AquaBuOY – The Offshore Wave Energy Converter

Numerical Modeling and Optimization

Alla Weinstein, Göran Fredrikson, Lennart Claeson, Jan Forsberg, Mary Jane Parks – AquaEnergy Group, USA
Dr. Kim Nielsen, Morton Sand Jenses – RAMBØLL, Denmark
Dr. Kambiez Zandiyeh – DUNLOP Oil & Marine, UK
Prof. Peter Frigaard, Morten Kramer, Thomas Lykke Andersen – Aalborg University, Denmark

AquaEnergy Group Ltd.
PO Box 1276
Mercer Island, WA 98040, USA
aqua@aeg-ltd.com

Abstract

This paper describes development of the mathematical model simulating ocean performance of an offshore wave energy point absorber device - AquaBuOY. The AquaBuOY is the next generation of the technology, based on the IPS point absorber system and the hose pump, both of Sweden.

AquaEnergy Group Ltd., USA, is developing the system in cooperation with RAMBØLL, Denmark. In March 2003 the Danish Energy Authority awarded a grant for a design study that includes development of the numerical model for the AquaBuOY operation, experimental testing and design optimisation.

The scale model tests will be carried out at Aalborg University, Denmark in order to optimise the device design, operation and installation configuration with the goal of minimising system footprint.

The paper provides an overview of the numerical modelling used in establishing system operating characteristics. The experimental results from the model tests on mooring forces under survival conditions will be presented during the conference in conjunction with different footprint configurations and different mooring systems. Finally the performance data based on theoretical and experimental results will be presented for the AquaBuOY in five representative generic sea states.

Ocean energy and offshore wave energy conversion in the United States is at a significant milestone. During the next year, ocean energy technology developers and energy officials have the potential to deploy pilot scale ocean power plants and transition to commercial plants in the US. This capability comes at a time of increased interest in ocean energies at the National Academy of Sciences and the US Department of Energy. AquaEnergy will conclude its presentation with a brief overview of current legislation affecting the industry. In 2004, ocean scientists, engineers, and developers can continue to lay the groundwork for government spending and interest in ocean energies.

ACKNOWLEDGEMENT

Several ideas for combining the two predecessor technologies (the Hose Pump and the IPS Buoy) into AquaBuOY system, originated with Bengt-**O**lov **Sjöström [Technocean], who, together with Y**ury **Avrutin, a co-founder of AquaEnergy Group, lost their lives while surveying a location for an offshore power plant in northern California on December 11, 2001. AquaEnergy Group has commemorated these gentlemen by using their given names initials, to name the combined system –** Aqua**BuOY**.

I. INTRODUCTION

Nineties has been a decade for greater appreciation of the detrimental effects from continues, and increasing, use of fossil fuels. Unfortunately, global warming is no longer a myth created by a few scientists, but rather a recognized man-made phenomenon. One renewable energy resource – ocean waves – is yet to be exploited to its initial potential. Wave energy has been estimated to have a potential of greater than 2 TW [1]. There are several regions around the world with sufficient wave energy resource that can be harvested in a cost-efficient manner. The last six years have seen a resurgence of interest in wave energy throughout the world, with several companies currently developing and deploying new devices. This paper presents system development and optimization efforts of AquaEnergy Group, Ltd. (AquaEnergy) - an ocean wave company - in cooperation with RAMBØLL, Denmark under funding provided by the Danish Energy Authority.

II. THE COMPANY

AquaEnergy is a technology holder and a developer of offshore power plants for the production of low-cost, renewable electricity from ocean wave energy. Ocean trials demonstrated successful resolution of major issues -- survivability, cost, and environmental impact -- historically afflicting the wave energy industry.

The company vision is to become a major supplier of renewable electrical power plants, generating energy from vast resources of the ocean. As a first step toward achieving this goal, AquaEnergy has formed an alliance with RAMBØLL, a Denmark engineering company, to optimize the third generation technology – AquaBuOY.

AquaEnergy has formed a consortium[1] for the installation of the Nation's first 1MW offshore power plant in Makah Bay, WA that is currently undergoing detail design and environmental permitting.

In support of the Makah Bay offshore pilot power plant, AquaEnergy has worked with the Washington State congressional delegation to assure that ocean energies will be a recognized renewable resource and will be included in the DOE office of Renewable Energy and Efficiency program.

