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EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF THE "ROLLING CYLINDER" WAVE ENERGY CONVERTER AND DESIGN OPTIMISATION

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1. Introduction

The world energy consumption will rise enormously over the next decades, and also the energy consumption in the European Union will increase in the same period. To satisfy this energy demand different European countries start to focus on generating electricity from renewable sources that are the only opportunity to supply electricity and overcome negative aspects connected with traditional methods of energy production. Being constantly reminded the seriously environmental problems caused by traditional methods, the dramatic increase in oil prices in 1973, the global attention to climate change and the rising level of CO_2, the governments of the Member States have seen the urgent need for pollution-free power generation. In the dynamic evolution of the renewable energy industry a wave energy industry is emerging. Although the technology is relatively new, and currently not economically competitive with more mature technologies such as wind energy, the interest from government and industry is steadily increasing. An important feature of sea waves is their high energy density, which is the highest among renewable energy sources [1].

Oceans waves are a huge, largely untapped energy resource, and the potential for extracting energy from waves in considerable. Research in this area is driven by the need to meet renewable energy targets, but is relatively immature compared to other renewable energy technologies.

2. The wave energy resource

The sea is a huge water tank of energy of particularly high density, the highest among the renewable. The utilization of this energy could cover a significant part of the energy demand in Europe, and, moreover, it could make a substantial contribution to a wide range of the objectives of environmental, social and economic policies of the European Union [1].

The possibility of converting wave energy into usable energy has inspired numerous inventors: more than thousand patents had been registered by 1980 [9] and the number has increased markedly since then. The earliest such patent was filed in France in 1799 by a father and a son named Girard [10].

In Europe intensive research and development study of wave energy conversion began, however, after the dramatic increase in oil prices in 1973. Different European countries with exploitable wave power resources considered wave energy as a possible sources of power supply and introduced support measures and related programs for wave energy. Several research programs with government and private support started thenceforth, mainly in the United Kingdom, Portugal, Ireland, Norway, Sweden and Denmark, aiming at developing industrially exploitable wave power conversion technologies in the medium and long term.

The efforts in research and development in wave energy conversion have gained the support of the European Commission, which has, since 1986, been observing the evolution in the wave energy field.

Starting in 1993, the Commission supported a series of international conferences in wave energy, which significantly contributed to the simulation and coordination of the activities carried out throughout Europe within universities, national research centres and industry.

In the last 25 years wave energy has gone through a cyclic process of phases of enthusiasm, disappointment and reconsideration. However, the persistent efforts in R&D, and the experience accumulated during the past years, have constantly improved the performance of wave power techniques and have led today to bringing wave energy closer to commercial exploitation than ever before.

Different schemes have proven their applicability on a large scale, under hard operational conditions, and a number of commercial plants are currently being built in Europe, Australia, Israel and elsewhere. Other devices are in the final stage of their R&D phase with certain prospects for successful implementation. Nevertheless, extensive R&D work is continuously required, at both fundamental and application level, in order to improve their steadily the performance of the particular technologies and to establish their competitiveness in the global energy market.

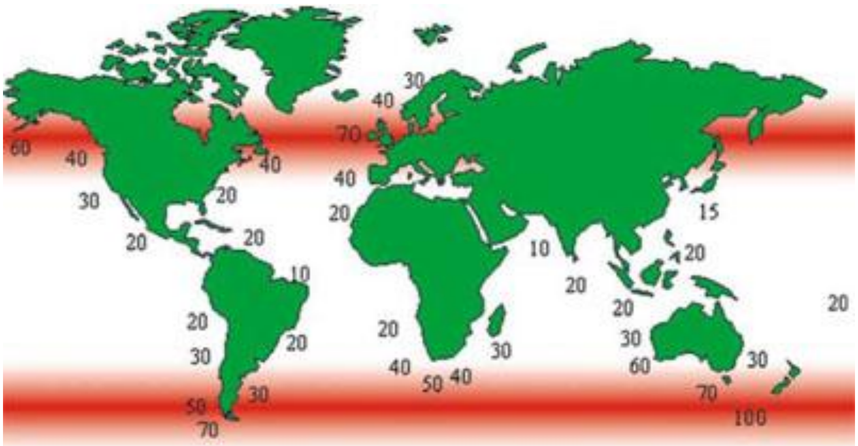


Figure 2.1: Wave power density around the world. The wave power density is very variable around the world and its highest values are detected in the Oceans between the latitudes of 30° and 60° on both hemispheres

2.1 General aspects of wave energy

The wave energy is very much suited for countries with vast coast line and high waves approaching the shore [12]. Waves are produced indirectly. The waves are produced by sun by the following processes.

The total power of solar radiation incident on Earth atmosphere is tremendous. When heated by sun, water evaporates, reducing the onset pressure. When there is pressure difference, wind flows along the surface. The large movement of air masses, vapour and water volumes creates the wind wave. Thus the main primary energy source for all processes near the earth surface is the sun.

The movements of the sea surface, or known as sea waves is also caused by external effects such as earthquakes, marine vehicles or attraction of gravity of the moon and sun. Sea waves due to the wind are more continuously compared to sea waves formed by other effects and therefore, they are considered primarily in obtaining energy. Wave energy potential, as it is found in nature, is called natural potential.

Technical potential is the transformed form of the natural potential to usable energy by technological systems. The economic potential is the economically defined amount when compared to the other energy sources [13].

In the past numerous researches [14-15] have been undertaken to quantify the amount of wave power available at a particular location based on the values of significant wave height (*H*s), peak wave period (*T*p) or energy wave period (*T*e). All these studies examined the combined effect of *H*s, *T*p or *T*e on the power estimation with a general aim to provide joint scatter plots.

The wave energy level is usually expressed as power per unit length (along the wave crest or along the shoreline direction); typical values for “good” offshore locations (annual average) range between 20 and 70 kW/m and occur mostly in moderate to high latitudes. Seasonal variations are in general considerably larger in the northern than in the southern hemisphere [16], which makes the southern coasts of South America, Africa and Australia particularly attractive for wave energy exploitation.

As a mathematical illustration of wave-energy extraction, we shall for simplicity we consider wave power. The wave power estimation using the wave data will give an account of the distribution of wave energy in space and time. Since the last few decades, the hydrodynamics of ocean waves have been thoroughly studied and now it is possible to determine the energy content of the sea with the help of large amount of wave data collected. The power in wave can be expressed by the formula [17]

$$P = 0.55\ H_s^2\ T\ ,\ \text{kW/m of crest length} \tag{2.1.1}$$

where H_s, is the significant wave height in meter and T, is wave energy period in seconds.

Waves are a very efficient way to transport energy: once created, waves can travel thousands of kilometers with little energy loss . The size of a wave is determined by three factors: wind speed, duration and the fetch, the distance over which the wind blows transferring energy to the water.

Nearer the coastline the average energy intensity of a wave decreases due to interaction with the seabed. Energy dissipation in near shore areas can be compensated for by natural phenomena such as refraction or reflection, leading to energy concentration (‘hot spots’).

2.2 Marine Energy and Wave Energy

It is essential to have an adequate knowledge of wave energy, to study the conversion of wave energy to electricity. Waves on the surface of the ocean are primarily generated by winds and are a fundamental feature of coastal regions of the world. Knowledge of these waves, the forces they generate and estimates of wave conditions are needed in almost all coastal engineering studies. In looking the sea surface, it is typically irregular and three-dimensional (3-D). The sea surface changes in time, and thus, it is unsteady. At this time, this complex, time-varying 3-D surface cannot be adequately described in its full complexity; neither can the velocities, pressures, and accelerations of the underlying water required for engineering calculations. In order to arrive at estimates of the required parameters, a number of simplifying assumptions must be made to make the problems tractable, reliable and helpful through comparison to experiments and observations. Some of the assumptions and approximations that are made to describe the 3-D, time-dependent complex sea surface in a simpler fashion for engineering works may be unrealistic, but necessary for mathematical reasons. Wave theories are approximations to reality. They may describe some phenomena well under certain conditions that satisfy the assumptions made in their derivation. They may fail to describe other phenomena that violate those assumptions. In adopting a theory, care must be taken to ensure that the wave phenomena of interest is described reasonably well by theory adopted, since shore protection design depends on the ability to predict wave surface profiles and water motion, and on the accuracy of such predictions.

Regular waves and linear wave theory

The most elementary wave theory is the *small-amplitude or linear wave theory*. This theory developed by Airy (1845), is easy to apply, and gives a reasonable approximation of wave characteristic for a wide range of parameters. Many engineer problems can be handled with ease and reasonable accuracy by this theory. For convenience, prediction method in coastal engineering generally have been based on simple waves. For some situations, simple theories provide acceptable estimates of wave conditions.

The linear theory represents pure oscillatory waves. Waves defined by finite-amplitude wave theories are not pure oscillatory waves but still periodic since the fluid is moved in the direction of wave advance by each successive wave. This motion is termed mass transport of the waves. Other assumptions made in developing the linear wave theory are:

- the fluid is homogeneous and incompressible; therefore the density ρ is a constant;
- surface tension can be neglected;
- Coriolis effect due to earth's rotation can be neglected;
- pressure at the free surface is uniform and constant;
- the fluid is ideal or inviscid (lacks viscosity);
- the particular wave being considered does not interact with any other water motions. The flow is irrotational so that water particles do not rotate;
- the bed is a horizontal, fixed, impermeable boundary, which implies that the vertical velocity at the bed is zero;
- the wave amplitude is small and the waveform is invariant in time and space;
- waves are plane or long-crested (two-dimensional).

A progressive wave may be represented by the variables x (spatial) and t (temporal) or by their combination (phase), defined as $\Phi = kx - \omega t$. A simple, periodic wave of permanent form propagating over a horizontal bottom may be completely characterized by the wave height H and wavelength L and water depth d. The highest point of the wave is the *crest* and the lowest point is the *trough*. For linear or small-amplitude waves, the height of the crest above the still-water level (SWL) and the distance of the trough below the SWL are each equal to the wave *amplitude a*. Therefore $a = H/2$, where H = *the wave height*. The time interval between the passage of two successive wave crests or trough at a given point is the *wave period T*. The *wavelength L* is the horizontal distance between two identical points on two successive wave crests or two successive wave troughs and η denotes the displacement of the water surface relative to the SWL and is a function of x and t. Other wave parameters include $\omega = 2\pi/T$ *the angular or* *radian frequency*, the *wave number k = 2π/L*, the phase velocity or *wave celerity c = L/T = ω/k*, the *wave steepness ε = H/L*. These are the most common parameters encountered in coastal practice.

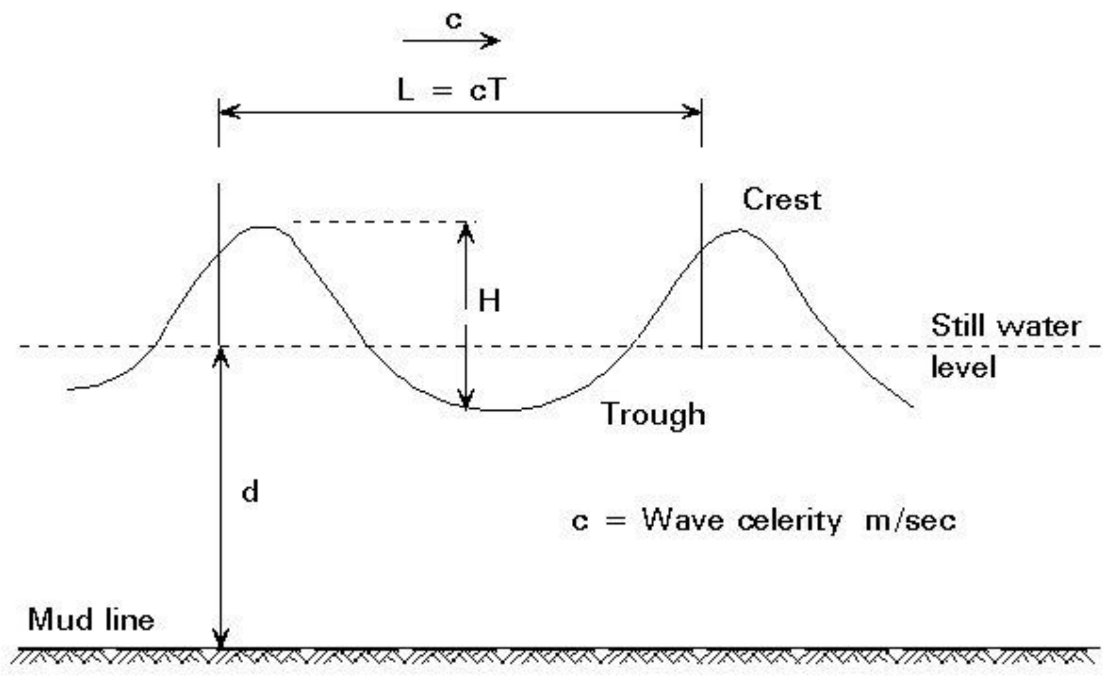


Figure 2.2: Main parameters of wave

An expression relating wave celerity (c) to wave length (L) and water depth (d) is given by:

$$c = \frac{gT}{2\pi} \tanh\left(\frac{2\pi d}{L}\right) \tag{2.2.1}$$

The values 2π/L and 2π/T are called the *wave number k* and the *wave angular frequency ω* respectively. From the equation c = L/T and from the Eq. 2.2.1 , an expression for wavelength as a function of depth and wave period may be obtained as:

$$L = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi d}{L}\right) = \frac{gT}{\omega} \tanh(kd) \qquad (2.2.2)$$

Waves may also be classified by the water depth in which they travel. The following classification are made according to the magnitude of *d/L* and the resulting limiting values taken by the function *tanh (2πd/L)*. Note that as the argument of the hyperbolic tangent *kd = 2πd/L* gets large, the *tanh (kd)* approaches 1, and for small values of kd, *tanh (kd)* ~ *kd*.

Classification	**d/L**	**kd**	**tanh (kd)**
Deep water	1/2 to ∞	π to ∞	= 1
Transitional	1/20 to 1/2	π/10 to π	tanh (kd)
Shallow water	0 to 1/20	0 to π/10	= kd

Table 2.1: Classification of Water Waves

In deep water, tanh (kd) approaches unity, Eq.2.2.1 reduce to:

$$c_0 = \frac{gT}{2\pi} = 1{,}56\, T \quad \left(\frac{m}{s}\right) \qquad (2.2.3)$$

and:

$$L_0 = \frac{gT^2}{2\pi} = 1{,}56\, T^2 \;\; (m) \qquad (2.2.4)$$

When the relative water depth (d/L) becomes shallow, Eq. 2.2.1 can be simplified to:

$$c = \sqrt{gd} \qquad (2.2.5)$$

Thus, when a wave travels in shallow water, wave celerity depends only on water depth.

In summary, as a wind wave passes from deep water to the beach its speed and length are first only a function of its period; then as the depth becomes shallower relative to its length, the length and speed are dependent upon both depth and period; and finally the waves reaches a point where its length and speed are dependent only on depth (and not frequency).

The equation describing the free surface as a function of time *t* and horizontal distance *x* for a simple sinusoidal wave can be shown to be:

$$\eta = a\cos(kx - \omega t) = \frac{H}{2}\cos\left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) = a\ \cos\Theta \qquad (2.2.6)$$

where:

- η = the elevation of the water surface relative to the SWL;
- H/2 = one-half the wave height equal to the wave amplitude a.

This expression represents a periodic, sinusoidal, progressive wave travelling in the positive x-direction.

Figure 2.2.2, a sketch of the local fluid motion, indicates that the fluid under the crest moves in the direction of wave propagation and returns during passage of the trough. Linear theory does not predict any net mass transport; hence, the sketch shows only an oscillatory fluid motion.

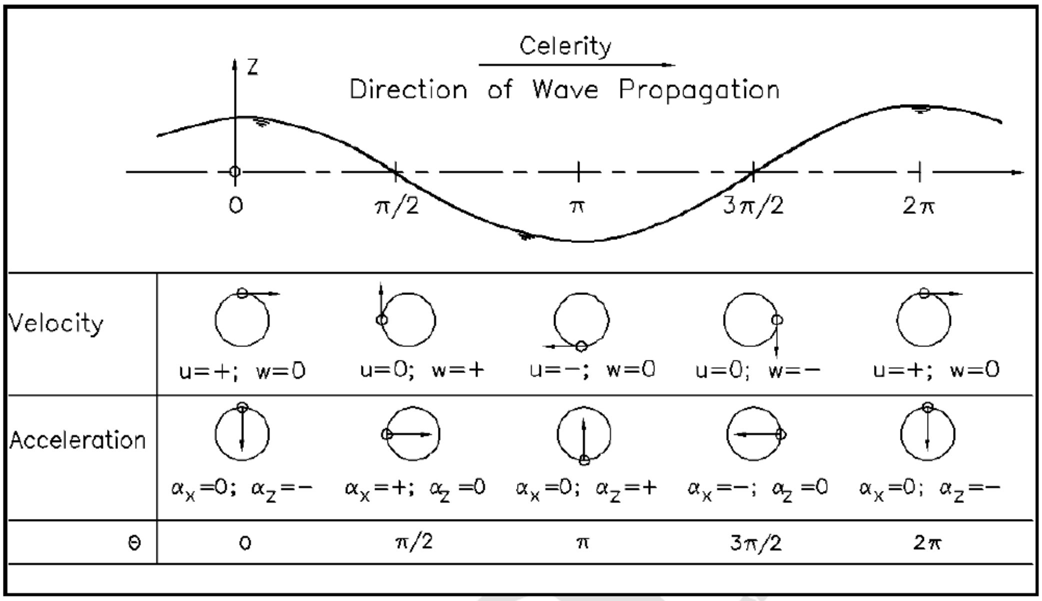


Figure 2.3: Local fluid velocities and accelerations

Another important aspect of linear wave theory deals with the displacement of individual water particles within the wave. Water particles generally move in elliptical paths in shallow or transitional depth water and in circular paths in deep water (Figure 2.2.3).

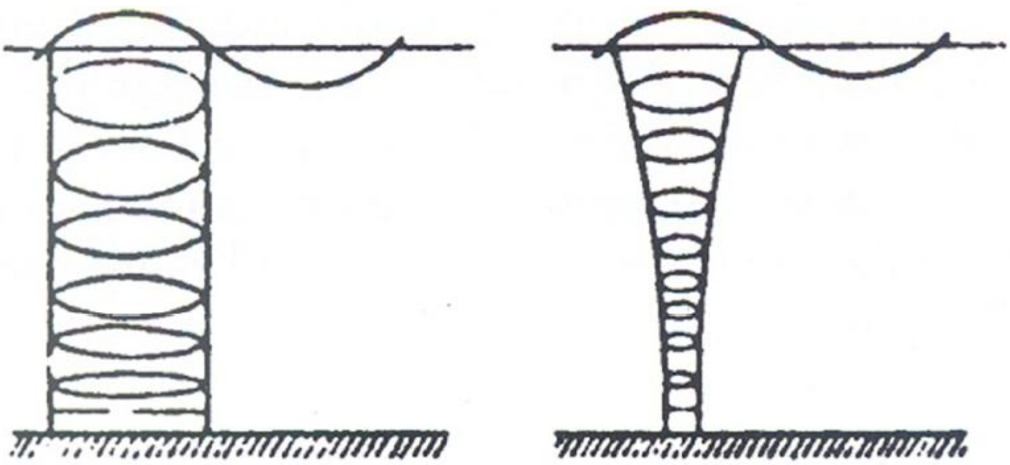


Figure 2.4: Elliptical paths in shallow or transitional depth water and in circular paths in deep water

It is desirable to know how fast wave energy is moving. One way to determine this is to look at the speed of wave groups that represents propagation of wave energy in space and time. The speed a group of waves or a wave train travels is generally not identical to the speed with which individual waves within the group travel. The group speed is termed the *group velocity Cg*; the individual wave speed is the *phase velocity* or *wave celerity* given by Eq. 2.2.1. For waves propagating in deep or transitional water with gravity as the primary restoring force, the group velocity will be less than the phase velocity.

In deep water the group velocity is one-half the phase velocity:

$$c_g = \frac{1}{2}\frac{L_0}{T} = \frac{1}{2}\, c_0 \;\; (deep\, water) \tag{2.2.7}$$

In shallow water the group and phase velocities are equal:

$$c_g = \frac{L}{T} = c = \sqrt{gd} \;\;\; (shallow\, water) \tag{2.2.8}$$

Thus, in shallow water, because wave celerity is determined by the depth, all component waves in a wave train will travel at the same speed precluding the alternate reinforcing and canceling of components. In deep and transitional water, wave celerity depends on wavelength; hence, slightly longer waves travel slightly faster and produce the small phase differences resulting in wave groups.

The total energy of a wave system is the sum of its kinetic energy and its potential energy.

The kinetic energy is that part of the total energy due to water particle velocities associated with wave motion. The kinetic energy per unit length of wave crest for a wave defined with the linear theory can be found from:

$$\bar{E}_k = \int_x^{x+L} \int_{-d}^{\eta} \rho\, \frac{u^2 + w^2}{2}\, dz\, dx \tag{2.2.9}$$

Where:

- ρ = density wave power [kg/m^3];
- u = fluid velocity in x-direction [m/s];
- w = fluid velocity in z-direction [m/s].

The Eq. 2.2.9 , upon integrations, gives:

$$\bar{E}_k = \frac{1}{16}\,\rho\, g\, H^2 L \tag{2.2.10}$$

Potential energy is that part of the energy resulting from part of the fluid mass being above the trough: the wave crest. The potential energy per unit length of wave crest for a linear wave is given by:

$$\bar{E}_p = \int_x^{x+L} \rho g \left[\frac{(\eta + d)^2}{2} - \frac{d^2}{2}\right] dx \tag{2.2.11}$$

which, upon integrations, gives:

$$\bar{E}_p = \frac{1}{16}\,\rho\, g\, H^2 L \tag{2.2.12}$$

According to the Airy theory, if the potential energy is determined relative to SWL, and all waves are propagated in the same direction, potential and kinetic energy components are equal, and the total wave energy in one wavelength per unit crest width is given by:

$$E = E_k + E_p = \frac{\rho g H^2 L}{16} + \frac{\rho g H^2 L}{16} = \frac{\rho g H^2 L}{8} \tag{2.2.13}$$

where subscripts k and p refer to kinetic and potential energies. Total average wave energy per unit surface area, termed the *specific energy* or *energy density*, is given by:

$$\bar{E} = \frac{E}{L} = \frac{\rho g H^2}{8} \tag{2.2.14}$$

Wave energy flux is the rate at which energy is transmitted in the direction of wave propagation across a vertical plan perpendicular to the direction of wave advance and extending down the entire depth.

Assuming linear theory holds, the average energy flux per unit wave crest width transmitted across a vertical plane perpendicular to the direction of wave advance is

$$\bar{P} = \frac{1}{T} \int_{t}^{t+r} \int_{-d}^{\eta} p\, u\, dz\, dt \tag{2.2.15}$$

Where:

- p = gauge pressure;
- t = start time;
- r = end time.

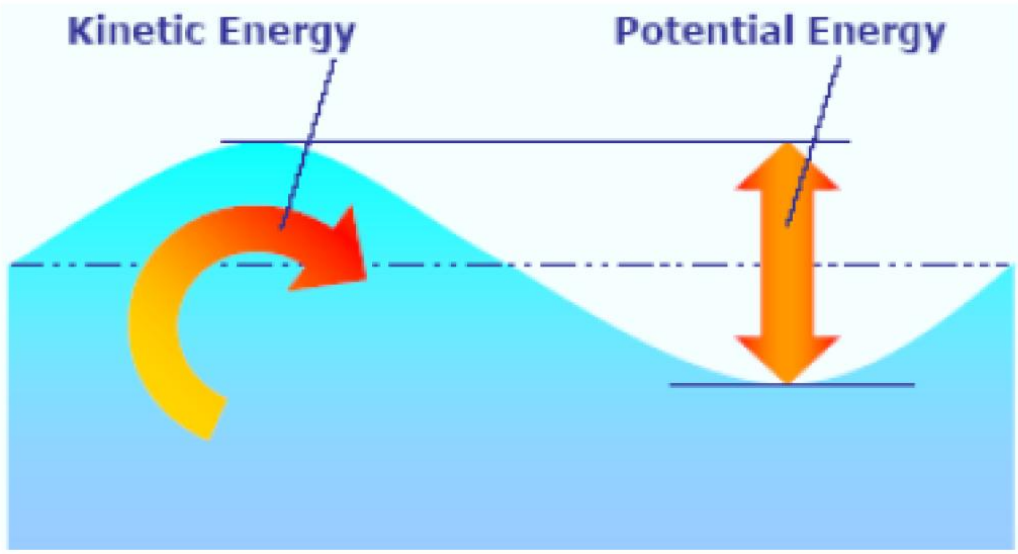


Figure 2.5: The kinetic and potential energy of the wave energy

The Eq. 2.2.15 , upon integrations, gives:

$$\bar{P} = \bar{E}nc = \bar{E}\ c_g \tag{2.2.16}$$

where $\bar{P}$ is frequently called *wave power*.

For deep and shallow water, the Eq. 2.2.16 becomes:

$$\bar{P} = \frac{1}{2}\ E_0 c_0\ (deep\ water) \tag{2.2.17}$$

$$\bar{P} = \ \bar{E}c_g = \ \bar{E}c\ (shallow\ water) \tag{2.2.18}$$

The wave energy flux (P) is also called *wave power*. The wave theory indicates that wave power is dependent on three basic wave parameters: wave height, wave period and water depth.

Nevertheless the real sea is composed by an irregular wave situations, in first approximation the following formula can be used to estimate the energy flux of an irregular wave in deep water conditions:

$$P = \frac{\rho g T H^2}{\beta \pi} \qquad (2.2.19)$$

Where:

- P= wave energy flux per unit wave crest length [kW/m];
- ρ = mass density of the sea water 1030 [kg/m^3];
- g = acceleration by gravity 9.81 [m/s^2];
- T= wave period [s];
- β = is a coefficient may be 64 for irregular waves or 32 for regular waves.

Irregular waves

In the first part of this chapter, waves on the sea surface were assumed to be nearly sinusoidal with constant height, period and direction. Visual observation of the sea surface and measurements indicate that the sea surface is composed of waves of varying heights and periods moving in differing directions. Once we recognize the fundamental variability of the sea surface, it becomes necessary to treat the characteristics of the sea surface in statistical terms. This complicates the analysis but more realistically describes the sea surface. The term *irregular waves* will be used to denote natural sea states in which the wave characteristics are expected to have a statistical variability in contrast to *monochromatic waves*, where the properties may be assumed constant. Monochromatic waves may be generated in the laboratory but are rare in nature.

Two approaches exist for treating irregular waves: *spectral methods* and *wave-by-wave (wave train) analysis*.

Unlike the wave train or wave-by-wave analysis, the spectral analysis method determines the distribution of wave energy and average statistics for each wave frequency by converting time series of the wave record into a wave spectrum. This is essentially a transformation from time-domain to the frequency domain, and is accomplished most conveniently using a mathematical tool known as the Fast Fourier Transform (FFT) technique.

The *wave energy spectral density E(f)* or simply the *wave spectrum* may be obtained directly from a continuous time series of the surface *η(t)* with the aid of the Fourier analysis. Using a Fourier analysis, the wave profile time trace can be written as an infinite sum of sinusoids of amplitude A_n, frequency ω_n , and relative phase ε_n, that is:

$$\eta\,(t) = \sum_{n=0}^{\infty} A_n \cos(\omega_n t - \varepsilon_n) \qquad (2.2.20)$$

Physically, m_0 represents the area under the curve of *E(f)* and the area under the spectral density represents the variance of a random signal.

The above definition of the variance of a random signal can be use to provide a definition of the significant wave height. For Rayleigh distributed wave heights, H_s may be approximated by:

$$H_s = H_{m0} \cong 4\,\sqrt{m_0} \qquad (2.2.21)$$

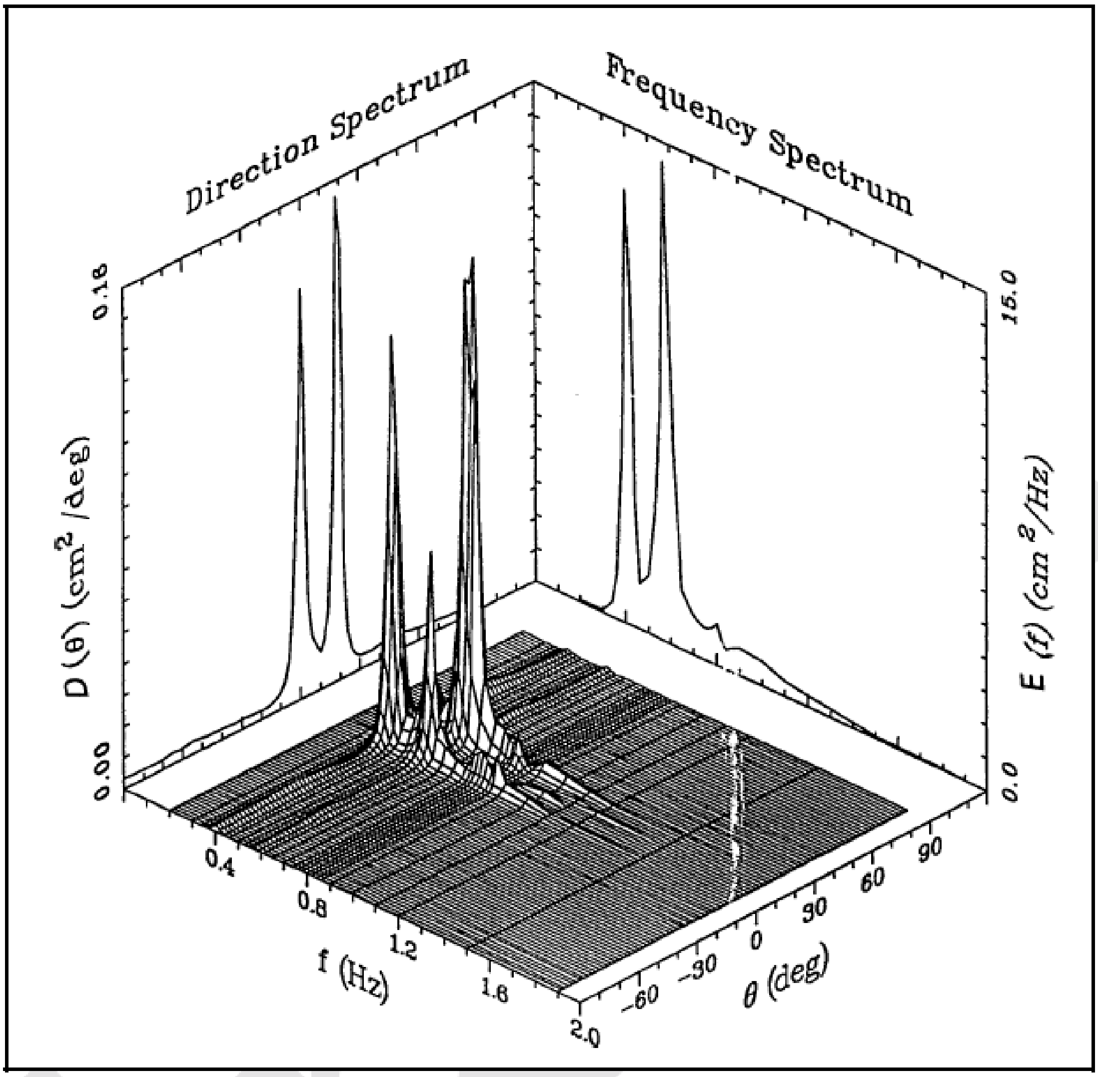


Figure 2.6 : A spectrum [28]

There are many forms of wave energy spectra used in practice, which are based on one or more parameters such as wind speed, significant wave height, wave period, shape factors, etc.

The most common spectrum is the *JONSWAP* spectrum. This is a five-parameter spectrum, although three of these parameters are usually held constant.

Characteristic wave height for an irregular sea state may be defined in several ways. These include the *mean height*, the *root-mean-square height*, and the *significant height*.

The root-mean-square height is a regular wave height parameter containing the same wave energy density as the measured irregular Tp wave record and can be determined as:

$$H_{RMS} = \frac{H_s}{\sqrt{2}} \qquad (2.2.22)$$

Significant wave height H_s can be estimated from a wave-by-wave analysis in which case it is denoted $H_{1/3}$ and is the average height of the third-highest waves in a record of time period but more often is estimated from the variance of the record or the integral of the variance in the spectrum in which case it is denoted H_{m0}.

The characteristic period could be the *mean period*, *energy period* (Te) or *peak period* (Tp).

Similarly to the equivalent wave height parameter, H_{RMS}, a regular wave period parameter is required with equivalent energy density to that of the irregular wave record. This regular wave period is called is called the energy period (T_e) and is determined by integrating the wave energy density spectrum.

The inverse of the frequency in the recorded wave energy density spectrum at which maximum energy density occurs is known as the peak period (Tp) of the record. This is a very important parameter frequently used in coastal engineering applications [28].

2.3 Advantages and disadvantages of wave energy

Using waves as a source of renewable energy offers both advantages and disadvantages over other methods of energy generation.

The most important difficulties facing wave power developments are:

- Irregularity in wave amplitude, phase and direction; it is difficult to obtain maximum efficiency of a device over the entire range of excitation frequencies.
- The structural loading in the event of extreme weather conditions, such as hurricanes, may be as high as 100 times the average loading.
- The wave power's variability in several time-scales: from wave to wave, with sea state, and from month to month.

It becomes apparent, that the design of a wave energy converter has to be highly sophisticated to be operationally efficient and reliable on the one hand, and economically feasible on the other. As with all renewable energy sources, the available resource and variability at the installation site has to be determinate first. The main wave energy barriers result from the energy carrier itself, the sea. As stated previously, the peak-to-average load ratio in the sea is very high, and difficult to predict. It is, for example, difficult to define accurately the 50-years return period wave for a particular site, when the systematic, in situ recording of wave properties started just a few years ago.

The result is either underestimation or overestimation of the design loads for a device. In the first case the total or partial destruction of the facilities is to be expected. In the second case, the high construction costs induce high power generation costs, thus making the technology uncompetitive. These constraints, together with misinformation and lack of understanding of wave technology by the industry, government and public, have often slowed down wave energy development [2].

On the other hand, the advantage of wave energy are obvious:

- Sea waves offer the highest energy density among renewable energy sources [1].
- Limited negative environmental impacts. The demand on land use is negligible and wave power is considered a clean source of renewable energy that not involving large CO_2 emissions. In general, offshore devices have the lowest potential impact.
- The development of wave energy is sustainable, as it combines crucial economic, environmental, ethical and social factors.
- Natural seasonal variability of wave energy, which follows the electricity demand in temperate climates.
- Waves can travel large distances with little energy loss. Storms on the western side of Atlantic Ocean will travel to the western coast of Europe, supported by prevailing westerly winds.
- Wave power devices can generate power up to 90 per cent of the time, compared to 20-30 per cent for wind and solar power devices [3,4].

To realize the benefits listed above, there are a number of technical challenges that need to be overcome to increase the performance and hence the commercial competitiveness of wave power devices in the global energy market.

A significant challenge is the conversion of the slow, random, and high-force oscillatory motion into useful motion to drive a generator with output quality acceptable to the utility network. As waves vary in height and period, their respective power levels vary accordingly. While gross average power levels can be predicted in advance, this variable input has to be converted into smooth electrical output and hence usually necessitates some type of energy storage system, or other means of compensation such ad an array of devices.

Additionally, in offshore locations, wave direction is highly variable, and so wave devices have to align themselves accordingly on compliant moorings, or be symmetrical, in order to capture the energy of the wave. The directions of waves near the shore can be largely determined in advance owing to the natural phenomena of refraction and reflection.

The challenge of efficiently capturing this irregular motion also has an impact on the design of the device. To operate efficiently, the device and corresponding systems have to be rated for the most common wave power levels. However, the device also has to withstand extreme wave conditions that occur very rarely, but could have power levels in excess of 2000 kW/m.

Not only does this pose difficult structural engineering challenges as the normal output of the device are produced by the most commonly occurring waves, yet the capital cost of the device construction is driven by a need to withstand the high power level of the extreme, yet infrequent, waves [11]. There are also design challenges in order to mitigate the highly corrosive environment of devices operating at the water surface [1].

Lastly, the research focus is diverse. To date, the focus of the wave energy developers and a considerable amount of the published academic work has been primarily on sea performance and survival, as well as the design and concept of the primary wave interface. However, the methods of using the motion of the primary interface to produce electricity are diverse. More detailed evaluation of the complete systems is necessary if optimized, robust yet efficient system are to be developed.

2.4 Wave Energy in Europe

Research and development on wave energy is underway in several European countries. The engagement in wave energy utilization depends strongly on the available wave energy resource. In countries with high resources, wave power could cover a significant part of the energy demand in the country and even become a primary source of energy. Countries with moderate, though feasible resources, could utilize wave energy supplementary to other available renewable and/or conventional sources of energy.

