4 Environmental Impact

Those in the renewable energy field have an enormous obligation to develop energy producing devices that have minimal environmental impact. The OWAP has been designed to use only standard materials in its construction that should not letch into the ocean. There are no hydraulic lines or oil that could leak into the water. The only moving part in the water, the float, is near the water surface and will have little impact on fish or similar ocean living creatures. The part that is in the water, the platform legs, has been shown to actually attract fish acting as a sort of artificial reef.

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 Initial Experiment

An initial experiment was performed on a 1/20th scaled model of the Ocean Wave Air Piston and the following results were obtained.

	70 lbs		80 lbs		90 lbs		100 lbs		110 lbs	
-	volts	amps	volts	amps	volts	amps	volts	amps	volts	amps
	2.43	0.347	2.83	0.357	3.24	0.406	3.2	0.569	3.55	0.743
	2.76	0.44	3.25	0.558	3.26	0.678	3.25	0.701	3.02	0.79
	2.86	0.36	3.06	0.479	3.23	0.467	3.24	0.476	3.32	0.575
	2.62	0.346	2.86	0.367	3.03	0.606	3.24	0.629	3.53	0.75
	2.5	0.393	2.84	0.385	2.92	0.547	2.85	0.528	3.2	0.728
	2.76	0.412	2.72	0.528	2.66	0.466	3.16	0.589	3.29	0.711
	2.47	0.438	3.1	0.554	2.86	0.429	2.52	0.531	3.73	0.662
	2.56	0.347	2.78	0.696	2.87	0.555	2.86	0.471	3.64	0.87
	2.47	0.474	3.24	0.647	3.43	0.758	3.09	0.541	3.21	0.714
Avg.	2.60	0.40	2.96	0.51	3.06	0.55	3.05	0.56	3.39	0.73
Avg. Pov	wer (W)	1.03		1.51		1.67		1.70		2.46

 Table 6.1 Average Power Reading with Weighted Float

Table 6.1 shows the average power readings with a weighted float using an air pump to simulate the motion of the wave. It can be concluded that as the force exerted on the float

is increased there is an increase in the current, which then increases the output power of the device.

Lbs of pressure	70	80	90	100	110
Period in seconds	1.8	1.6	2	2	1.8
Avg. High Volts on Up NFPA-Piston	3.25	3.37	3.28	3.33	3.45
Avg. Low Volts on Up NFPA-Piston	2.08	2.16	2.35	2.29	2.47
Avg. Volts per run on Up NFPA-Piston	2.66	2.76	2.81	2.81	2.96
Avg. High Volts on Down NFPA-Piston	2.57	2.98	3.32	3.48	3.61
Avg. Low Volts on Down NFPA-Piston	1.99	2.08	1.86	2.01	2.21
Avg. Volts per run on Down NFPA-					
Piston	2.28	2.53	2.59	2.74	2.91
Avg. Volts per run	2.47	2.65	2.7	2.77	2.94
Avg. High Amps on Up NFPA-Piston	0.65	0.73	0.64	0.68	0.79
Avg. Low Amps on Up NFPA-Piston	0.17	0.25	0.33	0.28	0.28
Avg. Amps per run on Up NFPA-Piston	0.41	0.49	0.49	0.48	0.53
Avg. High Amps on Down NFPA-Piston	0.37	0.51	0.72	0.75	0.85
Avg. Low Amps per run on Down					
NFPA-Piston	0.13	0.23	0.12	0.17	0.22
Avg. Amps on Down NFPA-Piston	0.25	0.37	0.42	0.42	0.53
Avg. Amps per run (A/run)	0.33	0.43	0.45	0.48	0.53
Avg. power in watts per run (W/run)	0.8151	1.1395	1.215	1.3296	1.5582

Table 6.2- Average Power Readings with 2-stroke Piston Attached to Float

The above table shows the average power readings of the device when a 2-stroke piston is attached at the bottom of the float to simulate the up and down motion of the wave. The table also shows the current and voltage readings on both the up stroke and down stroke of the piston.

6.2 ANSYS Simulation Results



6.2.1 2-D Model of OWAP

Figure 6.1 Velocity vector of airflow through the piston.

Figure 6.1 describes the velocity vector of airflow through the piston here the maximum velocity of air is 10.136 m/sec with the input pressure equal to standard air pressure in SI units which is 101.35 kPa.