A. *The Offshore Power Plant*

AquaEnergy's offshore plants consist of patented[2] wave energy converters – AquaBuOY - based on proven, survivable, buoy technology. Small, modular devices are moored several miles offshore where the wave resource is the greatest - no sensitive (and expensive) shore real estate is required for the system. AquaEnergy offshore power plants, Fig. 1, are non-polluting and have been shown to benefit the marine environment by providing artificial reef habitat.

Fig. 1. Artist rendition of an AquaBuOY offshore power plant

The offshore power plants are scalable from hundreds of kilowatts to hundreds of megawatts, able to supply power as a distributed generation to coastal communities, or a central generation for large population centers pollution-free and visually unobtrusive.

Fabrication and installation of offshore power plants are performed using local labor, bringing sustainable jobs to the community.

AquaEnergy projects for small plant (< 5MW) capital costs to be in the range of $1500 to $2000 per kW, while capital costs for large plants (over 10MW) are projected in the range of $500 to $1000 per kW. Electricity production costs will vary with resource and siting requirements. For larger plants at good sites, they are projected to be as low as $0.03/kWh, while many sites will produce costs in the $0.04 - $0.07/kWh range.

B. *Current Status*

Wave energy research and development is presently at a pre-commercial stage with two shore-based installations and no offshore installations.

Wavegen, UK has installed two shore-based operating systems - one in the Azores, Portugal, and the second on the Island of Islay, UK.

Offshore systems like IPS Buoy, Sweden, and Mighty Whale, Japan have provided some operating experience. A Wave Dragon, Denmark, is presently undergoing ocean trials and in the coming year additional prototypes are expected to be installed - UK – Ocean Power Delivery & Wavegen); Portugal – Archimedes Wave Swing.

In US, a consortium is working on the permitting and installation of the offshore wave energy power plant in Makah Bay, WA.

In California, CA State University in San Diego is working on ocean wave energy resource assessment in California.

The U.S. Congress 2003 Energy Bill now recognizes ocean energy as a renewable energy resource, along with biomass, solar, and wind resources, eligible for federal incentives for renewable energy production.

C. *Technology*

Fig. 2. IPS Buoy removal after ocean trials

AquaEnergy's wave energy converters rely on the heaving buoy concept developed and patented by AquaEnergy's partner IPS AB of Sweden – Fig. 2. Energy transfer from the motion of ocean waves takes place by converting the vertical component of wave kinetic energy into pressurized water flow by means of two opposing, full-cycle, hose pumps. Pumped water is directed into a conversion system consisting of a Pelton turbine driving a conventional electrical generator. Wave energy converters are located offshore where wave resources are the greatest and thus, they do not have the resource power density limitations associated with onshore installations. Offshore power plants are easily scalable to any size by adding as many buoys as required.

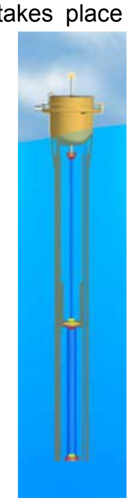

Fig. 3. AquaBuOY

Converters are installed offshore, in the water depth of 150 to 250 feet. The total number of converters determines the plant capacity. Along the U.S. and Canadian West Coast, each device is expected to generate up to 250 kW.

[1] The consortium includes the Makah Indian Nation, Clallam County PUD and the Northwest Energy Innovation Center, consisting of the Bonneville Power Administration, Energy Northwest, Pacific Northwest National Laboratory and Washington State University

[2] Eight patents have been issued on various parts of the system in major markets, including the U.S., Europe, Japan, and Australia.

Each buoy is approximately 15 feet in diameter. Converters are sized according to the energy content of the prevailing seas at the installation site.

AquaBuOY, Fig. 3, wave energy converter consists of two structural components—buoy body and acceleration tube. As the buoy moves up and down on the surface of the waves, water is drawn in and out of the submerged acceleration tube. The acceleration tube is a vertical hollow cylinder attached to the body of the buoy and open at both ends to allow unimpeded entry and exit of seawater in either direction. Alternating movement of water inside the acceleration tube acts upon piston, thus moving it out of phase relative to the motion of the body of the buoy. The motion of the piston is then converted to useful energy by a power takeoff system (PTO) – hose pumps. Conversion to electricity takes place either offshore or inland, depending on system configuration.