Denmark, Ireland, Norway, Portugal, Sweden and the United Kingdom considered wave power a long time ago as a feasible energy source. These countries have significant wave power resources and have been actively engaged in wave energy utilization under governmental support for many years [1].

Figure 2.7 : Wave power density in Europe. In Europe the West coasts of the U.K. and Ireland along with Norway and Portugal receive the highest power densities

Denmark

Denmark lies in a sheltered area in the southern part of the North Sea, however, in the North-western regions the wave energy resource is relatively favourable for potential developments. The annual wave energy resource of Denmark has been estimated to be about 30 TWh with an annual wave power between 7 and 24 kW/m coming from a westerly direction. The Danish Wave Energy Programme started in 1996 with Energy 21. The objective is to promote wave energy technology following the successful Danish experience of wind energy.

Ireland

Ireland has considerable potential for generating electricity from wave power. According to Lewis the total incident wave energy is around 187,5 TWh.

At present, a partnership of the Hydraulic & Maritime Research Centre, University College Cork, Irish Hydrodata Ltd, Ove Arup & Partners Ltd, the Department of Mechanical and Aeronautical Engineering, University of Limerick and the Marine Institute are finalizing a Strategic Study on Wave Energy in Ireland. The objective of the study is to provide a scaled selection of wave energy sites and to investigate a wave climate prediction methodology.

Norway

Norway has a long coastline facing the Eastern Atlantic with prevailing west winds and high wave energy resources of the order of 400 TWh/year. Even though there is high wave energy availability, due to the economics and the uncertainties of the available technology, the conclusion of Energy and Electricity Balance towards 2020 are that 0,5 MWh will be the wave energy contribution to the Norwegian electricity supply, mainly from small-scale developments.

All of Norway's electricity supply has traditionally been renewable hydropower, but the increased electricity demand of recent years has not been met by an equal increase in power plants, due to public opposition to large hydropower developments.

The government is promoting land based wind and biomass, with particular focus on hydrogen as an energy carrier and gas fuel cell pilot projects. The environmental concern of high CO_2 emission from power generation for oil and gas offshore installations could create the basis for a potential wave energy market.

Norway started its involvement in wave energy in 1973 in the Norwegian University of Science and Technology (NTNU). In the 1980s two shoreline wave converters were developed, the Multi-Resonant Oscillating Water Column, OWC and the Tapered Channel, Tapchan but the plants were seriously damaged during storms in 1988 and 1991. Anyway there are plans for re-opening the Tapchan plant.

Portugal

Portugal is characterised by an annual wave power of between 30 and 40 kW/m. The highest wave power is found off the northwestern coast of Portugal and in the archipelago of the Azores. It has been estimated that the overall resource of wave energy on continental Portugal is about 10 GW mean, and half of it can be potentially exploited.

The Portuguese government supports wave energy, as other renewable energy technologies, through different financial mechanisms. Since 1986, Portugal has been successfully involved in the planning and construction of the shoreline wave energy converter Oscillating Water Column in Pico of the Azores.

Sweden

Sweden has a few good areas for utilising wave energy. The north parts of the west coast facing the North Sea and the Baltic Sea around the islands of Oland and Gotland. The technically available resource is approx. 5–10 TWh per annum. This is to be compared with the annual electricity demand of 150 TWh in Sweden. Wave Energy research started in Sweden in 1976. In 1980 the first full scale point absorber buoy in the world was installed outside Goteborg. Another large project was the Hose-Pump project. It was also full scale tested at sea, 1983-1986.

United Kingdom

The United Kingdom is located at the eastern end of the long fetch of the Atlantic Ocean with the prevailing wind direction from the west, and it is surrounded by stormy waters. The available wave energy resource is estimated to be 120 GW. Wave energy started in the UK at the University of Edinburgh when the oil crisis in 1973 hit the whole world. In 1974, S. Salter published his initial research work on wave power and the research on the offshore wave energy converter, the Salter Ducks, was started.

In the meantime at least another ten wave energy projects were initiated in the UK. Furthermore, the success of the initial Limpet OWC project and its full decommissioning in 1999 has created the basis for including three wave energy projects in the third Scottish Renewable Obligation.

Other European Countries

Due to political reasons, mainly the focalisation to other energy sources, or lack of feasible resources, wave energy conversion has not undergone significant development in Belgium, Finland, France, Germany, Greece, Italy**,** the Netherlands and Spain in the past years.

Belgium, Germany and the **Netherlands** are characterized by a relatively limited length of coastline, shallow coastal water and high offshore traffic density. All these factors militate against significant interest in wave energy development.

France has a long coastline on the Atlantic and the Mediterranean Seas. Although a number of successful wave energy project were operated in France during the early part of the last century, wave energy conversion has not undergone significant development in the recent past.

Greece has a coastline of over 16000 km ones in the Aegean and Ionian Seas.

Wave power plants are particularly suitable for delivering electricity to the large number of islands, which are mainly supplied by diesel stations. The high cost of electricity on the islands will make wave energy competitive against conventional power producers; however, wind energy has already proven its feasibility in this region, and it is heavily supported by the government and private investors.

Italy has a long coastline in relation to its land area and would appear suitable for utilisation of ocean energy. Wave studies around the coastline, however, show that, in general, the wave power annual average is less than 5 kW/m. There are a number of offshore islands and specific locations, such as Sicily or Sardinia, where the mean wave energy is higher, up to approx. 10 kW/m.

3. Wave energy converters

In contrast to other renewable energy resource utilization, there is a wide variety of wave energy technologies, resulting from the different ways in which energy can be absorbed from the wave, and also depending on the water depth and on the location. This large number of concepts for wave energy converters (WECs) is generally categorized by location, type and working principle.

3.1 Location

Shoreline devices: they are fixed to the shoreline itself and have the advantage of being close to the utility network. Then they also have the advantage of being easy to maintain and to install. In addition they do not require deep-water moorings or long lengths of underwater electrical cable and as waves are attenuated as they travel through shallow water they have a reduced likelihood of being damaged in extreme conditions. However the wave power in the shallow water is lower and by nature of their location they have to satisfy specific requirements for shoreline geometry and preservation of coastal scenery.

An example of shoreline device is the SSG (Sea Slot-cone Generator), a wave energy converter of the overtopping type: the overtopping water of incoming waves is stored in different basins depending on the wave height. The structure consists of a number of reservoirs one on the top of each other above the mean water level in which the water of incoming waves is stored temporary. In each reservoir, expressively designed low head hydroturbines are converting the potential energy of the stored water into power. A key to success for the SSG is the low cost of the structure and its robustness.
Turbines play an important and delicate role on the power takeoff of the device. They must work with very low head values (water levels in the reservoirs) and wide variations in a marine aggressive environment. The main strength of the device consists on robustness, low cost and the possibility of being incorporated in breakwaters (layout of different modules installed side by side) or other coastal structures allowing sharing of costs and improving their performance while

reducing reflection due to efficient absorption of energy. Even though, an offshore solution of the concept could be investigated to reach more energetic sea climates [26].

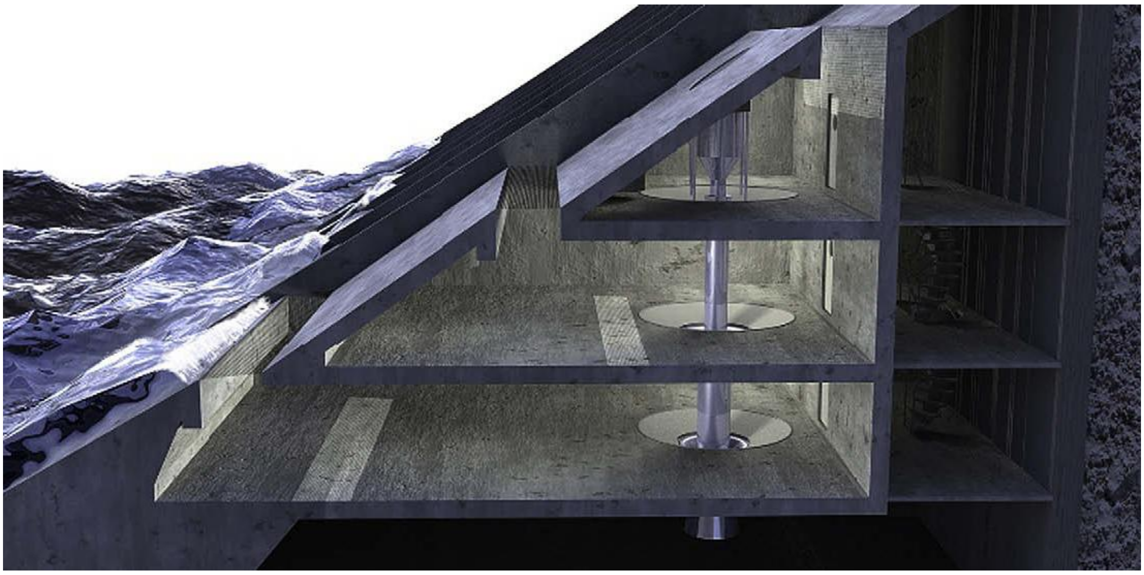


Figure 3.1: Lateral section of a three-levels SSG device [26]

Nearshore devices: they are for moderate water depths (i.e < 20 m). Devices in this location are often attached to the seabed, which gives a suitable stationary base against an oscillating body can work [5]. They have the same disadvantage of the shoreline devices, because the waves have reduced power in the shallow water.

An example of shoreline device is an oscillating water column device (OWC) called the OSPREY (Ocean Swell Powered Renewable EnergY), which incorporates a wind turbine.

The steel design is shown in Figure 3.2. It comprises a 20 m wide rectangular collector chamber in the centre, with hollow steel ballast tanks fixed to either side. These tanks face into the principal wave direction and focus the waves towards the opening in the collector chamber. The air flow from this chamber passes through two vertical stacks mounted on the chamber. Each of these contains two, contra-rotating Wells' turbines, each of which is attached to a 500 kW generator.

A control module is also mounted on top of the collector chamber, containing the power control equipment, transmission system, crew quarters, etc. Behind the collector chamber and power module is a conning tower on which can be mounted a “marinised” wind turbine.

The whole device is designed for installation in a water depth of approximately 14 m and weighs approximately 750 t.

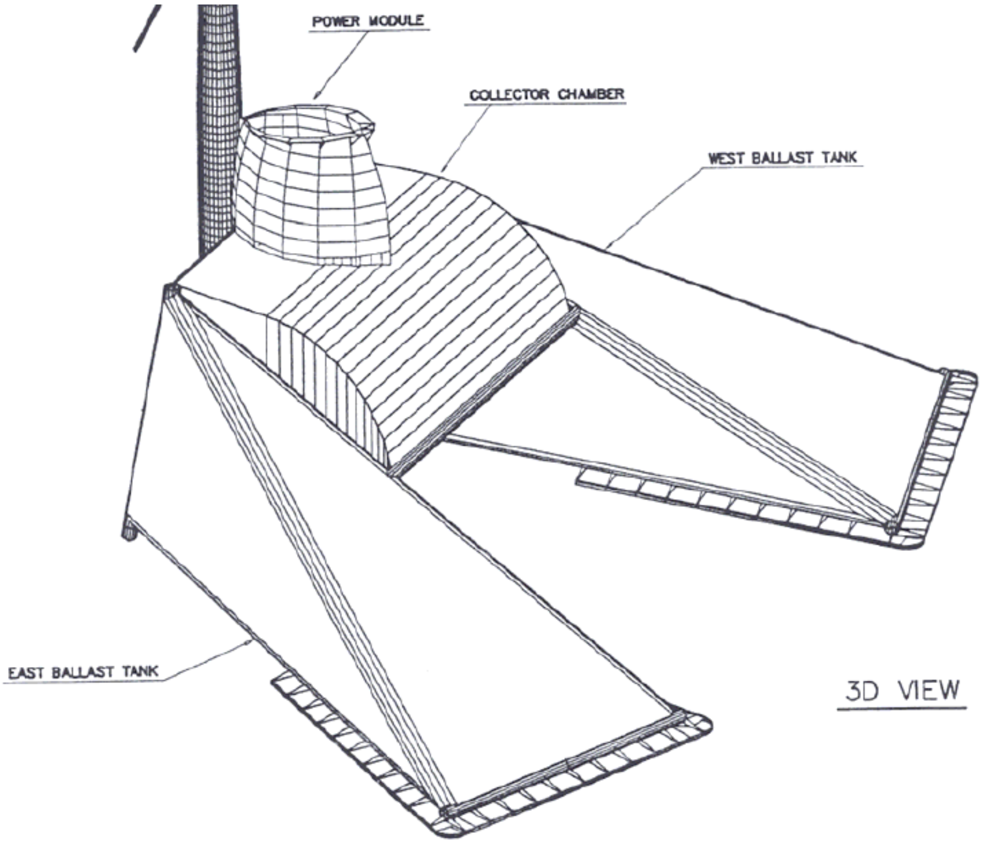


Figure 3.2: The steel OSPREY Design

Offshore devices: they are generally in deep water (> 40m). The advantage of locating a device in deep water is that they can obtain a big amount of energy because of the higher wave power in deep water. On the other hand these devices are more difficult to install and to maintain and they need to survive the more extreme conditions. Also the cost of construction is more expensive. Offshore devices are basically oscillating bodies, either floating or (more rarely) fully submerged and in general more complex compared with the nearshore devices. This, together with additional problems associated with mooring, access for maintenance and the need of long underwater electrical cables, has blindered their development, and only recently some systems have reached, or come close to, the full-scale demonstration stage [2].

An example of offshore devices is the “Mighty Wale”, which is a floating wave energy device based on the oscillating water column (OWC) principle. It converts wave energy into electric energy, and produces a relatively calm sea behind. This calm area can be utilized for varied applications such as fish farming. Jamsted completed the construction of the prototype device “Mighty Whale” by May 1998 for open sea tests to investigate practical use of wave energy. Following construction, the prototype was towed to the test location near the mouth of Gokasho Bay in Mie Prefecture. The open sea tests were begun in September 1998, after final positioning and mooring operations were completed.
The “Mighty Whale” is a steel floating structure with the appearance of a whale which has an air chamber section for adsorbing the wave power energy at the front (windward), buoyancy tanks and a stabilizer slope for reducing pitching motions in the waves. Each air chamber has an opening at the top where and air turbine power generator is installed. The under water front wall of each air chamber is open to allow entry of the wave. When a wave enters the air chamber, the water surface inside it moves up and down, producing an oscillating airflow, which passes through the opening at the top of the air chamber. This airflow is used to drive the air turbine and generator. This is a wave power energy converter of oscillating water column type. The air turbine mounted on the “Mighty Whale” are Wells turbines featuring stable rotation of the same direction in an oscillating airflow [27].

Figure 3.3: The prototype [27]

3.2 Type

Attenuator: these devices are arranged parallel to the predominant wave direction. An example of an attenuator WEC is the Pelamis.

The Pelamis is a floating device comprised of cylindrical hollow steel segments (diameter of 3,5 m) connected to each other by two degree-of-freedom hinged joints. Each hinged joint is similar to a universal joint, with the central unit of each joint containing the complete power conversion system. The wave-induced motion of these joints is resisted by four hydraulic cylinders that accommodate both horizontal and vertical motion. These cylinders act as pumps, which drive fluid through a hydraulic motor, which in turn drives an electrical generator. Accumulators are used in the circuit to decouple the primary circuit (the pumps) with the secondary circuit (the motor), and aid in regulating the flow of fluid to produce a more constant generation. The hydraulic power take off (PTO) system uses only commercially available components. Each Pelamis is 120 m long, and contains three power modules, each rated at 250kW. It is designed to operate in water depths of ~50 m. The shape and loose mooring of Pelamis lets it orient itself to the predominant wave direction, and its length is such that it automatically "detunes" from the longer-wavelenght high-power waves, enhancing its survivability in storms [9]. A wave farm using Pelamis was recently installed 3 miles from Portugal's northern coast, near Pòvoa do Vorzina. This followed full-scale prototype testing at EMEC facility in Orkney [10]. The wave farm initially uses three Pelamis machines developing a total power of 2,25 MW.

Figure 3.4: Attenuator device: Pelamis wave farm

Point absorber : these devices have a small dimensions in comparison with the incident wavelength, they are able to capture energy from a wave front greater than the physical dimension of the absorber and because of their small size wave direction is not important for these device and it is able to capture energy from waves arriving from any directions. They can be floating structures that moves up and down on the surface of the water or submerged below the surface. An example of point absorber is Ocean Power Technology's Powerbuoy. The Powerbuoy is a floating point absorber buoy, based on the relative movement between the inner and outer parts that constitute the device. The outer part of the buoy has a circular shape, it is floating near water's surface and it moves with the waves. The inner part of the buoy is a vertical pipe that contain a compressible volume of air. As the crest of the wave passes over the device, the air is compressed and the inner part moves downwards. This motion is used to spin a generator, and the electricity is transmitted to shore over a submerged transmission line.

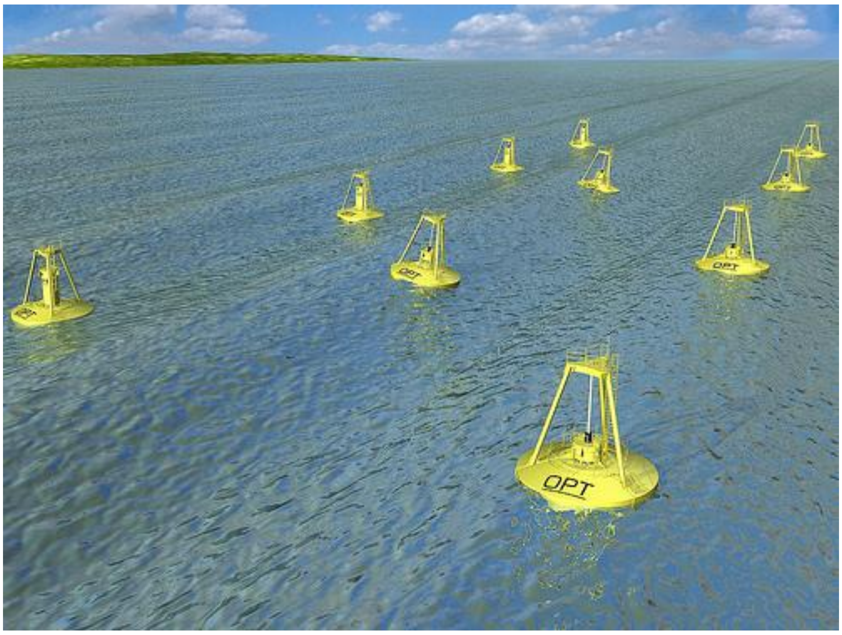


Figure 3.5: Point absorber device: OPT Powerbuoy

Terminator: the principal axis of these devices is perpendicular to the predominant wave direction, they obstruct the transit for the waves and they catch the wave energy. An example of a terminator-type WEC is the Salter's Duck. This device has a egg-shaped. Each incoming wave moves up and down the "duck" and this motion compresses air through the Duck driving turbines which create electricity.

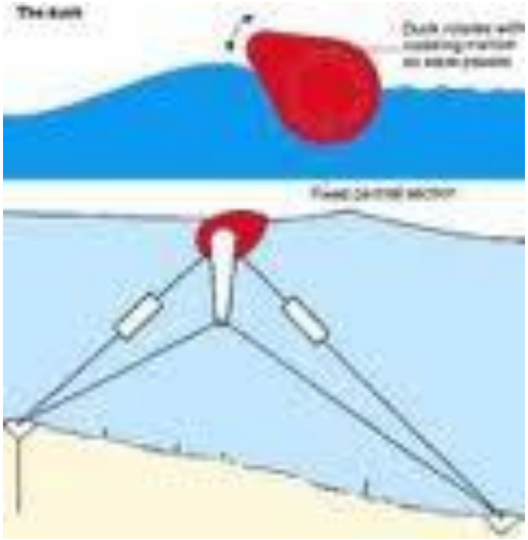


Figure 3.6: Terminator device: Salter's Duck

3.3 Working principle

Oscillating water column (OWC) : an OWC consists of a partly submerged concrete or steel chamber with an opening to the sea below the waterline and an opening to the air via one or more air turbines. When the incoming waves impact the device, the water is forced into the chamber, and the water level inside the chamber rises and falls, compressing and expanding an air column and driving it through the air turbine that drives an electrical generator. Since the air direction reverses halfway through each wave, a method of rectifying the airflow is required; although systems employing multiple turbines with one-way valves have been used, the currently favored method involves the use of a "self-rectifying" turbine that spins in only one direction regardless of the direction of airflow [6]. For this reason ,in this application is often used a low-pressure Wells turbine as it rotates in only one direction irrespective of the flow direction, removing the need to rectify the airflow [5]. Full sized OWC prototypes were built in Norway, Japan, India, Portugal, UK. The largest of all, a nearshore bottomstanding plant was destroyed by the sea shortly after having been towed and sunk into place near the Scottish coast.

An example of OWC systems is the Limpet, a shoreline device installed on the island of Islay, Western Scotland. This device has an inclined oscillating water column and water depth at the entrance of the OWC is typically seven metres. The design of the air chamber is important to maximize the capture of wave energy and the turbines are carefully matched to the air chamber to maximize power output.

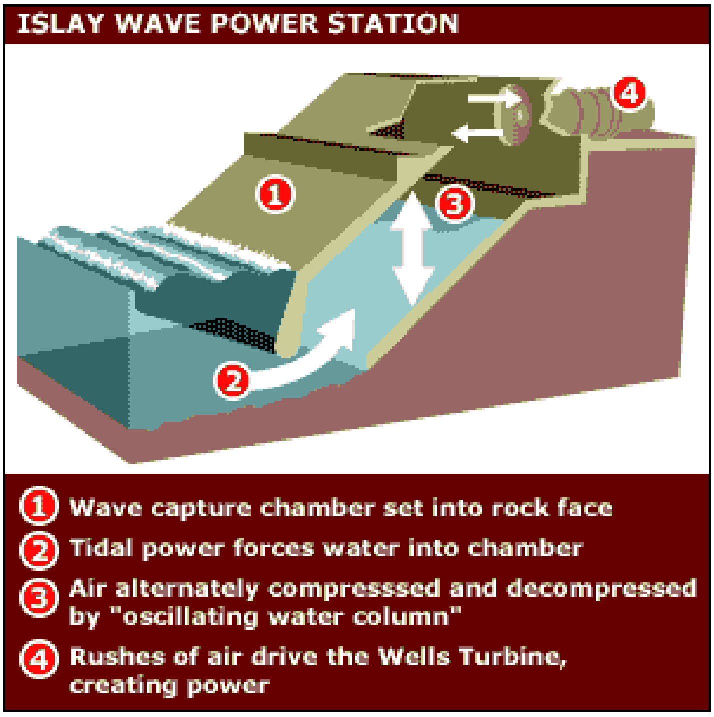


Figure 3.7: OWC: The Limpet

Overtopping device: this device captures the water that is close to the wave crest and introduce it, by over spilling, into a reservoir where it is stored at a level higher than the average free-surface level of the surrounding sea. . The energy is extracted by using the difference in water level between the reservoir and the sea and the potential energy of the stored water is converted into useful energy through more or less conventional low-head hydraulic turbines. Then the water is allowed to return to the sea through turbines. Overtopping devices do possess an advantage in that their turbine technology has already been in use in the hydropower industry for a long time and is thus well understood [6].

An example of such a device is the Wave Dragon, an offshore converter developed in Denmark. This device uses two large reflectors that stretch outwards from the device and orient waves towards the central receiving part. The sea water is collected in a raised reservoir from which water is released via a number of low-head turbine. A 57 m-wide, 237 t prototype of the Wave Dragon has been deployed in Nissum Bredning, Denmark, and has been tested for several years [2].

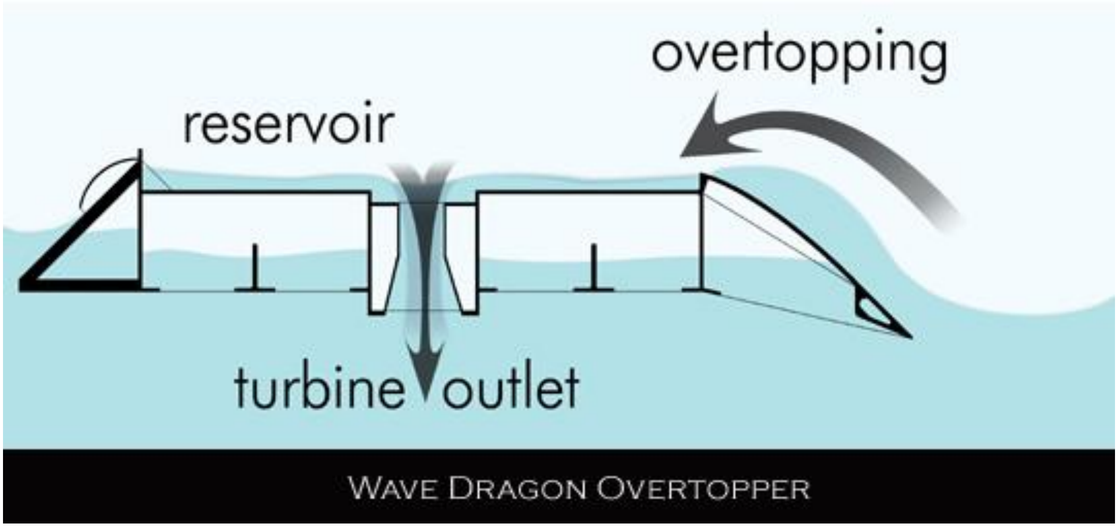


Figure 3.8: Overtopping principle

Wave activate body (WAB): in this device the waves activate the oscillatory motions of parts of the device relative to the other parts of the device or of one part relative to a fixed reference. Primarily heave, pitch and roll motions can be identified as oscillating motions whereby the energy is extracted from the relative motion of the bodies or from the motion of one body relative to its fixed reference by using typically hydraulic systems to compress oil, which is then used to drive a generator [8].

An example of WAB device is DEXA. Dexa is characterized by a simple structure. There are two pontoons connected together in the middle point of the device in order that each pontoon can rotate relative to the other.

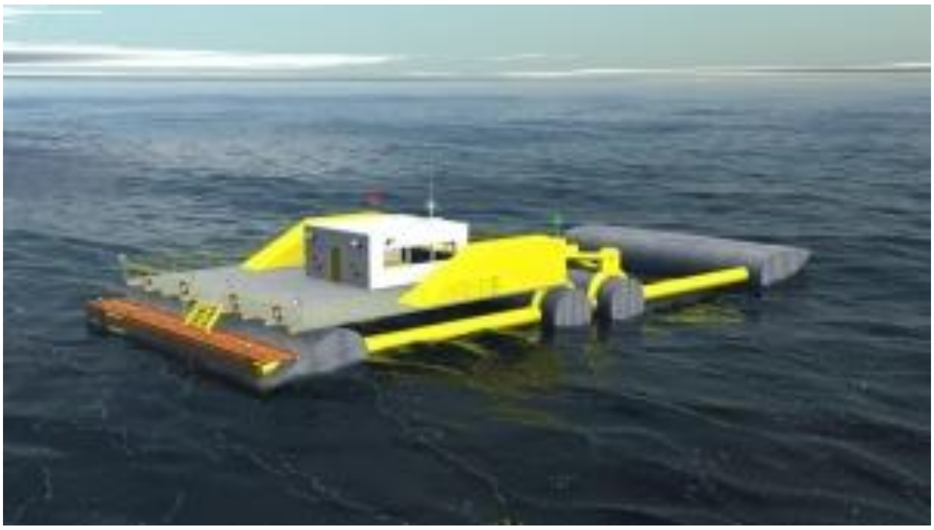


Figure 3.9: DEXA, an example of Wave Activate Body

3.4 Development for WEC tests and developments

Starting at the initial idea the development of a wave energy has to go through different phases before the first prototypes can be placed in open sea. Usually this development starts with theoretical analyses, then there are experiments in the wave tank at a small and an intermediate scale before to deploy the first prototype in the sea.

Now in Denmark there is a work that summarizes the best practice to put into practice a wave energy device. This practice is constituted by four phases. The main idea is that each phase has to give some specific information to the inventor and his investors. Secondary the idea is not to use too many resources before having an estimate on the potential.

The four phases used in Denmark are [7]:

- Phase 1: Proof of concept. Rough estimates of energy production in five specified wave states leading to an estimate of a yearly energy production. Suggestions for further development of the device. Typical small indicative laboratory tests followed by a ~10 page report. Cost 10.000 €.
- Phase 2: Design and feasibility study. Typically through detailed laboratory tests in scale 1:50 to 1:20. Detailed Numerical calculations, estimates on cost, feasibility studies, Power take-off (PTO) design, etc. Typical intensive laboratory tests (optimizations) or intensive numerical

modeling. This phase can consist of N (i.e. 10) detailed investigations followed by ~100 page reports. Cost 25.000-50.000 €.

- Phase 3: Testing in real seas in scale 1:10 to 1:3. Normally Nissum Bredning, a "small" benign piece of inner sea, a part of the Limfjord in the northern part of Denmark , has been used for this purpose. Cost 0.5-5 million €.
- Phase 4: Demonstration in half or full scale. Cost 5-20 million €.

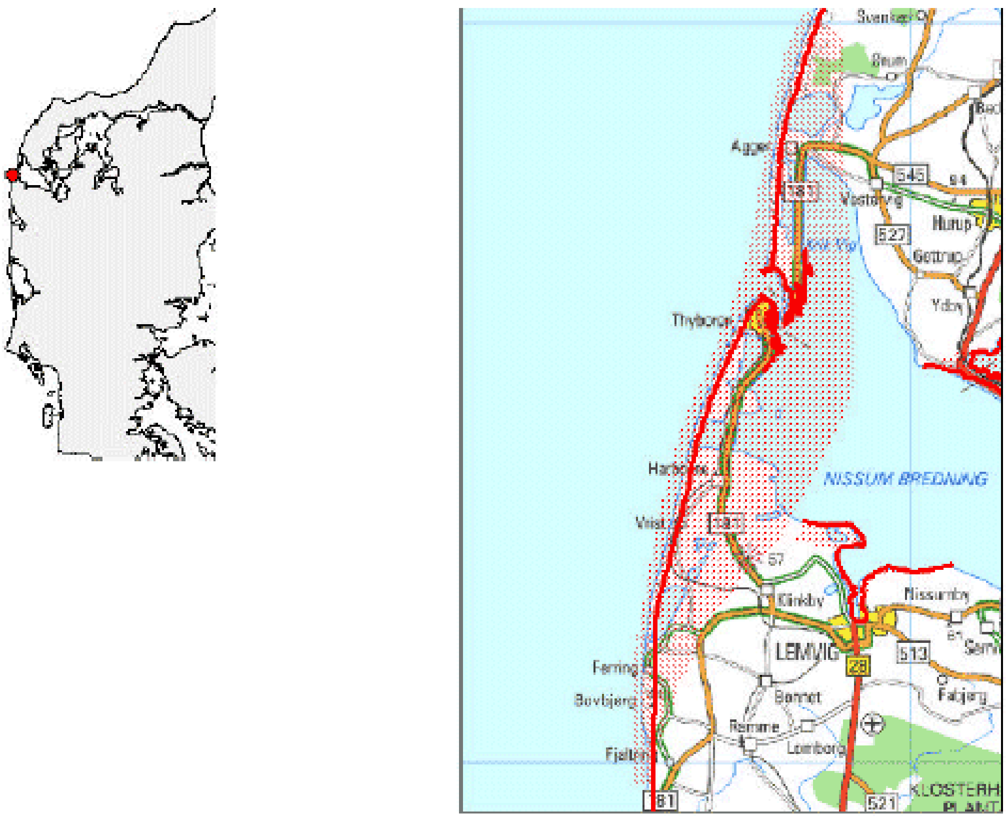


Figure 3.10: Location of Nissum Bredning in Denmark

The main instrument used under phase 1 and phase 2 to assess the wave energy devices is small scale testing in a hydraulic laboratory. These tests are performed in order to gain knowledge on the devices before they actually are built and deployed in the sea. The laboratory tests will give information on:

a. Loads on the device
b. Movements of the device
c. Run-up / overtopping of the device
d. Energy production

In phase 1 assessment, the test will give rough estimates (± 20%) on energy production, and knowledge from the tests will help to estimate costs. In a Phase 2 assessment, the test will give more detailed estimates (± 5%) on the expected energy production.

A phase 2 test could further include a parametric study making it possible to optimize the device. By far the most frequently used model law in relation to wave laboratory tests in Froudes Model Law, which requires:

- Inertia forces to dominate the physics. Friction forces must be negligible relative to the inertia forces. Inertia forces are forces proportional to the volume/mass of the device.
- The model must be geometrically similar to the full scale device.

The requirement of friction forces to be small relative to the inertia forces will tipically lead to a maximum scale ratio in the order of 1:50 for device models to be testes in wave laboratory. On the other hand, most power off systems cannot within reason be scaled more than 1:10 at the most, mainly due to frictional losses.

Wave basins are normally designed for hydraulic tests with marine constructions, ships, or coastal structures. In order to keep costs down, such tests are traditionally performed in scale 1:20 to scale 1:100. If a design wave height is 15 metres with a period of 12 seconds, a model test in scale 1:100 will be performed with a wave height of 15 cm and a period of 1.2 seconds.

The wave energy sector often wants to perform tests in i.e. scale 1:10. For the previous example, that would give a wave height equal to 1.5 metres with a period of 3.8 seconds. Model tests with such large waves can be performed in a very few laboratories around the world, and costs are enormous. Therefore model tests are performed in i.e. scale 1:40, which leads to scale effects on the modeling of the power take off.

Consequently, the power take off is modeled to perform in accordance with pre-specified characteristics. This is not a serious problem because one of the requirements to the outcome of the model tests often is a specification on the loading of the power take off. One should always remember that the dimensions of the power take off system cannot simply be scaled up. It is the performance which can.

Transferring measured data to full scale values follows the Froudes Model Law:

Parameter	Model	Full Scale
Length	1	S
Area	1	S^2
Volume	1	S^3
Time	1	$S^{0,5}$
Velocity	1	$S^{0,5}$
Force	1	S^3
Power	1	$S^{3,5}$

Table 3.1: Scale Froude

Waves are by nature irregular, short crested, and non-linear. The question is: How accurate is it necessary to model the sea.

The energy content in the seas around Denmark varies from location to location. Excluding the very extremes, the Danish seas have areas with average energy levels ranging from 5 to 22 kW/metre wave crest. Scatter diagrams exist for many parts of the Danish seas. It is obvious that a detailed design/optimization must take into account the actual waves existing on the proposed location for the wave energy device, but in order to make some comparison possible for devices being tested under phase 1 (and phase 2), devices are normally tested against 5 pre-defined wave states describing energy content of the sea.

wave state	Hs [m]	Tz [s]	Tp [s]	Energy flux [kW/m]	Prob. Occur. [%]
1	1.0	4.0	5.6	2.1	46.8
2	2.0	5.0	7.0	11.6	22.6
3	3.0	6.0	8.4	32.0	10.8
4	4.0	7.0	9.8	65.0	5.1
5	5.0	8.0	11.2	114.0	2.3

Table 3.2: Standardized wave state describing energy in the Danish seas

In phase 1, the sea is always modeled as linear irregular long crested waves using JONSWAP spectra with a peak enhance factor equal to 3.3.

Hs is significant wave height as defined by International Association of Hydraulic Engineering and Research, and *Tz* is average wave period based on zero-down crossing analysis, and *Tp* is peak period of the wave spectrum.

For tests to assess the energy production, the minimum duration of the tests in each irregular wave state is 500 waves.

A precise modeling of the power take off is important because of two reasons:

- The power production is responsible for all the income from the device.
- The load from the power take feeds back to the hydraulic performance of the device.

Therefore, the load from the power take off on the system has to be controllable.

In a full scale wave energy device, the power take off system as the load on the device varies. However, at small scale, the control on the power take off is often limited to a fixed level for a given wave state, disabling a “wave-to-wave” power take off control. Actually, it is impossible to implement a perfect control algorithm for the power take off system for tests performed in small scale. Furthermore, development of this control algorithm is often the goal of the whole mission, and a significant part of the challenge at phases 3 and 4.

Each of the wave states given in Table 3.2 is made equivalent with a periodic wave with same energy content as the original wave state, and with a period equal to the peak period *Tp* of the irregular wave state.

At first attempts (Phase 1 and sometimes also Phase 2), the power take off is tuned to best performance with the given equivalent wave, using regular waves.

Wave state	*Hs*	*Tz*	*Tp*	*H*	*T*
	m	*s*	*s*	*m*	*s*
1	1.0	4.0	5.6	0.7	5.6
2	2.0	5.0	7.0	1.4	7.0
3	3.0	6.0	8.4	2.1	8.4
4	4.0	7.0	9.8	2.8	9.8
5	5.0	8.0	11.2	3.5	11.2

Table 3.3: Equivalent periodic waves for tuning of power take off

When the power take off is tuned for each of the equivalent waves, the system is ready for the measurement of the power production. The reason for using the equivalent waves in the tuning process of the power take off is that experience has shown that tuning the power take off with irregular waves is a very time consuming process, and almost no difference is seen in the final results.

