Studying Buoy Motion for Wave Power

Experiments at the Lysekil Research Site

SIMON TYRBERG

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Division of Electricity
Department of Engineering Sciences

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Abstract

Since 2002, the Division for Electricity at Uppsala University has been running the Lysekil project. The project is an attempt to construct and evaluate a technology for extracting electrical energy from the motion of ocean waves. The idea is to let this up-and-down motion drive a linear generator. A buoy moves thus in the waves, and is connected through a line to the generator at the sea floor. Three such wave energy converters, L1, L2, and L3, and a marine substation have been deployed in the ocean southwest of Lysekil on the Swedish west coast, at the Lysekil research site. Measuring equipment has also been deployed, together with a number of buoys for studying environmental impact. A measuring station has been installed on the nearby island of Hermanö, and an observation tower has been built on the islet of Klammerskär, south of the research site.

This licentiate thesis describes the author’s work on studying wave buoy motion and is based on five scientific papers, covering mainly two areas. Firstly, changes in water levels, and thereby changes in the equilibrium point for the buoy and generator, have been related to the ability of L1 to absorb energy. The results indicate that there is a correlation between water levels and energy absorption for L1 for the studied time period. When the water level deviates from average, the absorption values decrease. This is not unexpected, since the linear generator has a finite stroke. The effect is however noticeable primarily for water level deviations of more than 25 cm, and is only visible for those cases where either wave height or water level deviation is large.

Secondly, the above mentioned observation tower has been designed and built. The tower is equipped with a network camera covering the research site, a wireless communication system and an energy system. The first acquired images of the buoy connected to L1, taken during the summer of 2008, have been analyzed, and buoy motion data has been extracted. The observation system has worked well, and the data on buoy motion (vertical motion in the range of ±0.5 m) correlates fairly well to measurements of significant wave height for the period \( H_{m0} = 0.82 \) m). A comparison with voltage data from the generator also indicates that the system has captured the dominating buoy motion. However, the system suffers from poor temporal resolution (about one image per second), and has not yet been synchronized with the other measurement systems at the site. Addressing these two problems is of high priority in the future.
Till Herta Lystedt och Gunnar Tyrberg
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


V  Tyrberg, S., Gravråkmo, H., Leijon, M. “Tracking a wave power buoy using a network camera - system analysis and first results”. Accepted to be published in the peer-reviewed Proceedings of the 28th International Conference on Offshore Mechanics and Arctic Engineering, OMAE, Honolulu, USA, 2009.

Reprints were made with permission from the publishers. The author has also contributed to the following paper, not included in the thesis.

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# Abbreviations and Nomenclature