III. AQUABUOY PERFORMANCE MODELING

The main objective of the joint project conducted under a grant from the Danish Energy Authority is to advance the numerical (mathematical) model – MacWavePower™, previously developed by Dr. Bengt-Olov Sjöström [2 - to represent the AquaBuOY device configuration that combines the IPS Buoy [3 and two hose pumps.

The numerical model is a tool for calculating AquaBuOY critical characteristics used to accurately predict an offshore power plant performance parameters and economics.

A developed numerical model allows AquaBuOY PTO design optimization. Model testing is being carried out at the Aalborg University to verify numerical calculations. The project will demonstrate performance projections for AquaBuOY operation at selected locations – the Orkney European Marine Test Center, UK, the Faroe Islands, Denmark and Figuera da Foz, Portugal.

A. Wave Generation

1.) Irregular Waves

Irregular waves can be created from Hs / Tz pairs with optional spectral form (ISSC, PM, JONSWAP, Ochitwo peak). The method used is Auto Regressive Moving Average, ARMA [4], which gives a very good correlation to real sea waves. In the generation of a wave series the shoaling effect and the amplitude reduction due to large buoy diameters are considered. There is also a possibility to generate regular sine waves.

2.) Hilbert transform

The wave series are Hilbert transformed to obtain the instantaneous frequency and the horizontal wave components. These are used to calculate the hydrodynamic coefficients and the horizontal wave force on the structure. The amplitude reduction, both vertical and horizontal component, of the wave below surface is calculated using the dispersion relation, thus valid for deep, intermediate, and shallow water.

3.) Site Data

The site data includes water depth, water surface and bottom density, sea current profile, and wind speed. In addition to these parameters wave files with corresponding weight (occurrence) factors are included. This enables automatic calculation of produced energy during the time span of the site data.

B. Parametric study of the AquaBuOY performance

The initial design of the AquaBuOY is based on a numerical model of the system developed using MathCAD a software tool for solving the linear system model in the frequency domain.

The AquaBuOY system is modelled as two vertically oscillating masses, one mass representing the float and the other representing the enclosed water mass in the tube acting on the piston.

The forces on the float is the wave force proportional to the wave amplitude, a restoring force proportional to the displacement of the float, a hydrodynamic damping force proportional to the float velocity of the float and finally a force proportional to the acceleration of the float the factor of proportionality being the added mass.

The motion of the mass of water in the tube is assumed affected only by the force of the power takeoff system providing a force proportional the relative velocity between the float and the piston and optionally a restoring force proportional to the relative displacement is included in the model.

The force from the power take off will affect the float but in opposite direction.

In this way the system can be modelled as a spring damper system of two degrees of freedom as schematically shown below.

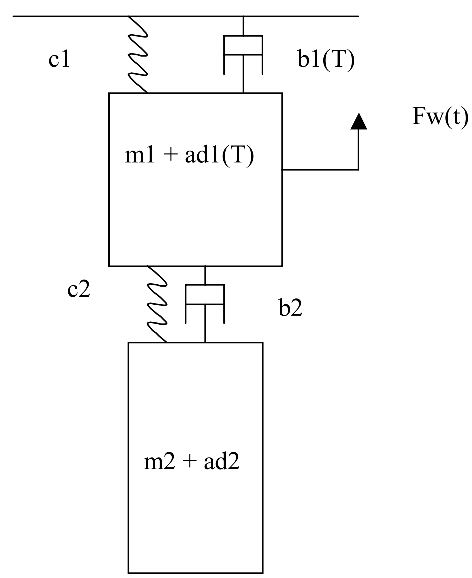

Fig. 4. Schematic representation of a spring damper system with two degrees of freedom

C. The hydrodynamic parameters:

The hydrodynamic parameters such as the non-dimensional wave exiting force, added mass and damping are functions of the non-dimensional wave period. Using a commercially available program Aqua these hydrodynamic parameters were calculated for a float of 6 m in diameter with a 2.5 m draught, disregarding the presences of the acceleration tube. Such parameters can be scaled to any float diameter with the same ratio between diameter and draught. The geometry of the resulting float is shown in Fig. 5.