The yearly production is calculated using the probabilities of occurrence for the five different wave states listed in Table 3.2.

$$E_y = \sum_{i=1}^{N} P_i * p_i * 24 * 365 \tag{3.4.1}$$

With E_y being the yearly power production in kWh, N the number of wave state and p the corresponding probability of occurrence.

When evaluating the power production, it is important to note where in the power chain the power has been measured. Typically, at small scale testing, the power is measured as early as possible in the power chain to avoid including losses, which normally are heavily exaggerated at small scale. However, this also means that realistic losses should be estimated and accounted for in the scaling up of the measured power production numbers.

After the yearly production the performance in the individual wave states is presented as efficiencies, here meaning the ratio between the power produced and the wave power reaching the width of the device.

The overall efficiency is then given as ratio between the total amount of power produced (over all the considered wave states, with the given probabilities applied) and the corresponding power in the waves reaching the width of the device.

At the early phases of development, attempts to predict not only the power production potential of a device, but also the cost per produce power unit are normally associated with extremely large uncertainties. This is due to the fact that a large part of the cost drivers are not only the cost of structure, but also maintenance cost, availability, reliability of components, etc., which cannot be estimates based on early stage testing. To get reliable data regarding these parts, there is a need to get full scale devices in the sea operating for long periods of time, and this stage has until now hardly begun.

When arriving at Phase 3 (1:3-10), and later also at Phase 4 (1:1-2), the development has to be taken to real sea conditions. At this stage, the power take off system is tested in its real layout, enabling detailed testing of control algorithms, etc. In the real sea conditions, there is no control on the waves arriving at the device. Therefore, it is important to measure the wave conditions at the site, and then refer the performance of the device to the measured wave states. Based on this and the full scale wave conditions, with corresponding probabilities of occurence, the full scale power production can again be estimated.

The main idea of the Danish practice is that each of the phases should provide valuable information for the developers and investors to use when deciding whether or not the project will be taken to the next phase. Using this approach, both technical and financial risks are minimized, and it eases comparison of the performance of different technologies at the same phase of development.

It is advocated that through all the phases, the same template for concept evaluation should be applied. For each increase in development phases, the level of details are raised and correspondingly the uncertain are lowered.

Through the evaluation and classification of the concepts, the uncertainty on the individual elements has to visible, a large uncertainty level should be punished, and a small uncertainty level should be rewarded. The level of reward or punishment should be weighed with importance of the element.

Thus, the project development is focused towards dealing with the most important items with the largest uncertainties first.

4. A new wave energy converter: the Rolling Cylinder

In this report it will focus the attention on Rolling Cylinder tests and development. The Rolling Cylinder is a new wave energy converter.

4.1 Objectives of the experimental activity

The purpose of these tests is:

1. Find the best overall configuration for the device in term of:
   - fin thickness
   - number of fin sets mounted on the model
   - number of fins per each set
   - bouyancy level.

2. Evaluate the potential power production running the tests with the best design configurations in irregular waves.

To optimize the short model and find the best configuration all the test were run in regular waves. To compare the different configuration and find the best one, the power production and the efficiency were calculated.
Then to evaluate the real potential power production some tests were run in irregular waves with the best configuration figured out from the tests in regular waves.

4.2 Aalborg Laboratory - The facility

All the test with the Rolling Cylinder were run in the laboratory of Aalborg University.
The University of Aalborg is quite relevant in Denmark for its wave laboratory where students and companies can study the behavior and the efficiency of different kind of wave energy converters.
This laboratory is provided with a rectangular wave basin (commonly called the deep 3D wave basin) whose dimension are 15,7 m x 8,5 m and the maximum

water depth obtainable is 1,5 m. Inside the basin there is a paddle system and a beach realized with small rocks. The paddle system is a snake-front piston type with a total of ten actuators, enabling generation of short-crested waves.

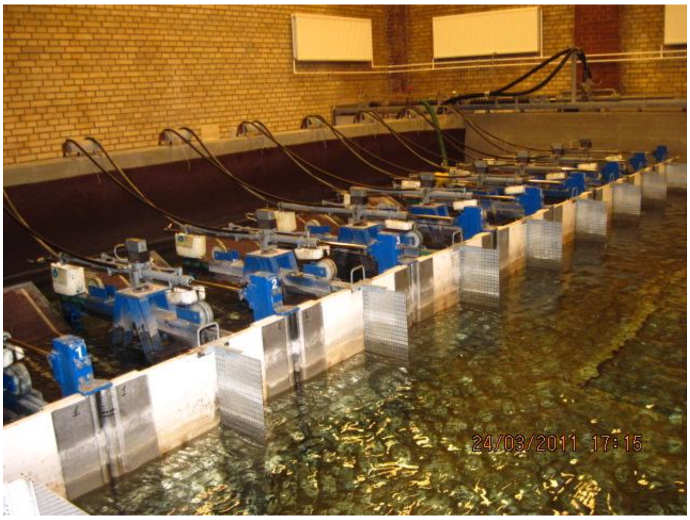


Figure 4.1: Paddle system

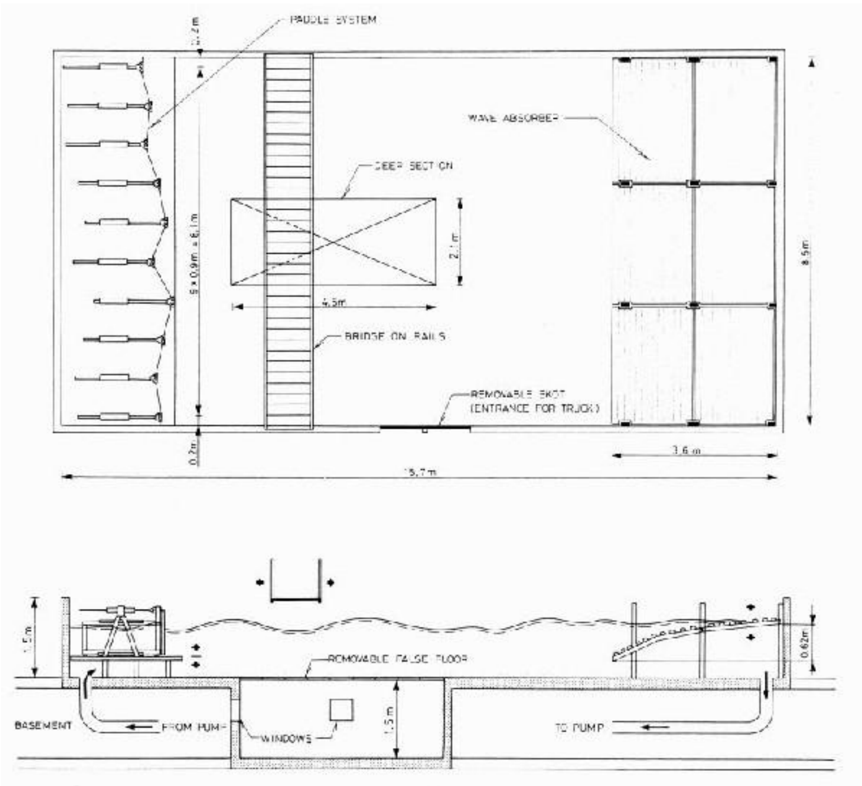


Figure 4.2: Layout and section of the laboratory

The wave generation software used for controlling the paddle system is AWASYS, developed by the laboratory. The conditions required from this software are: kind of wave, wave height, wave period, water depth, duration of the test.

In the first tests the kind of wave was regular, the wave height and the wave period were five different wave states characteristics of the North Sea, the water depth was always 0,64 m, the duration of the test was 5 minutes.

In the other tests the kind of wave was irregular, the wave height and the wave period were five different wave states characteristics of the North Sea, the water depth was always 0,65 m, the duration of the test was 25 minutes.

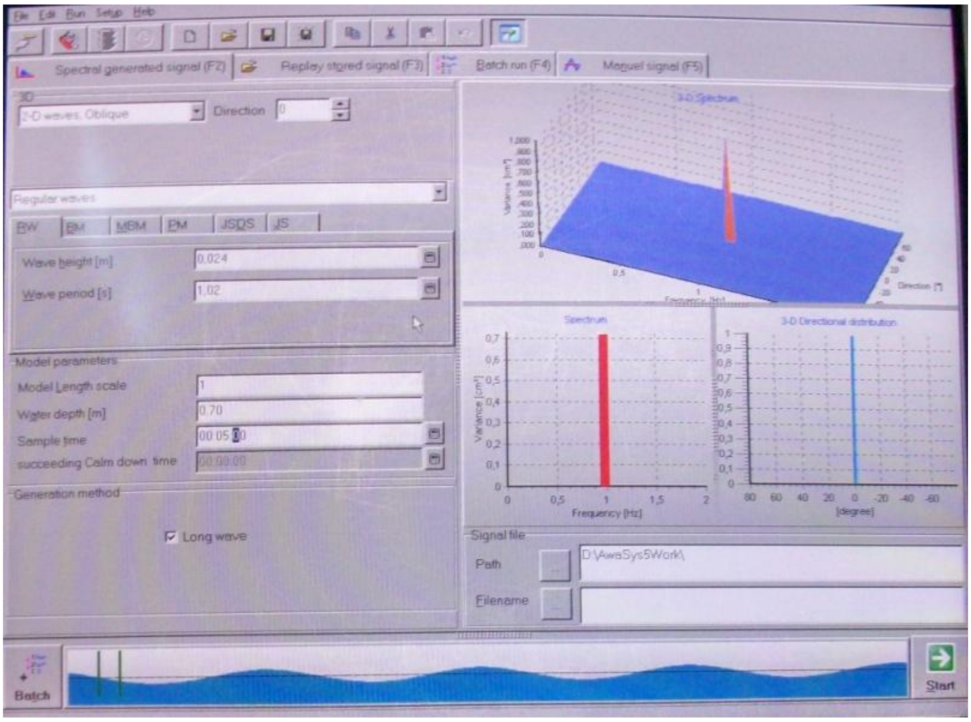


Figure 4.3: Screen of the Awasys5

Finally there is another software, called WaveLab 3.3, for the data acquisition. The requirements for acquiring the data are: sample frequency, number of channels, sample duration and the data file name.

In these tests the sample frequency was 20 Hz, the number of channel was 3 (3 wave gauges) , the sample duration was 1800s and the data file name had a structure like this: 111_2222_333_44_555.

- ✓ 111 indicates if the wave is regular (RW) or irregular (IR) and the number of the wave state. E.g . 1RW = regular wave, wave condition number 1.
- ✓ 2222 indicated how many fins set are mounted on the model. E.g. 4set means there are 4 set of fins mounted on the model.
- ✓ 333 indicates the thickness of the fins. E.g. 075= thickness of 0,75 mm.
- ✓ 44 indicates how many fins there are in each set of fins. E.g. n6= 6 fins per each set of fins
- ✓ 555 indicated the buoyancy.

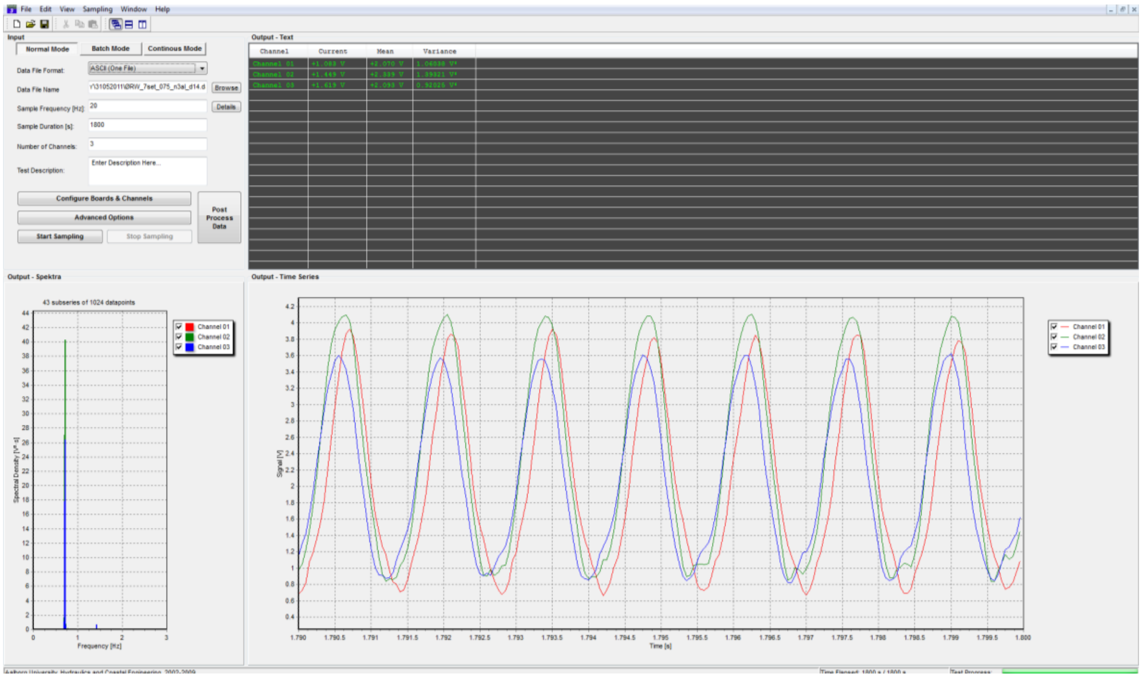


Figure 4.4: Screen of the WaveLab3.33 “Acquisition Data”

In addition to acquire the data, WaveLab 3.3 is also used to analyze the wave gauges data through the reflection analysis. It has as input the name of the file, the three gauges channel, the distance between the gauges and the water depth and we obtain as results the average wave height and the average wave period.

In all the tests there were three wave gauges collocated vertically in front of the device and the distance between the first and the second was 12,5 cm and the distance between the second and the third was 33 cm.

The wave gauges enable the measurement of the true wave height. These have to be calibrated every day before testing to avoid problems with the variation of the water's temperature.

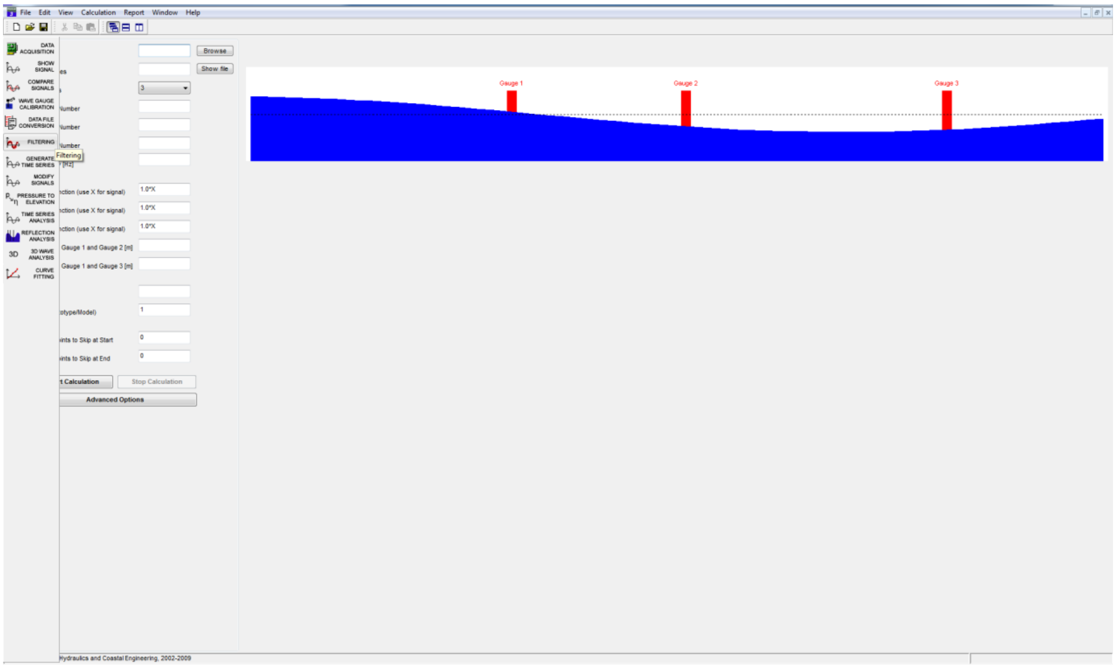


Figure 4.5: Screen of the WaveLab3.33 "Reflection Analysis"

4.3 The model

Rolling Cylinder is the ultimate wave machine. Rolling Cylinder is inspired by the world's best developer - Mother Nature. The developer has been inspired by how fish and whales energy efficient moves in the wet element.
The wave machine consists of a cylinder which is submerged just below the water surface and has a large number of "fish fins" located across the wave direction. The genius of this invention is that water molecules circular motion pattern are converted to energy not seen before in other wave machines. Furthermore, there is no energy wasted on start-stop movements, since the fins affect the cylinder to a continuing rotation, easily exploited by a simple power generator known from the wind industry.
Unlike the other types of plants, the Rolling Cylinder is also equipped with a system which ensured that the plant can escape unscathed through even the worst storm. Just like a submarine diving to a secure depth!
The idea for the Rolling Cylinder has been develop though many years and is looking to be as the most promising project. It should not be too much expensive and return of energy in relation to the investment should be big enough.

The first approach with this machine has been in 2009, when the professional inventor and businessman Lars Storper invested in the project to develop the first scale model, a 20 meter for testing in Limfjorden, Denmark.

Then other experiments were made in Nordisk Folkecenter for Renewable Energy, in June 2010. The Rolling Cylinder was in scale 1:100, the device’s length was 30 cm with 6 fins per each wreath. The fins were constructed in plastic and their thickness was 0,13 mm.

The most recent approach is the prototype studied in Aalborg University wave tank. The model is in scale 1:25 and is built in steel with fins constructed of composite.

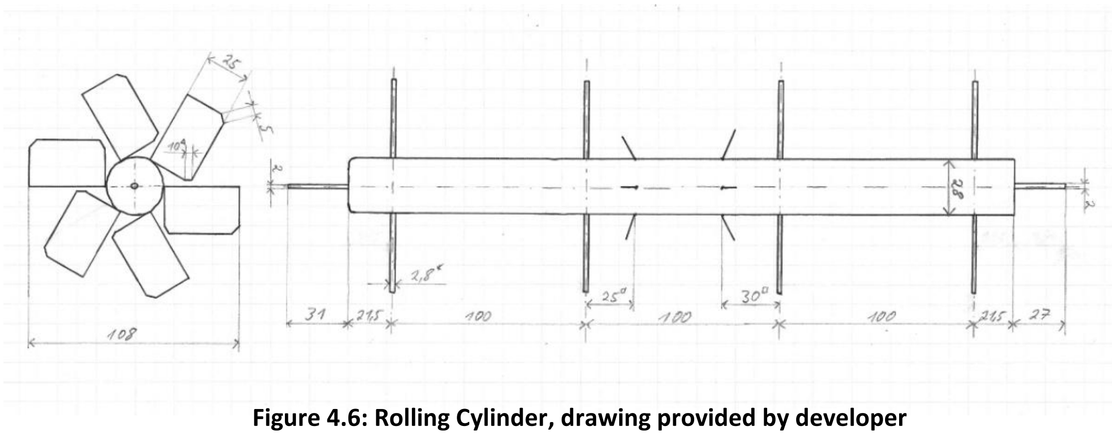


Figure 4.6: Rolling Cylinder, drawing provided by developer

First a short section of the model 1.40 m long has been realized. The model has been constructed in such a way to allow easy change of fins, change of number of sets of fins as well as easy interconnection with other sections to be realized later. This, in order to have a flexible model that allows the required investigations. The model should nevertheless be resistant (hard plastic and metal) as failure do occur also in controlled laboratory environment.

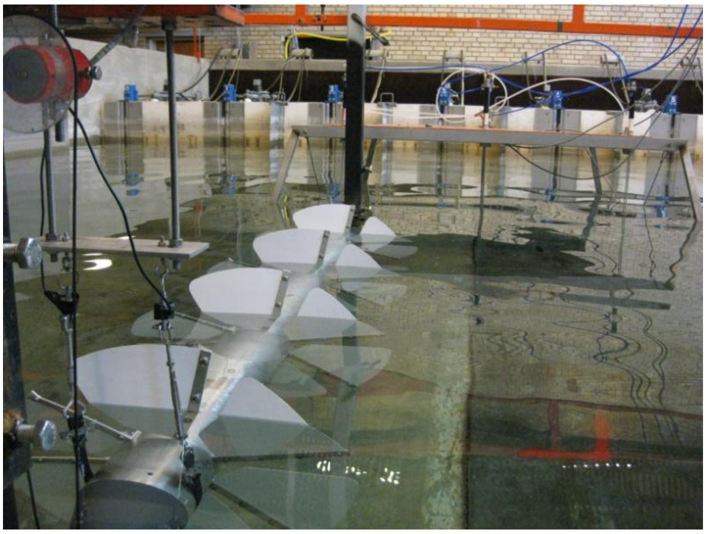


Figure 4.7: Rolling Cylinder's prototype with 4 set of fins, 6 fins per each set and thickness of the fins of 1 mm

Figure 4.8: Rolling Cylinder's prototype with 7 set of fins, 6 fins per each set and thickness of the fins of 0,75 mm

After the design optimization of the short model, a full length model of the Rolling Cylinder device in scale 1:25 was constructed.

The main body of the long model has been realized with three tube of aluminum steel of 1,4 m and ∅= 12 cm, with two hard plastic cones fixed at the two extremities of 12 cm each. The fins have been fixed to the main body by mean of an “L” element rigidly connected to the tube by mean of two screws.
The total length of the device is 4,44 m [(1,4m *3) + 0,24 cm)] with 11 set of fins of 0.75 mm thickness, 6 fin´s par set and distance between one set and the other of 40 cm. The device was placed in the middle of the deep wave basin at AAU laboratory with d=0.65 m water depth (Figure 4.3.4).

The device was rigidly fixed to the two bridges above the basin and constrained to two spherical bearings on the small rod (∅ =17 mm) at the two endings [29].

Figure 4.9: The full length model of the Rolling Cylinder device in the laboratory of Aalborg University

4.4 Test program

The Rolling Cylinder was subjected to different tests. For each wave state different weights were put on the device and for each weight the times was measured three times the time in order to obtain a measure as precise as possible. The table below shows an overview of all the laboratory experiments in regular waves.

Tasks	Variable	Number of tests
Optimization of fin thickness	0,4 mm	9
	0,75 mm	29
	1 mm	22
Optimization of number of fin	4 set	29
sets mounted on the model	7 set	32
	3 set	26
Optimization of fin number par set	6 fins	32
	3 fins	13
	3 fins alternate	18
Optimization of the buoyancy level	14	8
	22	4
	27	4
	6	4

Table 4.2: Planned tests in regular waves

Meaning of the buoyancy level:

14 = half of the fin is submerged (6cm + 8cm) where 6 cm is the radius of the cylinder and 8 cm is half height of the fin.

22 = all the fin is submerged (6cm + 16cm) where 6 cm is the radius of the cylinder and 16 cm is the height of the fin.

27 = the fin is submerged 5 cm below the water surface (6cm + 16cm + 5cm) where 6 cm is the radius of the cylinder, 16 cm is the height of the fin and 5 cm is the water on the fin.

6 = the fin is completely outside of the water, so we have only 6 cm, the radius of the cylinder.

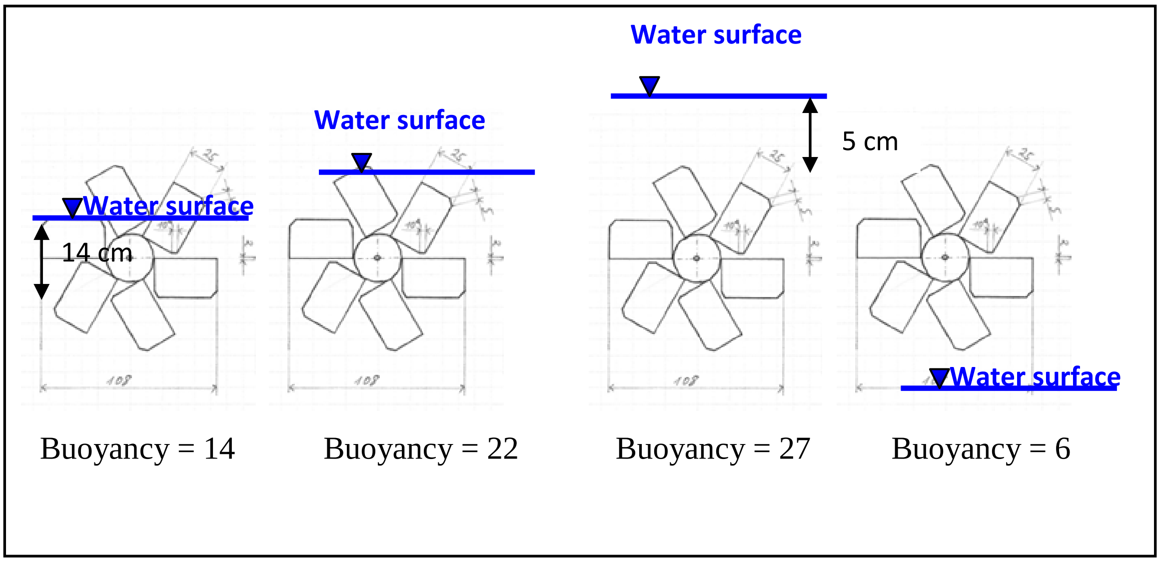


Figure 4.10: Different buoyancy levels

Later more tests in irregular waves were run with different sea states and different load on the full length device. The test program is shown below.

Wave conditions	Load
W3	L1
W4	L1
W5	L1
W2	L2
W3	L2
W4	L2
W3	L3
W4	L3
W3	L4
W4	L4
W5	L4

Table 4.2: Planned tests in irregular waves

4.5 Description of the wave state

In order to optimize the short section of the model and to evaluate the potential power production regular and irregular wave states were made. The Danish sea is characterized by five wave state and for each one there is the probability of occurrence.

wave state	Hs [m]	Tz [s]	Tp [s]	Energy flux [kW/m]	Prob. Occur. [%]
1	1.0	4.0	5.6	2.1	46.8
2	2.0	5.0	7.0	11.6	22.6
3	3.0	6.0	8.4	32.0	10.8
4	4.0	7.0	9.8	65.0	5.1
5	5.0	8.0	11.2	114.0	2.3

Table 4.3: Standardized wave states describing the Danish seas [7]

To describe the real situation in the laboratory a scale Froude was used, in order to obtain the five wave states to reproduce in the laboratory.

Parameter	Model	Full Scale
Length	1	S
Area	1	S^2
Volume	1	S^3
Time	1	$S^{0,5}$
Velocity	1	$S^{0,5}$
Force	1	S^3
Power	1	$S^{3,5}$

Table 4.4: Scale Froude

Scale 1:25 Irregular waves			Scale 1:25 Regular waves		
Wave state	Hs [m]	Tp [s]	Wave state	H [m]	T [s]
1	0,04	1,12	1	0,028	1,12
2	0,08	1,4	2	0,057	1,4
3	0,12	1,68	3	0,085	1,68
4	0,16	1,96	4	0,113	1,96
5	0,2	2,24	5	0,141	2,24

Table 4.5: Wave height and wave period for regular and irregular waves in scale 1:25

In addition to this wave conditions the developer of the model wanted to test a new wave condition. This wave condition will be called number 6 and the wave height is 0,16 m and the wave period is 1,4 s.

In these tests the wave state 1 and 2 were never used because with this wave parameters the device did not turn and wave state 3 was only used sometimes. With wave states 4,5 and 6 the device did not show any problems and always turned.

4.6 First measuring setup

At the beginning the instrumentation available to calculate the power production were two load cells to measure the force difference resulting in a torque moment M(t) and one potentiometer to measure the rotational speed ω (rad/s).

From these measurement the power of a device can be defined by:

$$P(t) = M(t) * \omega(t) \tag{4.6.1}$$

and the efficiency can be defined by:

$$\text{Efficiency [\%]} = \frac{P(t)}{Pwaves} \tag{4.6.2}$$

Where:

P*waves* is the wave power and it is the wave energy flux. The wave theory indicated that the wave power is dependent on three wave parameters: wave height, wave period and water depth. In this case the wave power was obtained from the reflection analysis in WaveLab and the efficiency was calculated with a Matlab procedure.

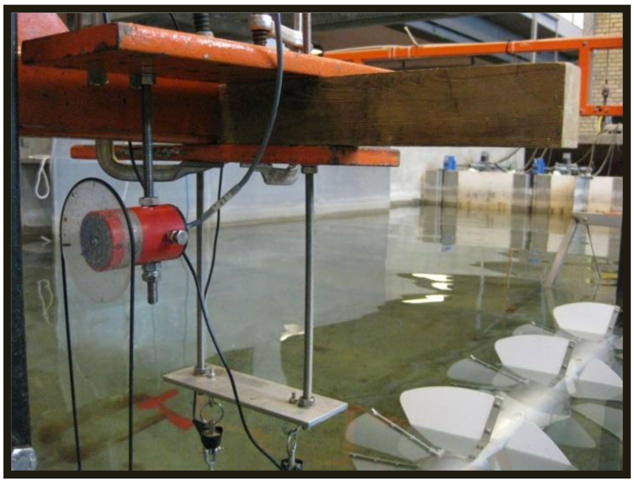


Figure 4.11: Potentiometer to measure the rotational speed

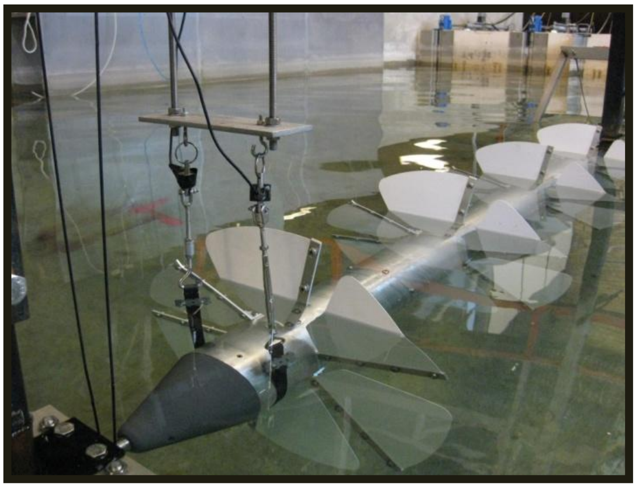


Figure 4.12: Load cells to measure the force

This measuring equipment was only used to test the fin's thickness of 0,4 mm. Then there were a lot of problems with the friction measuring system and amplifiers, and because those amplifiers were no longer available, it was decided to continue testing with a traditional system that foresees the use of weights for calculation of power for a specific wave height.

Then this measuring setup was also used to run all the tests in irregular waves, with two changes:

- the load cells were connected to the boundary section of the device.
- the system was implemented with two springs in order to reduce its stiffness (Figure 4.13).

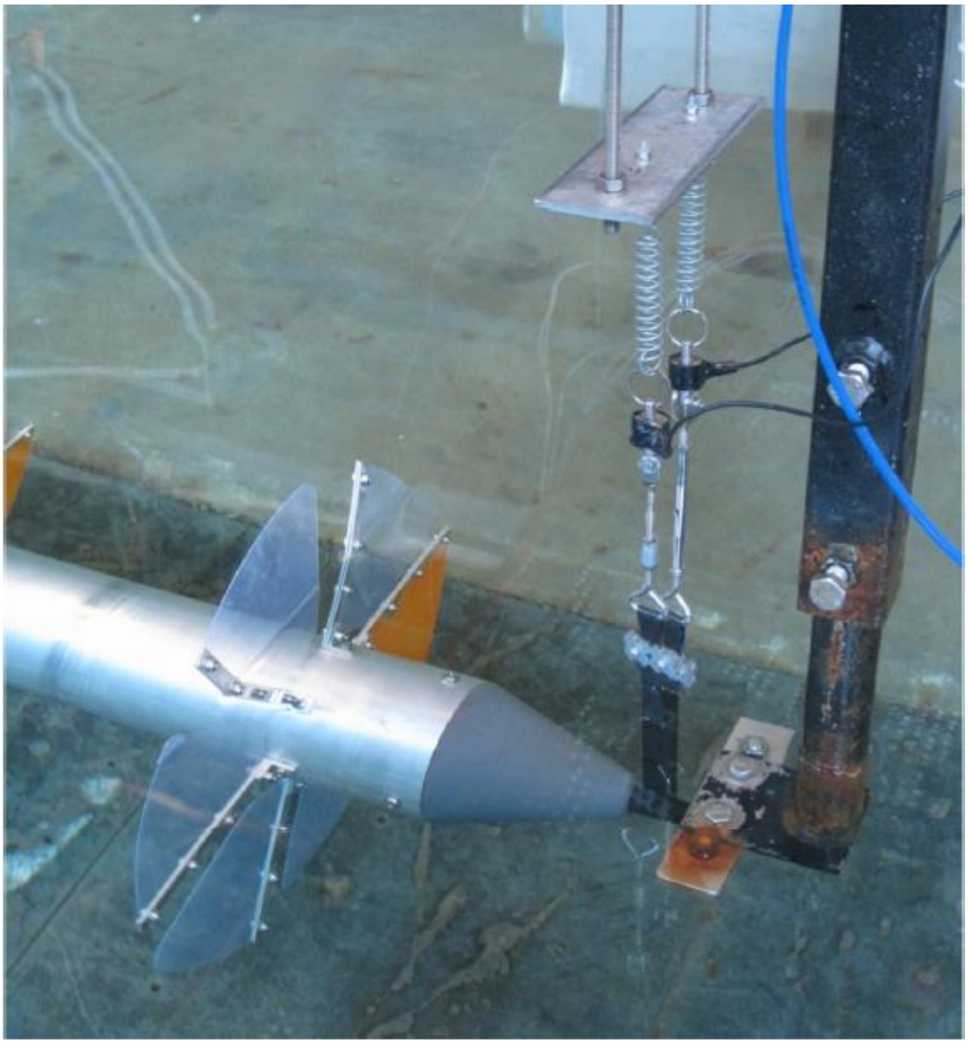


Figure 4.13: The measuring setup used to run the tests in irregular waves

4.7 Second measuring setup

The traditional system consists of putting different weights on the device and for each weight the time to cover the whole length of a string was measured three times in order to obtain a result as precise as possible. The length of the string is known.

From this measurement of the time it is possible to calculate the power:

$$P = \frac{mgh}{t} \text{ [W]} \tag{4.7.1}$$

Where:

m = mass of the weight [kg];

g = acceleration of gravity 9,82 [m/s^2];

h = length of the string 3,1 [m];

t = time measured with a stopwatch [s].

and the efficiency can be defined by:

$$\text{Efficiency [\%]} = \frac{P}{Pwaves * m} \tag{4.7.2}$$

Where:

-P*waves* is the wave power and in first approximation the following formula can be used to estimate the wave energy flux per unit wave crest lenght:

$$Pwaves = \frac{\rho g^2 H_m{}^2 T_m}{\beta\pi} \text{ [W/m]} \tag{4.7.3}$$

Where:

ρ = mass density of the water 1000 [kg/m^3];

g = acceleration of gravity 9.82 [m/s^2];

T_m = average wave period [s] from reflection analysis in WaveLab;

H_m = average wave height [m] from reflection analysis in WaveLab;

β = is a coefficient may be 64 for irregular waves or 32 for regular waves.

-m = cylinder's diameter plus fin's height, where cylinder's diameter is 12 cm and fin's height is 16 cm. So m = 12 + 16 + 16 = 44 cm = 0,44 m.

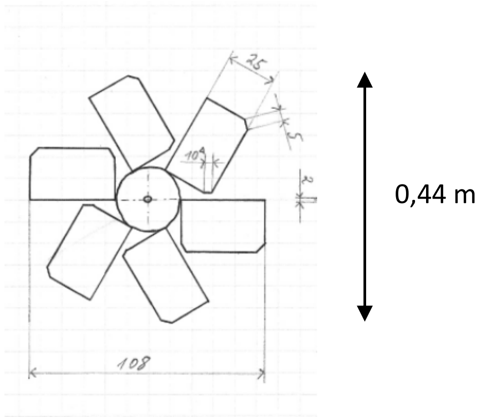


Figure 4.14: Section of the device

5. Power production and optimization of design parameters

5.1 Optimisation of fin thickness

The first goal of this project is to find the best thickness of the fins. The first section of the model had 4 set of fins of 6 fins each. With this original configuration three different fin thicknesses for regular waves were investigated : 0,4 mm; 0,75 mm and 1 mm.

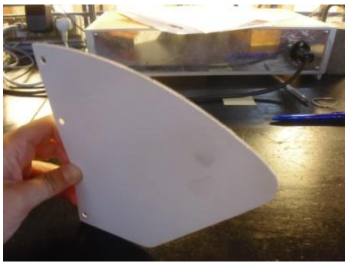


Figure 5.1: Thickness 1

Figure 5.2: Thickness 0,75

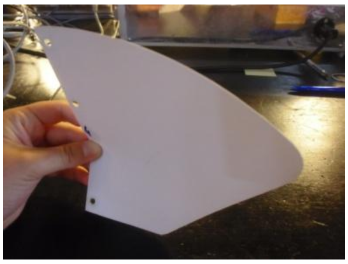


Figure 5.3: Thickness 0,4 mm

For each wave state an adequate number of weights were put on the device in order to always obtain a curve with a peak of the efficiency.