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<th>Meaning</th>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>LRS</td>
<td>The Lysekil Research Site</td>
</tr>
<tr>
<td>RGB</td>
<td>Red, Green, Blue</td>
</tr>
<tr>
<td>WEC</td>
<td>Wave Energy Converter</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Entity</th>
</tr>
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<tr>
<td>λ</td>
<td>m</td>
<td>Wave length</td>
</tr>
<tr>
<td>Φ</td>
<td>Wb</td>
<td>Magnetic flux</td>
</tr>
<tr>
<td>ϕ</td>
<td>m²/s</td>
<td>Velocity potential</td>
</tr>
<tr>
<td>ω</td>
<td>rad/s</td>
<td>Angular frequency</td>
</tr>
<tr>
<td>ω₀</td>
<td>rad/s</td>
<td>Fundamental angular frequency</td>
</tr>
<tr>
<td>ζ</td>
<td>m</td>
<td>Surface displacement at one point in space</td>
</tr>
<tr>
<td>ν</td>
<td>m²/s</td>
<td>Kinematic viscosity</td>
</tr>
<tr>
<td>η</td>
<td>m</td>
<td>Surface displacement</td>
</tr>
<tr>
<td>ρ</td>
<td>kg/m³</td>
<td>Density</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Entity</td>
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<td>--------</td>
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<td>------------------------------------------------</td>
</tr>
<tr>
<td>$c$</td>
<td>m/s</td>
<td>Phase velocity</td>
</tr>
<tr>
<td>$c_g$</td>
<td>m/s</td>
<td>Group velocity</td>
</tr>
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<td>$E_k$</td>
<td>J/m$^2$</td>
<td>Kinetic energy per ocean unit area</td>
</tr>
<tr>
<td>$E_p$</td>
<td>J/m$^2$</td>
<td>Potential energy per ocean unit area</td>
</tr>
<tr>
<td>$E_{tot}$</td>
<td>J/m$^2$</td>
<td>Total energy per ocean unit area</td>
</tr>
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<td>$f$</td>
<td>s$^{-1}$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$f_0$</td>
<td>s$^{-1}$</td>
<td>Fundamental frequency</td>
</tr>
<tr>
<td>$\ddot{f}$</td>
<td>N</td>
<td>External force</td>
</tr>
<tr>
<td>$g$</td>
<td>m/s$^2$</td>
<td>Acceleration of gravity</td>
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<tr>
<td>$H$</td>
<td>m</td>
<td>Vertical distance from wave trough to crest</td>
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<tr>
<td>$H_{m0}, H_S$</td>
<td>m</td>
<td>Significant wave height</td>
</tr>
<tr>
<td>$h$</td>
<td>m</td>
<td>Water depth</td>
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<td>$I$</td>
<td>A</td>
<td>Current</td>
</tr>
<tr>
<td>$J$</td>
<td>W/m</td>
<td>Energy flux</td>
</tr>
<tr>
<td>$k$</td>
<td>m$^{-1}$</td>
<td>Wave number</td>
</tr>
<tr>
<td>$m_n$</td>
<td>-</td>
<td>Spectral moment</td>
</tr>
<tr>
<td>$m_0$</td>
<td>m$^2$</td>
<td>Zeroth spectral moment</td>
</tr>
<tr>
<td>$m_{-1}$</td>
<td>m$^2$s</td>
<td>Negative first spectral moment</td>
</tr>
<tr>
<td>$N$</td>
<td>-</td>
<td>Number of coil turns</td>
</tr>
<tr>
<td>$P$</td>
<td>W</td>
<td>Power</td>
</tr>
<tr>
<td>$p$</td>
<td>Pa</td>
<td>Pressure</td>
</tr>
<tr>
<td>$p_0$</td>
<td>Pa</td>
<td>Pressure at sea surface</td>
</tr>
<tr>
<td>$R$</td>
<td>Ω</td>
<td>Resistance</td>
</tr>
<tr>
<td>$S$</td>
<td>m$^2$/Hz</td>
<td>Spectral density function</td>
</tr>
<tr>
<td>$T$</td>
<td>s</td>
<td>Period</td>
</tr>
<tr>
<td>$T_0$</td>
<td>s</td>
<td>Fundamental period</td>
</tr>
<tr>
<td>$T_{m0-1}, T_E$</td>
<td>s</td>
<td>Energy period</td>
</tr>
<tr>
<td>$t$</td>
<td>s</td>
<td>Time</td>
</tr>
<tr>
<td>$U$</td>
<td>V</td>
<td>Voltage</td>
</tr>
<tr>
<td>$\bar{v}$</td>
<td>m/s</td>
<td>Velocity field</td>
</tr>
<tr>
<td>$w$</td>
<td>m</td>
<td>Water level</td>
</tr>
<tr>
<td>$z_n$</td>
<td>m</td>
<td>Complex Fourier coefficients</td>
</tr>
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</table>
Part I:
Introduction

In this part, a basic introduction to wave power is given, along with a description of the Lysekil project, a wave power research project at Uppsala University. The background to the work done within this thesis is also given.
1. Introduction

1.1 Thesis layout
This thesis deals with the motion of wave buoys, for extraction of energy from waves. The work has been carried out within the frames of The Lysekil Project, which is run at Uppsala University, and which is described in more detail in the following chapter. In chapter three, the background to the work performed by the author is also described. Part two of this comprehensive summary then deals with some of the theory behind the research. Finally, part three gives a brief summary of the papers upon which the thesis is based, and discusses the work performed. The details of each paper is not repeated however; the interested reader is advised to head to the full texts at the end of the thesis.

1.2 Wave energy
The ever increasing need for energy in the world, and the dangers of further use of fossil fuels have during the last couple of years put a focus on renewable energy technologies. The vast amounts of energy in ocean waves have been known for a long time (see e.g. [1, 2]), and become very evident to anyone who spends time out at sea. The exact amount of power available from waves is impossible to determine, since it depends on the performance of the technology chosen, but an estimation that about one TW continuously descends on the coastlines of the world was made in [3]. Regardless of the precision in that statement, it is clear that our oceans carry enough energy for wave power to be interesting to study further.

Numerous projects have tried to harvest the energy in waves. There are quite a few projects still active around the world, the most famous of which are possibly the Pelamis project, Wave Dragon and Archimedes Wave Swing (see details e.g. in [4–6]). Historically however, most attempts have failed in creating a technology that can survive the harsh ocean wave climates, or in designing a technology that is economically viable. There are some considerable advantages in using wave energy in comparison to other intermittent energy sources, such as wind or solar energy. But there are also some fundamental difficulties. On the positive side, wave energy is a concentrated form of energy, since waves absorb the energy from winds blowing over large areas. This also means that waves, in comparison with winds, are more predictable.
and more evenly distributed in time. Even if the wind abates, waves will keep rolling in for some time.