Figure 6.2 Stagnation Pressure inside piston.

2-D Model of OWAP with 16 inch Outlet



Figure 6.3 Velocity of airflow through the piston with a 16-inch outlet.



Figure 6.4 Velocity vector of airflow through the piston with 16-inch outlet.

Figure 6.3 and Figure 6.4 shows change in velocity and the velocity vector of airflow through the piston. In Figure 6.3 it can be observed that the maximum velocity is 18.705 m/sec and Figure 6.4 describes the behavior of the air velocity vector inside the piston, the input pressure for both cases is equal to standard air pressure in SI units which is 101.35 kPa. The Ansys Code for figures 6.1 to 6.4 can be found in Appendix A.1.



Figure 6.5 Air Pressure inside the piston with 16-inch outlet.



Figure 6.6 Stagnation Pressure inside piston with 16-inch outlet.

Figure 6.5 and Figure 6.6 shows pressure and stagnation pressure inside the piston. In Figure 6.5 it can be observed that the maximum pressure is 186.719 kPa and in Figure 6.6, stagnation pressure is 213.578 kPa. The input pressure for both cases input to the piston is equal to standard air pressure in SI units, which is 101.35 kPa. The Ansys Code for Figures 6.5 and 6.6 can be found in Appendix A.1.



6.2.2 3-D Model of OWAP Piston

Figure 6.7 3-D Model of Piston with 16-inch outlet.

The Ansys Source code for Figure 6.7 can be found in Appendix A.2. This is a 3-D model of the air piston.

3-D Model of OWAP Piston with 8-inch Outlet



Figure 6.8 Velocity vector of airflow through OWAP Piston with 8-inch outlet.



Figure 6.9 Pressure within OWAP Piston with 8-inch outlet.

Figure 6.8 and Figure 6.9 shows change in velocity and the velocity vector of airflow through the piston in 3-D. In Figure 6.8 it can be observed that the maximum velocity is 32.859 m/sec and in Figure 6.9 it can be observed that the maximum pressure is 503.311 kPa for both cases input to the piston is equal to standard air pressure in SI units, which is 101.35 kPa. The Ansys Code for figures 6.8 to 6.9 can be found in Appendix A.3.

3-D Model of OWAP Piston with 16-inch Outlet



Figure 6.10 Velocity vector of airflow through OWAP Piston with 16-inch outlet.



Figure 6.11 Pressure within OWAP with 16-inch outlet.

Figure 6.10 and Figure 6.11 shows change in velocity and the velocity vector of airflow through the piston in 3-D. In Figure 6.8 it can be observed that the maximum velocity is 48.035 m/sec and in Figure 6.9 it can be observed that the maximum pressure is 1028 kPa for both cases input to the piston is equal to standard air pressure in SI units, which is 101.35 kPa. The Ansys Code for Figures 6.10 to 6.11 can be found in Appendix A.3.

6.2.3 3-D Model of OWAP Lever Arm Mechanism



Figure 6.12 3-D Model of Lever Arm.

The Ansys Source code for Figure 6.12 can be found in Appendix A.4.

6.3 Mathematical Analysis of Lever Arm

In order to find the input force to the piston a mathematical model of the lever arm is discussed below.



Figure 6.13 Lever arm with forces.

 L_1 = Length of arm form the end attached to buoy to the pivot

 L_2 = Length of arm from pivot to the end attached to the piston

 L_3 = Length of arm from pivot to the mid point of length L_2

 F_b = Force acting on lever arm due to buoy

mg = Force acting at the mid point of L_2

From Figure 6.13

$$\sum M_0 = I \frac{\partial^2 \theta}{\partial t^2}$$

$$F_b L_1 + mgL_3 = I \frac{\partial^2 \theta}{\partial t^2}$$

Lets assume the lever arm to be a beam of

- $L = Length \ of \ beam(\ L_1 + L_2 \)$
- W = Width of the beam

D = Thickness of the beam

M = Mass of the beam





The moment of inertia of the beam is given as

$$I = I_g + mL_3^2$$

Where
$$I_g = \frac{1}{12}M(D^2 + L^2)$$

Therefore
$$\frac{\partial^2 \theta}{\partial t^2} = \frac{F_b L_1 + mgL_3}{\frac{1}{12}m(D^2 + L^2) + mL_3^2}$$

Using the above formula the angular velocity θ is calculated.