For each weigh the efficiency was calculated with the Eq. 4.7.2 and it was plot on a graph with the torque, where the torque is mass of the weight times 9,82 m/s^2 times the radius of the cylinder.

In the secondary axis the angular velocity in rad/s and the torque were plot.

With the wave state 3 the device turned only with the fins of 0,75 millimeters of thickness, so this graph was not drawn because a comparison with the other thickness was not possible.

From the graphics below it is possible to observe that when the wave parameters increase, higher value of the torque and higher value of the efficiency were obtained but the angular velocity decreases when the torque increases.

The graphics below show the behavior of the device for each wave state and with different thickness of the fins.

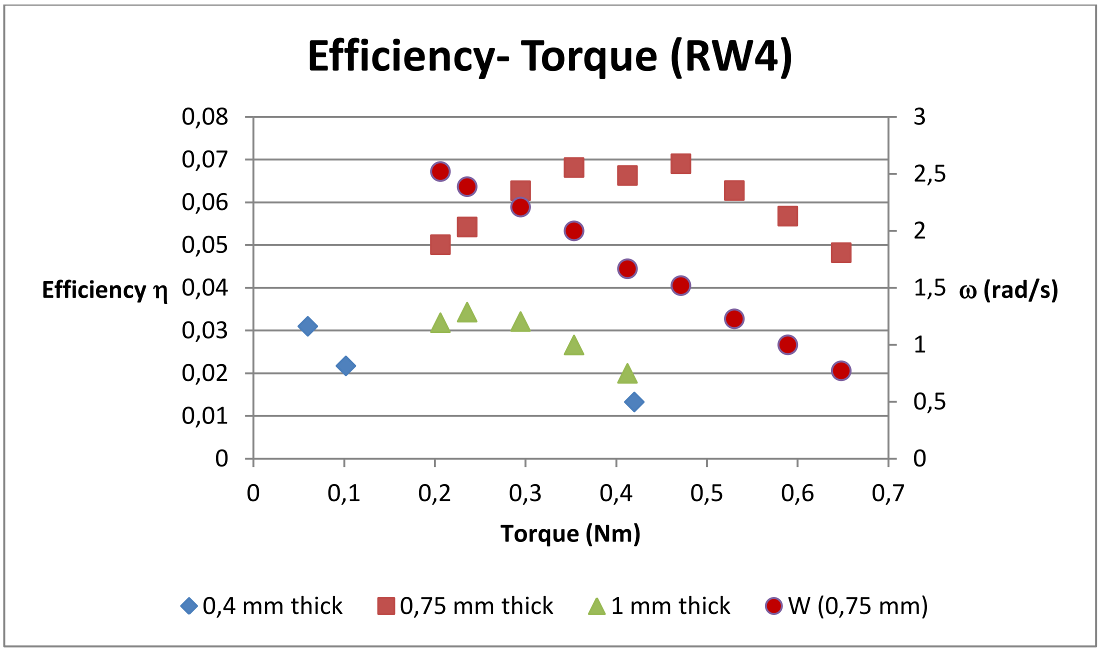


Figure 5.4: Representation of the efficiency for different values of the torque, for the fin's thickness of 0,4 mm, 0,75 mm and 1 mm. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 4 (H= 0,113 m e T= 1,96 s)

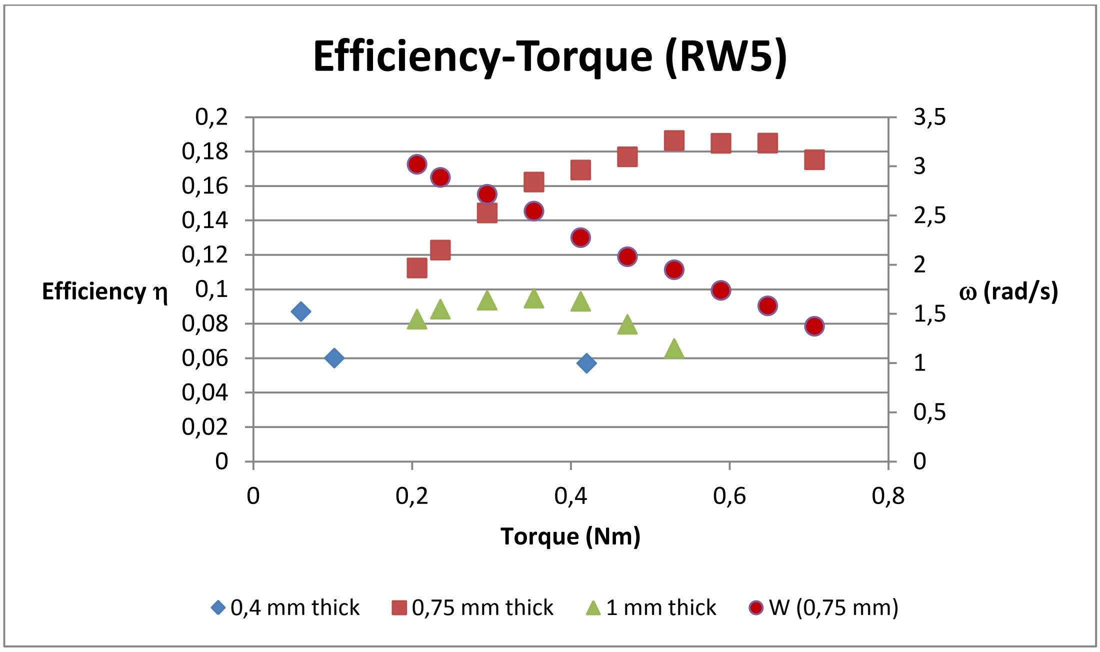


Figure 5.5: Representation of the efficiency for different values of the torque, for the fin's thickness of 0,4 mm, 0,75 mm and 1 mm. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 5 (H=0,141 m e T=2,24 s)

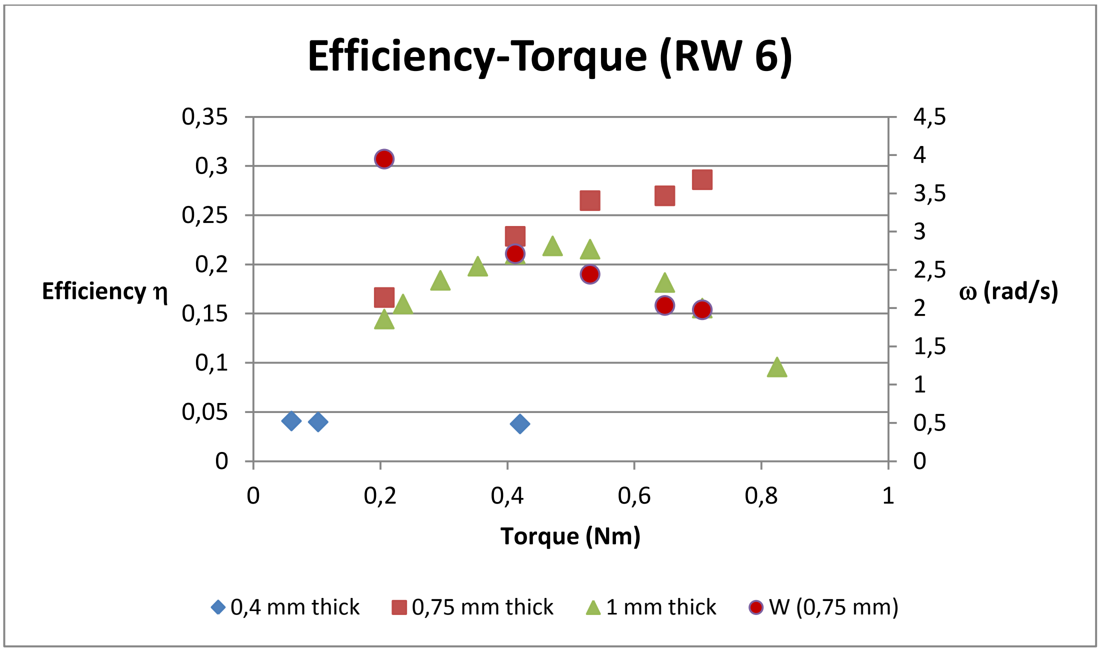


Figure 5.6: Representation of the efficiency for different values of the torque, for the fin's thickness of 0,4 mm, 0,75 mm and 1 mm. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 6 (H=0,16 m e T=1,4 s)

From the graphics above it is possible to observe that the gap between 0,75 mm and 1 mm is not negligible so it is easy to deduce that the best thickness is 0,75 mm for all the wave states, because is the thickness with the highest value of the efficiency.

Later an optimum load for each thickness was calculated by means of a weighted average of the probability of occurrence of the different wave states. To calculate the optimum load the wave state 6 was not considered because it is not characteristic of the Danish Sea, it is steeper than the others and its probability of occurrence was not available.

	0,4 mm	
	Optimum Load (N)	Efficiency η
RW 4 (H=0,113 m T=1,960 s)	1	0,093
RW 5 (H= 0,141 m T= 2,240 s)	1	0,087
	0,75 mm	
	Optimum Load (N)	Efficiency η
RW 4 (H=0,113 m T=1,960 s)	8,1612	0,2072
RW 5 (H= 0,141 m T= 2,240 s)	8,1612	0,1864
	1 mm	
	Optimum Load	Efficiency η
RW 4 (H=0,113 m T=1,960 s)	4,5384	0,1030
RW 5 (H= 0,141 m T= 2,240 s)	4,5384	0,0948

Table 5.1: Optimum Load and Efficiency for each value of fin's thickness and for different wave states

The graphs below want to represent the variation of the efficiency with the optimum load for the three different fin's thickness and then the efficiency trend with the wave states 4 and 5 for different optimum load.

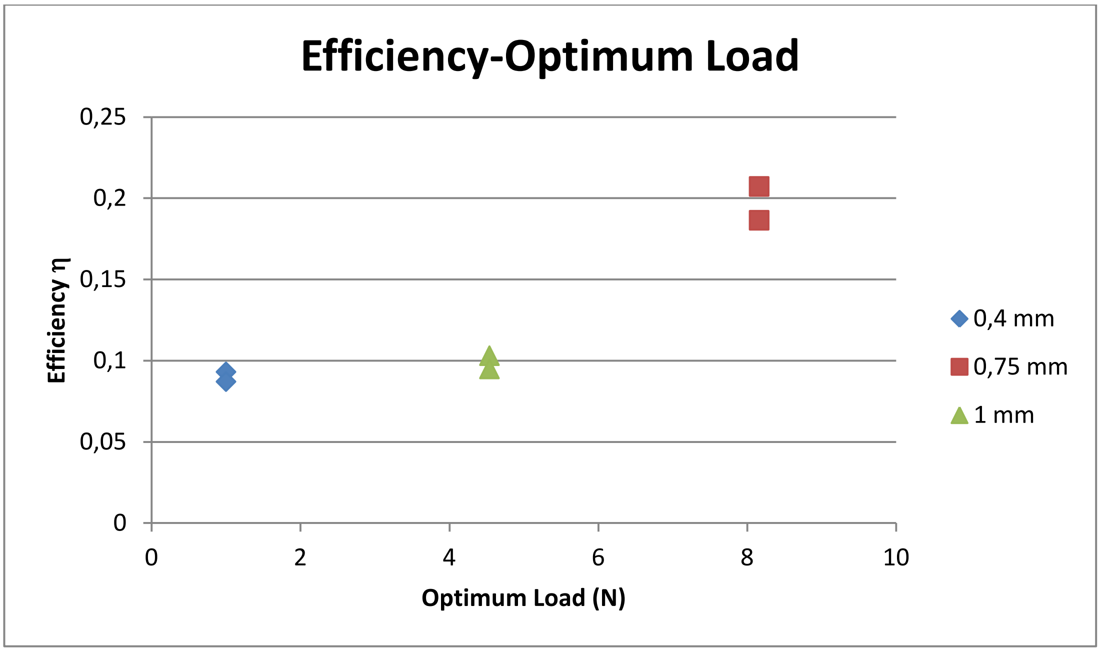


Figure 5.7: Representation of the efficiency with the optimum load, for the fin's thickness of 0,4 mm, 0,75 mm and 1 mm

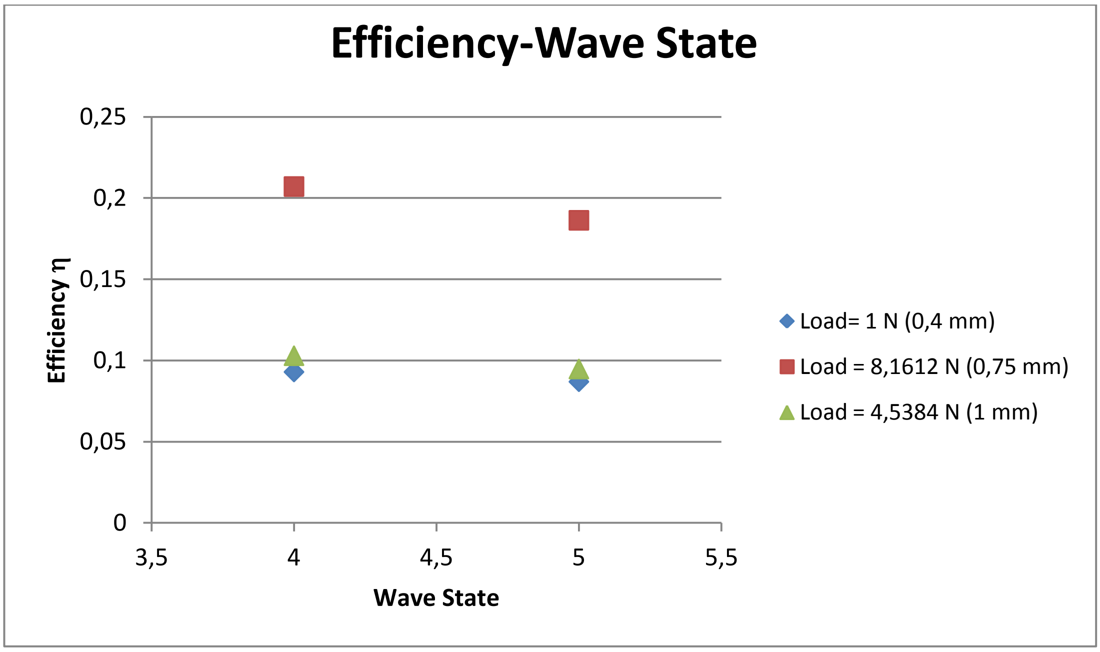


Figure 5.8: Representation of the efficiency with the wave state, for the fin's thickness of 0,4 mm, 0,75 mm and 1 mm

The graphs above are according with the previous graphs and the highest efficiency is always reach with the fin's thickness of 0,75 mm.

5.2 Optimisation of the number of fin sets mounted on the model

The "short model" now optimized for fin thickness, will be used with different number of fin sets mounted on the model, in fact the second goal of this project is to run the tests with different number of fin sets for the best thickness obtained from the previous results.

All the tests were run in regular waves for 3 different number of fin sets mounted on the model: 4 set of fins of 6 fins each, distance 0,4 m between them, 7 set of fins of 6 fins each, distance 0,2 m between them and 3 set of fins of 6 fins each, distance 0,6 m between them.

Figure 5.9: 7 set of fins mounted on the model

Figure 5.10: 4 set of fins mounted on the model

For each wave state an adequate number of weights were put on the device in order to always obtain a curve with a peak of the efficiency.

For each weigh the efficiency was calculated with the Eq. 4.7.2 and it was plot on a graph with the torque, where the torque is mass of the weight times 9,82 m/s^2 times the radius of the cylinder.

In the secondary axis the angular velocity in rad/s and the torque were plot.

In all of these tests the device was always turning, also with the wave state 3, because the thickness of the fins is 0,75 mm, that was the only thickness with which the device was turning before.

From the graphics below it is possible to observe that when the wave parameters increase, higher value of the torque and higher value of the efficiency were obtained but the angular velocity decreases when the torque increases.

The graphics below show the behavior of the device for each wave state and with different number of fins set mounted on the model.

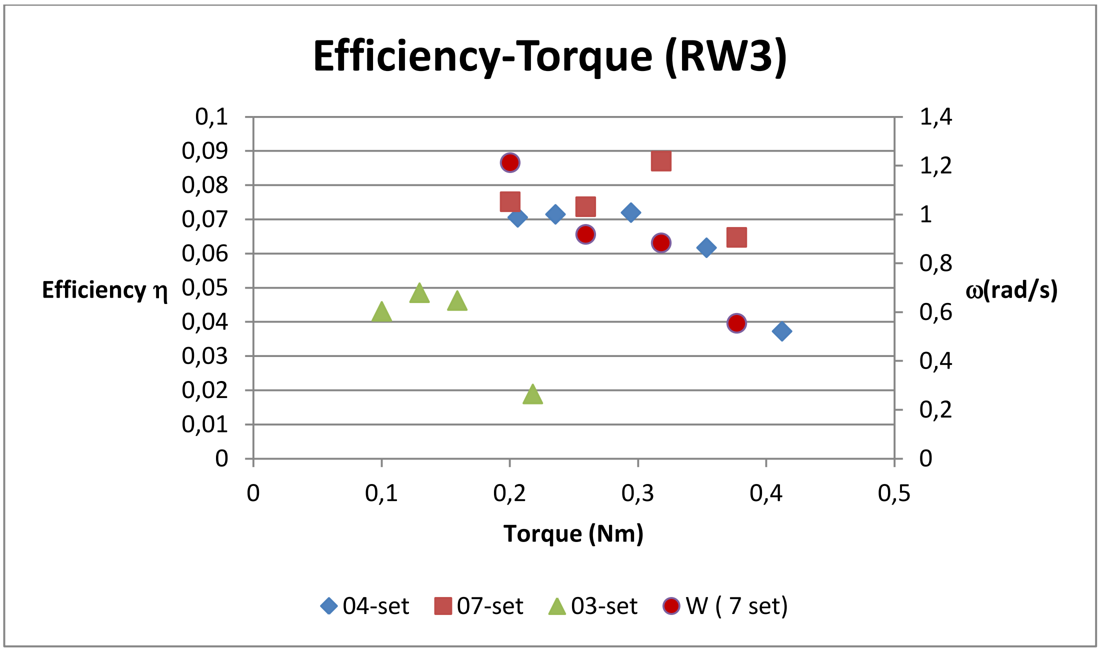


Figure 5.11: Representation of the efficiency for different values of the torque, for different number of fins set mounted on the model. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 3 (H = 0,085 m e T = 1,68 s)

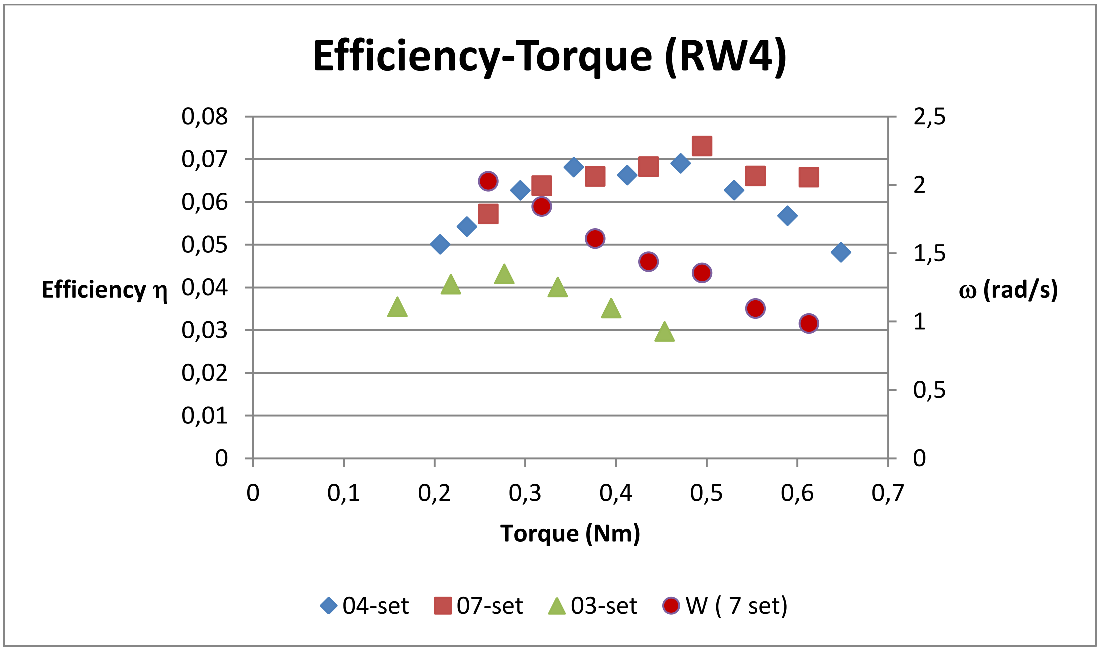


Figure 5.12: Representation of the efficiency for different values of the torque, for different number of fins set mounted on the model. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 4 (H= 0,113 m e T= 1,96 s)

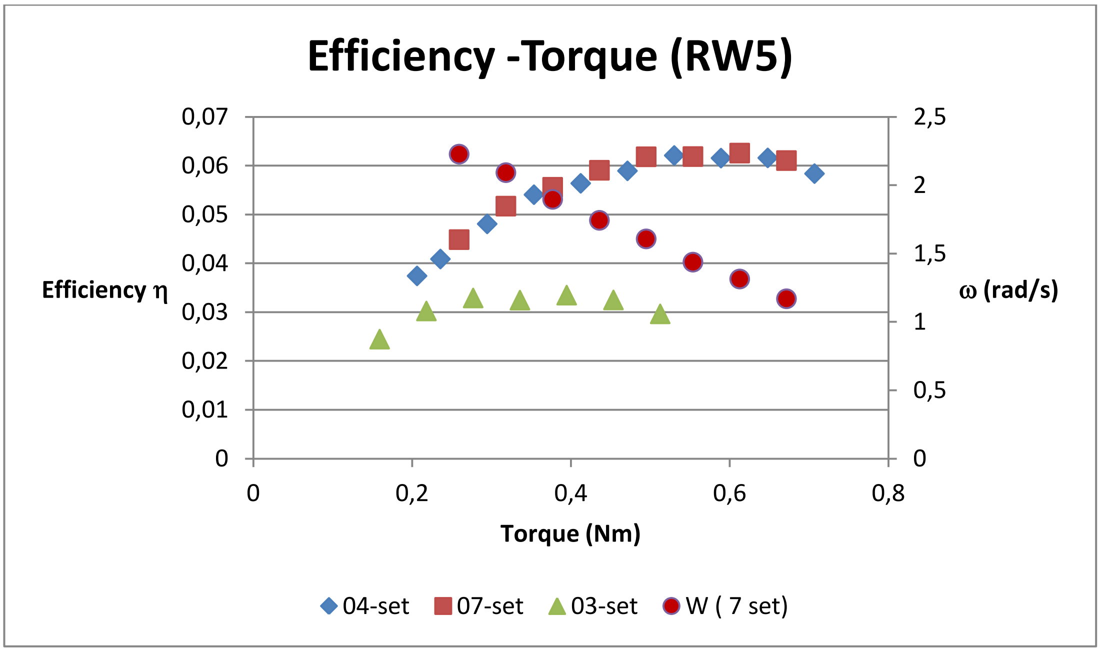


Figure 5.13: Representation of the efficiency for different values of the torque, for different number of fins set mounted on the model. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 5 (H=0,141 m e T=2,24 s)

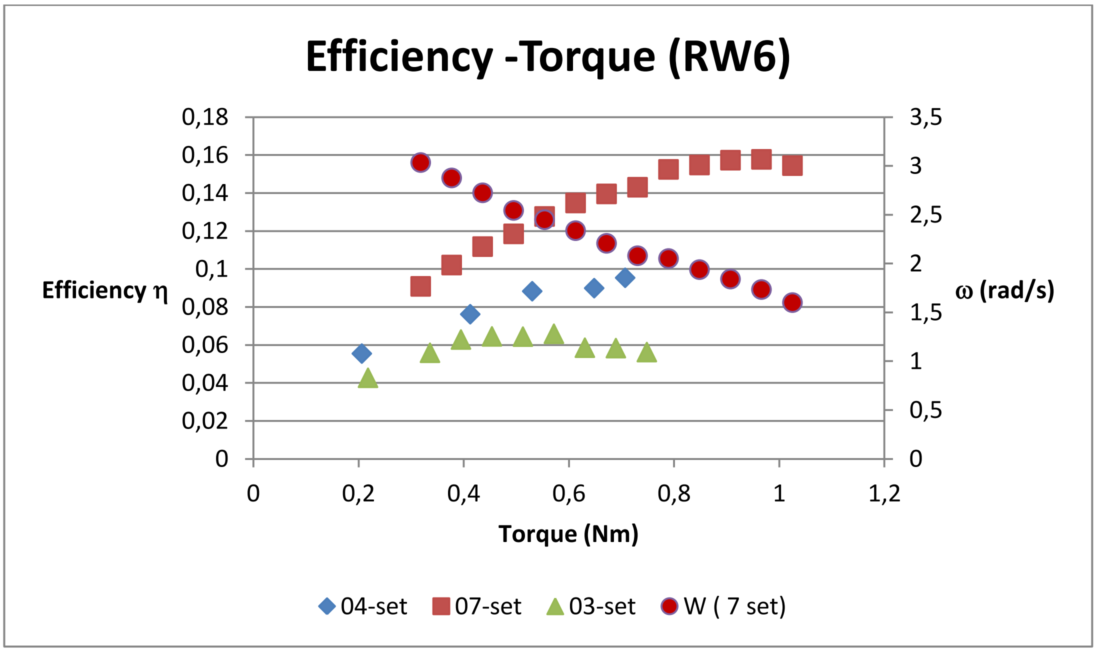


Figure 5.14: Representation of the efficiency for different values of the torque, for different number of fins set mounted on the model. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 6 (H=0,16 m e T=1,4 s)

From the graphics above it is possible to figure out that the best number of fin sets mounted on the model is 7 sets for all the wave states, because is the number of set with the highest value of the efficiency. However, except for the wave state 6, the gap between 4 sets and 7 sets is low. This means that is possible to take economics into consideration and maybe is better to put 4 sets. In this way the efficiency is lower but it is possible to save money.
In the wave state 6 there is a bigger difference between the efficiency obtained with 4 sets mounted on the model and the efficiency obtained with 7 sets mounted on the model. This could be caused by the steepness of the wave state 6 that is higher in comparison with the steepness of the other wave states.

Later an optimum load for different number of fins set mounted on the model was calculated by means of a weighted average of the probability of occurrence of the different wave states. To calculate the optimum load the wave state 6 was not considered because it is not characteristic of the Danish Sea, it is a steeper wave than the others and its probability of occurrence was not available.

	4 set of fins	
	Optimum Load (N)	**Efficienza η**
RW 3 (H=0,085 m T= 1,680 s)	6,2319	0,2161
RW 4 (H=0,113 m T=1,960 s)	6,2319	0,2072
RW 5 (H= 0,141 m T= 2,240 s)	6,2319	0,1864
	7 set of fins	
	Optimum Load (N)	**Efficienza η**
RW 3 (H=0,085 m T= 1,680 s)	6,7488	0,2613
RW 4 (H=0,113 m T=1,960 s)	6,7488	0,2194
RW 5 (H= 0,141 m T= 2,240 s)	6,7488	0,1878
	3 set of fins	
	Optimum Load (N)	**Efficienza η**
RW 3 (H=0,085 m T= 1,680 s)	3,4068	0,1458
RW 4 (H=0,113 m T=1,960 s)	3,4068	0,1296
RW 5 (H= 0,141 m T= 2,240 s)	3,4068	0,1006

Table 5.2: Optimum Load and Efficiency for different number of fins set mounted on the model and for different wave states

The graphs below want to represent the variation of the efficiency with the optimum load for the three different number of fins set mounted on the model and then the efficiency trend with the wave states 3, 4 and 5 for different optimum load.

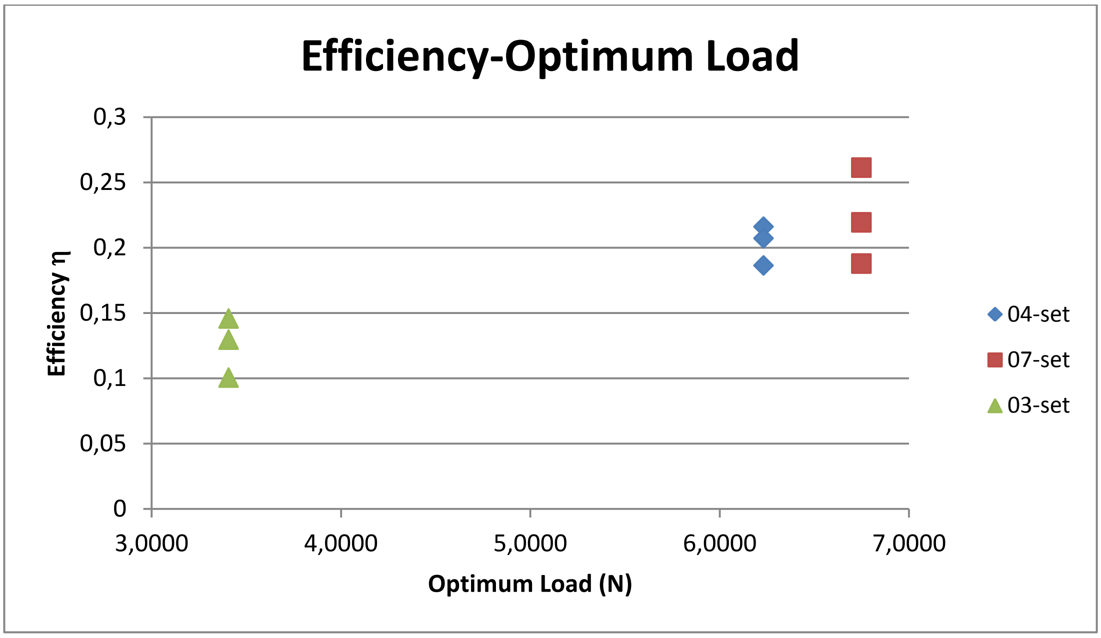


Figure 5.15: Representation of the efficiency with the optimum load, for different number of fins set mounted on the model (4 set, 7 set and 3 set)

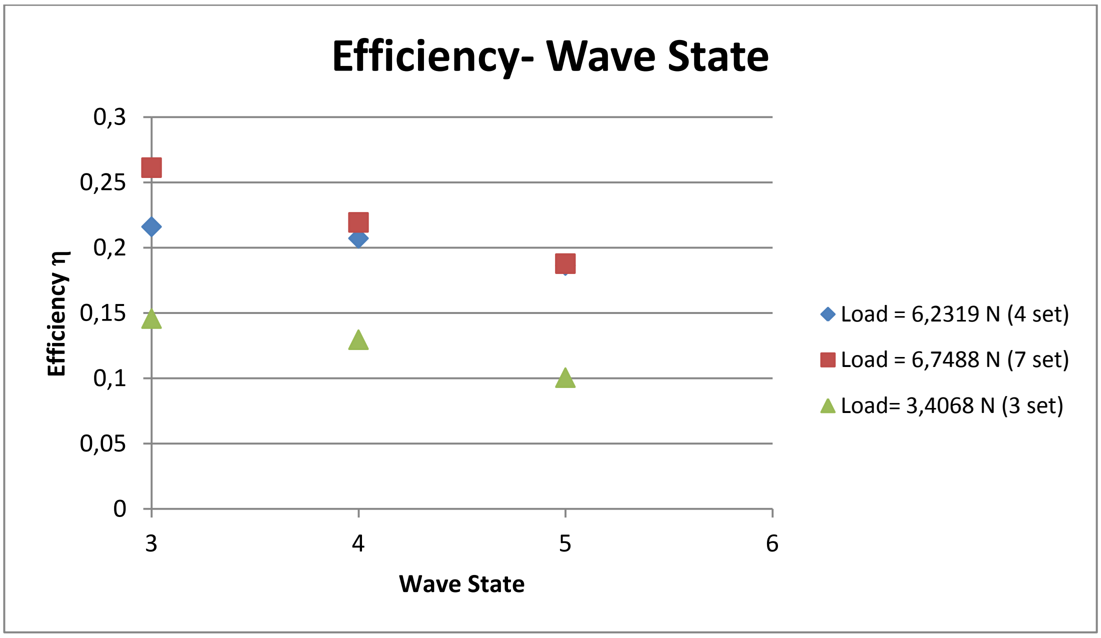


Figure 5.16: Representation of the efficiency with the wave state, for different number of fins set mounted on the model (4 set, 7 set and 3 set)

The graphs above are according with the previous graphs and the highest efficiency is always reach with 7 set of fins mounted on the model.

5.3 Optimisation of the number of fins par set

The third goal of the project is to find the best fin number par set for the best thickness and the best number of fin sets mounted on the model, both obtained from the previous results. All the tests were run in regular waves for 3 different fin number par set: 6 fins par set, 3 fins par set and 3 fins par set but putting the fins alternatively.

Figure 5.17: 6 fins par set

Figure 5.18: 3 fins par set

Figure 5.19:3 fins par set alternate

For each wave state an adequate number of weights were put on the device in order to always obtain a curve with a peak of the efficiency.

For each weigh the efficiency was calculated with the Eq. 4.7.2 and it was plot on a graph with the torque, where the torque is mass of the weight times 9,82 m/s^2 times the radius of the cylinder.

In the secondary axis the angular velocity in rad/s and the torque were plot.

The device was able to turn with the wave state 3 only with 6 fins par set, so this graph was not drawn because a comparison with the different number of fins par set was not possible.

From the graphics below it is possible to observe that when the wave parameters increase, higher value of the torque and higher value of the efficiency were obtained but the angular velocity decreases when the torque increases.

The graphics below show the behavior of the device for each wave state and with different number of fin number par set.