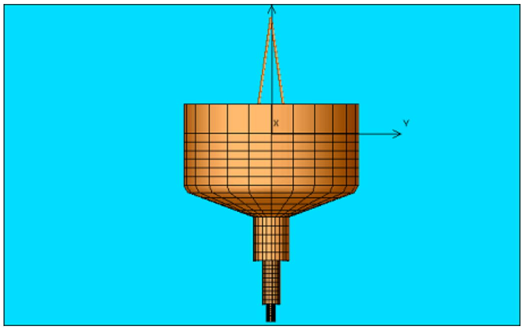

Fig. 5. Float geometry used to calculate hydrodynamic parameters

1.) The float

The vertical wave force on the float $F_w(t)$ (1.2) is assumed to vary harmonically in time proportional to the wave amplitude A and a wave exciting force fF(x) a function of the wave period, where x=T, and the float geometry and some arbitrary phase ϕ. The variation of the wave exiting force non-dimensional with the hydrostatic stiffness S of the float is shown in Fig. 6 and 7 as a function of wave period, where A_w is the water plane area.

$$S = A_w \times \rho \times g \tag{1.1}$$

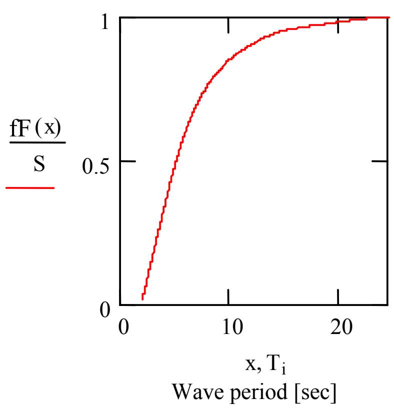

Fig. 6. Wave exciting force as a function of wave period T

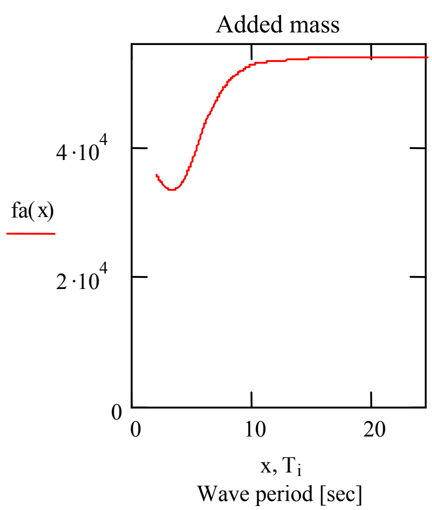

Fig. 7. Added mass [Kg] as a function of wave period.

$$F_w(t) = A \times f_1(T) \times (\cos(\omega \times t + \phi) \tag{1.2}$$

The float mass m_1, Fig. 4, represents the structural mass including ballast attached to the float. The hydrodynamic added mass ad1(T) = fa(x), where x=T, is a function of the wave period T as shown in Fig. 8.

The damping related to the radiated waves is b1(T) =fb(x), where x=T, depends on the wave period T as shown in Fig. 8.

A spring stiffness c1 = S is related to the waterline area A_w of the float.

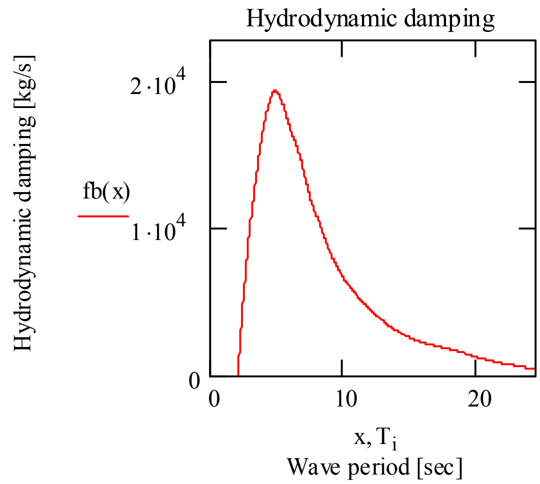

Fig. 8 Hydrodynamic damping as function of wave period.