50

In order to find the force F_a , θ is evaluated in three different cases,

Case 1: When $\theta = 0$



Figure 6.15 Forces acting on Lever arm when $\theta = 0$ degrees.

From Figure 6.15 using summation of forces we get

$$-\mathbf{N} = \mathbf{M}_{p}\mathbf{A}_{r}$$
$$\mathbf{F}_{a} = \mathbf{M}_{p}\mathbf{A}_{o} - \mathbf{mg}$$

Where

 M_p = Mass of the lever arm on the piston side.

 A_0 = Acceleration of the lever arm in the Y direction

 A_r = Acceleration of lever arm in the X direction





Figure 6.16 Forces acting on Lever arm when $\theta < 0$ degrees.

From Figure 6.16 using summation of forces we get

For the positive F_a direction

$$F_a = M_p A_o$$
$$N \sin \theta + F_a + mg \cos \theta = M_p A_a$$

For the negative F_a direction

$$F_a = M_p A_r$$
$$mg \sin \theta - N \cos \theta = M_p A_r$$





Figure 6.17 Forces acting on Lever arm when $\theta > 0$ degrees.

From Figure 6.17 using summation of forces we get

For the positive F_a direction

$$F_a = M_p A_o$$

$$F_a + mg\cos\theta - N\sin\theta = M_p A_o$$

For the negative F_a direction

$$F_a = M_p A_r$$
$$-mg\sin\theta - N\cos\theta = M_p A_r$$

Therefore, the input to the piston is given by



Figure 6.18 Input to the piston.

The input to the piston = $F_a + M_p g$

CHAPTER 7

CONCLUSIONS

7.1 Ocean Wave Air Piston

Ocean wave power conversion technologies have made significant progress during the past five years. Despite this progress, technologies remain immature as shown by a large number of a variety of technologies and device sizes. Reliability, Operations and Management aspects and in-ocean handling become critical cost drivers which are not well understood at present, largely because of a lack of operational experience with such devices. Current cost projections and experience from offshore wind projects suggest that device size and reliability will be critical elements in driving down costs.

The ultimate determinant if an ocean wave energy converter is a success or failure is whether it can be commercially viable. In order for it to become commercially viable, it has to be able to be scaled to a meaningful size.

A 1/20th scaled model of the Ocean wave air piston was built and tested. Data such as current, voltage and power was recorded. In order to be able to successfully scale the device ANSYS software was used to create a 2-D Model, which then helped us study the air flow through the piston apart from looking at the velocity and pressure of the air flow. The velocity and pressure data obtained can then be used to calculate the power output of the device.

Also a 3-D model of the piston with a 16-inch outlet and the lever arm mechanism of the ocean wave air piston were modeled. Also included is the mathematical analysis of this lever arm and the output force that it translates to the piston head.

55

7.2 Future Work

The Ocean wave air piston device can be divided into three main parts the piston, lever arm mechanism and the buoy. The shape and size of the buoy is an important aspect of the device, as it is the part of the device that is in contact with the ocean wave. In order to better understand the design and working of this part developing an ANSYS model would provide us with the necessary data needed. Also, like any other large scale renewable energy system a final cost per watt calculation is needed in order to be able to commercially deploy such a system.
APPENDIX A

ANSYS SOURCE CODE

A.1 Ansys Source Code for a 2-D Model of Air Piston

The following is the source code in ANSYS for the simulation of a 2-D Model of the air

piston.

/PREP7 piston = 16exit = 1.3ET.1.141 /COM,----- Build 2D model starting with key-points k.1.0.0 k,2,0,(piston)*25.4/1000 k,3,0,(piston+4)*25.4/1000 k,4,piston*25.4/1000,(piston+4)*25.4/1000 k,5,piston*25.4/1000,piston*25.4/1000 k,6,(piston+1)*25.4/1000,piston*25.4/1000 k,7,(piston+1)*25.4/1000,(piston*2)*25.4/1000 k,8,(piston+1)*25.4/1000,(piston*3)*25.4/1000 k,9,(piston+1+piston)*25.4/1000,(piston*3)*25.4/1000 k,10,((piston+1+piston)+(piston/2))*25.4/1000,(piston*3piston/2+exit/2)*25.4/1000 k,11,((piston+1+piston)+(piston/2))*25.4/1000,(piston*3-piston/2exit/2)*25.4/1000 k,12,((piston+1)+piston)*25.4/1000,(piston*2)*25.4/1000 k,13,((piston+1)+piston)*25.4/1000,(piston)*25.4/1000 k,14,((piston+1)+piston)*25.4/1000,0 k,15,(piston+1)*25.4/1000,0 k,16,piston*25.4/1000.0

/COM,----- Build 2D model with lines.