The major difficulty of tapping into the huge energy resource of ocean waves is the tremendous powers involved. For a system to be sustainable, it needs to produce energy at average wave climates, but still survive harsh weathers and storms. There is therefore a risk of ending up with systems that are either too bulky to be economically viable, or conversely: too fragile to survive in the long run. The Lysekil project, described in the next chapter, is an attempt to design a wave energy system which is sturdy enough, without becoming too expensive.

Systems for wave energy conversion can be classified in many different ways. In figure 1.1, wave energy devices have been divided into Wave activated bodies, Overtopping devices, and Oscillating water columns. The first of these describes systems where the motion of the waves is directly transferred to the wave energy converter (WEC). Examples of this technology include the Pelamis mentioned above. Overtopping devices let water run up a slope into a reservoir, from where the potential energy is converted using a low-head turbine. The Wave Dragon is an example of such a technology. Oscillating water columns use a fluctuating air pressure above the ocean surface to drive a turbine. One way to achieve such a varying air pressure is to partially submerge a pipe into the water. The LIMPET is an example of a technology using an oscillating water column [7]. The technology used in the Lysekil project can be classified as a wave activated body. It is also a point absorber, meaning that the width of the WEC is small in comparison to the wave length.

Figure 1.1: A classification of wave energy devices. A: Wave activated bodies, B: Overtopping devices, C: Oscillating water columns. Illustration by Rafael Waters, from [8].
2. The Lysekil Project

2.1 The basic ideas

The Lysekil wave energy project was initiated with simplicity as a guiding principle, since the harsh conditions at sea mean that complex systems have a high risk of failure, and are associated with high maintenance costs. The idea of simplicity meant that direct drive (i.e. without gearboxes or energy storage) was favored, and led to the wave energy converter concept illustrated in figure 2.1. The buoy follows the motion of the waves, and through the line transmits this motion to the translator in the linear generator, thus producing electricity. The chosen system means that the most complex part (i.e. the generator) is placed on the bottom, away from the extreme forces of the waves. The direct drive means that the system becomes more robust, but also that it is impossible to transmit the converted electricity directly to the grid, since voltages will vary both in amplitude and frequency. There is a need for an intermediate step, using power electronics to rectify the voltages from several WECs, add them together and then invert the voltage to the grid frequency.

![Figure 2.1: The concept used in the Lysekil Project. From paper IV, illustration by Rafael Waters.](image-url)
The experimental work within the project has taken place both at the Ångström Laboratory in Uppsala, and out at sea near Lysekil on the West Coast, at the Lysekil Research Site (LRS) (see also figure 2.3 on page 18).

2.2 Areas of research

Apart from the focus on simplicity, the importance of a broad view of the system has been stressed. This means that the system as a whole needs to be studied, as well as all the key parts involved. Research is therefore being conducted within the following areas:

- Electric power systems
- Hydrodynamics
- Generator technology
- Measurement technology
- Wave resource description
- Structural mechanics
- Environmental impact

Four doctoral and three licentiate theses have been published regarding the Lysekil project: [8–14].

2.3 Timeline

2002–2004

- The project is started during the spring of 2002.
- Investigations are made of bottom conditions at LRS during the summer of 2003.
- A laboratory version of the linear generator is finished in December of 2003.
- A wave measuring buoy is deployed at LRS in April of 2004
- Sediment samples from the bottom of LRS are taken in the summer of 2004 to investigate the marine infauna.
- The National Maritime Administration deploys buoys to mark LRS to the public in October of 2004.

2005

- An experimental setup to measure forces on a cylindrical buoy is deployed at LRS in March.
• The four first “biology buoys” are deployed at LRS during the fall. The purpose of these is to study the environmental impact of installing buoys and foundations in an otherwise empty ocean area.
• The construction of the first wave energy converter, L1, is started.

2006
• A measurement station is built on Härmanö, close to the research site, during the first months of the year.
• L1 is deployed at LRS on the 13th of March, and the first set of experimental data from the generator is gathered.

2007
• Additional biology buoys are deployed. A total of 21 buoys are put in place during March and May.
• In the beginning of April, L1 is run against a DC load for the first time.
• In July, a tower is erected on the islet of Klammerskär, near the research site, to form the base for a future observation system. The tower is equipped with an energy system during the fall. A picture of the research site, taken from the tower, can be seen in figure 2.2.

Figure 2.2: The Lysekil research site, as seen from the observation tower

2008
• A toroidal buoy is attached to L1 in May, to investigate if the design can help decrease the peak forces on the generator.
• In June, a marine substation that will be used to connect several WECs is tested in Uppsala.
• In the beginning of July, a network camera is installed in the tower on Klammerskär, enabling real time observation of the park from Uppsala.
• During the fall and winter, WECs number two and three (L2 and L3) are finished and transported to Lysekil.
2009

- L2 and L3 are deployed at LRS in February.
- In March, the substation is deployed at LRS.