2.) The Acceleration Tube

The mass m_2 is the mass of water in the pipe, the damping b2(cd) (1.3) is related to the power takeoff and represents a coefficient that multiplied with the relative velocity between the float and "piston" in the pipe provides a force that will dampen the relative motion. The coefficient cd is assumed constant, but its value has to be selected in order to optimise the power output.

$$b2(cd) = cd \times \sqrt{S \times Mf} \tag{1.3}$$

The spring stiffness c_2 can represent a force in the PTO system proportional to the relative displacement between the piston and the float, a force that will return the piston to a equilibrium position. Initially c_2 is set to zero.

D. Solving the linear system mode

The motion of the two masses in monochromatic waves of amplitude A and period T can be written on Matrix form – (1.4)

$$X(T,A,cd) := \left[C - \left(\frac{2\cdot\pi}{T}\right)^2 \cdot M(T) - i\cdot\frac{2\cdot\pi}{T}\cdot B(cd,T)\right]^{-1} \cdot \begin{pmatrix} A\ f1(T)\cdot e^{i\cdot\phi 1} \\ 0 \end{pmatrix}$$

(1.4), where:

$$C = \begin{Bmatrix} c_1 + c_2 & -c_2 \\ -c_2 & c_2 \end{Bmatrix}$$

$$M(T) = \begin{Bmatrix} m_1 + ad1(T) & 0 \\ 0 & m_2 + ad2 \end{Bmatrix}$$

$$B(cd,T)=\begin{Bmatrix} b_1(T)+b_2(cd) & -b_2(cd) \\ -b_2(cd) & b_2(cd) \end{Bmatrix}$$

The float motion and the piston motion as a function of the wave period T, amplitude A and damping coefficient cd can be written as:

$X(T,A,cd)_0$	Float motion
$X(T,A,cd)_1$	Piston motion

The amplitude of the relative motion between the float and the piston in the tube can be written as:

$$xamp(T,A,cd) = |X(T,A,cd)_0 - X(T,A,cd)_1|$$

Input data regarding the dimensions of the float and tube geometry is specified.

Float diameter:	6 m
Float draught:	2.5 m
Float mass:	71 ton
Tube diameter:	4 m
Tube length:	30 m
Water mass in tube:	382 ton

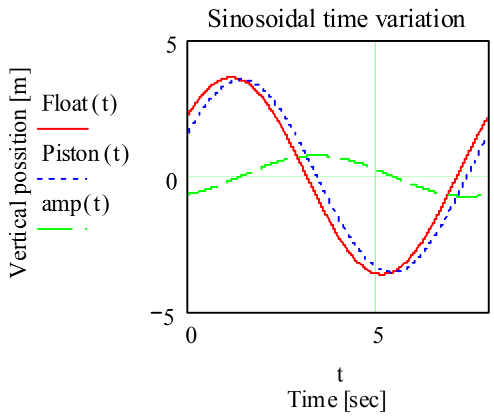

Fig. 9 Time variation of float, piston and relative motion

The motion of the Float(t), the Piston(t) in the tube and the relative motion amp(t) of the system in a regular wave of amplitude 1 meter, a wave period 8 sec and damping factor cd =10 is shown in Fig. 9.

It can be seen that at this wave period the amplitude response of the float and the piston is almost the same, about 4 times the wave amplitude, but with a slight phase delay, such that the amplitude of the relative motion between the piston and the float is about 1 meter.

The amplitude response depends on the wave period. The largest resonant response for the chosen geometry is about 4.5 in wave periods of about 8.5 seconds. The wave period in which the system resonates depends on the geometry of the system and the damping factor of the PTO.

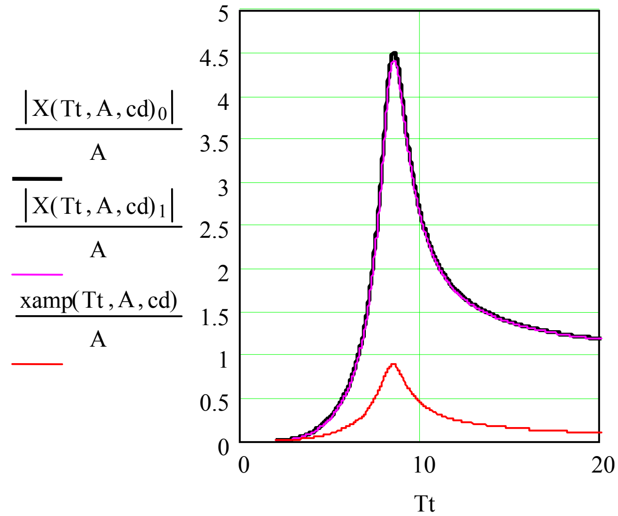

Fig.10. Response amplitude operators of the float piston and relative motion

An important feature of the AquaBuOY is the “working” range of wave periods for the float and tube, depending on the damping between the piston and the float.