L,1,2

L,2,3

L,3,4

L,4,5

L,5,6

L,6,7

L,7,8 L,8,9 L,9,10 L,10,11 L,11,12 L,12,13 L,13,14 L,14,15 L,15,16 L,16,1 L,5,16 L,6,15 L,2,5 L,7,12 L,9,12 L,6,13

/COM,----- Build areas from lines 10 promps max

A,1,2,5,16 A,2,3,4,5 A,5,6,15,16 A,15,6,13,14 A,6,7,12,13 A,7,8,9,12 A,9,10,11,12

FLDATA7, PROT, DENS, AIR-SI FLDATA7, PROT, VISC, AIR-SI

A.2 Ansys Source Code for a 3-D Model of Air Piston

The following is the source code in ANSYS for the simulation of a 3-D Model of the air

piston.

/PREP7 piston = 16exit = 1.3ET,1,141 /COM,----- Build 3-D model starting with key-points k,1,0,0 k,2,0,(piston)*25.4/1000 k,3,0,(piston+4)*25.4/1000 k,4,piston*25.4/1000,(piston+4)*25.4/1000 k,5,piston*25.4/1000,piston*25.4/1000 k,6,(piston+1)*25.4/1000,piston*25.4/1000 k,7,(piston+1)*25.4/1000,(piston*2)*25.4/1000 k,8,(piston+1)*25.4/1000,(piston*3)*25.4/1000 k,9,(piston+1+piston)*25.4/1000,(piston*3)*25.4/1000 k,10,((piston+1+piston)+(piston/2))*25.4/1000,(piston*3piston/2+exit/2)*25.4/1000 k,11,((piston+1+piston)+(piston/2))*25.4/1000,(piston*3-piston/2exit/2)*25.4/1000 k,12,((piston+1)+piston)*25.4/1000,(piston*2)*25.4/1000 k,13,((piston+1)+piston)*25.4/1000,(piston)*25.4/1000 k,14,((piston+1)+piston)*25.4/1000,0 k,15,(piston+1)*25.4/1000,0 k,16,piston*25.4/1000,0 k,17,((piston+1+piston)+piston)*25.4/1000,(piston*3-piston/2+exit/2)*25.4/1000 k,18,((piston+1+piston)+piston)*25.4/1000,(piston*3-piston/2-exit/2)*25.4/1000 k,19,((piston+1+piston)+(piston/2))*25.4/1000,(piston*3piston/2+exit/4)*25.4/1000 k,20,((piston+1+piston)+(piston/2))*25.4/1000,(piston*3-piston/2exit/4)*25.4/1000

/COM,----- Build 3-D model starting with key-points

L,1,2

L,2,3

L,3,4

L,4,5

L,5,6

L,6,7

L.7.8
L.8.9
L.9.10
L.10.11
1.11.12
1 12 13
1 13 14
1 14 15
1 15 16
L, 16, 10
1 5 16
L,0,10
125
L,Z,J
L, 7, 12
L,9,12
L,0,13
L, 10, 17
1 47 40
L,17,18
L,17,18 L,18,11

/COM,----- Build areas from Key points.

A,1,2,5,16 A,2,3,4,5 A,5,6,15,16 A,15,6,13,14 A,6,7,12,13 A,7,8,9,12 A,9,10,11,12 A,10,17,18,11

FLDATA7, PROT, DENS, AIR-SI

FLDATA7, PROT, VISC, AIR-SI

A.3 Ansys Source Code for 3-D Model of Air Piston with 8 and 16-inch Outlet

The following is the source code in ANSYS for the 3-D Model of the air piston with a 8

and 16 inch outlet.