2.4 The geography of LRS

In figure 2.3, a sea chart of LRS and its surroundings can be seen, before the deployment of L2 and L3. The research site is enclosed within the dashed line in the top left corner of the map. The bullets represent biology buoys, the cross represents L1 and the asterisk represents the wave measuring buoy deployed in 2004. The dashed-dotted line heading southeast from the site represents the cable drawn from L1 to Hermanö. Western and Eastern Klammerskär are located directly south of LRS, and the observation station is built on Western Klammerskär. The horizontal distance from the station to L1 is approximately 300 m.

![Figure 2.3: The Lysekil research site and its surroundings. Taken from paper V.](image)

2.5 General results

Apart from the results presented in papers I–V, a number of results have been published on the different topics mentioned in section 2.2. See for example [15, 16] for a discussion of wave energy economy and potential, [17, 18]...

In figure 2.4, a number of pictures have been put together to illustrate some of the practical work performed and results achieved over the past years. In the first row, L2 can be seen in the workshop in Uppsala, as well as being deployed at LRS. In the top right corner, the deployment of a biology buoy can be seen. On the second row, there is an underwater shot of a biology buoy, and an image of a crab clinging on to the line to the generator of L1. The top of the linear generator of L1, with the piston coming out of it through a sealing device, can be seen to the left in the third row. There are also two pictures from Klammerskär in the third row. The left picture is from the casting of the concrete foundation for the observation tower, and the right picture is from working with the installation of the energy system. In the right-most picture in the third row a heavy diver is getting ready to do some work on L1. In the bottom row, the cylindrical buoy connected to L1 can be seen in the middle, and to the right is the toroidal buoy that was installed in 2008. The bottom left picture shows the observation tower on Klammerskär and Nereis, the boat used in the project.
Figure 2.4: An illustration of some of the work within the Lysekil project.
3. Background of the presented work

As the Lysekil project has evolved, some initial questions have been answered, while new questions have surfaced along the way. There is a wish to understand the system as a whole, as well as to increase the knowledge of all the separate parts in the project. After the deployment of L1 in 2006, data was gathered on voltages and currents in the generator, and energy captured by the system. From voltage data it is also possible to deduce data on translator motion. Since the translator and the buoy are not rigidly connected however, questions remained on the magnitude and character of the buoy motion. Some questions could be answered through the use of accelerometers in the buoy, others could not. For instance, it is not possible to relate buoy motion to the position of the ocean surface using only accelerometers. Accelerometers also have drifting errors since they work through twice integrating a signal of acceleration to get data on movement and position. This means that it is possible to compare motions at two different instances in terms of the magnitude of the motion, but not where in space the motion took place. All this, in combination with a wish to visually look at buoy motion and get an overview of the research site, led to the decision to construct an observation system. The design of the system was initiated within the frames of a Master’s thesis in 2006, and has since then become a PhD project, part of which is this licentiate thesis. One specific impact on buoy motion is the effect of tides and changing water levels, and work on this is also incorporated in the thesis.

A number of commercial systems for optical motion tracking, using one or several cameras, can be found on the market. If more than one camera is used, it is possible to measure motions in six degrees of freedom, whereas one-camera systems are limited to two dimensions, from which other parameters can be estimated in some cases. Examples of usages of such systems can be found in [30] (for studying wave surface profiles), [31] (for experiments on a Salter’s Duck) and [32] (for studying the motion of a discus buoy). These examples are all within a laboratory setting, however. Other systems have been designed to work at sea (see e.g. [33]), but use high precision equipment for very short-range measurements. Such devices will not work for the distances in question at LRS. The choice was made not to use a commercial tracking system initially, but rather to use an ordinary network camera with pan, tilt, and zoom capabilities. There were several reasons for this. For one, the priority at this stage was general monitoring rather than detailed measurements; there was simply a wish to “see what was happening” out to sea. The physical
size of Klammerskär also puts limits on a tracking system using more than one camera. It is not possible to achieve a distance of more than a few meters between two cameras. This is a very small distance in comparison to the distance to the buoy (in the ideal case, the angle between the two cameras should be $90^\circ$). Finally, it was far from evident that the equipment would actually work in the harsh conditions of the research site. Thus, installing a relatively cheap network camera was a first step, to possibly be complemented with a more advanced (and more expensive) system later on.
Part II:

Theory

This part of the thesis introduces some basic theory within three fields of science involved in the presented papers: wave theory, generator technology and digital image analysis. For each chapter there is also one or several references to more detailed descriptions in the literature.
4. Describing Waves

The purpose of this chapter is to introduce the mathematical tools used to describe wave motions and the properties of waves over time. For a more elaborate description of the derivation of wave motion equations, see e.g. [34] or [35].