Case 1: No damping

If there is no damping on the piston motion, the float will respond as shown by the circle line on Fig. 11 with corresponding amplitude of about 3.5 times the wave height with a period of 3.5 seconds. With no damping forces, the piston will not move as there is no force to activate its movement. The relative motion will therefore be equal to the motion of the float.

Case 2: Very large damping

If the damping is very large (say cd=1000) the float and the piston will move as a solid mass having the same corresponding amplitudes with a maximum of about 8 times the wave height with a longer wave period of about 5 seconds.

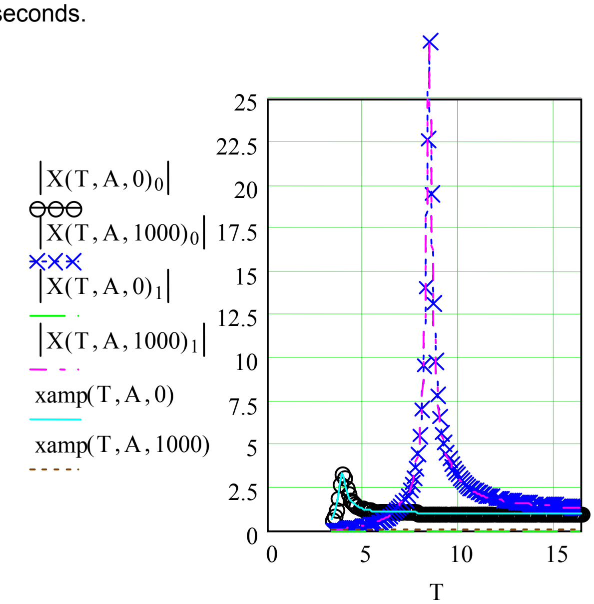

Fig. 11. The float and the acceleration tube response as a function of damping forces on the piston

$$T_{max} = 2\pi \cdot \sqrt{\frac{m_1 + m_2}{S}} \quad (1.5)$$

$$T_{min} = 2\pi \cdot \sqrt{\frac{m_1}{S}} \quad (1.6)$$

In both cases above the absorbed power is zero. The wave energy can be absorbed from the waves in the range of wave periods between T_{min} (1.6) and T_{max} (1.5). Off course response amplitudes of 25 times the wave height are unrealistic; however it clearly indicates that the AquaBuOY as a point absorber has the ability to oscillate in resonance.

The next section will address the amount of energy the system can absorb from the waves depending on the damping provided by the PTO.

E. Calculations of the Absorbed Power and Capture Width Ratio in Regular Waves

The average absorbed power $P_{abs,}$ (1.7) or the useful power P_u (1.8) the AquaBuOY can absorb over a wave cycle depends on the damping force b2(cd)*vr(t) times the relative velocity vr(t)=xamp(T,A,cd)ω(T)sin(ω(T)t) integrated over a wave period:

$$\text{Pabs}(T,A,cd) := \frac{1}{T}\cdot\int_0^T b2(cd)\cdot(\text{xamp}(T,A,cd)\cdot\omega(T)\cdot\sin(\omega(T)\cdot t))^2\, dt$$

(1.7) or

$$\text{Pu}(T,A,cd) := \frac{1}{2}\, b2(cd)\cdot\omega(T)^2\cdot\text{xamp}(T,A,cd)^2 \quad (1.8)$$

For the incoming power in deep water regular waves over the diameter D of the float, the capture width ratio becomes:

$$\varepsilon(x,cd) := \frac{\text{Pu}(x,1,cd)}{\text{Pw}(x,1)} \quad (1.9)$$

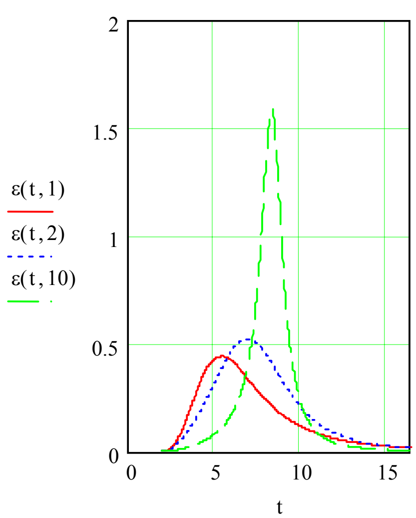

Fig. 12. Regular wave system efficiencies for various values of a damping factor cd as a function of the wave period T=t