/PREP7 piston = 16 exit = ((piston)*25.4/1000)*.156 ET,1,141

BOTTOM OUTLET

```
k,1001,((piston)*25.4/1000)*.9,0,0
k,1002,(piston)*25.4/1000,0,0
k,1003,exit+(((piston)*25.4/1000)-(((piston)*25.4/1000)*.9)),(piston)*25.4/1000,0
k,1004,exit,(piston)*25.4/1000,0
k,1005,0,0,0
k,1006,0,1,0
```

L,1001,1002 L,1002,1003 L,1003,1004 L,1004,1001

A,1001,1002,1003,1004

SWEEP AREA ABOUT AXIS PICK k1005 & k1006

BROLEANS ADD ALL VOLUMES TOGETHER

MOVE BOTTOM OUTLET

X-AXIS:0

Y-AXIS : ((piston)*25.4/1000)*3

Z-AXIS:0

TOP ELBOW

torus,(piston)*25.4/1000,((piston)*25.4/1000)*.9,.4,270,360

MOVE TOP ELBOW

X-AXIS : -(piston)*25.4/1000

Y-AXIS : ((piston)*25.4/1000)*3 Z-AXIS : 0

OFF-SET WP BY INCREMENTS -y 90

SECONDARY CYLINDER

cylind,(piston)*25.4/1000,((piston)*25.4/1000)*(.9),(piston)*25.4/1000,(piston*25.4/1000)*4,0,360

MOVE SECONDARY CYLINDER

X-AXIS: 0

Y-AXIS : ((piston)*25.4/1000)*2

Z-AXIS:0

OFF-SET WP BY INCREMENTS +y 90

BOTTOM ELBOW

torus,(piston)*25.4/1000,((piston)*25.4/1000)*.9,.4,90,270

MOVE ELBOW

vgen,0,1,((piston)*25.4/1000)*4

X-AXIS : -((piston)*25.4/1000)*4

Y-AXIS: .4

Z-AXIS:0

OFF-SET WP BY INCREMENTS -y 90

MAIN CYLINDER

cylind,(piston)*25.4/1000,((piston)*25.4/1000)*.9,0,((piston)*25.4/1000)*4,0,360

TOP OUTLET

cylind,(piston)*25.4/1000,((piston)*25.4/1000)*.8,0,-((piston)*25.4/1000)*.5,0,330

CYLINDER TOP

cylind,(piston)*25.4/1000,((piston)*25.4/1000)*.1,-((piston)*25.4/1000)*.5,(-((piston)*25.4/1000)*.5)-((piston)*25.4/1000)*.1,0,360

MERGE ALL ITEMS

PISTON RING

cylind,(((piston)*25.4/1000)*.9)*.9,0,((piston)*25.4/1000)*3,(((piston)*25.4/1000)* 3)-((piston)*25.4/1000)*.1,0,360

PISTON ROD

cylind,((piston)*25.4/1000)*.09,0,(((piston)*25.4/1000)*3)-((piston)*25.4/1000)*.1,-((piston)*25.4/1000)*6,0,360

BROLEANS ADD VOLUMES RING & ROD

A.4 Ansys Source Code for 3-D MODEL of Lever Arm Mechanism

The following is the source code in ANSYS for the simulation of a 3-D Model of the

Lever arm mechanism.

/PREP7 piston = 16 exit = ((piston)*25.4/1000)*.156 ET,1,141

/COM,-----BUILD ARM WITH HOLES

block,-((piston)*25.4/1000)*.8,((piston)*25.4/1000)*2.6,-((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.3,0,((piston)*25.4/1000)*.15

cylind,((piston)*25.4/1000)*.1,0,0,((piston)*25.4/1000)*.15,0,360

CYL5,-((piston)*25.4/1000)*.425,((piston)*25.4/1000)*(-.05),-((piston)*25.4/1000)*.375,((piston)*25.4/1000)*.05,((piston)*25.4/1000)*.15

CYL5,((piston)*25.4/1000)*2.425,((piston)*25.4/1000)*(-.05),((piston)*25.4/1000)*2.375,((piston)*25.4/1000)*.05,((piston)*25.4/1000)*.15

/COM,-----SUBTRACT BOOLEAN, VOLUMES

MOVE ARM

ZAXIS -((piston)*25.4/1000)*.075

/COM,-----BUILD BEARING

block,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.75,((piston)*25.4/1000)*.75-((piston)*25.4/1000)*.2

cylind,((piston)*25.4/1000)*.1,0,((piston)*25.4/1000)*.75,((piston)*25.4/1000)*.75-((piston)*25.4/1000)*.2,0,360