4.1 Linear wave theory

The mathematical descriptions of waves are based on two equations, namely the continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

(4.1)

and Navier–Stokes equation

$$\frac{D\mathbf{v}}{Dt} \equiv \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{v} + \frac{1}{\rho} \mathbf{f},$$

(4.2)

where \(\rho\) is the density of the fluid element under study, \(\mathbf{v}\) is the velocity field, \(p\) is the pressure, \(\nu\) is the kinematic viscosity coefficient, and \(\mathbf{f}\) is an external force applied on the fluid. The continuity equation states that the mass is conserved, and describes how any change of the density at a point in the fluid is matched by a flow to or from that point. Navier–Stokes equation is an application of Newton’s second law to a fluid element. The left-hand side describes the convective derivative, i.e. the acceleration of the fluid, whereas the right-hand side describes the different forces acting on the fluid. The first term describes the forces from the pressure gradient, the second term the forces from internal friction, and the third one the external forces, such as e.g. gravity.

For the case of ocean waves, a number of assumptions can be made to simplify the equations above:

I. The fluid under consideration is incompressible, meaning that \(\rho\) is constant, and \(\frac{\partial \rho}{\partial t} = 0\).

II. The fluid is irrotational, i.e. \(\nabla \times \mathbf{v} = 0\). This means that \(\mathbf{v}\) can be described as a vector field with a scalar potential \(\phi\), such that \(\mathbf{v} = \nabla \phi\).

III. Viscosity can be neglected, i.e. \(\nu = 0\).

IV. Gravity is the only external force, i.e. \(\mathbf{f} = -g\rho \mathbf{z}\).
The velocity $\bar{v}$ is of small magnitude, implying that terms of $v^2$ can be neglected in comparison to terms of $v$.

Assumption I means that the continuity equation simplifies to

$$\nabla \cdot \bar{v} = 0,$$

which according to assumption II can be written as

$$\nabla^2 \phi = 0.$$  \hfill (4.4)

This is Laplace’s equation for the velocity potential. Using vector algebra and assumptions II–V, Navier–Stokes equation simplifies to

$$\frac{\partial \phi}{\partial t} + \frac{p}{\rho} + gz = C,$$

where $C$ is an integration constant. Equation 4.5 is the so-called Bernoulli equation. The equations above hold for fluids in general, as long as assumptions I–V are valid. For ocean waves, we can furthermore apply specific boundary conditions that will allow us to find solutions to equations 4.4 and 4.5.

Let us consider a free water surface, the displacement of which is denoted $\eta$. This is a function of time and the surface coordinates: $\eta = \eta(x,y,t)$, see figure 4.1. The pressure at the surface is denoted $p_0$, and we have a scalar velocity potential $\phi$, as was described above. We consider only small surface displacements, i.e. $\eta \ll \lambda$, where $\lambda$ is the wave length. We can thus approximate the vertical motion of the water particles with a Taylor expansion around $z = 0$:

$$\frac{\partial \eta}{\partial t} = v_z|_{z=\eta} = \frac{\partial \phi}{\partial z}|_{z=\eta} = \frac{\partial \phi}{\partial z}|_{z=0} + \eta \cdot \frac{\partial^2 \phi}{\partial z^2}|_{z=0} + \eta^2 \cdot \frac{1}{2} \frac{\partial^3 \phi}{\partial z^3}|_{z=0} + \cdots$$  \hfill (4.6)

In order to simplify the expression, and since $\eta$ is small, we will neglect all terms but the first one. This is the approximation giving name to the linear wave theory:

$$\frac{\partial \eta}{\partial t} = \frac{\partial \phi}{\partial z}|_{z=0}. $$  \hfill (4.7)

In order to find solutions for the wave motion, we need to set up a number of boundary conditions. Since we know that there can be no vertical motion of the water particles at the bottom, we can set up a sea floor boundary condition:

$$v_z|_{z=-h} = 0 \Rightarrow \frac{\partial \phi}{\partial z}|_{z=-h} = 0.$$
Furthermore, we can set up a surface boundary condition by studying the Bernoulli equation (eq. 4.5) for $z = \eta$:

$$\frac{\partial \phi}{\partial t} \bigg|_{z=\eta} + g \eta = C - \frac{p_0}{\rho}. \quad (4.9)$$