The green curve on Fig. 12 indicates that in wave periods of about 8 seconds the float will absorb energy from a wave front at 1.5 times the diameter of the float. Compared to the figure of the damped response of the float this is achieved by oscillations of about 4.5 times the wave amplitude with a relative motion response of the piston of only about 0.8 times the wave height.

The relative motion of the piston is dependent on the tube diameter and length. The performed parametric study and the resulting geometry presented here have been chosen to produce an average of 250 kW of power in severe sea conditions of 5 meter significant wave height. In addition the performance in a range of sea states from 1 to 5 meters has been calculated using the linear model below in combination with statistical wave from site locations of interest for future deployment.

F. Modelling of irregular wave conditions.

The significant wave height (Hs) is measured in meters and the average wave period (T02) in seconds. Both are determined from a site scatter diagrams. The most likely average wave period in a sea state Hs and the linear relation are calculated using (1.10)

$$\text{Pw}(T,A) := \frac{\rho\cdot g^2}{32\pi}(2\cdot A)^2\cdot fT(T)\cdot D \quad (1.10)$$

For calculation purposes, the Hs was calculated based on the offshore site conditions at the Orkney Marine Test Center:

$$\text{T02}(Hs) := Hs\cdot 0.668 + 4.84 \quad (1.11)$$

The sea state is modelled by a PM spectrum (Pierson Moscovits) defined by two parameters As (1.12) and Bs (1.14) both functions of Hs and Tp(Hs) where the peak period of the spectrum is defined as:

$$\text{As}(Hs) := \frac{5\cdot Hs^2\cdot\left(\frac{1}{\text{Tp}(Hs)}\right)^4}{16} \quad (1.12)$$

$\text{Tp}(Hs)=1.4 * T_{02}(Hs)$ (1.13)

$$\text{Bs}(Hs) := \frac{5\cdot\left(\frac{1}{\text{Tp}(Hs)}\right)^4}{4} \quad (1.14)$$

$$S(t,Hs) := \frac{\text{As}(Hs)}{\left(\frac{1}{t}\right)^5}\cdot\exp\left[\frac{-\text{Bs}(Hs)}{\left(\frac{1}{t}\right)^4}\right] \quad (1.15)$$

The wave power at each period (t) of the spectrum can be calculated as a value of the spectrum times the group velocity of the wave (1.16)

$$P(t,Hs) := S(t,Hs)\cdot\frac{g}{2\cdot\left(2\frac{\pi}{t}\right)} \quad (1.16)$$

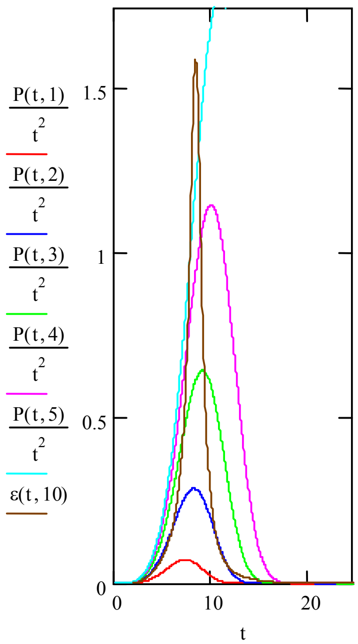

Fig. 13. Distribution of power over wave periods in sea states with significant wave heights from 1 to 5 meters, including system efficiency, ε.