/COM,-----SUBTRACT HOLE BOOLEANs, VOLUMES

/COM,----COPY BEARING ON Z AXIS

Z AXIS : -((piston)*25.4/1000)*(2*.65) /COM,-----BUILD ROD cylind,((piston)*25.4/1000)*.1,0,((piston)*25.4/1000)*.75,-((piston)*25.4/1000)*.75,0,360

/COM,-----BUILD SMALL BEARING

blc5,((piston)*25.4/1000)*.4,0,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.1

CYL5,-((piston)*25.4/1000)*.425,((piston)*25.4/1000)*(-.05),-((piston)*25.4/1000)*.375,((piston)*25.4/1000)*.05,((piston)*25.4/1000)*.1

/COM,----SUBTRACT BOOLEAN, VOLUMES

/COM,-----MOVE SMALL BEARING Z AXIS

Z AXIS : ((piston)*25.4/1000)*.25

/COM,-----COPY SMALL BEARING

Z AXIS : -(piston)*25.4/1000*(.5+.1)

/COM,-----SMALL ROD

cyl4,-

((piston)*25.4/1000)*.4,0,((piston)*25.4/1000)*.05,0,360,(piston)*25.4/1000*.7

/COM,-----MOVE SMALL ROD Z AXIS

Z AXIS : ((piston)*25.4/1000)*.35

/COM,----COPY AND MOVE SMALL BEARING AND ROD

MOVE VOLUMES (vgen) ALONG Y_AXIS

Y AXIS : -((piston)*25.4/1000)*2.8

/COM,-----CONNECTING TO FLOAT

block,-((piston)*25.4/1000)*.45,((piston)*25.4/1000)*.35,((piston)*25.4/1000)*.15,-((piston)*25.4/1000)*(2.8.15),((piston)*25.4/1000)*.35,((piston)*25.4/1000)*.35-((piston)*25.4/1000)*.1

/COM,-----COPY SQUARE ROD AND

MOVE VOLUMES (vgen) ALONG Z_AXIS Z AXIS : -(piston)*25.4/1000*(.5+.1)

/COM,-----MAKE PARTIAL CYLINDER

CYL4,0,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*(2.425-.15),320,((piston)*25.4/1000)*(2.425+.15),359.9,((piston)*25.4/1000)*.075

/COM,-----CREATE HOLES

CYL5,((piston)*25.4/1000)*2.425,((piston)*25.4/1000)*(.05),((piston)*25.4/1000)* 2.375,((piston)*25.4/1000)*.05,((piston)*25.4/1000)*.075

CYL5,((piston)*25.4/1000)*1.9,((piston)*25.4/1000)*(1.2),((piston)*25.4/1000)*2,((piston)*25.4/1000)*(-1.1),((piston)*25.4/1000)*.075

/COM,-----SUBTRACT BOOLEANs, VOLUMES

/COM,-----MOVE HORSEHEAD

ALONG Z AXIS : ((piston)*25.4/1000)*(.375-.1)

/COM,----COPY HORSEHEAD

ALONG Z AXIS : -(piston)*25.4/1000*(2*.3125){.3125=(.7-.075)/2}

/COM,----COPY AND MOVE SMALL ROD

MOVE VOLUMES (vgen) ALONG X_AXIS ((piston)*25.4/1000)*2.8

/COM,-----BUILD SMALL ROD 2

CYL5,((piston)*25.4/1000)*1.9,((piston)*25.4/1000)*(1.2),((piston)*25.4/1000)*2,((piston)*25.4/1000)*(-1.1),((piston)*25.4/1000)*.7

/COM,----COPY AND MOVE SMALL ROD 2 ON Z AXIS

-((piston)*25.4/1000)*.35

/COM,-----BUILD BEARING FOR ROD 2

blc5,((piston)*25.4/1000)*.4,0,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.3,((piston)*25.4/1000)*.1

CYL5,-((piston)*25.4/1000)*.425,((piston)*25.4/1000)*(-.05), ((piston)*25.4/1000)*.375,((piston)*25.4/1000)*.05,((piston)*25.4/1000)*.1 /COM,-----SUBTRACT BOOLEAN,VOLUMES