The left-hand side of this equation depends on time, whereas the right-hand side does not, for constant atmospheric pressure $p_0$. This means that both sides must vanish, and we get an expression for the constant $C$:

$$C = \frac{p_0}{\rho}. \quad (4.10)$$

Eq. 4.9 now becomes

$$\frac{\partial \phi}{\partial t} \bigg|_{z=\eta} = -g \eta. \quad (4.11)$$

For small $\eta$, we can again make a Taylor expansion around $z = 0$, and make the approximation

$$\frac{\partial \phi}{\partial t} \bigg|_{z=\eta} \approx \frac{\partial \phi}{\partial t} \bigg|_{z=0}, \quad (4.12)$$

which means we can set up an expression for $\eta$:

$$\eta = -\frac{1}{g} \frac{\partial \phi}{\partial t} \bigg|_{z=0}. \quad (4.13)$$

Taking the time derivative of this equation, and combining with eq. 4.7 we end up with the final form of the surface boundary condition:

$$\left[ \frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} \right]_{z=0} = 0. \quad (4.14)$$
4.2 Solving the equations for harmonic waves

In a first step, we will try to find solutions to Laplace’s equation (eq. 4.4) on the form:

\[ \phi(x, y, z, t) = Z(z) \sin(kx - \omega t), \]  

(4.15)

where \( \omega = 2\pi f = \frac{2\pi}{T} \) is the angular frequency, corresponding to the frequency \( f \) and the period \( T \), and \( k = \frac{2\pi}{\lambda} \) is the wave number corresponding to the wave length \( \lambda \). We are in other words assuming a harmonic wave (i.e. a single sinus), traveling in the \( x \)-direction, and having an amplitude which depends on the depth by a function \( Z(z) \). Inserting the proposed solution into Laplace’s equation gives:

\[ \nabla^2 (Z(z) \sin(kx - \omega t)) = Z''(z) \sin(kx - \omega t) - Z(z) k^2 \sin(kx - \omega t) = 0 \]

\[ \Rightarrow Z''(z) = k^2 Z(z). \]  

(4.16)

This equation has general solutions of the form:

\[ Z(z) = Ae^{kz} + Be^{-kz}, \]  

(4.17)

where in our case the constants \( A \) and \( B \) can be found using the surface and sea floor boundary conditions (equations 4.8 and 4.14). Inserting eq.s 4.15 and 4.17 into eq. 4.8 gives:

\[ Z'(-h) = 0 \Rightarrow kAe^{-kh} - kBe^{kh} = 0 \Rightarrow \frac{A}{B} = e^{2kh}. \]  

(4.18)

Using the surface boundary condition (eq. 4.14) gives:

\[ \left[ -Z(z) \omega^2 \sin(kx - \omega t) + gZ'(z) \sin(kx - \omega t) \right]_{z=0} = 0 \]

\[ \Rightarrow gZ'(0) - Z(0) \omega^2 = 0 \Rightarrow \frac{Z'(0)}{Z(0)} = \frac{\omega^2}{g}. \]  

(4.19)

Inserting eq. 4.17 into this gives

\[ \frac{\omega^2}{g} = \frac{k(A - B)}{A + B} = \frac{k}{A/B + 1} = \frac{k}{A/B - 1} = [\text{using eq. 4.18}] = \frac{e^{kh} - e^{-kh}}{e^{kh} + e^{-kh}} = k \tanh(kh). \]  

(4.20)

Solving for \( \omega^2 \):

\[ \omega^2 = gk \tanh(kh). \]  

(4.21)

This is the dispersion relation for gravity waves, and describes how the wave period and wave length are related.
4.2.1 Approximations for deep water

Eq. 4.21 can be simplified if \( h \) is assumed to be large in comparison to \( \lambda \), i.e. for deep water. If \( kh \to \infty \), then \( \tanh(kh) \to 1 \), and the dispersion relation becomes:

\[
\omega^2 = gk. \tag{4.22}
\]

Using the criteria \( h \geq \lambda/2 \) for making the above approximation is common. Indeed, for \( h = \lambda/2 \), we get:

\[
kh = k\frac{\lambda}{2} = \pi \Rightarrow \tanh kh \approx 0.996. \tag{4.23}
\]

Looking at eq. 4.17 we can also say that the constant \( B \) must be equal to zero, since the wave amplitude otherwise would grow to infinity as we move to greater depths. This would be physically unrealistic. Thus, we have:

\[
Z(z) = Ae^{kz}, \tag{4.24}
\]

and the expression for the velocity potential becomes:

\[
\phi = Ae^{kz} \sin(kx - \omega t). \tag{4.25}
\]

Using eq. 4.13 to express the surface displacement gives:

\[
\eta = -\frac{1}{g} \frac{\partial \phi}{\partial t} \bigg|_{z=0} = -\frac{1}{g} Ae^{kz} \cos(kx - \omega t)(-\omega) = \frac{A\omega}{g} \cos(kx - \omega t). \tag{4.26}
\]