The average wave power per unit crest width can be derived by integration of the power over all wave period components of the spectrum (1.17).

$$Pave(Hs) := \int_{0.04}^{10 \cdot D^{0.5}} P(t, Hs) \cdot \left(1 \cdot t^{-2}\right) \cdot g \, dt \qquad (1.17)$$

The average absorbed power in a sea state with significant wave height Hs and applied damping factor cd can be calculated by integrating the efficiency and power over the spectrum range of wave periods (1.18).

$$Pabs(cd, Hs) := \int_{Tfirst}^{Tlast} P(t, Hs) \cdot \left(1 \cdot t^{-2}\right) \cdot g \cdot \varepsilon(t, cd) \cdot D \, dt \qquad (1.18)$$

The average capture width ratio in a sea state Hs = 2 meter with applied damping factor cd=10 can be expressed by (1.19).

$$\frac{Pabs(10, 2)}{Pave(2) \cdot D} = 0.57 \qquad (1.19)$$

This indicates that on an average about 57% of the incoming wave power over the float diameter in the sea-state Hs = 2 meter will be absorbed.

G. System performance

The model is now used to predict the performance of the AquaBuOY system at a specific site taking the Orkney test site as an example.

The data relating to the float are:

Float diameter:	6 m
Float draught:	2.5 m
Float mass:	71 ton
Accel. Tube diameter:	4 m
Accel. Tube length:	30 m
Water mass in tube:	382 ton

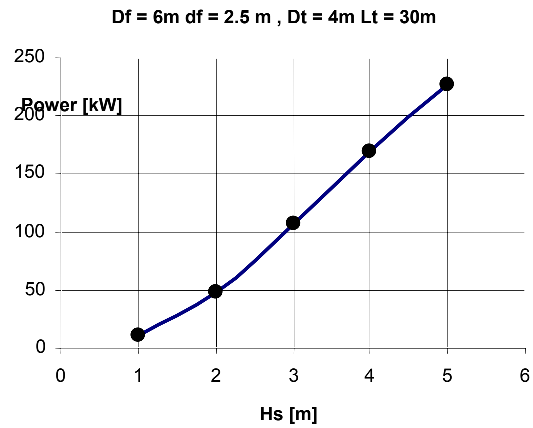

Fig. 14. Projected AquaBuOY performance

Table I shows evaluated significant wave heights, the most likely average wave period T02, the wave power per unit crest width Pw, the projected, calculated power absorbed by AquaBuOY P and the number of hours per year the significant wave height occur.

TABLE 1
Calculated Energy Production at the Orkney site

Hs [m]	To2[s]	Pw[kW/m]	P[kW]	Hours
1	5.5	3.2	11	3120
2	6.1	14.3	48	2640
3	6.8	35.5	107	1519
4	7.5	69.4	170	707
5	8.2	118	226	311

These data provides the following summary data related to the system and the chosen site.

Average wave power level	22 kW/m
Annual absorbed energy	522 MWh
Rated power (nameplate capacity)	226 kW
Average generated power	61 kW
Average capture width ratio	46%
Capacity factor	27%

IV. ON GOING DEVELOPMENT

Using its own resources and the grant from the Danish Energy Authority, AquaEnergy, jointly with other project participants is continuing development work towards an installation of a pilot AquaBuOY offshore power plant:

A. Numerical Modelling

A numerical time domain model, a model able to include non-linear features required modelling the real PTO system that included the hose-pumps, accumulators, Pelton turbine and a generator is under development by RAMBØLL and Jan Forsberg of AquaEnergy.

Hose pump samples are planned to undergo experimental testing at Dunlop to verify hose pump operation relative to the theoretical predictions in elongation, system pressure and loads.

Initial structural designs are being developed and evaluated by Ross Deeptech, UK and RAMBØLL, and AquaEnergy's Lenart Claeson.

Mooring configurations for a four float systems are being evaluated in a 1:50 scale model at Aalborg University.

V. CURRENT LEGISLATION RELATIVE TO WAVE ENERGY

Wave energy is an infant industry. Even though to date there is less than one megawatt of installed capacity, there are thousands of patens on various wave energy concepts. It is time for those concepts to move from the R&D arena into commercial installation.

In order to accomplish such migration, the industry needs legislative support that can a) streamline permitting process [5, and b) can provide financial support for a high risk demonstration plants. So far, only two states – California and Massachusetts have established programs to promote and assist wave energy companies to move from a wave tank into an open ocean.

The U.S. government needs to promote adaptation of new renewable technologies by establishing a simplified permitting process for demonstration projects and providing access to financing tools that can be used to move technology from an R&D to commercial stage.

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