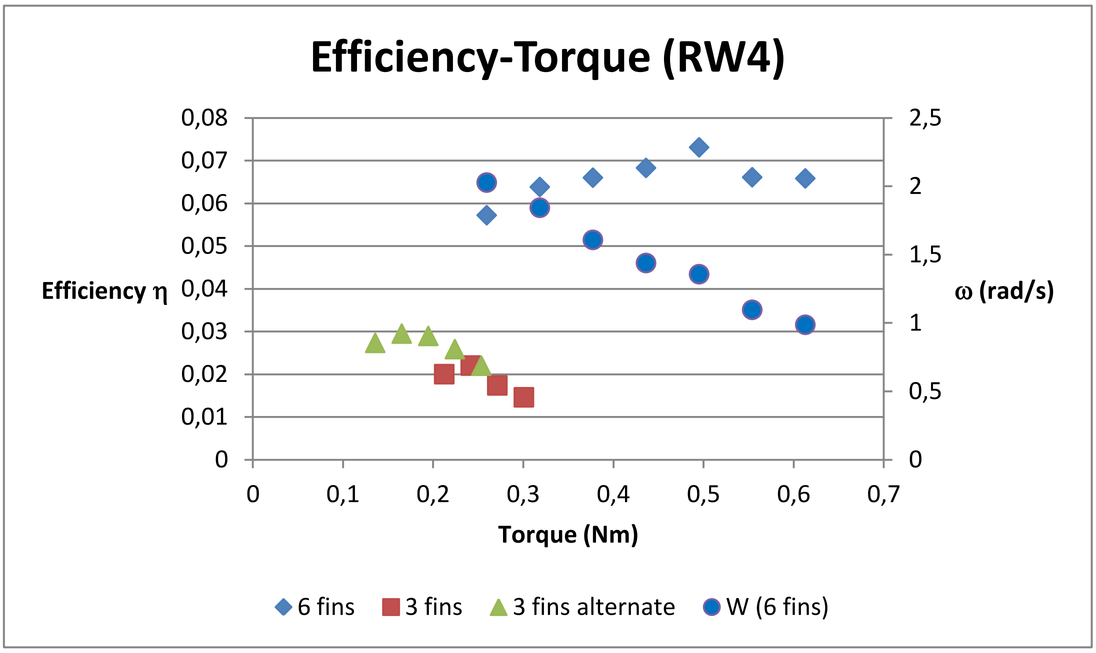


Figure 5.20: Representation of the efficiency for different values of the torque, for different number of fins par set. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 4 (H= 0,113 m e T= 1,96 s)

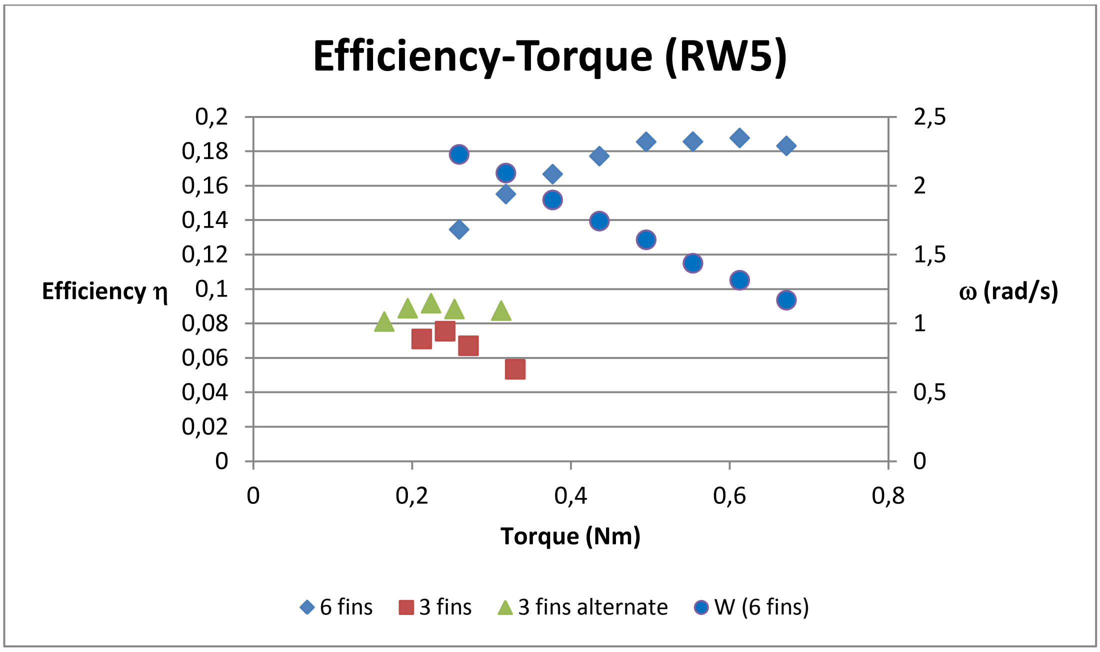


Figure 5.21: Representation of the efficiency for different values of the torque, for different number of fins par set. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state wave state 5 (H=0,141 m e T=2,24 s)

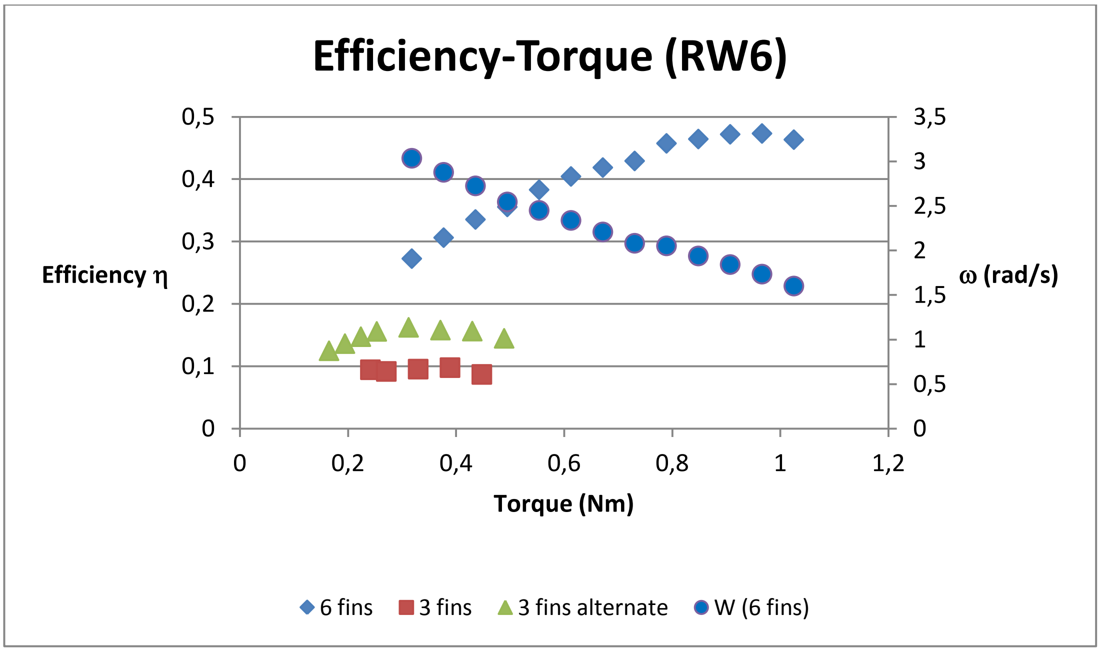


Figure 5.22: Representation of the efficiency for different values of the torque, for different number of fins par set. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 6 (H=0,16 m e T=1,4 s)

It is easy to understand that 6 is the best number of fins par set. Even if with 3 fins is possible to save material and money, the difference between the efficiency achieved with 6 fins and the efficiency achieved with 3 fins is too big and it is the right solution choose the configuration with 6 fins par set.

Later an optimum load for different number of fins par set was calculated by means of a weighted average of the probability of occurrence of the different wave states. To calculate the optimum load the wave state 6 was not considered because it is not characteristic of the Danish Sea, it is a steeper wave than the others and its probability of occurrence was not available.

	6 fins par set	
	Optimum Load (N)	**Efficienza η**
RW 4 (H=0,113 m T=1,960 s)	8,8592	0,2194
RW 5 (H= 0,141 m T= 2,240 s)	8,8592	0,1878
	3 fins par set	
	Optimum Load (N)	**Efficienza η**
RW 4 (H=0,113 m T=1,960 s)	4,0262	0,0661
RW 5 (H= 0,141 m T= 2,240 s)	4,0262	0,0756
	3 fins par set poste alternate	
	Optimum Load (N)	**Efficienza η**
RW 4 (H=0,113 m T=1,960 s)	3,0548	0,0886
RW 5 (H= 0,141 m T= 2,240 s)	3,0548	0,0919

Table 5.3: Optimum Load and Efficiency for different number of fins par set and for different wave states

The graphs below want to represent the variation of the efficiency with the optimum load for the three different number of fins par set and then the efficiency trend with the wave states 4 and 5 for different optimum load.

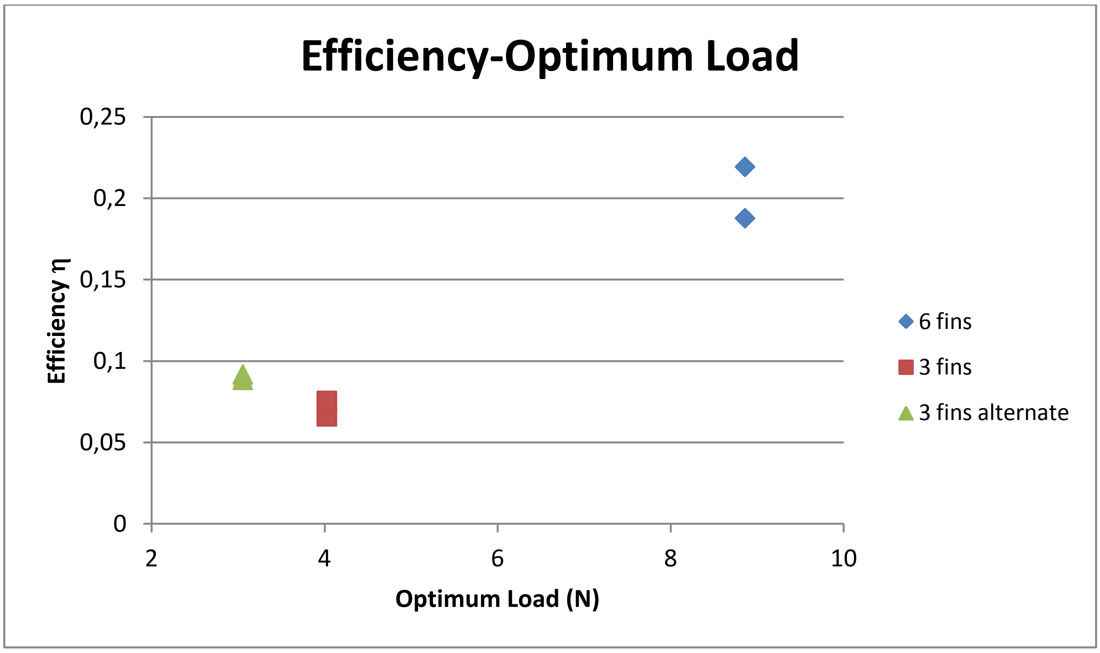


Figure 5.23: Representation of the efficiency with the optimum load, for different number of fins par set (6 fins, 3 fins and 3 fins alternate par set)

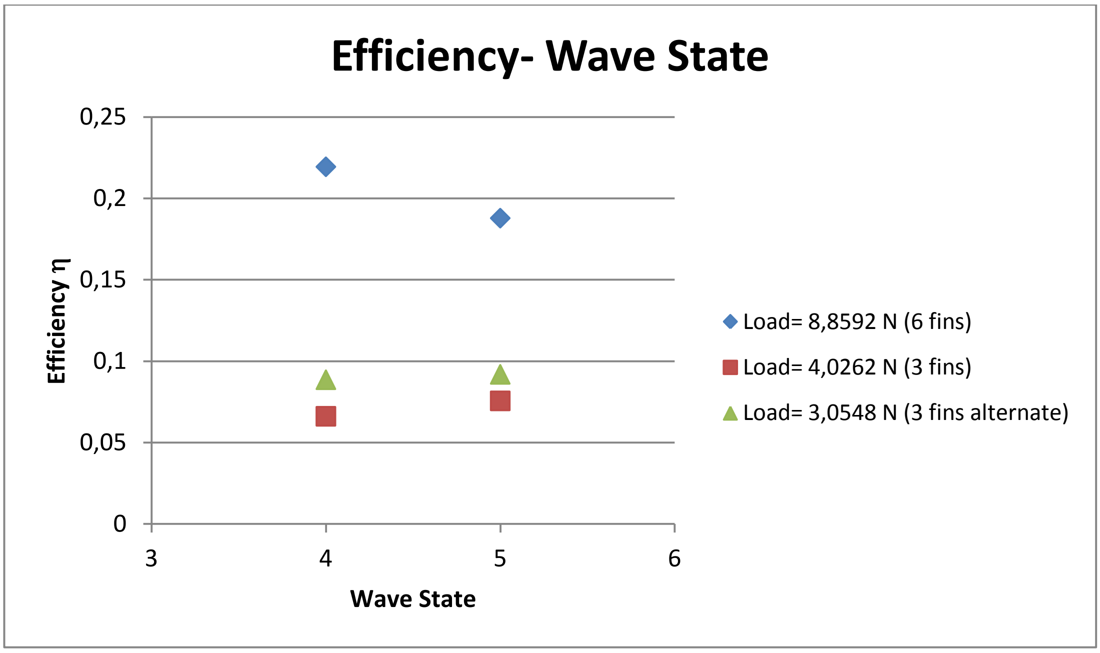


Figure 5.24: Representation of the efficiency with the wave state, for different number of fins par set (6 fins, 3 fins and 3 fins alternate par set)

The graphs above are according with the previous graphs and the highest efficiency is always reach with 6 fins par set.

5.4 Optimisation of the best buoyancy level

The "short model" now optimized for fin thickness, distance between two consecutive set of fins and fin number par set, will be used with different buoyancy levels and the last goal of the project is to find the best buoyancy level. From the previous results was obtained that the best thickness of the fins is 0,75 mm, the best number of fin sets is 7 and the best fin number par set is 6.

All the tests were run in regular waves for 4 different buoyancy levels: 6 cm, means the fin is completely outside the water; 14 cm, means half of the fin is submerged, 22 cm, means all the fin is submerged and 27 cm, means the fin is submerged 5 cm below the water surface.

To find the best buoyancy level the tests were only run with the wave state 5 because it is possible to foresee that the behavior of the device is almost the same with all the wave states.

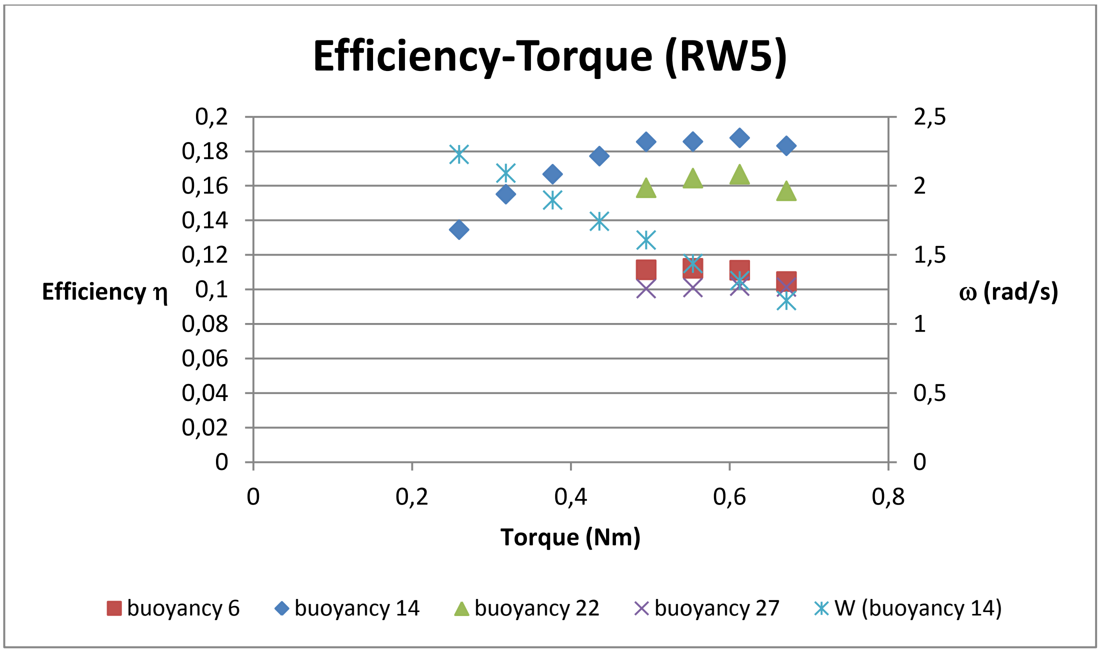


Figure 5.25: Representation of the efficiency for different values of the torque, for different level of buoyancy. In the secondary axis there is the variation of ω (angular velocity) with different values of the torque. This graph is for the wave state 5 (H=0,141 m e T=2,24 s)

It is easy to deduce that 14 is the best buoyancy level, because is the buoyancy level with the highest value of the efficiency.

Buoyancy level 14 is also the ones used for all the tests.

Maybe if the power loss is not too much big it is also possible to use the buoyancy 22 because the device is under the water and it is safer and less weathered during a storm.

Later the graphs below were drawn to represent the variation of the efficiency with the load for four different buoyancy levels and then the efficiency trend with the wave states 5 for different buoyancy levels.

In this case it was not possible to calculate an optimum load because the tests were only run with the wave state 5, so it was available only the value of the load corresponding to that wave state.

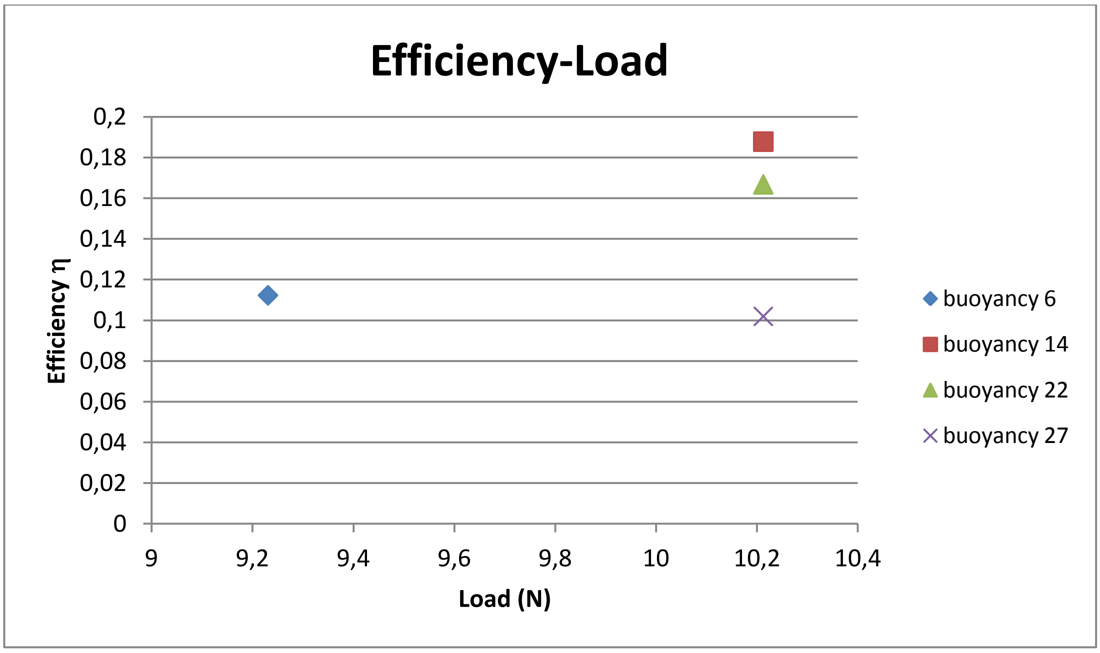


Figure 5.26: Representation of the efficiency with the load, for different buoyancy levels

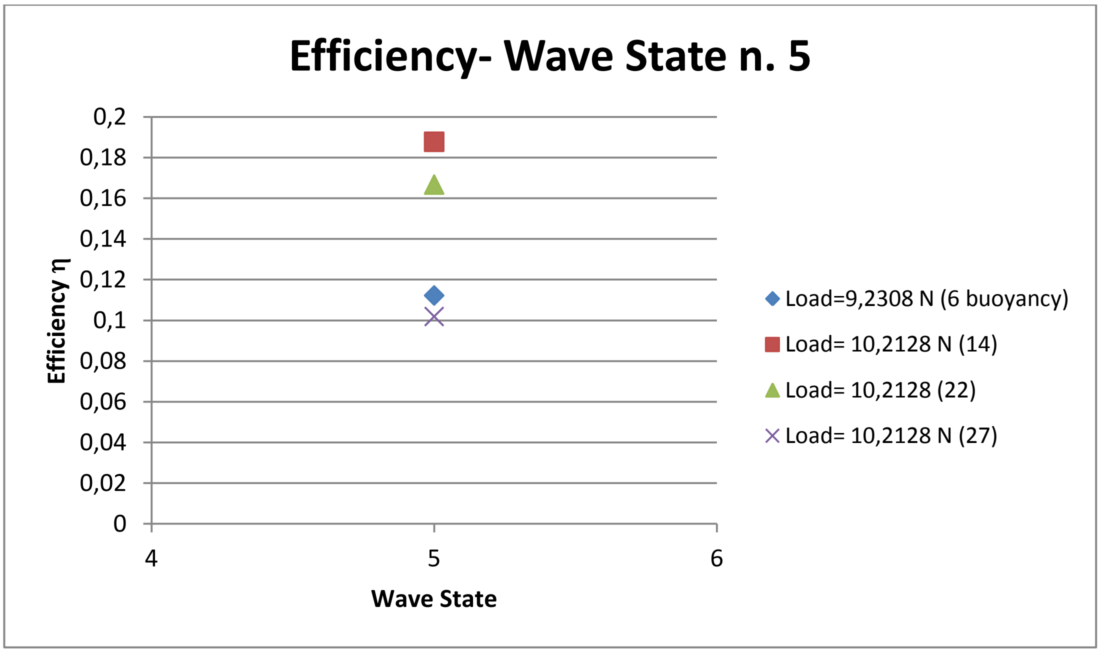


Figure 5.27: Representation of the efficiency with the wave state 5, for different buoyancy levels

The graphs above are according with the previous graphs and the highest efficiency is always reach with the buoyancy level 14, which mean that half of the fin is submerged.

5.5 Evaluation of the potential power production under regular waves

After the design optimization, an evaluation of the potential power production in regular waves was done. In these way we have an idea of the overall behavior of the device. The yearly average wave power, the yearly average power production, the overall efficiency and the yearly energy power production were calculated.
This results do not reflect the real production and the same results running tests in irregular waves are necessary, in fact the power production in regular waves is higher than the power production in irregular waves.

The table below summarize the wave parameters describing the Danish seas.

WS	H [m]	T [s]	Energy flux [kW/m]	Prob.	Prob.*Pwave [kW/m]	Eff.	Pgen [kW/m]	Pgen.*Prob. [kW/m]
1	1	5,6	2,1	0,468	0,98	0,05	0,11	0,05
2	2	7	11,6	0,226	2,62	0,12	1,39	0,31
3	3	8,4	32	0,108	3,46	0,261	8,35	0,90
4	4	9,8	65,6	0,051	3,35	0,219	14,37	0,73
5	5	11,2	114	0,024	2,74	0,186	21,20	0,51

Table 5.4: Summarize of the performance of the Rolling Cylinder in regular waves and full scale

Where:

- Pwave and Probability of occurance are the value from the "wave state describing energy in Danish seas"

- Pgen is the Efficiency*Pwave

The values of the efficiency for the wave condition number 1 and 2 are not realistic because the test with these wave states were not run as the device did not turn, but two values that could be realistic were chosen.

From the values in this table the parameters were calculated in order to have an idea of the performance of the device:

- Yearly average wave power = $\sum_{Ws=1}^{5}(Prob * Pwave)$ = (5.5.1)

= 0,98+2,62+3,46+3,35+2,74=13,15 kW/m

-Yearly average power production = $\sum_{Ws=1}^{5}(Prob * Pgen) =$ (5.5.2)

= 0,05+0,31+0,90+0,73+0,51=2,5 kW/m

-Overall efficiency = $\frac{\text{Yearly average power production}}{\text{Yearly average wave power}}$ = (5.5.3)

$$\frac{2,5}{13,15} = 0,19$$

-Yearly energy power production = Yearly average power production* 365*24 (5.5.4)

= 2,5*365*24 = 21,9 MWh/y/m

Yearly average wave power [kW/m]	13,15
Yearly average power production [kW/m]	2,5
Overall efficiency	0,19
Yearly energy power production [MWh/y/m]	21,9

Table 5.5: Summary of the performance of the Rolling Cylinder wave energy converter in regular waves and full scale

It is worthy of remind that this parameters are calculated with the results obtained in regular waves. The yearly energy power production available with irregular waves should be lower.

5.6 Evaluation of the power production under irregular waves

After the design optimization with the "short model" and with regular waves, tests in irregular waves were run with the "full length model" described before, recording data with the first measuring setup.

The graph below shows the relation between the efficiency and the torque moment for different wave states.

The device was not moving (or moving very little) under wave conditions number two (W2) even with no load, and result is presented for only one test.

By adjusting the load on the rid, it was possible run tests with optimal loads for W3, W4 and W5 (Figure 5.28).

Arguably, the only presented efficiency for W2 is the maximum corresponding to 0.082 for Hs=0.07 m and Tp=1.40 s. The maximum efficiency recoded was 0.111, for Hs=0.10 m and Tp=1.60 s (target W3). For Hs=1.15 m and Tp=1.97 s. (Target W4) the maximum efficiency was 0.103 while for target wave W5 the result was found by extrapolation and the maximum efficiency was calculated to be 0.079 [29].

The device is performing better for W3, which is also the highest in Power*Prob.

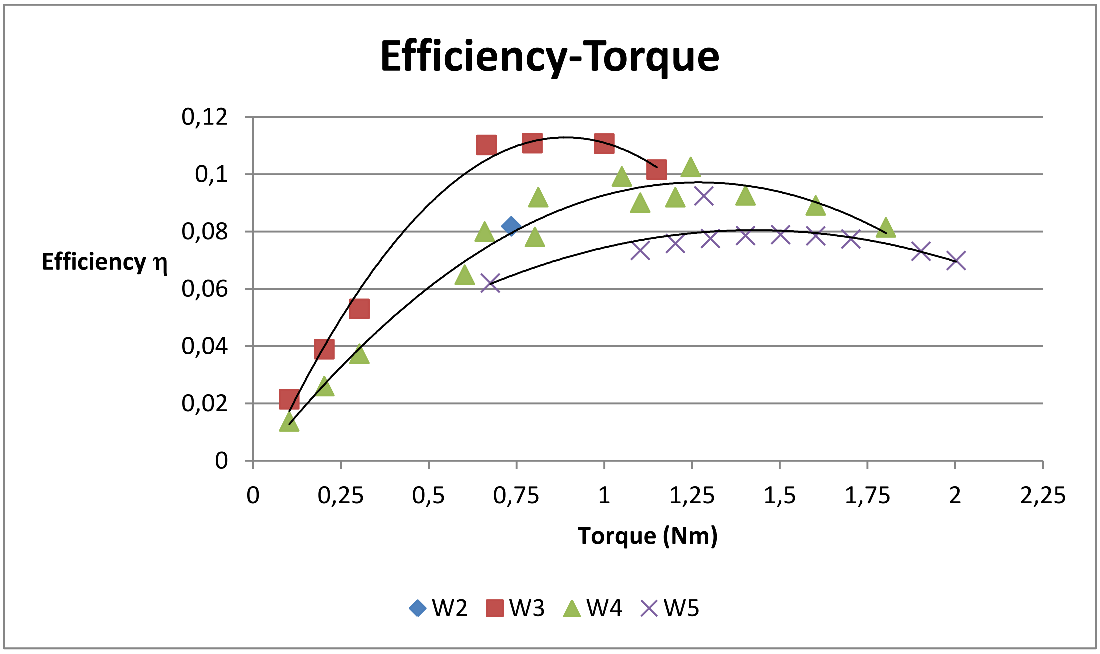


Figure 5.28: Efficiency depending on the mean torque for different wave conditions in scale 1:25

The angular velocity decreases when increasing the torque as expected (Figure 5.29). By comparing the values of the angular velocities with the results in regular waves, it is possible to notice that the ones presented here are lower. This could be the consequence “down time” (when the device is not rotating) that does not occur in regular waves, because the angular velocity presented in the results is a mean over the test´s duration.

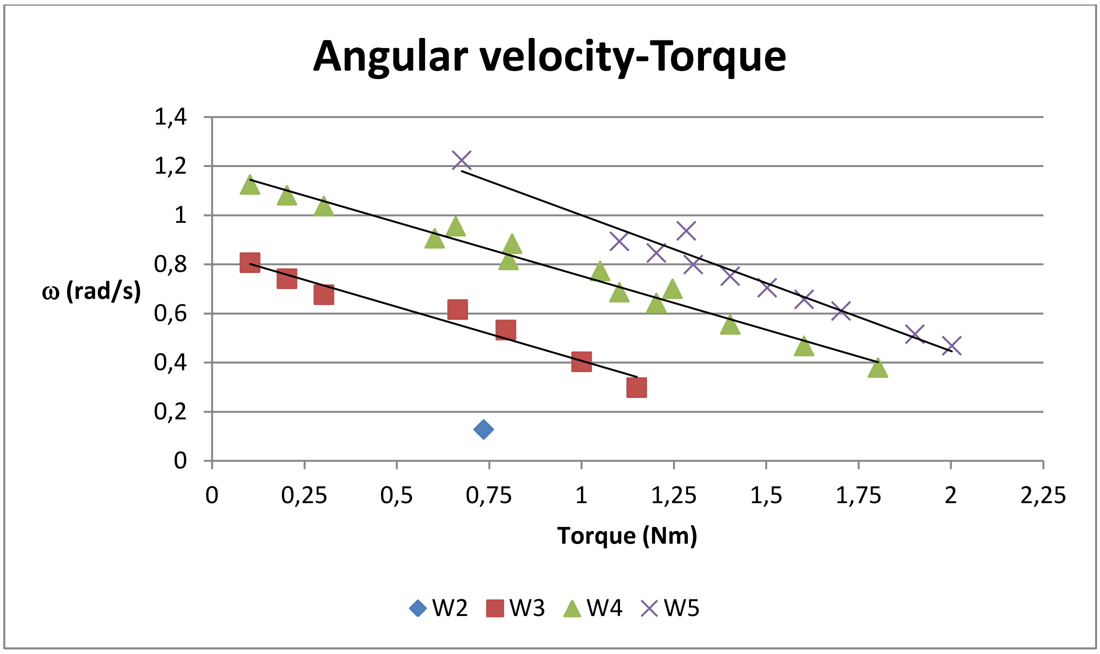


Figure 5.29: Angular speed as function of the mean torque, for the tested wave conditions with trend lines and corresponding equations. Scale 1:25

From this tests in irregular waves it is possible to calculate a reliability evaluation of the potential power production to have an idea of the overall behavior of the device. The yearly average wave power, the yearly average power production, the overall efficiency and the yearly energy power production were calculated.

The following table summarize the wave parameters describing the Danish seas.

WS	H [m]	T_p [s]	Energy flux [KW/m]	Prob.	Prob.*Pwave	Eff.	Pgen [kW/m]	Pgen.*Prob. [kW/m]
1	1	5,6	2,1	0,468	0,98	0,0317	0,07	0,03
2	2	7	11,6	0,226	2,62	0,082	0,95	0,21
3	3	8,4	32	0,108	3,46	0,111	3,55	0,38
4	4	9,8	65,6	0,051	3,35	0,103	6,76	0,34
5	5	11,2	114	0,024	2,74	0,079	9,01	0,22

Table 5.6: Summarize of the performance of the Rolling Cylinder in irregular waves and full scale

The values of the efficiency for the wave condition number 1 is not realistic because the test with this wave state was not run as the device did not turn, but one value that could be realistic was chosen.

From the values in this table the parameters were calculated in order to have an idea of the performance of the device:

- Yearly average wave power = $\sum_{Ws=1}^{5}(Prob * Pwave)$ = (5.6.1)

$$= 0{,}98+2{,}62+3{,}46+3{,}35+2{,}74= 13{,}15 \text{ kW/m}$$

-Yearly average power production = $\sum_{Ws=1}^{5}(Prob * Pgen)$ = (5.6.2)

$$= 0{,}03+0{,}21+0{,}38+0{,}34+0{,}22= 1{,}18 \text{ kW/m}$$

$$\text{-Overall efficiency} = \frac{\text{Yearly average power production}}{\text{Yearly average wave power}} = \qquad (5.6.3)$$

$$= \frac{1{,}18}{13{,}15} = 0{,}09$$

-Yearly energy power production = Yearly average power production* 365*24 (5.6.4)

= 1,18*365*24 = 10 MWh/y/m

Yearly average wave power [kW/m]	13,15
Yearly average power production [kW/m]	1,18
Overall efficiency	0,09
Yearly energy power production [MWh/y/m]	10

Table 5.7: Summary of the performance of the Rolling Cylinder wave energy converter in irregular waves and full scale

If we compare this power production with the power production in regular wave (Table 5.5.) we can deduce that the efficiency is lower as we expected.

By the way this power production is very low.

Indeed, in regular waves there was not the start up problem that seems to influence the overall behavior of the device: once a small wave with not enough force to rotate the cylinder comes, the device is steady: not producing and it then requires a wave that will be strong enough to win the static forces and induce rotation every time a stop occurs. This means that the total force Ftot(t) = F1(t)-F2(t) is equal to zero many times during a test. It can definitely be said that the stops and start cycles showed to be not negligible and are probably the major reason for lack of production.

Indeed, by making the device longer the condition for having continuous rotation it is only partially granted because even for Hs = 4 m, it is possible that a group of 1-2 m waves occur, stopping the device.

In addition, the device it is not exactly 3 times longer than the short model previously tested in regular waves.

Indeed, the short model had 7 sets of fins of 0.75 mm, 6 fins each set, for a length of 1400 mm +240 mm. But for the long model we do not have 3 times the amount of fins as we only have 11 sets of fins and not 21.

This could also be a reason for the smaller recorded efficiencies.

Due to the problems with the friction based system, it is here stated that the accuracy and the precision of the results is uncertain (maybe between 5-25%) [29].

6. Future development

All the results described in this thesis constitute only the first phase of the assessments of the device. A rough estimate of a yearly energy production was obtained, but there are a lot of other features to be worth considering.

Some of the aspects that could be developed are:

- the shape and material of the fins;
- the mooring of the device;
- limit of the measuring setup and PTO (Power Take Off).

6.1 Shape and material of the fins

The shape and the material of the fins were not take into consideration when the experiments were carried out, but it is a main feature for a future full-scale installation.

Rolling Cylinder is the first device with blades, so the marine rotors and marine turbines were considered as references.

The sub-marine structures have to withstand the notoriously aggressive marine environment with its corrosive salt water, fouling growth and abrasive suspended particles.

Designers first considered producing the required stiff, unyielding marine rotors in steel. However, achieving the necessary compound-curved profile in steel proved to be expensive. Moreover, steel is heavy, prone to fatigue and susceptible to corrosion induced by salt water.

These disadvantages prompted a decision to adopt composites instead. Composite materials can have many advantages when they are used in marine renewable energy structures. Plastic-based materials ease the fatigue problem, both through their inherent fatigue tolerance and by reduced blade weight. Calculations also showed that, appropriately applied, they could deliver the required stiffness.

There are many marine turbines currently being developed and the prototypes are mostly built with conventional materials. Currently, on a few marine turbines, the only application of composite materials is on the rotor blades. The only

commercial scale tidal turbine to be installed has rotor blades made from composite materials [20].
This observation about marine rotor and marine turbine can be assume also for the Rolling Cylinder.

Composite material

A composite material is a material that consists of two components: the fibres and the matrix as shown in Figure 6.1.

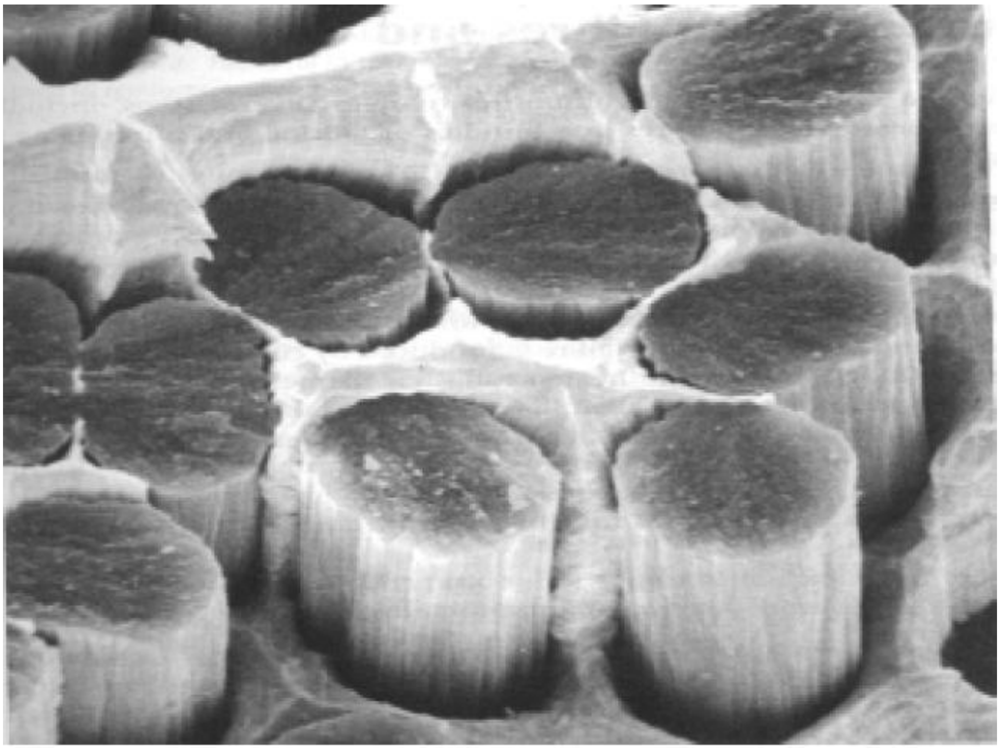


Figure 6.1: A composite laminate cross section [20]

The fibres are the part of the composite material that contributes to the strength whilst the matrix hold the fibres together. The fibres generally have a high modulus of elasticity and a high ultimate strength. The fibres can be in continuous form or chopped strand form. In advanced composite applications, continuous fibres are generally used. Continuous fibres can be made from many different types of materials but the common ones are made out of Glass, Carbon and Aramid. The fibres can come in the form of uni-directional or woven cloth. The purpose of the matrix is to bind the fibres together, protect the fibres from damage, to transfer the stresses to the fibres and to disperse the fibres.

The matrix consists of a resin and examples of common structural resin systems are polyester, vinlyester or epoxy. Polyster and vinlyster resin are low in cost but produce high styrene emissions during production. Although epoxy resins are more expensive, they generally have superior mechanical properties.

Advanced composite such as glass/epoxy or carbon/epoxy are used for high performance applications.
A composite ply consists of a layer of fibres that is impregnated with resin. A composite laminate is formed of several composite plies. These plies can vary in direction (orientation) through the stack of plies as shown in Figure 6.2.