/COM,-----MOVE SMALL BEARING X,Y,Z AXIS

X AXIS : ((piston)*25.4/1000)*2.35 Y AXIS : -((piston)*25.4/1000)*1.15 Z AXIS : -((piston)*25.4/1000)*0.05

REFERENCES

- 1. United States Department of Energy, www.usdoe.org, December 2009
- 2. Chris Carroll, In hot water, National Geographic, vol. 208, no.2, Aug. 2005, pp. 72-85.
- Richard Boud, Status and Research and Development Priorities, Wave and marine current energy, UK Dept. of Trade and Industry (DTI), DTI Report # FES-R-132, AEATReport # AEAT/ENV/1054, United Kingdom, 2003.
- 4. Jennifer Guinevere Vining, Ocean Wave Energy Converters: overview, legal and economic aspects, and direct-drive power take-off, University of Wisconsin Madison, January 2007.
- 5. Waves and Swell, NOAA Library's oceanic and atmospheric sciences, http://www.lib.noaa.gov/docs/windandsea6.html#waves, February 2010.
- 6. Wave energy paper, IMech and European directory of renewable energy, Trident Energy Limited, 1991.
- A. Sarmento, A. Melo, and M. Pontes, The Influence of the Wave Climate on the Design and Annual Production of Electricity by OWC Wave Power Plants, Journal of Offshore Mechanics and Arctic Engineering, ASME, vol. 125, May 2003, pp. 139-144.
- 8. J.F. Manwell, J.G. McGowan, A.L. Rogers, Wind Energy Explained: Theory, Design, and Application. John Wiley & Sons Inc., England, 2002.
- 9. A. Brito-Melo, L.M.C. Gato, A.J.N.A. Sarmento, "Analysis of Wells turbine design parameters by numerical simulation of the OWC performance," Ocean Engineering, vol. 29, Aug. 2002.
- 10. http://www.pico-owc.net/files/33/cms_576d026223582a390cd323bef4bad026.jpg, January 2010
- 11. "Marine Energy Challenge," The Carbon Trust, http://www.thecarbontrust.co.uk, January 2010.
- 12. C. Carroll and M. Bell, Wave Energy Converters Utilizing Pressure Differences, US Patent 6,933,623, to Ocean Power Technologies, Inc., Patent and Trademark Office, Washington, D.C., 2004.13. http://www.gitam.edu/eresource/nano/NANOT ECHNOLOGY/role_of_bottomup _and topdown_a.htm figure top-down March 2010.

- H. Polinder, B. Mecrow, A. Jack, P. Dickinson, and M. Mueller, Conventional and TFPM Linear Generators for Direct-Drive Wave Energy Conversion, IEEE Transactions on Energy Conversion, vol. 20, no. 2, June 2005.
- Richard Boud, Status and Research and Development Priorities, Wave and Marine Current Energy, UK Dept. of Trade and Industry (DTI), DTI Report # FES-R-132, AEAT Report # AEAT/ENV/1054, United Kingdom, 2003.
- 15. http://www.sustainabilityninja.com/wp-content/uploads/2009/12/oyster-wave-energy, February 2010.
- 16. http://www.greenoceanenergy.com/index.php/about/Ocean Treader, February 2010.
- 17. http://www.greenoceanenergy.com/index.php/wave-treader, February 2010.
- 18. http://pelamiswave.websitedesign.co.zm/media/boat_copy1.gif, February 2010.
- 19. Bringing Ocean Power to the World, *Seabased Energy AB*, http://www.seabased.com, January 2010.
- 20. http://www.seabased.com/images/stories/energyeng2, January 2010.
- University of Michigan College of Engineering, Wave Energy Conversion, Department of Naval Architecture and Marine Engineering, www.name.engin.umich.edu, February 2010.
- 22. Archimedes Wave Swing Theory, www.wavesing.com, February 2010.
- 23. Ocean Power Technologies, http://go635254.s3.amazonaws.com /cleantechnica/files /2009/10/opt.jpg, February 2010.
- 24. Wave Aquabouy, http://www.portlandmonthlymag.com /image_cache /assets/0000 /2016 /0807_pg101_wave_aquabuoy2.jpg, March 2010.
- 25. Oscillating Water Column, http://www.physics-edu.org/tech/floating5.gif, January 2010.
- 26. Ocean wave air piston (US Patent No.: 7,468,563), Joseph Torch, December 23 2008.