Introducing the letter \( H \) to describe the vertical distance from wave crest to wave trough, the amplitude of the wave will become \( H/2 \), and \( A \) can be expressed in terms of \( H \) according to:

\[
\frac{A\omega}{g} = \frac{H}{2} \Rightarrow A = \frac{gH}{2\omega}. \tag{4.27}
\]

We can then express the velocity potential as:

\[
\phi = \frac{gH}{2\omega} e^{kz} \sin(kx - \omega t) \tag{4.28}
\]

and the surface displacement as:

\[
\eta = \frac{H}{2} \cos(kx - \omega t). \tag{4.29}
\]
4.2.2 Describing the motion below the surface

Using assumption II and eq. 4.29, we can study the velocity of water particles below the surface:

\[
\vec{v} = \nabla \phi = \left( \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) \frac{gH}{2\omega} e^{kz} \sin(kx - \omega t) = \frac{gHk}{2\omega} e^{kz} (\cos(kx - \omega t), 0, \sin(kx - \omega t)) = \omega^2 = gk = H \frac{\omega}{2} e^{kz} (\cos(kx - \omega t), 0, \sin(kx - \omega t)). \tag{4.30}
\]

This means that the water particles move in circular orbits, with an amplitude that decreases exponentially with depth. See figure 4.2.

![Figure 4.2: The motion of water particles. Illustration by Rafael Waters, from [8].](image)

4.3 Phase and group velocity

The phase velocity \( c \) is the speed with which a particular phase of the wave propagates. For deep water, this is different from the group velocity \( c_g \), which is the velocity with which a group of waves propagates. The group velocity also describes the velocity with which the energy of the waves travels. The expression for phase velocity is rather straightforward:

\[
c = \frac{\lambda}{T} = \frac{\omega}{k}, \tag{4.31}
\]

whereas the expression for group velocity is somewhat less intuitive. Group velocity is defined as:

\[
c_g \equiv \frac{\partial \omega}{\partial k}. \tag{4.32}
\]
Using the dispersion relation for deep water \((\omega^2 = gk)\), we can simplify the expressions for phase and group velocities:

\[
c = \frac{\omega}{k} = \frac{\omega g}{\omega^2} = \frac{g}{\omega} = \frac{g}{2\pi} T \approx 1.56T
\]

\[
c_g = \frac{\partial}{\partial k} \left[ \sqrt{gk} \right] = \frac{1}{2} \frac{g}{\sqrt{gk}} = \frac{1}{2} \frac{g}{\omega} = \frac{1}{2} c.
\]

This means that at deep water, a group of waves will travel with half the speed of the waves making up the group. Furthermore, it may be pointed out that the phase velocity is linearly dependent on the period of the waves, which means that waves with longer period (or longer wave length) will travel faster.

### 4.4 Energy content of harmonic waves

The energy per square meter of ocean surface can be described as a sum of the potential and kinetic energy of the water particles within that square. The potential energy is found through:

\[
E_p = \frac{1}{S} \int \int g \cdot \frac{\eta}{2} \cdot \rho \eta dS,
\]

where \(S\) is the surface over which we are integrating. The formula above is an applied version of \(E = mgh\), where the mass is described by \(\rho \eta dS\), and the height of the centre of mass is described by \(\eta/2\). Evaluating this integral using eq. 4.29, the average potential energy per unit area becomes:

\[
\bar{E}_p = \frac{H^2}{16} g \rho,
\]

where the bar denotes an average. The kinetic energy can be found through:

\[
E_k = \frac{1}{S} \int \int \frac{1}{2} v^2 \rho \eta dS,
\]

which is an applied version of the general formula for kinetic energy \(E = \frac{mv^2}{2}\), where again the mass is described by \(\rho \eta dS\). Evaluating this integral in the same way as above, the average kinetic energy per unit area becomes:

\[
\bar{E}_k = \frac{H^2}{16} g \rho,
\]

which is the same expression as in the case of potential energy. Thus, the total energy per unit area of ocean is:

\[
E_{tot} = E_p + E_k = \frac{H^2}{8} g \rho.
\]
The total energy can also be written as twice the potential energy (compare eq. 4.35):

\[ E_{\text{tot}} = g \rho \cdot \frac{1}{S} \iint \eta^2 dS = g \rho < \eta^2 >, \]  

(4.40)

where the brackets denote a space average in this case, but could also denote a time average. We call \(< \eta^2 >\) the variance of \( \eta \). The total energy depends linearly on the variance of sea surface displacement.

4.4.1 Energy flux

It is more common to describe waves in terms of power than energy. The unit is then W/m, where we describe the power coming in across one meter of the surface, parallel to the wave crest. Since we know the group velocity of deep water harmonic waves (eq. 4.34), we can describe the average energy flux (the rate at which energy is transported) \( J \) as:

\[ J = c_g E_{\text{tot}} = \frac{g}{2\omega} \cdot \frac{H^2}{8} \rho g = \frac{\rho g^2}{32\pi} T H^2 = k T H^2. \]  

(4.41)

The letter \( k \) is usually used to describe the constant \( \frac{\rho g^2}{32\pi} \). This constant must not be confused with the wave number, which (unfortunately) is also denoted \( k \).