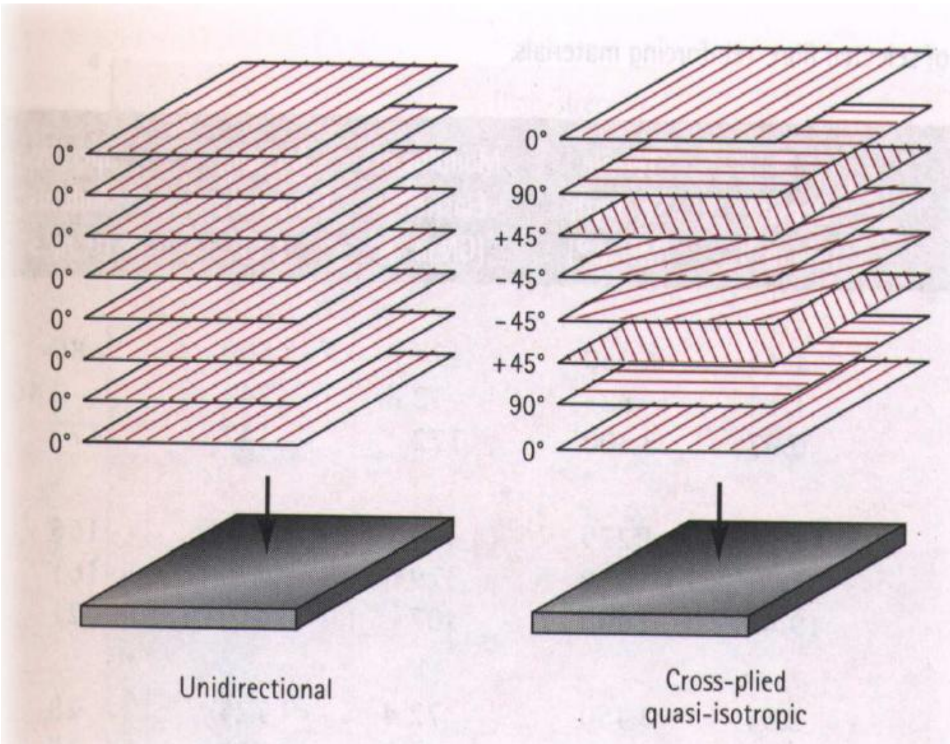


Figure 6.2 : A composite laminate [20]

One of the main advantages of composite material is the ability to choose the material, laminate and manufacturing method to suit the design requirements. In general, composite material have a high strength to weight ratio. This enables lightweight structures to be designed which can help to achieve neutral buoyancy. Also lightweight structures require less expensive lifting equipment for the installation of an underwater turbine.

By using composite materials and moulds, complex shapes can be made with high geometric tolerances. A composite underwater turbine will also be easy to maintain through out its life cycle as it is resistant to marine boring organisms and resistant to corrosion. Composite materials such as E-glass are also non-conductive which makes it ideal for use in some designs of underwater turbines.

There are many variables that can affect the cost, quality and weight of a composite material. By taking these variables into account simultaneously during the design phase, a structure that is optimized for mechanical properties, weight and cost can be produced. These variables include materials constituent, laminate and manufacturing methods.

- *Materials constituent:* when using composite materials, the type of fibre/resin combination can depend on the structure and its application. The type of material chosen also affects the cost and the weight of the product. Hence the appropriate type of material has to be chosen to meet the requirement.
- *Laminate:* one of the main advantages of using composite material is the ability to tailor the laminate to achieve the required mechanical properties by varying the fibre orientation and the position of the ply in the laminate stock. Hence a laminate can be designed to suit the structural requirements. This sort of laminate tailoring can have a significant effect on the cost and weight of the final structure.
- *Manufacturing method:* with composite materials, the manufacturing method has a large impact on the fibre volume fraction, which affects the quality of the laminate. Hence, the type of manufacturing method used affects the strength, stiffness and weight of a composite structure. Since the choice of manufacturing method has an impact on the cost, weight and quality of a product, the appropriate manufacturing method has to be chosen to meet customer's requirement.

Design considerations of the full size turbine

For the design of the full size Rolling Cylinder consideration has to be given to the type of materials used. As the device increases in size, the design driver might change. The strength to weight ratio and stiffness to weight ration could become a critical factor in material choice [20].

With the prototype Rolling Cylinder, a laminate of a minimum thickness was both very strong and very stiff. For the full size device, the larger size means that it probably needs a lot of glass/epoxy laminate to achieve the required strength and stiffness. If the full size device is made from carbon/epoxy laminate, a lot less laminate will be required to achieve the same sort of stiffness and strength. This is because carbon/epoxy laminates have a much high strength to weight ratio and stiffness to weight ratio than glass/epoxy.

Cost also plays an important role in material selection as carbon/epoxy laminates are more expensive than glass/epoxy laminate. The decision on which material to choose ultimately relies on a trade off between strength to weight ratio, stiffness to weight ratio and cost.

Regarding the shape of the fins a deeper analysis with a Computation fluid dynamics could be a good development.

Computational fluid dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved. Ongoing research yields software that improves the accuracy and speed of complex simulation scenarios such as transonic or turbulent flows. Initial validation of such software is performed using a wind tunnel with the final validation coming in full-scale testing, e.g. flight tests.

6.1.1 Bio-fouling and marine antifouling coatings

Bio-fouling is the accumulation of marine organisms on the marine energy converters and associated equipment. Offshore oil and gas installations provide attachment surfaces for a variety of algae and invertebrates, so wave energy converters would be colonised by fouling organisms. The species recruited to these sites would depend on the species' communities within the vicinity of the device, distance offshore, water depth and clarity, prevailing weather conditions and position relative to coastal currents and the speed of those currents [24]. There would be a seasonal factor involved in the build up of this community with the main build up of fouling extending from about April to November.

Bio-fouling is more likely to occur on or in non-moving parts of the equipment, so anchors and mooring cables may be more susceptible. Similarly very active environments such as wave breaking zones and areas of high current speed are unlikely to attract much bio-fouling.

The fouling contributes to higher species richness and diversity in the area and thus has a positive ecological effect [25] but it can have negative impact on the devices and they can be expected to be affected by fouling in the following ways:

- increased weight of structure;
- increased volume of structure;
- increased roughness;
- increased drag coefficients;
- masking of surfaces during inspection and maintenance;
- changes in corrosion rates and mechanisms;
- changes in corrosion fatigue life;
- damage to protective coatings;
- more complex interactions between devices and the marine environment.

To avoid all these problems antifouling systems are required wherever unwanted growth of biological organisms occurs.

Antifouling methods

Methods for inhibiting both organic and inorganic growth on wetted substrates are varied but most antifouling systems take the form of protective coatings. The use of antifouling coatings for protection from the marine environment has a long history, but the last ten years has seen an increase in the focus on environmentally acceptable alternatives.

Many traditional antifouling systems are 'paints', which is a comprehensive term covering a variety of materials: enamels, lacquers, varnishes, undercoats, surfacers, primers, sealers, fillers, stoppers and many other. Most antifouling coatings are organic and consist of a primer and a topcoat both of which can include anticorrosive functions, however, the topcoat is often porous [21].

At the beginning the use of toxic antifoulants on marine structures has been a historic method of controlling fouling but biocides such as lead, arsenic, mercury and their organic derivatives have been banned due to the environmental risks that they posed. A revolutionary self-polishing copolymer technique employing a similar heavy metal toxic action to deter marine organisms was used with the antifoulant tributyltin (TBT). The use of organotins was eventually banned due to severe shellfish deformities and the bioaccumulation of tin in some ducks, seals and fish, resulting in legislation that culminated in the global ban of tributyltin.

Heavy metals

The ban of TBT in 2003 created a gap in the market and research began into environmentally acceptable replacements. In the interim, other metallic species, such as copper and zinc are in current use as substitutes and are delivered in a modified self-polishing copolymer delivery mechanism. The self-polishing copolymer (SPC) technique uses both hydrolysis and erosion to control the antifouling activity. Seawater ingress allows for the hydrolysation of the antifouling compound from the polymer backbone and the coatings solubility leaves the surface polished. This controlled dissolution of the surface of the coating allows for a longer lifetime.

However, the heavy metal are often toxic to marine organism and humans due to the partitioning of metabolic functions. The reticent use of heavy metal to control fouling in the marine environment due to the TBT ban and increased legislation on toxicity requirements is being replaced in favour of alternatives approaches.

Booster biocides approach

As well as increased scepticism over the use of copper, booster biocides have been incorporated to increase the length and functionality of copper-based antifouling coating systems. Terrestrial pesticides have also been adapted for marine antifouling systems but have increasingly had issues with their persistence and toxicity. This approach is often too species specific or conversely too broad, influencing non-target organism. The effectiveness of the copper-based coatings is restricted by the ability of the coatings to consistently leach the booster biocides. The concentrations of biocide released in free association paints requires better control; also their persistence in marine sediments due to such mechanisms as incorporation within degraded paint particles needs continued monitoring. The use of booster biocides provides an interim solution in response to the demand for an effective antifouling strategy to replace TBT.

Foul release approach

Foul release coatings (FRCs) function due to a low surface energy which degrades an organism's ability to generate a strong interfacial bond with the surface. These non-stick surfaces aid removal of fouling through shear and tensile stresses as well as their own weight by lowering the thermodynamic work of adhesion. A combination of the critical surface free energy and low elastic modulus allows the interface/joint between the organism adhesive and the coating surface to fracture and fail. There are two types of FRCs, namely fluoropolymer and silicone based polymer coatings. A thicker coating is more successful as it requires less energy to fracture the bond between the foulant/coating. The purely physical deterrent effects of these low energy coatings provide a unique approach to developing an environmentally acceptable alternative to biocide-based antifoulants. It offers a broad spectrum antifoulant without incurring the issues of biodegradation, legislative standards and fees necessary to register an active antifouling compound. This is an effective passive means of approaching the aggressive marine environment and its production and use in the future should be economically viable.

A biomimetics approach

The term "biomimetics" deals with the bio-inspired based design rather than direct copying of natural biological functions. The term implies the use of the natural world as a model to base an engineering development or device upon or as a "bottom-up" strategy for hierarchical structures.

The diverse mechanism that marine organism use to protect their own surfaces from fouling have been investigated for the development of certain antifouling properties. Marine organism have both physical and chemical methods to protect themselves from the harmful process of biofouling.

The key chemical antifouling mechanism of marine organisms occurs via the production of natural products which deter foulers. Despite research into the use of antifouling natural products over the past 20 years, their incorporation into a functioning system to resist biofouling over a working timescale has yet to occur.

On the other hand the physical defence mechanisms used by marine organism to defend against biological coverage range from the spicules of an echinoderm to the mechanical breaching of cetaceans. On the macro scale, whales and dolphins have recently been studied for their antifouling skin properties. There is an increased interest in natural micro-topography and synthetic microtextured surfaces with antifouling properties. The sensitivity of some organisms' settlement to the size and periodicity of surface topography has also led to the synthetic development of such architectural coatings. Surface properties of shells both physically and chemically are under further investigation [21].

The surface free energy, polar properties and the tailored micro-architecture of materials have also been investigated with the aim of developing novel antifouling surfaces.

The limitations of this approach are the practical application of a design solution which successfully mimics an ecologically significant antifouling effect found in the marine natural world. A natural antifouling compound that has both broad spectrum activity and species specific antifouling performance is potentially difficult to isolate from one organism. Also, as biological foulers have a diverse size range and preferential surface attachment criteria one single pattern of tailored micro-architecture will not be effective. A synergistic and more realistic biomimetic approach could be found through the combination of an organism's chemical and physical antifouling attributes and may even more accurately reflect antifouling strategies adopted by organism in nature.

A modern approach is the process of surface flocking where electrostatically charged fibres are adhered to a coating perpendicular to the surface and is currently undergoing trials as an antifoulant mechanism. The fibres can be made of polyester, polyamide, nylon or polyacryl.

There are three key aspects that need attention, the engineered protective coating bounded on either side by the substrate and the environment, both of which have unique properties that will affect coating integrity and effectiveness. An optimal antifouling coatings must be anticorrosive, environmental acceptable, economically viable, resistant to abrasion, biodegradation and erosion, smooth and additional factors that need to be considered include its life cycle parameters and measurable effectiveness which incorporate toughness, erosion and release of the antifouling compound.

Present modern methods of biofouling control are effective alternatives to the TBT antifouling coating, but not yet their equal. Therefore, research into varied approaches to the design and implementation of antifouling coating technology must continue.

Figure 6.3: Marine bio-fouling grew on a boat

6.2 Moorings of the device

In all the laboratory tests the device was fixed at the bridge set in the laboratory but not moored. It could be interesting develop a reasonable mooring to anchor the device to the seabed.

There are two different alternatives. The first idea is to fix the device with chains and anchors to the seabed, the second one is to link the device to a buoy. In this way we have a floating device and it can rotate around the buoy.

As tests to study the best mooring were not run, it is not possible to compare the two alternatives.

It is only possible to say that the wave energy converters may have a variety of effects on the wave climate, tidal propagation and wave regime. A decrease in incident wave energy could influence the nature of the shore and shallow sub-tidal area and the communities of plants and animals they support. Fixed structures are more likely to alter the wave climate than floating devices. [18].

6.3 Limit of the measuring setup and PTO (Power Take Off)

All tests described in this thesis were run with two different measuring setups but both of them have some limits and can be improved.

In the first measuring setup there are different limits in the instrumentation:

- the wave gauges, to measure the wave incident's height, are too close to the device. This choice was taken for space reasons, but for a reliable results a minimum distance of 1-1,5 meter between the device and the wave gauge should be preserved.
- the forces and the load applied on the device are measured with two different load cells linked to the device. The signal recording from this load cells oscillates a lot, so the final results are not completely true. For the future tests new load cells should be used because this instrumentation maybe was not working.
- the load cells were set on the border section of the device. This is not a right option because the device's behavior at the boundary is not representative of the real behavior of the device. For this reason more tests should be run with a difference measurement's section and link the instrumentation with a central section of the device.

In the second measuring setup the main limit is the use of a stopwatch. With this instrumentation there are "systematic mistakes" in all the results. To improve the results the time can be recorded with a professional instrumentation.

At last the developer of the device has not idea about the Power Take Off (PTO).
It is suggested that if the developer considers that it is worth going on with a second phase of investigations, this should focus on Power Take Off design, possibly with the collaboration of experts from the wind sector.
Indeed, it seems that there may be synergies between wind turbines power takeoff and the one of the Rolling Cylinder and a power take off with adjustable load could improve the "down time" issue.

6.4 Considerations of the environmental impact of wave energy devices

The generation of electricity from wave power can be clean and reliable. However, because most wave energy devices remain at the conceptual stage, their impacts on the environment are largely unknown and it possible to form only an incomplete picture of possible environmental effects caused by wave power devices. There are several common elements among the technologies that may have adverse environmental effects [18,19]. These elements include:

- interference with animal movements;
- navigation hazard;
- noise during construction and operation.

Many of the potential impacts would be site specific and could not be evaluated until a location for the wave energy scheme is chosen. The main effects that wave devices may have are discussed below, together with areas of uncertainty with our present level of knowledge.

6.4.1 Interference with animal movements

Marine renewable devices are at a relatively early stage of development when compared to other renewable technologies such as wind turbines. There are few devices in the oceans and these are mainly developmental or test units. The collision risk to marine mammals, fish and birds from these devices is uncertain and may remain so until more devices are installed and monitored. However it is essential to consider the possibility of collisions before installation to highlight the potential areas of concern.

We consider a collision to be an interaction between a marine vertebrate and a marine renewable energy device that may result in a physical injury (however slight) to the organism. A collision may therefore involve actual physical contact between the organism and device or an interaction with its pressure field [22].

There are a series of potential mitigation measures to reduce the probability and severity of collisions. The applicability of the measures will depend heavily on the device design, location and species at risk.

Mitigation measures that have potential to increase the options for avoidance are desirable as they will reduce the number of close encounters between device and animal. However they also have to be considered in relation to their potential for habitat exclusion. For example, loud underwater acoustic alarms may give marine mammals or fish good warning of renewable devices but if too loud they may banish the animals from valuable habitat.

On the other hand, there is a high potential that marine mammals will avoid marine renewable devices.

The magnitude of these reactions will depend on the species and any sensory output from the devices. Species like harbour porpoises tend to be wary of novel installations where as seals may be positively attracted. It is likely therefore that the more timid species or those individuals that have had previous negative interactions with devices will show the strongest avoidance reactions. This behavior response is likely to have little ecological impact unless it constitutes habitat exclusion whereby animals are driven from key areas for their foraging, breeding, transits or resting.

The geographic placement of renewable devices is therefore key to habitat exclusion issues. There has been much research work on disturbance impacts on marine mammals.

Many human activities are known to change cetacean behavior on the short term but longer term impacts are generally less well understood. Of the most critical impacts of disturbance, the energetic penalties of repeatedly swimming around a disturbing object and habitat exclusion appear to be most relevant to disturbance and avoidance. Another consequence, that has been little studied, is the increased risk of attack from predators in disturbance situations.

Further, many devices have a positive impact on fish or benthic organism populations because they act as fish aggregation devices or artificial reefs.

The Rolling Cylinder is the first rotating device, so the interactions between this device and fishes are unknown. By the way we can compare this device with a marine hydrokinetic (MHK) turbine. Both rotate and both are in the sea water, even if the turbine is at a lower altitude than the device and the device is not completely submerged.

Few empirical data exist for MHK technologies, more data are available for other man-made structures.

Hydro Green Energy (HGE), LLC, investigated the survival, injury, and entrainment of fish that passed through its hydrokinetic system in Hastings, Minnesota. For this project, two HGE turbines were installed in the tailrace of the Mississippi Lock and Dam No. 2. They reported little if any impact on the fish populations in the vicinity of the dam hydroelectric project. Specifically, survival estimates for small and large fish passing through the HGE hydrokinetic turbine were 99%. Further, no turbine blade passage injuries were observed [19].

6.4.2 Navigation Hazard

Most forms of wave devices will be located some distance from shore and partially, if not fully, submerged. For these reasons their visual impacts may be limited to navigation warning lights at night with little or no evidence of their presence during daylight. Detailed recording of the positions of devices together with proper marking of devices using lights and transponders should minimise this risk. In large arrays navigational channels would have to be allowed for. Several of the areas proposed for wave energy devices around European coasts are in major shipping channels and hence there is always an element of risk that a collision may occur. The result, for example, of an oil tanker colliding with an array may have consequences for colonies of seabirds in the locality.

Nearshore devices, like oscillating water column or terminator devices, which have bulky superstructures above the waterline will be more visible, particularly in nearshore locations. Wavedragon, the developer of a large terminator device, is planning its first project in South Wales but the devices will be at least 5 km from shore and their visual impact from the beach will be limited.

In some areas, the water depth required by the near shore devices might be attained only a few hundred yards offshore. Such schemes and shoreline devices would have a visual impact. Such schemes may be particularly sensitive in areas of designated coastline and those used for recreational purposes. Considerable work is now being done within the UK, by the Department of the Environment, local authorities and voluntary organisations, to examine the issue of coastal zone management and it may be necessary to plan for the future inclusion of wave power in management plans developed.

Offshore and nearshore devices could have an effect on some forms of recreation. The precise effect would vary with the type of recreation (e.g. sub-aqua diving and water skiing might benefit from the shelter provided by these devices but sailing and wind surfing might suffer) [18]

6.4.3 Noise during construction and operation

Some wave energy devices are likely to be noisy especially in rough conditions. Noise travels long distances underwater and this may have implications for the navigation and communication system of certain animals principally seals and cetaceans. It is thought unlikely that cetaceans would be affected as much of the noise likely to be generated is below the threshold hearing level (frequency) for dolphins. Whales use a number of wave lengths for communication and sonar. Simple experimental evidence could be derived using hydrophones to measure both whale and device sound spectrum in order to determine if there are any areas of overlap which may cause interference to whales.

For near shore/shoreline devices, the levels of noise may potentially constitute a nuisance on the shore. However, when the device is fully operational the device noise is likely to be masked by the noise of the wind and waves, providing adequate sound baffling is used.

As written before the Rolling Cylinder is comparable with an underwater turbine.

Underwater turbines may produce low frequency sound from the action of the turbines. Propagation levels are unknown, but the total noise production is likely to be less than that produced by a passing ship, and in high current conditions is unlikely to exceed ambient sound levels [19].

Other major impacts of wave energy conversion on the natural environment would result from the construction and maintenance of devices and any general associated development. Many of these implications are unlikely to be peculiar to wave energy devices but it is essential that they are taken into account in the environmental assessment process. It is probable that existing shipyard sites would be used with minimal additional environmental impact.

7. Example application in the Mediterranean Sea

The objective of this part is to understand the performance of the Rolling Cylinder device in the Mediterranean Sea and then compare the performance of a Rolling Cylinder device's farm with the performance of a Wave Piston device's farm.

The font of every sea data in Italy is the *Rete Ondametrica Nazionale*. The *Rete Ondametrica Nazionale* (RON) is active since July 1989 and now is composed by 14 buoys located off the coast of La Spezia, Alghero, Ortona, Ponza, Monopoli, Crotone, Catania, Mazara del Vallo, Cetraro, Ancona, Capo Linaro, Capo Gallo, Punta della Maestra and Capo Comino. Each buoy is able to following the surface motion and is equipped with a satellite system to monitoring its position and registers data about elevation, inclination, Hx, Hy, Hz. The data are usually acquired every three hours for a period of 30 minutes. In significant storm surges the data acquisition is automatic and continuous every half hour.

From the elaboration centre some parameters are made as the significant wave height (H_s), the peak wave period (Tp), the medium wave period (T_m), the main wave direction, etc.

Figure 7.1: Position of the 14 Italian buoys

It is been decided to study the performance of the Rolling Cylinder device in Mazara del Vallo.

7.1 Wave climate in Mazara del Vallo, Italy

Analyzing all the data recorded from the buoy in Mazara del Vallo it is possible to obtain the wave state describing the sea in that place.

Wave State	Hs [m]	T_p [s]	P wave [KW/m]	Prob.
1	0,25	5,48	0,13	0,268
2	0,75	5,78	1,23	0,3339
3	1,25	6,63	3,91	0,1928
4	1,75	7,24	8,37	0,1074
5	2,25	7,88	15,05	0,0492
6	2,75	8,56	24,41	0,0244

Table 7.1: Wave State describing Mazara del Vallo Sea

7.2 Efficiency and yearly energy power production in Mazara del Vallo

The first aim of this part is to calculate the efficiency of the Rolling Cylinder device in the Mediterranean Sea.

First of all a comparison between the Danish wave state and the Italian wave state is required in order to evaluate if the trend are similar.

Wave State	Hs (m)	T_p (s)
1	1,0	5,6
2	2,0	7,0
3	3,0	8,4
4	4,0	9,8
5	5,0	11,2

Table 7.2: Wave State describing the Danish Sea

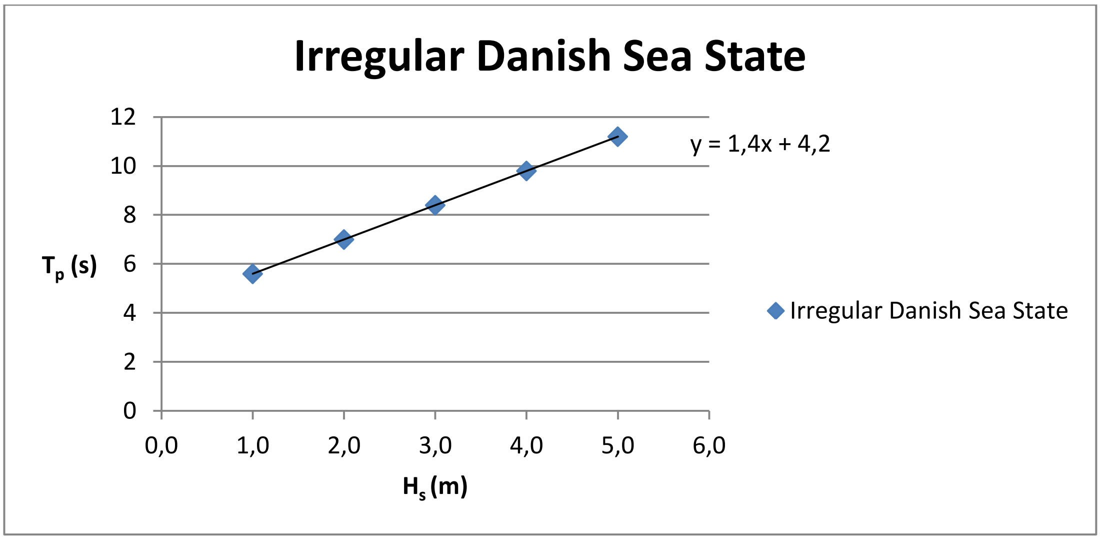


Figure 7.2: Trend of the Irregular Danish Sea

Wave State	Hs [m]	T_p [s]
1	0,25	5,48
2	0,75	5,78
3	1,25	6,63
4	1,75	7,24
5	2,25	7,88
6	2,75	8,56

Table 7.3: Wave State describing the Italian Sea in Mazara del Vallo

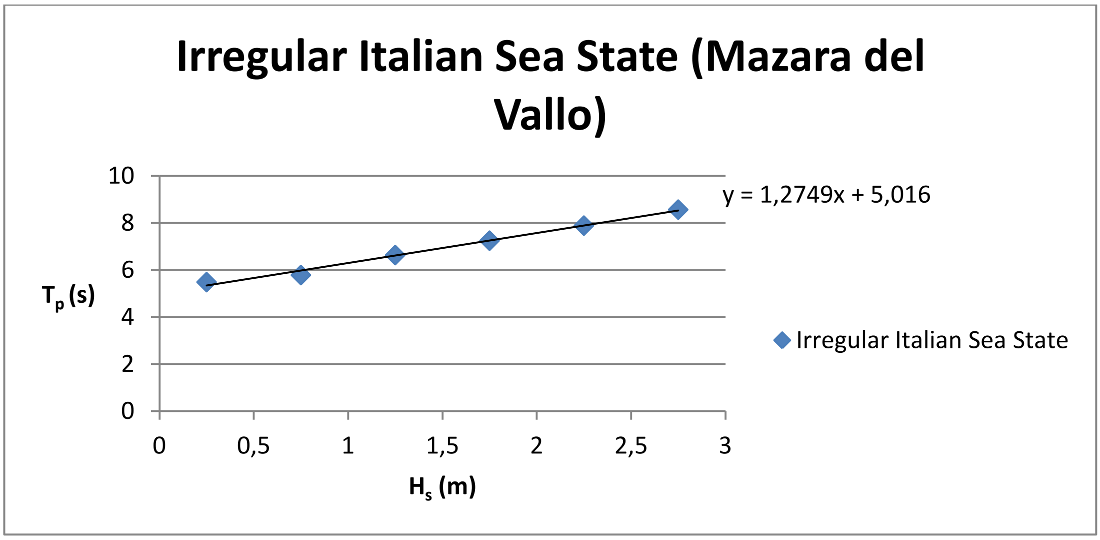


Figure 7.3: Trend of the Irregular Italian Sea

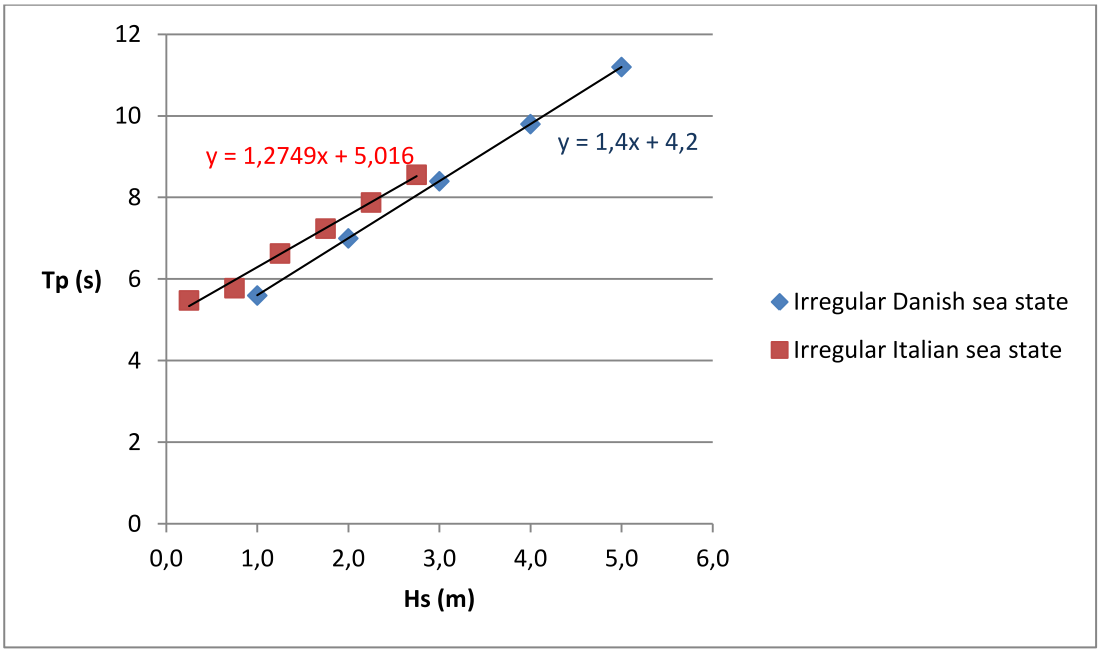


Figure 7.4: Comparison between the trend of the Irregular Italian Sea and the trend of the Irregular Danish Sea

From the graph above it is easy to deduce that the trend are similar, so it is appropriate to find a Danish efficiency trend and then use this equation to calculate the Italian efficiency.

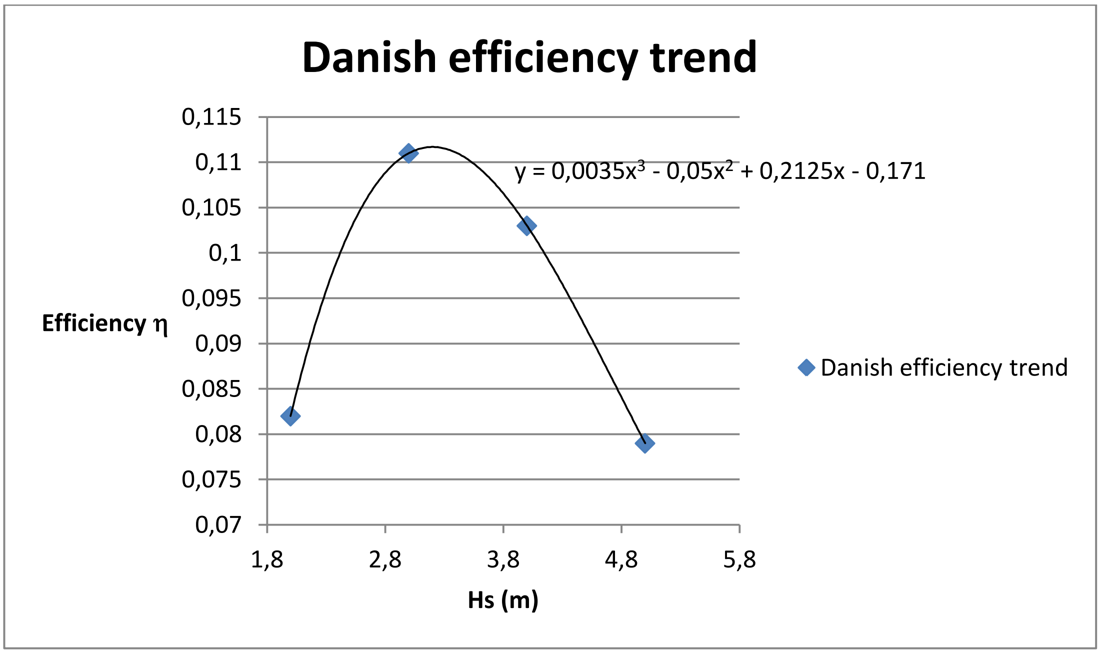


Figure 7.5: Danish efficiency trend for the Rolling Cylinder device

With the equation representing the Danish trend it is possible to calculate the efficiency in the Italian sea.

y = Efficiency η	x = Hs (from wave state in Mazara del Vallo)
-0,120945313	0,25
-0,038273438	0,75
0,023335938	1,25
0,066507813	1,75
0,093867188	2,25
0,108039063	2,75

Table 7.4: Efficiency for the Italian Sea

For the first and the second wave state the efficiency is negative. It means that for these wave states the device does not produce and its power production is zero.

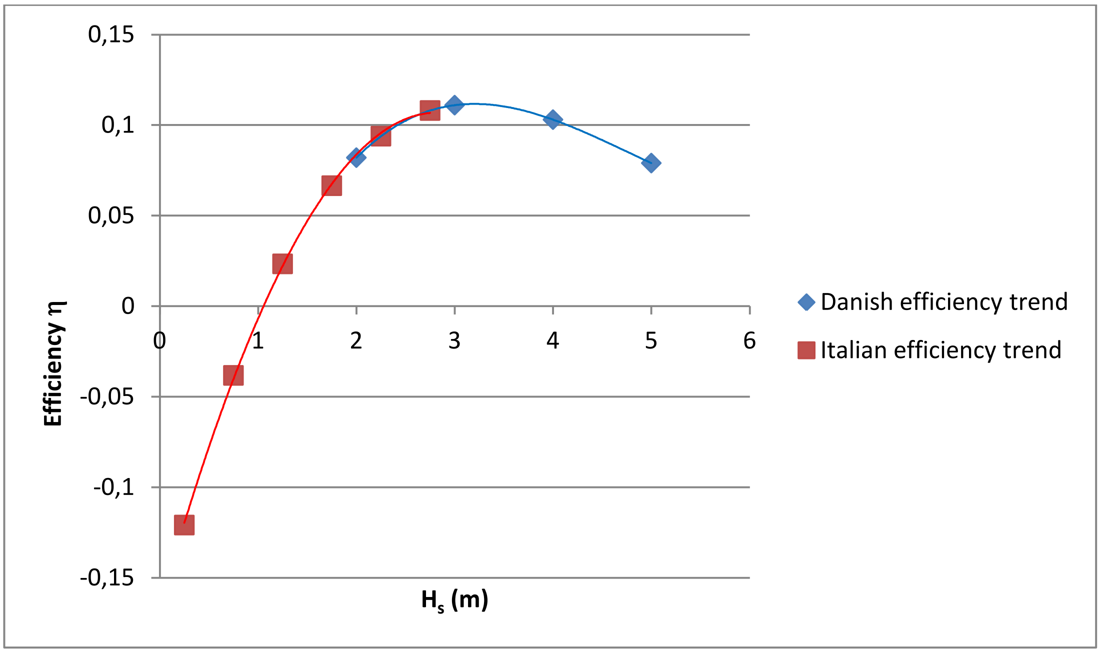


Figure 7.6: Danish efficiency trend and Italian efficiency trend

Note the efficiency all the data are available to calculate the yearly energy wave power, the yearly energy power production and the overall efficiency as we did in the previous chapter.

WS	H [m]	T_p [s]	P wave [KW/m]	Prob.	Prob.*Pwave [KW/m]	Eff.	Pgen [kW/m]	Pgen.*Prob. [KW/m]
1	0,25	5,48	0,13	0,268	0,03	0	0,00	0,00
2	0,75	5,78	1,23	0,3339	0,41	0	0,00	0,00
3	1,25	6,63	3,91	0,1928	0,75	0,023	0,09	0,02
4	1,75	7,24	8,37	0,1074	0,90	0,067	0,56	0,06
5	2,25	7,88	15,05	0,0492	0,74	0,094	1,41	0,07
6	2,75	8,56	24,41	0,0244	0,60	0,108	2,64	0,06

Table 7.5: Summarize of the performance of the Rolling Cylinder in irregular waves, in full scale and in an Italian installation

From the values in the table above, the parameters were calculated in order to have an idea of the performance of the device:

- Yearly average wave power = $\sum_{Ws=1}^{5}(\Pr ob * Pwave)$ = (7.2.1)

= 0,03+0,41+0,75+0,90+0,74+0,60 = 3,43 kW/m

-Yearly average power production = $\sum_{Ws=1}^{5}(\Pr ob * Pgen)$ = (7.2.2)

= 0,02+0,06+0,07+0,06 = 0,21 kW/m

-Overall efficiency = $\dfrac{\text{Yearly average power production}}{\text{Yearly average wave power}}$ = (7.2.3)

= $\dfrac{0,21}{3,43}$ = 0,06

-Yearly energy power production = Yearly average power production* 365*24 (7.2.4)

= 0,21*365*24 = 1,84 MWh/y/m

Yearly average wave power [kW/m]	3,43
Yearly average power production [kW/m]	0,21
Overall efficiency	0,06
Yearly energy power production [MWh/y/m]	1,84

Table 7.6: Summary of the performance of the Rolling Cylinder wave energy converter in irregular waves, in full scale and in an Italian installation

7.3 Comparison between a hypothetical farm of Rolling Cylinder and Wave Piston devices

The aim of this part is to drawn a comparison between the yearly energy power production of a Rolling Cylinder device's farm and the yearly energy power production of a Wave Piston device's farm.

The Wave Piston is a device similar to the Rolling Cylinder. The Wave Piston is a new WEC belonging to the OWC category, invented by a Danish group including Martin Von Bülow and Kristian Glejbøl, from Copenhagen. This near-shore floating device is composed of large and thin plates (i.e. energy collectors) placed perpendicularly to the sea bottom.

These plates can slide back and forth along a static structure, constituted by a pipe, and are kept in place by a spring. The pipe transports the pressurized sea-water to the turbine station.
Experiments to investigate the power production were carried out in February 2010, in the deep water wave basin of the Department of Civil Engineering, Water and Soil, at Aalborg University (DK) [30].

The full-scale Wave Piston is intended to have a floating structure with a flexible mooring whereas the down-scaled device has a fixed structure (2.40 m long) composed by a support structure with iron "legs" and attached 4 collectors. These collectors (each 0.5m wide and 0.1m high) in the model rotate instead of translate. In order to reduce the effect of an arm rotating around a fixed pivot, the legs are sufficiently lengthy.

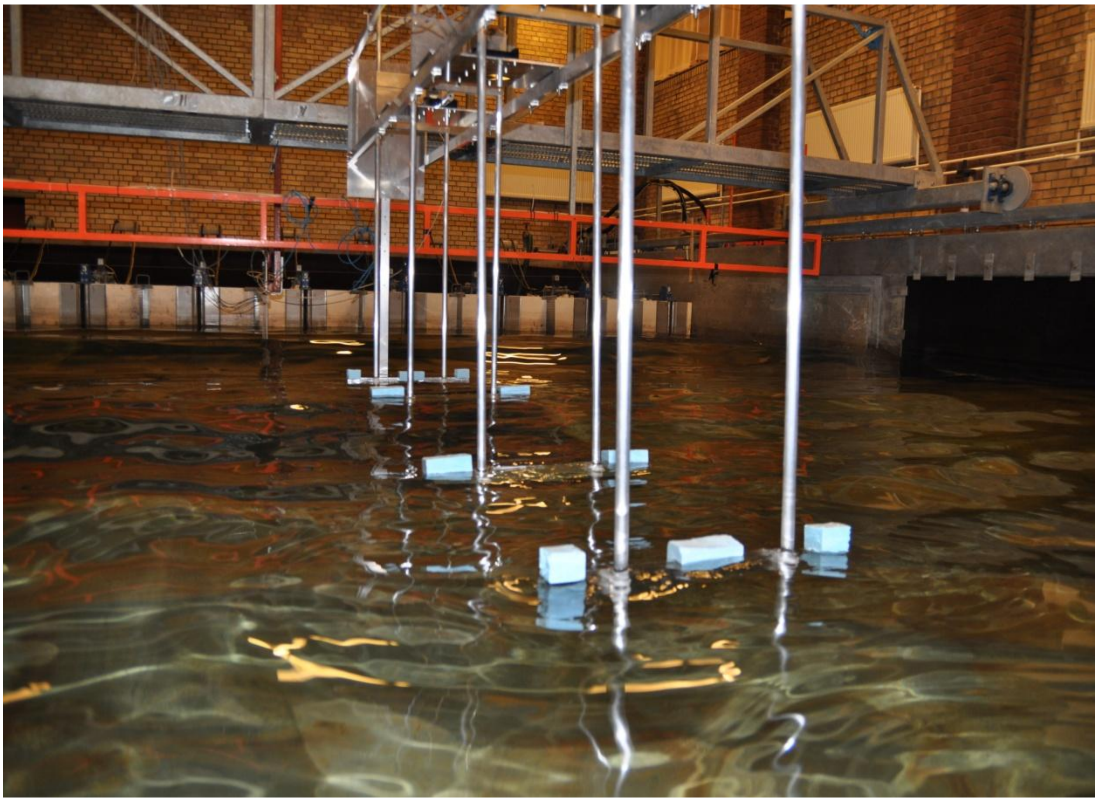


Figure 7.7: Wave Piston prototype in scale 1:30 in the laboratory of Aalborg University

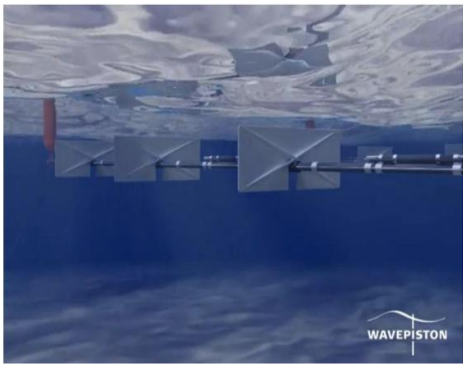


Figure 7.8: Simulation of the device in the real sea

Figure 7.9: A plate of the Wave Piston

The tables below show the output energy of the Wave Piston wave energy converter for an hypothetical installation in Mazara del Vallo. The yearly available average wave power is 3,43 kW/m and the yearly power generated is about 0,30 kW/m compared to 0,21 kW/m of the Rolling Cylinder, corresponding to a yearly energy production per meter of 2,63 MWh/y/m compared to the Rolling Cylinder of 1,84 MWh/y/m [31].

WS	Hs [m]	T_p [s]	P wave (KW/m)	Prob.	Prob.*Pwave	Eff.	Pgen [kW/m]	Pgen.*Prob.
1	0,25	5,48	1,94	0,268	0,52	0,22	0,4268	0,114
2	0,75	5,78	18,4	0,3339	6,14	0,160	2,9440	0,983
3	1,25	6,63	58,58	0,1928	11,29	0,110	6,4438	1,242
4	1,75	7,24	125,49	0,1074	13,48	0,080	10,0392	1,078
5	2,25	7,88	225,68	0,0492	11,10	0,060	13,5408	0,666
6	2,75	8,56	366,09	0,0244	8,93	0,040	14,6436	0,357

Table 7.7: Summary of the performance of the Wave Piston wave energy converter in an Italian installation. The value of the power that can be converted from the waves into useful mechanical power by the Wave Piston model is referred to one plate of 15m of width . The device is subjected to irregular wave [31]

Yearly average wave power [kW/m]	3,43
Yearly average power production [kW/m]	0,30
Overall efficiency	0,09
Yearly energy power production [MWh/y/m]	2,63

Table 7.8: Summary of the performance of the Wave Piston wave energy converter in irregular waves, in full scale and in an Italian installation [31]

The goal of this part is to realize a wave energy converter farm whose dimensions are about 2 km longshore and 500 meters crosshore. To calculate the yearly energy power production of this farm we need to calculate the yearly energy power production of one Rolling Cylinder's device and the yearly energy power production of one Wave Piston's device and then compare the two results.

ROLLING CYLINDER		
Yearly energy power production	1,84	MWh/y/m
Width of the device	11	m
Yearly energy power production for each device	20,24	MWh/y
WAVE PISTON		
Yearly energy power production	2,63	MWh/y/m
Width of the device	15	m
Collectors for each device	4	
Yearly energy power production for each device	157,8	MWh/y

Table 7.9: Comparison between the performance of the Rolling Cylinder device and the Wave Piston device

For the Wave Piston, 4 collectors are considered because measurements for each plate were done and the energy power production was almost the same for each collector.

To calculate the yearly energy production of that farm, it is necessary to know the real dimensions in full scale of each device in order to calculate how many device it is possible to place in a farm of that dimensions (2 km length and 500 m width). Note the number of the devices and the yearly energy power production of each device it is easy to calculate the yearly energy power production for the whole farm.

ROLLING CYLINDER		
Length of the device (1:25)	4,44	m
Length of the device (1:1)	111	m
Width of the device (1:25)	0,44	m
Width of the device (1:1)	11	m
WAVE PISTON		
Length of the device (1:30)	2,40	m
Length of the device (1:1)	72	m
Width of the device (1:30)	0,5	m
Width of the device (1:1)	15	m

Table 7.10: Dimension in full scale of the Rolling Cylinder device and Wave Piston device

For planning an hypothetical farm of Rolling Cylinder devices, it is supposed to realize a farm whose dimensions are 1943 m longshore and 555 m crosshore. In this way it is possible to place 3 rows of device crosshore and 70 devices for each row, for a total amount of 210 devices. If each device produce 20,24 MWh/y and each family average need 8kWh/d, this farm can supplied about 1456 families.

The distance between two devices is 17 m and the distance between two rows is 111 m.

Figure 7.10: An hypothetical farm of Rolling Cylinder devices in the Mediterranean Sea, Mazara del Vallo

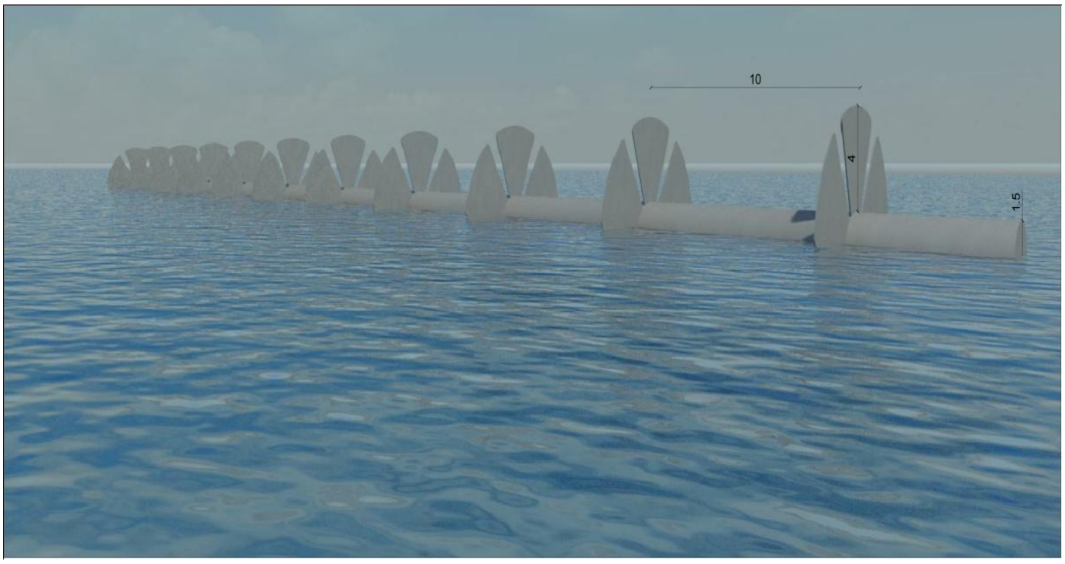


Figure 7.11: 3D-Rendering of the Rolling Cylinder device in the real sea

ROLLING CYLINDER		
Dimensions of the farm	1943*555	m^2
Number of devices in the farm	210	
Yearly energy production of each device	20,24	MWh/y
Yearly energy production of the whole farm	4250,4	MWh/y
Daily energy demand for a family	8	kWh/d
Number of families supplied	1456	

Table 7.11: Summary of the performance of an hypothetical farm of Rolling Cylinder devices

Regarding an hypothetical farm of Wave Piston devices, it is supposed to realize a farm whose dimensions are 1953 m longshore and 504 m crosshore. In this way it is possible to place 4 rows of device crosshore and 52 devices for each row, for a total amount of 208 devices. If each device produce 157,8 MWh/y and each family average need 8kWh/d, this farm can satisfy about 11240 families.

The distance between two devices is 23 m and the distance between two rows is 72 m.

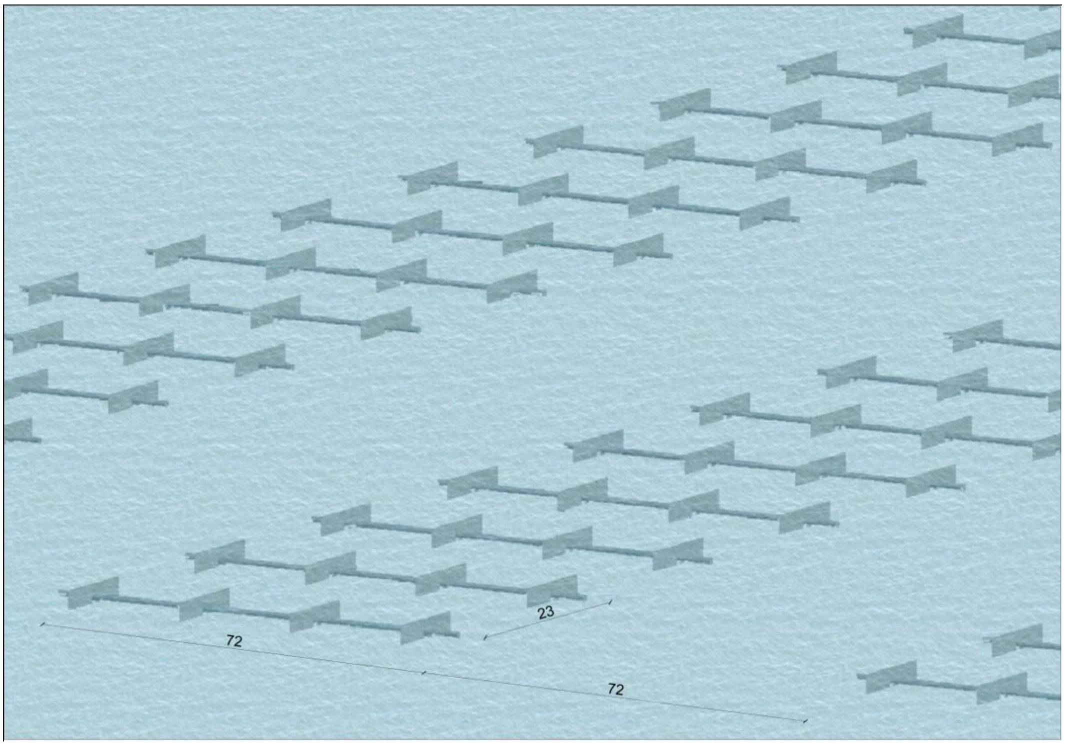


Figure 7.12: An hypothetical farm of Wave Piston devices in the Mediterranean Sea, Mazara del Vallo

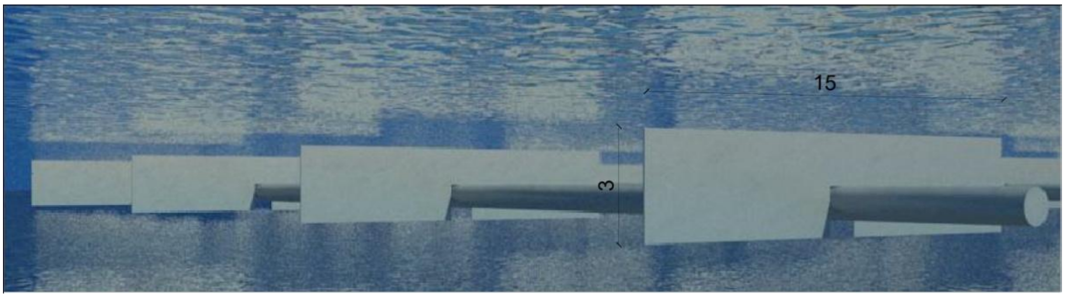


Figure 7.13: 3D-Rendering of the Rolling Cylinder device in the real sea

WAVE PISTON		
Dimensions of the farm	1953*504	m^2
Number of devices in the farm	208	
Yearly energy production of each device	157,8	MWh/y
Yearly energy production of the whole farm	32822,4	MWh/y
Daily energy demand for a family	8	kWh/y
Number of families supplied	11241	

Table 7.12: Summary of the performance of an hypothetical farm of Wave Piston devices

8. Conclusion

The goal of this thesis was to optimize the design of the new wave energy converter: Rolling Cylinder and then analyze the performance and the power production of that device.

The best overall configuration of the device was achieved running all the tests under regular waves, using the “short model” device in scale 1:25 (1,4 m in length and 0,44 m wide). The results are shown below:

- Best fin thickness; 0,75 mm
- Best number of fin sets mounted on the model: 7 sets.
  The difference, in term of efficiency, between 7 sets and 4 sets is almost negligible. It is possible to delve into this aspect and maybe from the economic point of view is better to put 4 sets. In this way the power production is less but it is possible to save money.
- Best number of fins par set: 6 fins par set
- Best buoyancy level: 14 cm.
  This means that half of the fin is submerged. It is also possible to elaborate this aspect because if the power loss between 14 cm and 22 cm is low is better to use the buoyancy level 22. In this case the fins are totally submerged and they are safer during a storm.

Fin thickness	Fin sets mounted on the model	Fins par set	Buoyancy level
0,75 mm	7 sets	6 fins	14 cm (half of the fin submerged)

Table 8.1 : Design optimization under regular waves

After the design optimization of the short model, a full length model of the Rolling Cylinder device in scale 1:25 was constructed, to achieve the second objective of this project, hence evaluate the potential power production.

The total length of the "full length model" is 4,44 m with 11 set of fins of 0.75 mm thickness, 6 fins par set and distance between one set and the other of 40 cm. The device was placed in the middle of the deep wave basin at AAU laboratory with d=0.65 m water depth and all the tests were run under irregular waves. The results are shown in the table below.

Wave State	**Efficiency η**
1	0,0317
2	0,082
3	0,111
4	0,103
5	0,079

Table 8.2: Efficiency of the device under irregular waves

The yearly energy power production obtained under irregular waves was 10 MWh/y/m with an efficiency of 0,09. This result is lower in comparison with the yearly energy production obtained in regular waves that was 21,9 MWh/y/m. The difference can be explained by the fact that the optimized "short" model had 7 set of fins and the "full length model" (3 times longer than the short model) had 11 set of fins instead of 21. So the yearly energy production should be the double, 20 MWh/y/m. Since the tests with 21 set of fins were not run, it would be better advised to use a factor of safety equal to 2/3 and write that the yearly energy power production under irregular is 15MWh/y/m with a factor of safety equal to 2/3.

Moreover, to be borne out of the facts and to understand better the performance of the Rolling Cylinder, an hypothetical application of this device in the Mediterranean Sea was done.

The result are shown in the table below.

Yearly average wave power [kW/m]	3,43
Yearly average power production [kW/m]	0,21
Overall efficiency	0,06
Yearly energy power production [MWh/y/m]	1,84

Table 8.3: Summary of the performance of the Rolling Cylinder wave energy converter under irregular waves, in full scale and in an Italian installation, Mazara del Vallo

The yearly energy power production of 1,84 MWh/y/m was obtained doing the calculation with the yearly energy production in the Danish sea equal to 10MWh/y/m. If this value is higher also the energy in the Italian sea increase and it is equal to 2,76 MWh/y/m.

To match expectations, the performance of the device and the power production in the Mediterranean Sea are lower than in the Danish Sea, but it is interesting to notice that Rolling Cylinder is comparable with Wave Piston device that has a similar performance and a similar geometrical configuration of the Rolling Cylinder.

Yearly average wave power [kW/m]	3,43
Yearly average power production [kW/m]	0,30
Overall efficiency	0,09
Yearly energy power production [MWh/y/m]	2,63

Table 8.4: Summary of the performance of the Wave Piston wave energy converter under irregular waves, in full scale and in an Italian installation, Mazara del Vallo

Hence, the last step is to draw a comparison between a hypothetical farm of Rolling Cylinder and Wave Piston devices.

Setting the dimensions of the farm, note the dimensions of the device in full scale and the yearly energy production of each device, it is easy to calculate how many families can be supplied from these two farms.

ROLLING CYLINDER		
Dimensions of the farm	1943*555	m^2
Number of devices in the farm	210	
Yearly energy production of each device	28,5	MWh/y
Yearly energy production of the whole farm	6006	MWh/y
Daily energy demand for a family	8	kWh/d
Number of families supplied	2057	

Table 8.5: Summary of the performance of an hypothetical farm of Rolling Cylinder devices

WAVE PISTON		
Dimension of the farm	1953*504	m^2
Number of devices in the farm	208	
Yearly energy production of each device	157,8	MWh/y
Yearly energy production of the whole farm	32822,4	MWh/y
Daily energy demand for a family	8	kWh/d
Number of families supplied	11241	

Table 8.6: Summary of the performance of an hypothetical farm of Wave Piston devices

Of course this is only the first phase of the whole assessment of the device.

In the proof of concept a lot of aspects are not take into consideration, like the mooring of the device, the material of the device in full-scale, the accumulation of marine organism on the device and the PTO system. This does not mean that they are not important but if they are negligible in the first phase they are necessary since the second phase of the assessment of the device.

Appendix A: Data Processing

Thickness= 0,4 mm (4 set, 6 fins)

RW 4 (H=0,113 m T=1,960 s)

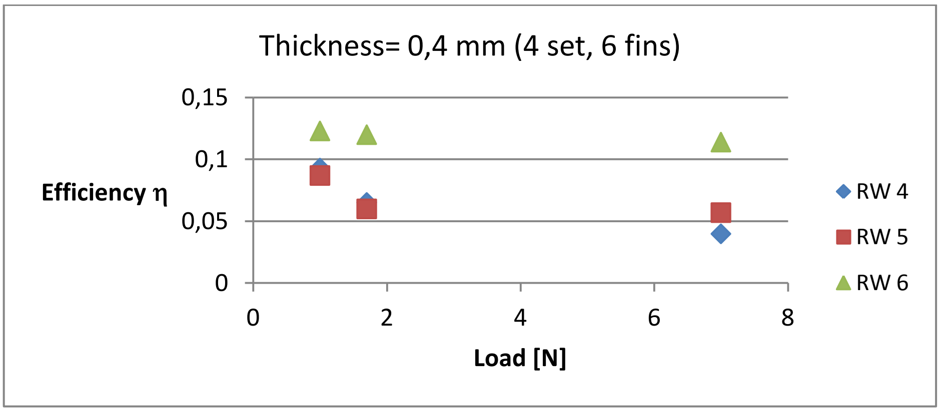
Load (N)	Efficiency
1	0,093
1,7	0,06522
7	0,03987

RW 5 (H= 0,141 m T= 2,240 s)

Load (N)	Efficiency
1	0,087
1,7	0,06
7	0,057

RW 6 (H= 0,16 m T= 1,40 s)

Load (N)	Efficiency
1	0,123
1,7	0,12
7	0,114



Thickness= 0,75 mm (4 set, 6 fins)

RW 3 (H=0,085 m T= 1,680 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437	37,00	36,07	35,70	36,26	0,293868714	0,211861
0,16	0,24	0,4	3,928	40,68	41,45	40,63	40,92	0,297575758	0,214533
0,16	0,34	0,5	4,91	51,14	50,31	50,92	50,79	0,299684977	0,216054
0,16	0,44	0,6	5,892	73,57	70,15	69,57	71,10	0,256906559	0,185213
0,16	0,54	0,7	6,874	133,07	142,81	136,03	137,30	0,155199437	0,111889

h =	**3,1**	**m**	lenght of the string
g =	**9,82**	**m/s^2**	
d =	**0,44**	**m**	fin's diameter+ cylinder's diameter
Ro =	**1000**	**kg/m^3**	density of the water
Tm =	**1,679**	**s**	from wavelab
Hm =	**0,07663**	**m**	from wavelab
β =	**32**		for regular wave 32
P =	**4,161253**	**W**	

RW 4 (H=0,113 m T=1,960 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437	20,33	20,45	20,70	20,49	0,51991054	0,15035
0,16	0,24	0,4	3,928	21,37	21,93	21,60	21,63	0,562872111	0,162774
0,16	0,34	0,5	4,91	23,95	23,16	23,04	23,38	0,650933713	0,18824
0,16	0,44	0,6	5,892	26,06	25,56	25,86	25,83	0,707222509	0,204517
0,16	0,54	0,7	6,874	31,00	29,94	32,00	30,98	0,68784377	0,198913
0,16	0,64	0,8	7,856	34,65	33,33	34	33,99	0,716422828	0,207178
0,16	0,74	0,9	8,838	42,64	41,4	42,15	42,06	0,651346382	0,188359
0,16	0,84	1	9,82	51,46	51,01	52,52	51,66	0,589238015	0,170398
0,16	0,94	1,1	10,802	66,74	70,55	63,44	66,91	0,500466298	0,144727

h =	3,1	m	lenght of the string
g =	9,82	m/s^2	
d =	0,44	m	fin's diameter+ cylinder's diameter
Ro =	1000	kg/m^3	density of the water
Tm =	1,949	s	from wavelab
Hm =	0,1123	m	from wavelab
β =	32		for regular wave 32
P =	10,37402	W	

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
20,49333	3,1	0,151268705	0,06	2,521145
21,63333		0,143297381		2,38829
23,38333		0,132573058		2,209551
25,82667		0,120030976		2,000516
30,98		0,100064558		1,667743
33,99333		0,091194352		1,519906
42,06333		0,073698391		1,228307
51,66333		0,060003871		1,000065
66,91		0,046330892		0,772182

RW 5 (H= 0,141 m T= 2,240 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437				17,11	0,622717709	0,112347
0,16	0,24	0,4	3,928				17,90	0,680268156	0,12273
0,16	0,34	0,5	4,91				19,03	0,799842354	0,144303
0,16	0,44	0,6	5,892				20,31	0,899320532	0,16225
0,16	0,54	0,7	6,874	22,53	22,84	22,78	22,72	0,938051357	0,169238
0,16	0,64	0,8	7,856	25,05	25,08	24,38	24,84	0,980550262	0,176905
0,16	0,74	0,9	8,838	26,98	26,09	26,5	26,52	1,032969712	0,186363
0,16	0,84	1	9,82	29,83	29,87	29,49	29,73	1,023948873	0,184735
0,16	0,94	1,1	10,802	33,05	32,77	32,22	32,68	1,024669523	0,184865
0,16	1,04	1,2	11,784	38,62	38,25	35,99	37,62	0,971036683	0,175189

h =	**3,1**	**m**	lenght of the string
g =	**9,82**	**m/s^2**	
d =	**0,44**	**m**	fin's diameter+ cylinder's diameter
Ro =	**1000**	**kg/m^3**	density of the water
Tm =	**2,204**	**s**	from wavelab
Hm =	**0,1337**	**m**	from wavelab
β =	**32**		for regular wave 32
P =	**16,62839**	**W**	

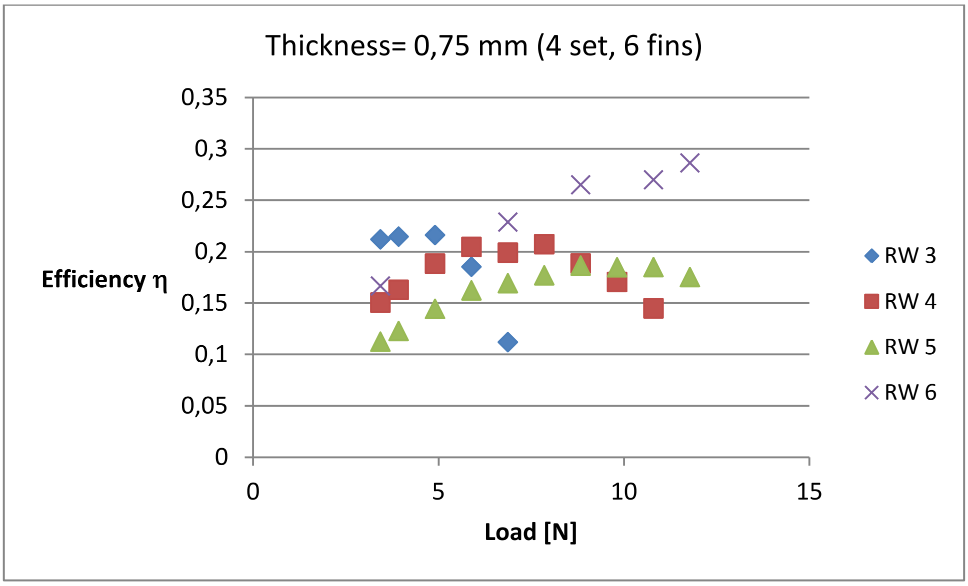
Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
17,11	3,1	0,181180596	0,06	3,019677
17,9		0,173184358		2,886406
19,03		0,162900683		2,715011
20,31		0,15263417		2,543903
22,71667		0,136463683		2,274395
24,83667		0,124815461		2,080258
26,52333		0,11687822		1,94797
29,73		0,104271779		1,737863
32,68		0,094859241		1,580987
37,62		0,082402977		1,373383

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			**Load (N)**	**Time (s)**			**Mean Time (s)**	**Power (W)**	**Efficiency**
Friction	**Weight**	**Tot. Mass**		**T1**	**T2**	**T3**			
0,16	0,19	0,35	3,437				13,08	0,814579511	0,166509
0,16	0,54	0,7	6,874	19,42	18,93	18,79	19,05	1,11879944	0,228695
0,16	0,74	0,9	8,838	21,49	21,06	20,85	21,13	1,296425868	0,265004
0,16	0,94	1,1	10,802	25,72	25,33	25,04	25,36	1,320260218	0,269876
0,16	1,04	1,2	11,784	26,25	26,18	25,83	26,09	1,400347559	0,286247

h =	**3,1**	**m**	lenght of the string
g =	**9,82**	**m/s²**	
d =	**0,44**	**m**	fin's diameter+ cylinder's diameter
Ro =	**1000**	**kg/m³**	density of the water
Tm =	**1,4**	**s**	from wavelab
Hm =	**0,1576**	**m**	from wavelab
β =	**32**		for regular wave 32
P =	**14,67629**	**W**	

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
13,08	3,1	0,237003058	0,06	3,950051
19,04667		0,162758138		2,712636
21,13333		0,146687697		2,444795
25,36333		0,122223682		2,037061
26,08667		0,118834654		1,980578



Thickness= 1 mm (4 set, 6 fins)

RW 3 (H=0,085 m T= 1,680 s) the device does not turn

RW 4 (H=0,113 m T=1,960 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437	32,70	33,50	33,20	33,13	0,3215704	0,095557
0,16	0,24	0,4	3,928	35,30	35,00	35,10	35,13	0,3465882	0,102991
0,16	0,34	0,5	4,91	47,10	47,10	46,60	46,93	0,3243111	0,096371
0,16	0,44	0,6	5,892	69,80	67,20	66,70	67,90	0,2690015	0,079936
0,16	0,54	0,7	6,874	109,80	107,90	99,00	105,57	0,2018573	0,059983

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,959**	**s**
Hm =	**0,1105**	**m**
β =	**32**	
P =	**10,09566**	**W**

RW 5 (H= 0,141 m T= 2,240 s)

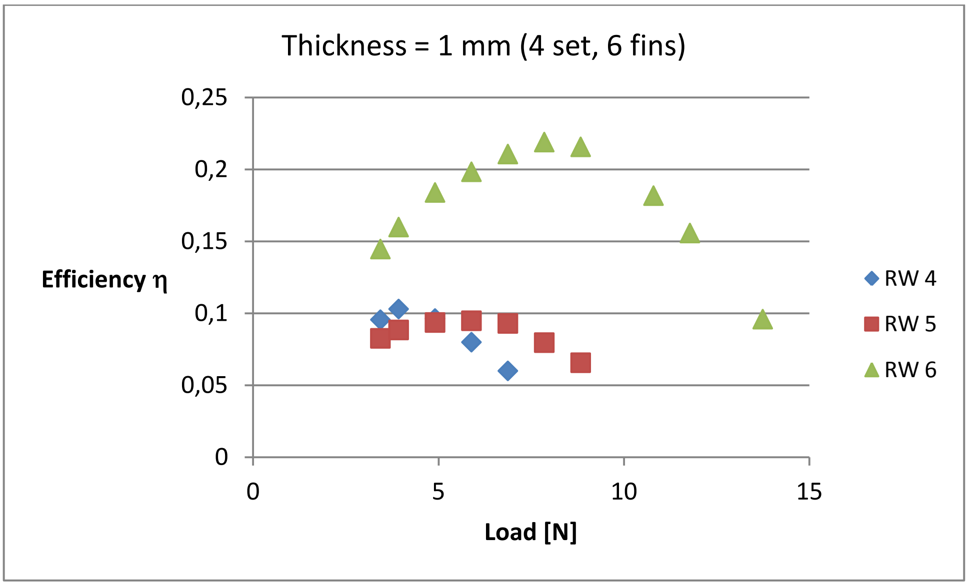
Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437	23,44	23,00	24,03	23,49	0,4535845	0,082605
0,16	0,24	0,4	3,928	25,02	25,51	24,70	25,08	0,4855829	0,088433
0,16	0,34	0,5	4,91	29,43	29,61	29,79	29,61	0,5140493	0,093617
0,16	0,44	0,6	5,892	34,42	35,68	35,14	35,08	0,5206727	0,094823
0,16	0,54	0,7	6,874	41,35	41,29	42,59	41,74	0,5104863	0,092968
0,16	0,64	0,8	7,856	55,66	54,9	56,56	55,71	0,4371757	0,079617
0,16	0,74	0,9	8,838	76	76		76,00	0,3604974	0,065653

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**2,24**	**s**
Hm =	**0,132**	**m**
β =	**32**	
P =	**16,47296**	**W**

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437	17,50	16,78	16,83	17,04	0,6253982	0,144673
0,16	0,24	0,4	3,928	17,64	17,73	17,46	17,61	0,6914708	0,159958
0,16	0,34	0,5	4,91	19,08	19,21	19,12	19,14	0,7953841	0,183996
0,16	0,44	0,6	5,892	21,16	21,28	21,46	21,30	0,8575211	0,19837
0,16	0,54	0,7	6,874	23,44	23,49	23,26	23,40	0,9107879	0,210692
0,16	0,64	0,8	7,856	25,56	25,87	25,74	25,72	0,9467513	0,219012
0,16	0,74	0,9	8,838	29,79	29,16	29,2	29,38	0,9324265	0,215698
0,16	0,94	1,1	10,802	42,88	43,42	41,53	42,61	0,7858766	0,181797
0,16	1,04	1,2	11,784	56,02	54,04	52,65	54,24	0,673537	0,155809
0,16	1,24	1,4	13,748	106,1	99,4		102,75	0,4147815	0,095951

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm=	1,399	s
Hm =	0,1482	m
β =	32	
P =	12,96851	W



Set of fins = 4 (0,75 mm, 6 fins)

RW 3 (H=0,085 m T= 1,680 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437	37,00	36,07	35,70	36,26	0,293868714	0,211861
0,16	0,24	0,4	3,928	40,68	41,45	40,63	40,92	0,297575758	0,214533
0,16	0,34	0,5	4,91	51,14	50,31	50,92	50,79	0,299684977	0,216054
0,16	0,44	0,6	5,892	73,57	70,15	69,57	71,10	0,256906559	0,185213
0,16	0,54	0,7	6,874	133,07	142,81	136,03	137,30	0,155199437	0,111889

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,679	s
Hm =	0,07663	m
β =	32	
P =	4,161253	W

RW 4 (H=0,113 m T=1,960 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437	20,33	20,45	20,70	20,49	0,51991054	0,15035
0,16	0,24	0,4	3,928	21,37	21,93	21,60	21,63	0,562872111	0,162774
0,16	0,34	0,5	4,91	23,95	23,16	23,04	23,38	0,650933713	0,18824
0,16	0,44	0,6	5,892	26,06	25,56	25,86	25,83	0,707222509	0,204517
0,16	0,54	0,7	6,874	31,00	29,94	32,00	30,98	0,68784377	0,198913
0,16	0,64	0,8	7,856	34,65	33,33	34	33,99	0,716422828	0,207178
0,16	0,74	0,9	8,838	42,64	41,4	42,15	42,06	0,651346382	0,188359
0,16	0,84	1	9,82	51,46	51,01	52,52	51,66	0,589238015	0,170398
0,16	0,94	1,1	10,802	66,74	70,55	63,44	66,91	0,500466298	0,144727

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,949	s
Hm =	0,1123	m
β =	32	
P =	10,37402	W

RW 5 (H= 0,141 m T= 2,240 s)

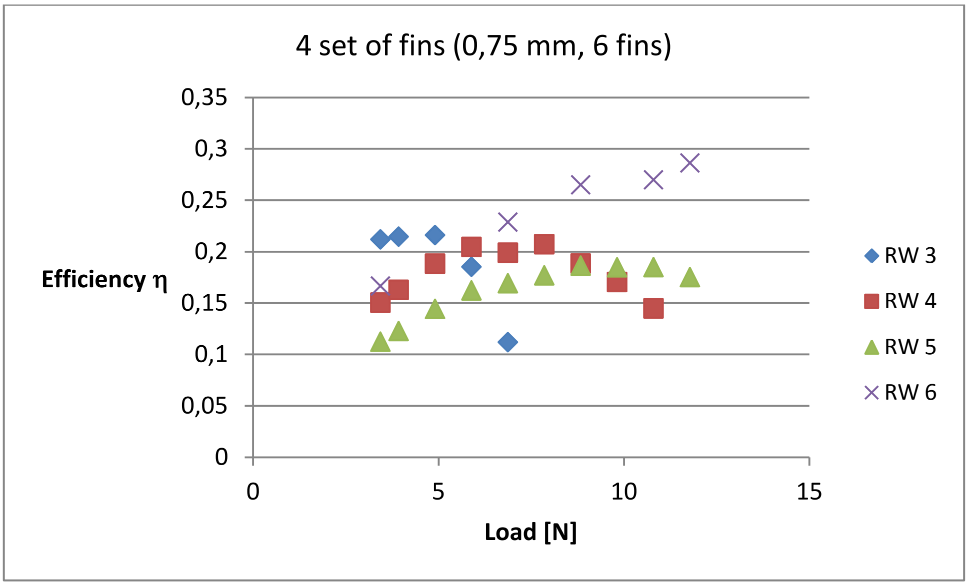
Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437				17,11	0,622717709	0,112347
0,16	0,24	0,4	3,928				17,90	0,680268156	0,12273
0,16	0,34	0,5	4,91				19,03	0,799842354	0,144303
0,16	0,44	0,6	5,892				20,31	0,899320532	0,16225
0,16	0,54	0,7	6,874	22,53	22,84	22,78	22,72	0,938051357	0,169238
0,16	0,64	0,8	7,856	25,05	25,08	24,38	24,84	0,980550262	0,176905
0,16	0,74	0,9	8,838	26,98	26,09	26,5	26,52	1,032969712	0,186363
0,16	0,84	1	9,82	29,83	29,87	29,49	29,73	1,023948873	0,184735
0,16	0,94	1,1	10,802	33,05	32,77	32,22	32,68	1,024669523	0,184865
0,16	1,04	1,2	11,784	38,62	38,25	35,99	37,62	0,971036683	0,175189

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**2,204**	**s**
Hm =	**0,1337**	**m**
β =	**32**	
P =	**16,62839**	**W**

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,16	0,19	0,35	3,437				13,08	0,814579511	0,166509
0,16	0,54	0,7	6,874	19,42	18,93	18,79	19,05	1,11879944	0,228695
0,16	0,74	0,9	8,838	21,49	21,06	20,85	21,13	1,296425868	0,265004
0,16	0,94	1,1	10,802	25,72	25,33	25,04	25,36	1,320260218	0,269876
0,16	1,04	1,2	11,784	26,25	26,18	25,83	26,09	1,400347559	0,286247

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,4	s
Hm =	0,1576	m
β =	32	
P =	14,67629	W



Set of fins = 7 (0,75 mm, 6 fins)

RW 3 (H=0,085 m T= 1,680 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,2	0,14	0,34	3,3388	45,13	44,19	38,47	42,60	0,242983332	0,225635
0,2	0,24	0,44	4,3208	53,19	56,92	58,54	56,22	0,238265283	0,221254
0,2	0,34	0,54	5,3028	60,61	57,51	57,15	58,42	0,281371826	0,261283
0,2	0,44	0,64	6,2848	93,06	92,29	93,96	93,10	0,209260821	0,19432

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,679	s
Hm =	0,06752	m
β =	32	
P =	3,230661	W

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
42,59666667	3,1	0,072775648	0,06	1,212927459
56,21666667		0,055143789		0,919063149
58,42333333		0,053060992		0,88434986
93,10333333		0,033296337		0,554938957

RW 4 (H=0,113 m T=1,960 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,2	0,24	0,44	4,3208	25,20	25,87	25,38	25,48	0,525617266	0,171672
0,2	0,34	0,54	5,3028	27,54	27,94	28,62	28,03	0,586397622	0,191523
0,2	0,44	0,64	6,2848	32,08	32,99	31,32	32,13	0,606376595	0,198049
0,2	0,54	0,74	7,2668	35,46	36,99	35,28	35,91	0,627320524	0,204889
0,2	0,64	0,84	8,2488	38,08	38,52	37,62	38,07	0,671632289	0,219362
0,2	0,74	0,94	9,2308	47,98	46,94	46,44	47,12	0,607289474	0,198347
0,2	0,84	1,04	10,2128	54,18	50,04	52,83	52,35	0,604769436	0,197524

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,959	s
Hm =	0,1054	m
β =	32	
P =	9,18526	W

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
25,48333333	3,1	0,121648136	0,06	2,027468934
28,03333333		0,11058264		1,843043995
32,13		0,096483038		1,608050628
35,91		0,086326928		1,438782141
38,07333333		0,081421818		1,357030292
47,12		0,065789474		1,096491228
52,35		0,05921681		0,986946832

RW 5 (H= 0,141 m T= 2,240 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,2	0,24	0,44	4,3208	23,17	22,95	23,44	23,19	0,577680276	0,13466
0,2	0,34	0,54	5,3028	24,61	24,70	24,75	24,69	0,66589306	0,155222
0,2	0,44	0,64	6,2848	26,82	27,28	27,58	27,23	0,715580803	0,166805
0,2	0,54	0,74	7,2668	29,92	29,66	29,29	29,62	0,760450546	0,177264
0,2	0,64	0,84	8,2488	32,22	32,08	32,07	32,12	0,796034451	0,185559
0,2	0,74	0,94	9,2308	36,27	35,73	35,77	35,92	0,796570845	0,185684
0,2	0,84	1,04	10,2128	40,18	38,92	38,78	39,29	0,805726502	0,187818
0,2	0,94	1,14	11,1948	44,77	42,16	45,52	44,15	0,786044847	0,18323

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**2,239**	**s**
Hm =	**0,1167**	**m**
β =	**32**	
P =	**12,86979**	**W**

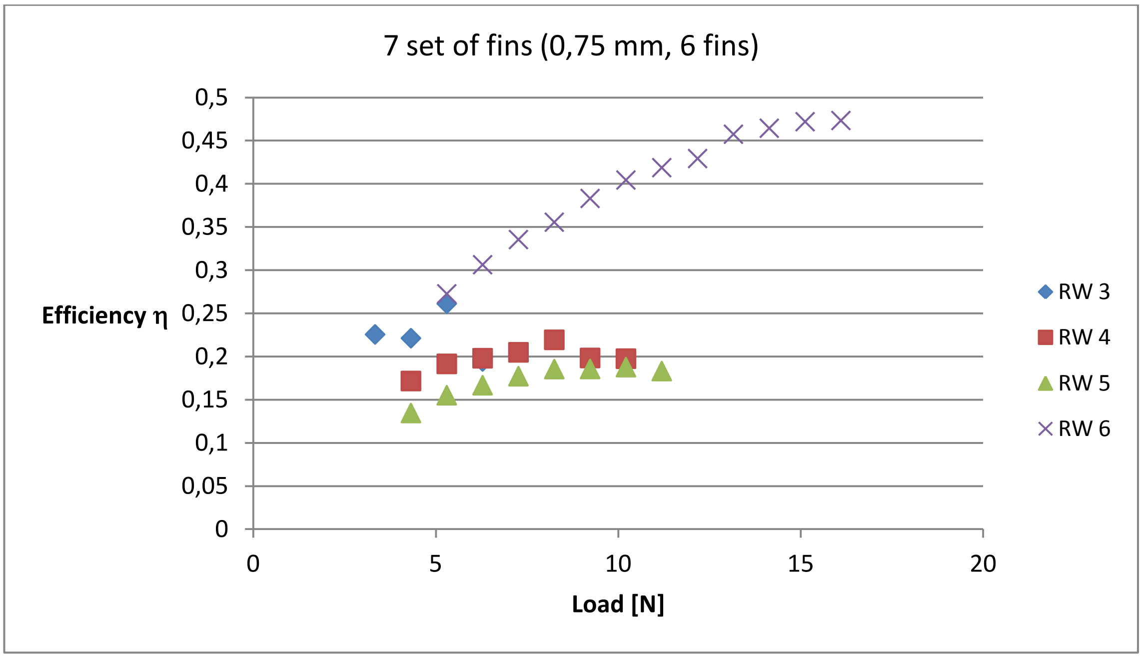
Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
23,18666667	3,1	0,133697527	0,06	2,228292122
24,68666667		0,125573859		2,092897651
27,22666667		0,113858962		1,897649363
29,62333333		0,104647238		1,744120626
32,12333333		0,096503061		1,608384352
35,92333333		0,086294887		1,438248121
39,29333333		0,07889379		1,314896505
44,15		0,070215176		1,170252926

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			**Load (N)**	**Time (s)**			**Mean Time (s)**	**Power (W)**	**Efficiency**
Friction	**Weight**	**Tot. Mass**		**T1**	**T2**	**T3**			
0,2	0,34	0,54	5,3028	17,32	16,60	17,14	17,02	0,965844888	0,272689
0,2	0,44	0,64	6,2848	17,91	17,95	18,00	17,95	1,085195693	0,306385
0,2	0,54	0,74	7,2668	18,58	18,99	19,30	18,96	1,188346052	0,335508
0,2	0,64	0,84	8,2488	20,49	20,25	20,16	20,30	1,259668966	0,355645
0,2	0,74	0,94	9,2308	21,46	21,64	20,16	21,09	1,357041416	0,383136
0,2	0,84	1,04	10,2128	22,34	22,18	21,78	22,10	1,432564706	0,404459
0,2	0,94	1,14	11,1948	23,34	23,31	23,54	23,40	1,483283089	0,418778
0,2	1,04	1,24	12,1768	25,2	24,3	24,97	24,82	1,520669263	0,429333
0,2	1,14	1,34	13,1588	25,34	24,88	25,3	25,17	1,620456038	0,457506
0,2	1,24	1,44	14,1408	26,31	27,2	26,43	26,65	1,645101826	0,464465
0,2	1,34	1,54	15,1228				28,04	1,671921541	0,472037
0,2	1,44	1,64	16,1048	29,93	28,92	30,48	29,78	1,676644352	0,47337
0,2	1,54	1,74	17,0868	32,25	32,37	32,18	32,27	1,641603719	0,463477

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,4**	**s**
Hm =	**0,1341**	**m**
β =	**32**	
P =	**10,62579**	**W**

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
17,02	3,1	0,18213866	0,06	3,03564434
17,95333333		0,172669885		2,877831415
18,95666667		0,16353086		2,725514331
20,3		0,15270936		2,545155993
21,08666667		0,14701233		2,450205501
22,1		0,140271493		2,33785822
23,39666667		0,132497507		2,208291779
24,82333333		0,124882503		2,08137505
25,17333333		0,123146186		2,052436441
26,64666667		0,116337253		1,938954216
28,04		0,110556348		1,842605801
29,77666667		0,104108362		1,735139371
32,26666667		0,09607438		1,601239669



Set of fins = 3 (0,75 mm, 6 fins)

RW 3 (H=0,085 m T= 1,680 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,13	0,04	0,17	1,6694	32,08	32,4	32,87	32,45	0,159480431	0,12941
0,13	0,09	0,22	2,1604	37,32	37,58	36,94	37,28	0,179646996	0,145774
0,13	0,14	0,27	2,6514	47,90	45,87	50,27	48,01	0,171188698	0,13891
0,13	0,24	0,37	3,6334	158,26	178,70	144,73	160,56	0,070150138	0,056923

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,679**	**s**
Hm =	**0,07223**	**m**
β =	**32**	
P =	**3,697105**	**W**

RW 4 (H=0,113 m T=1,960 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,13	0,14	0,27	2,6514	20,83	21,25	21,65	21,24	0,386913855	0,106523
0,13	0,24	0,37	3,6334	25,01	24,98	26,04	25,34	0,444437985	0,12236
0,13	0,34	0,47	4,6154	30,10	30,40	30,68	30,39	0,470752577	0,129604
0,13	0,44	0,57	5,5974	39,08	40,72	39,25	39,68	0,437260143	0,120384
0,13	0,54	0,67	6,5794	50,55	54,81	54,16	53,17	0,38357836	0,105604
0,13	0,64	0,77	7,5614	68,53	72,74	75,72	72,33	0,324074934	0,089222

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,959	s
Hm =	0,1148	m
β =	32	
P =	10,89668	W

RW 5 (H= 0,141 m T= 2,240 s)

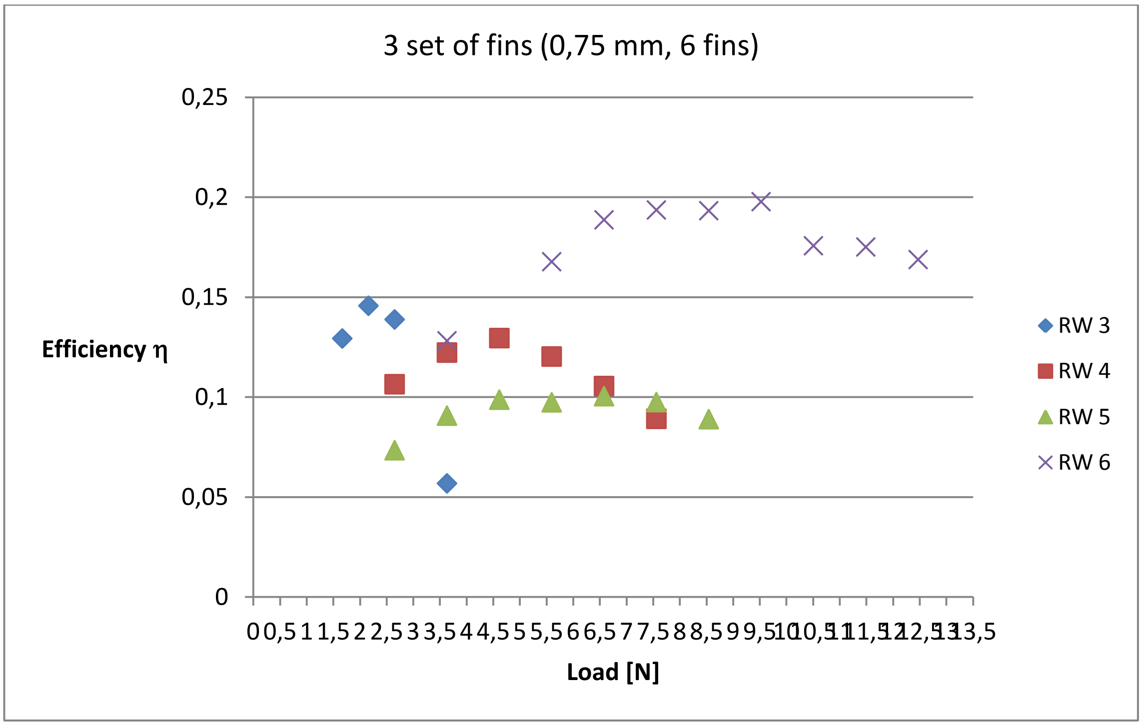
Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,13	0,14	0,27	2,6514	19,81	17,89	18,65	18,78	0,437586868	0,07351
0,13	0,24	0,37	3,6334	20,86	20,59	21,05	20,83	0,54064992	0,090823
0,13	0,34	0,47	4,6154	24,49	23,90	24,59	24,33	0,588150452	0,098803
0,13	0,44	0,57	5,5974	29,84	30,35	29,51	29,90	0,580332441	0,097489
0,13	0,54	0,67	6,5794	33,86	34,32	34,04	34,07	0,598595383	0,100557
0,13	0,64	0,77	7,5614	39,42	40,28	41,34	40,35	0,580973397	0,097597
0,13	0,74	0,87	8,5434	49,66	48,84	51,38	49,96	0,530114892	0,089053

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	2,238	s
Hm =	0,1375	m
β =	32	
P =	17,85835	W

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,13	0,24	0,37	3,6334	17,44	17,50	17,74	17,56	0,641431663	0,128263
0,13	0,44	0,57	5,5974	20,84	21,64	19,55	20,68	0,839203934	0,16781
0,13	0,54	0,67	6,5794	20,87	21,45	22,50	21,61	0,943974391	0,188761
0,13	0,64	0,77	7,5614	25,82	22,91	23,87	24,20	0,968609091	0,193687
0,13	0,74	0,87	8,5434	26,41	29,28	26,49	27,39	0,966824288	0,19333
0,13	0,84	0,97	9,5254	30,18	28,89	30,47	29,85	0,989348001	0,197834
0,13	0,94	1,07	10,5074	36,38	36,43	38,34	37,05	0,879161673	0,1758
0,13	1,04	1,17	11,4894	40,15	40,42	41,41	40,66	0,875974914	0,175163
0,13	1,14	1,27	12,4714	45,69	45,83	45,81	45,78	0,844564334	0,168882

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,399	s
Hm =	0,1594	m
β =	32	
P =	15,00273	W



Fins per set = 6 (0,75 mm, 7 set)

RW 3 (H=0,085 m T= 1,680 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,2	0,14	0,34	3,3388	45,13	44,19	38,47	42,60	0,242983332	0,225635
0,2	0,24	0,44	4,3208	53,19	56,92	58,54	56,22	0,238265283	0,221254
0,2	0,34	0,54	5,3028	60,61	57,51	57,15	58,42	0,281371826	0,261283
0,2	0,44	0,64	6,2848	93,06	92,29	93,96	93,10	0,209260821	0,19432

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,679**	**s**
Hm =	**0,06752**	**m**
β =	**32**	
P =	**3,230661**	**W**

RW 4 (H=0,113 m T=1,960 s)

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Mass (kg)			**Load (N)**	**Time (s)**			**Mean Time (s)**	**Power (W)**	**Efficiency**
Friction	**Weight**	**Tot. Mass**		**T1**	**T2**	**T3**			
0,2	0,24	0,44	4,3208	25,20	25,87	25,38	25,48	0,525617266	0,171672
0,2	0,34	0,54	5,3028	27,54	27,94	28,62	28,03	0,586397622	0,191523
0,2	0,44	0,64	6,2848	32,08	32,99	31,32	32,13	0,606376595	0,198049
0,2	0,54	0,74	7,2668	35,46	36,99	35,28	35,91	0,627320524	0,204889
0,2	0,64	0,84	8,2488	38,08	38,52	37,62	38,07	0,671632289	0,219362
0,2	0,74	0,94	9,2308	47,98	46,94	46,44	47,12	0,607289474	0,198347
0,2	0,84	1,04	10,2128	54,18	50,04	52,83	52,35	0,604769436	0,197524

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,959**	**s**
Hm =	**0,1054**	**m**
β =	**32**	
P =	**9,18526**	**W**

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
25,4833	3,1	0,121648136	0,06	2,027469
28,0333		0,11058264		1,843044
32,13		0,096483038		1,608051
35,91		0,086326928		1,438782
38,0733		0,081421818		1,35703
47,12		0,065789474		1,096491
52,35		0,05921681		0,986947

RW 5 (H= 0,141 m T= 2,240 s)

Mass (kg)			**Load (N)**	**Time (s)**			**Mean Time (s)**	**Power (W)**	**Efficiency**
Friction	**Weight**	**Tot. Mass**		**T1**	**T2**	**T3**			
0,2	0,24	0,44	4,3208	23,17	22,95	23,44	23,19	0,577680276	0,13466
0,2	0,34	0,54	5,3028	24,61	24,70	24,75	24,69	0,66589306	0,155222
0,2	0,44	0,64	6,2848	26,82	27,28	27,58	27,23	0,715580803	0,166805
0,2	0,54	0,74	7,2668	29,92	29,66	29,29	29,62	0,760450546	0,177264
0,2	0,64	0,84	8,2488	32,22	32,08	32,07	32,12	0,796034451	0,185559
0,2	0,74	0,94	9,2308	36,27	35,73	35,77	35,92	0,796570845	0,185684
0,2	0,84	1,04	10,2128	40,18	38,92	38,78	39,29	0,805726502	0,187818
0,2	0,94	1,14	11,1948	44,77	42,16	45,52	44,15	0,786044847	0,18323

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**2,239**	**s**
Hm =	**0,1167**	**m**
β =	**32**	
P =	**12,86979**	**W**

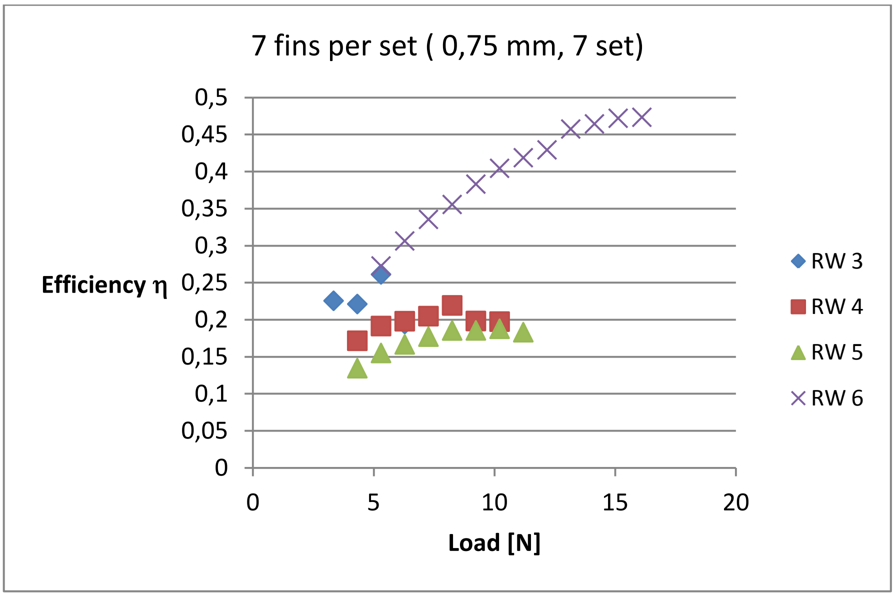
Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
23,1867	3,1	0,133697527	0,06	2,228292
24,6867		0,125573859		2,092898
27,2267		0,113858962		1,897649
29,6233		0,104647238		1,744121
32,1233		0,096503061		1,608384
35,9233		0,086294887		1,438248
39,2933		0,07889379		1,314897
44,15		0,070215176		1,170253

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			**Load (N)**	**Time (s)**			**Mean Time (s)**	**Power (W)**	**Efficiency**
Friction	**Weight**	**Tot. Mass**		**T1**	**T2**	**T3**			
0,2	0,34	0,54	5,3028	17,32	16,60	17,14	17,02	0,965844888	0,272689
0,2	0,44	0,64	6,2848	17,91	17,95	18,00	17,95	1,085195693	0,306385
0,2	0,54	0,74	7,2668	18,58	18,99	19,30	18,96	1,188346052	0,335508
0,2	0,64	0,84	8,2488	20,49	20,25	20,16	20,30	1,259668966	0,355645
0,2	0,74	0,94	9,2308	21,46	21,64	20,16	21,09	1,357041416	0,383136
0,2	0,84	1,04	10,2128	22,34	22,18	21,78	22,10	1,432564706	0,404459
0,2	0,94	1,14	11,1948	23,34	23,31	23,54	23,40	1,483283089	0,418778
0,2	1,04	1,24	12,1768	25,2	24,3	24,97	24,82	1,520669263	0,429333
0,2	1,14	1,34	13,1588	25,34	24,88	25,3	25,17	1,620456038	0,457506
0,2	1,24	1,44	14,1408	26,31	27,2	26,43	26,65	1,645101826	0,464465
0,2	1,34	1,54	15,1228				28,04	1,671921541	0,472037
0,2	1,44	1,64	16,1048	29,93	28,92	30,48	29,78	1,676644352	0,47337
0,2	1,54	1,74	17,0868	32,25	32,37	32,18	32,27	1,641603719	0,463477

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,4**	**s**
Hm =	**0,1341**	**m**
β =	**32**	
P =	**10,62579**	**W**

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
17,02	3,1	0,18213866	0,06	3,035644
17,9533		0,172669885		2,877831
18,9567		0,16353086		2,725514
20,3		0,15270936		2,545156
21,0867		0,14701233		2,450206
22,1		0,140271493		2,337858
23,3967		0,132497507		2,208292
24,8233		0,124882503		2,081375
25,1733		0,123146186		2,052436
26,6467		0,116337253		1,938954
28,04		0,110556348		1,842606
29,7767		0,104108362		1,735139
32,2667		0,09607438		1,60124



Fins per set = 3 (0,75 mm, 7 set)

RW 3 (H=0,085 m T= 1,680 s) does not turn

RW 4 (H=0,113 m T=1,960 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,22	0,14	0,36	3,5352	50,57	49,94	49,89	50,13333333	0,218599468	0,060079
0,22	0,19	0,41	4,0262	54,48	51,43	49,72	51,87666667	0,240594101	0,066124
0,22	0,24	0,46	4,5172	69,50	80,42	71,33	73,75	0,189875525	0,052184
0,22	0,29	0,51	5,0082	102,59	108,13	81,26	97,33	0,159518666	0,043841

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,959**	**s**
Hm =	**0,1149**	**m**
β =	**32**	
P =	**10,91567**	**W**

RW 5 (H= 0,141 m T= 2,240 s)

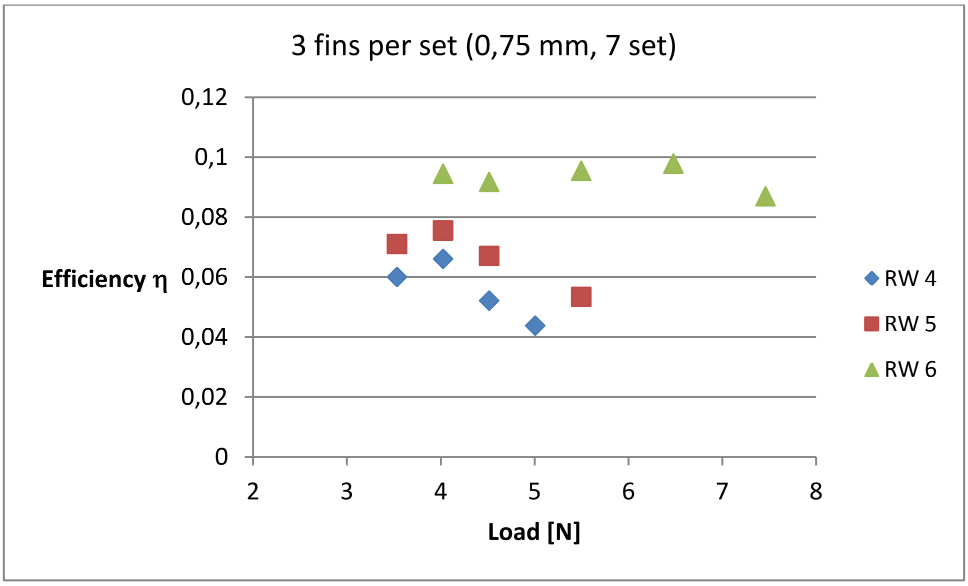
Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,22	0,14	0,36	3,5352	24,92	25,17	28,57	26,22	0,417967963	0,071079
0,22	0,19	0,41	4,0262	27,46	28,65	28,13	28,08	0,444487892	0,075589
0,22	0,24	0,46	4,5172	32,76	37,00	36,70	35,49	0,394607928	0,067106
0,22	0,34	0,56	5,4992	54,85	53,22	54,66	54,24	0,314278621	0,053445

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**2,24**	**s**
Hm =	**0,1366**	**m**
β =	**32**	
P =	**17,64108**	**W**

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			**Load (N)**	**Time (s)**			**Mean Time (s)**	**Power (W)**	**Efficiency**
Friction	**Weight**	**Tot. Mass**		**T1**	**T2**	**T3**			
0,22	0,19	0,41	4,0262	24,54	29,88	29,29	27,90	0,447302114	0,094527
0,22	0,24	0,46	4,5172	33,12	31,43	32,17	32,24	0,434346154	0,091789
0,22	0,34	0,56	5,4992	35,48	40,07	37,62	37,72	0,451909163	0,0955
0,22	0,44	0,66	6,4812	46,42	43,37	40,30	43,36	0,463334307	0,097915
0,22	0,54	0,76	7,4632	58,02	59,91	50,64	56,19	0,411744439	0,087013

h =	**3,1**	**m**
g =	**9,82**	**s**
d =	**0,44**	**m**
Ro =	**1000**	**kg/m^3**
Tm =	**1,4**	**s**
Hm =	**0,155**	**m**
β =	**32**	
P =	**14,19604**	**W**



Fins per set = 3 alternate (0,75 mm, 7 set)

RW 3 (H=0,085 m T= 1,680 s) does not turn

RW 4 (H=0,113 m T=1,960 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,19	0,04	0,23	2,2586	29,18	28,31	27,84	28,44	0,246161725	0,082061848
0,19	0,09	0,28	2,7496	31,33	32,34	32,56	32,07666667	0,265730853	0,088585522
0,19	0,14	0,33	3,2406	38,99	38,31	38,25	38,51666667	0,26081852	0,086947919
0,19	0,24	0,43	4,2226	70,05	65,05	63,19	66,10	0,198044178	0,066021113
0,19	0,19	0,38	3,7316	49,09	49,40	50,40	49,63	0,233084022	0,077702192

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,96	s
Hm =	0,1043	m
β =	32	
P =	8,999129	W

RW 5 (H= 0,141 m T= 2,240 s)

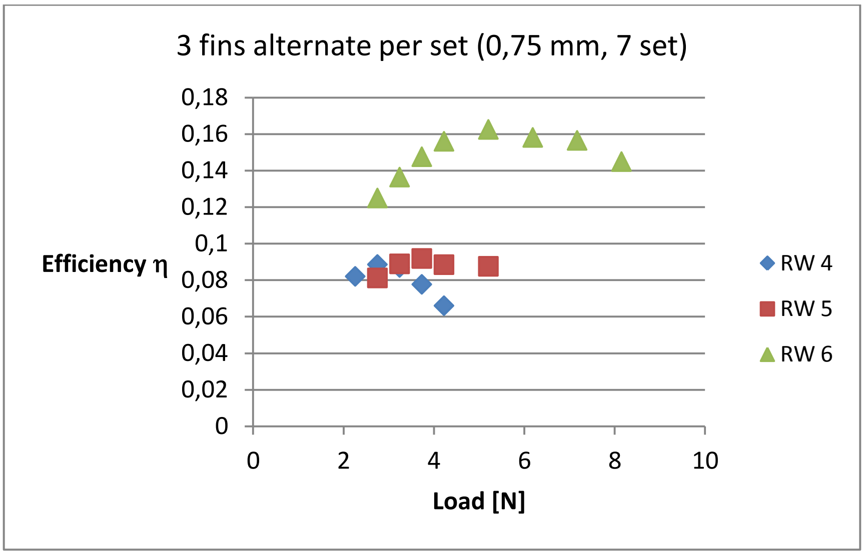
Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,19	0,09	0,28	2,7496	23,62	22,69	23,14	23,14	0,368356093	0,081207609
0,19	0,14	0,33	3,2406	25,08	25,01	24,63	24,90666667	0,403340203	0,08892019
0,19	0,19	0,38	3,7316	27,16	27,66	28,46	27,76	0,416713256	0,091868407
0,19	0,24	0,43	4,2226	32,65	32,89	32,30	32,61333333	0,401371423	0,088486153
0,19	0,34	0,53	5,2046	40,90	40,67	40,27	40,61333333	0,397265102	0,087580876

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	2,239	s
Hm =	0,12	m
β =	32	
P =	13,60794	W

RW 6 (H= 0,16 m T= 1,40 s)

Mass (kg)			Load (N)	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass		T1	T2	T3			
0,19	0,09	0,28	2,7496	19,16	19,01	18,99	19,05	0,447363191	0,124996508
0,19	0,14	0,33	3,2406	20,78	20,61	20,33	20,57	0,488295204	0,136433208
0,19	0,19	0,38	3,7316	22,32	21,50	21,88	21,90	0,528217352	0,147587745
0,19	0,24	0,43	4,2226	23,12	23,61	23,59	23,44	0,558449659	0,15603487
0,19	0,34	0,53	5,2046	27,27	27,61	28,33	27,74	0,581694268	0,162529582
0,19	0,44	0,63	6,1866	34,57	33,75	33,33	33,88	0,56601456	0,158148558
0,19	0,54	0,73	7,1686	38,89	39,94	40,18	39,67	0,560188051	0,156520589
0,19	0,64	0,83	8,1506	48,79	45,92	51,44	48,72	0,518649196	0,144914333

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	1,4	s
Hm =	0,1348	m
β =	32	
P =	10,73702	W



Different levels of buoyancy

RW 5 (H= 0,141 m T= 2,240 s)
buoyancy= 22

Mass (kg)			Load (N)	Torque	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass			T1	T2	T3			
0,2	0,64	0,84	8,2488	0,494928	35,13	36,59	36,29	36,00	0,71024757	0,158956
0,2	0,74	0,94	9,2308	0,553848	38,27	38,71	39,78	38,92	0,735238438	0,164549
0,2	0,84	1,04	10,2128	0,612768	42,48	42,13	42,82	42,48	0,745342855	0,166811
0,2	0,94	1,14	11,1948	0,671688	50,12	48,16	49,95	49,41	0,702365513	0,157192

RW 5 (H= 0,141 m T= 2,240 s) buoyancy =27

Mass (kg)			Load (N)	Torque	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass			T1	T2	T3			
0,2	0,64	0,84	8,2488	0,494928	43,72	40,03	38,62	40,79	0,626900711	0,100531
0,2	0,74	0,94	9,2308	0,553848	47,16	45,38	43,56	45,37	0,630760029	0,10115
0,2	0,84	1,04	10,2128	0,612768	50,90	49,36	49,12	49,79	0,635821663	0,101962
0,2	0,94	1,14	11,1948	0,671688	53,81	57,06	53,73	54,87	0,632513001	0,101431

RW 5 (H= 0,141 m T= 2,240 s) buoyancy =6

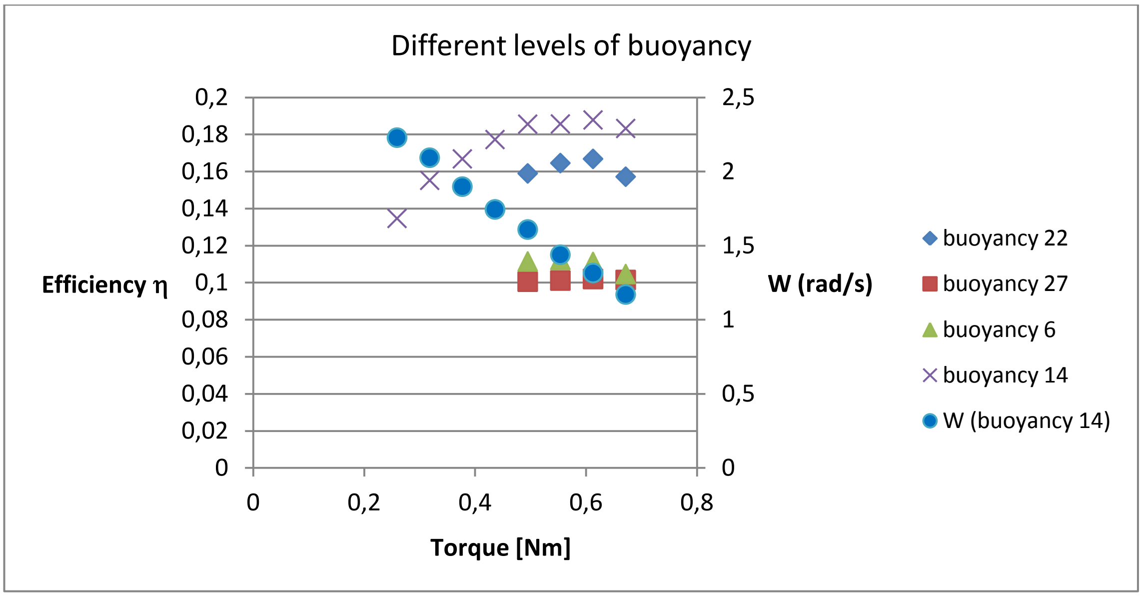
Mass (kg)			Load (N)	Torque	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass			T1	T2	T3			
0,2	0,64	0,84	8,2488	0,494928	37,33	36,22	37,64	37,06	0,689934706	0,11143
0,2	0,74	0,94	9,2308	0,553848	41,05	40,27	41,69	41,16	0,695225462	0,112285
0,2	0,84	1,04	10,2128	0,612768	46,76	45,37	45,85	45,99	0,688353674	0,111175
0,2	0,94	1,14	11,1948	0,671688	54,33	54,14	52,22	53,56	0,647903665	0,104642

RW 5 (H= 0,141 m T= 2,240 s) buoyancy = 14

Mass (kg)			Load (N)	Torque	Time (s)			Mean Time (s)	Power (W)	Efficiency
Friction	Weight	Tot. Mass			T1	T2	T3			
0,2	0,24	0,44	4,3208	0,259248	23,17	22,95	23,44	23,19	0,577680276	0,13466
0,2	0,34	0,54	5,3028	0,318168	24,61	24,70	24,75	24,69	0,66589306	0,155222
0,2	0,44	0,64	6,2848	0,377088	26,82	27,28	27,58	27,23	0,715580803	0,166805
0,2	0,54	0,74	7,2668	0,436008	29,92	29,66	29,29	29,62	0,760450546	0,177264
0,2	0,64	0,84	8,2488	0,494928	32,22	32,08	32,07	32,12	0,796034451	0,185559
0,2	0,74	0,94	9,2308	0,553848	36,27	35,73	35,77	35,92	0,796570845	0,185684
0,2	0,84	1,04	10,2128	0,612768	40,18	38,92	38,78	39,29	0,805726502	0,187818
0,2	0,94	1,14	11,1948	0,671688	44,77	42,16	45,52	44,15	0,786044847	0,18323

h =	3,1	m
g =	9,82	s
d =	0,44	m
Ro =	1000	kg/m^3
Tm =	2,239	s
Hm =	0,1407	m
β =	32	
P =	18,70760061	kW

Time (s)	Lenght (m)	Velocity (m/s)	Radius (m)	W (rad/s)
23,18667	3,1	0,133697527	0,06	2,228292
24,68667		0,125573859		2,092898
27,22667		0,113858962		1,897649
29,62333		0,104647238		1,744121
32,12333		0,096503061		1,608384
35,92333		0,086294887		1,438248
39,29333		0,07889379		1,314897
44,15		0,070215176		1,170253



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