4.5 Real ocean waves

In reality, ocean waves are not harmonic. However, in most cases they can be described as a sum of harmonic waves using Fourier series. This means that the surface displacement signal is divided into its frequency components. In the discrete and complex Fourier notation, the surface displacement can be written as:

\[ \zeta(t) = \sum_{n=-\infty}^{\infty} z_n e^{in\omega_0 t}. \]  

(4.42)

where \( \zeta(t) \) has been used instead of \( \eta(x, y, t) \) to indicate that we are studying one specific point over time. In the expression above, \( \omega_0 \) is the fundamental angular frequency, chosen so that all other frequencies can be expressed as multiples of it. \( \omega_0 \) also relates to the fundamental frequency and period through \( \omega_0 = 2\pi f_0 = \frac{2\pi}{T_0} \). The complex Fourier coefficients \( z_n \) are written as:

\[ z_n = \frac{1}{T_0} \int_{-T_0/2}^{T_0/2} \zeta(t) e^{-in\omega_0 t} dt. \]  

(4.43)
We will henceforth assume that $z_0 = 0$, meaning that $\zeta$ varies around 0. In section 4.4, it was shown that the total energy is linearly dependent on the variance of the surface displacement. Taking the variance of the surface displacement as it is written in eq. 4.42 gives:

$$\langle \zeta(t)^2 \rangle = \langle \zeta \zeta^* \rangle = \frac{1}{T_0} \int_0^{T_0} \zeta \zeta^* dt = \sum_{n=0}^{\infty} 2z_n z_n^*. \quad (4.44)$$

We use this relation to define the spectral density function $S(n f_0)$:

$$S(n f_0) \Delta f \equiv 2z_n z_n^*, \quad (4.45)$$

which has the unit $m^2/Hz$. Thus, we can write $\langle \zeta(t)^2 \rangle$ as:

$$\langle \zeta(t)^2 \rangle = \sum_{n=0}^{\infty} S(n f_0) \Delta f. \quad (4.46)$$

Moving over to the continuous case, this becomes:

$$\langle \zeta(t)^2 \rangle = \int_0^{\infty} S(f) df. \quad (4.47)$$

The spectral density function describes the energy content of a sea state, as a function of frequency. An example of a spectral density function, taken from the Lysekil research site, can be seen in figure 4.3. The area under the graph describes $\langle \zeta(t)^2 \rangle$ (or $\langle \eta(x,y,t)^2 \rangle$), and is related to the total energy in accordance with eq. 4.40. It can be seen in figure 4.3 that in this case, waves with frequencies just above 0.1 Hz contain the main part or the energy.

### 4.5.1 Spectral moments and descriptions of energy

To find more concise expressions for energy content and energy flux for ocean waves, we will introduce the notion of spectral moments $m_n$:

$$m_n = \int_0^{\infty} f^n S(f) df. \quad (4.48)$$

It is clear that the zeroth moment $m_0$ is the same thing as $\langle \zeta(t)^2 \rangle$, and thus we can now express the total energy per square meter as:

$$\overline{E_{tot}} = \rho g m_0. \quad (4.49)$$

The significant wave height $H_{m0}$ (or $H_S$) is then defined as:

$$H_{m0} \equiv 4\sqrt{m_0}. \quad (4.50)$$

Through this definition, we have used the spectral moments to introduce a quantity to describe sea states that do not in reality have one single wave.
Figure 4.3: A wave energy spectrum from the Lysekil research site. Illustration by Rafael Waters, from [8]. For this period, the significant wave height is $H_{m0} = 3.1 \text{ m}$ and the energy period $T_E = 7.7 \text{ s}$. The energy flux is $J = 35 \text{ kW/m}$.

Based on this relation, and in analogy with the definition of significant wave height, we define the energy period $T_E$ (or $T_{m0-1}$) as:

$$T_E \equiv \frac{m_{-1}}{m_0}. \tag{4.52}$$

As is the case with the significant wave height, the energy period is a mathematical tool to describe sea states that in reality do not have one single period. The reason for choosing the definition above is that the energy flux now can be described as:

$$J = \frac{\rho g^2}{64\pi} T_E H_{m0}^2, \tag{4.53}$$

which is an equation on the same form as eq. 4.41 (i.e. a constant times a period times a wave height squared). In this case, however, we must keep in mind that the wave height and period are not the straightforward physical entities they were in eq. 4.41.
5. Generators and Circuits

The purpose of this chapter is to give a short introduction to generator theory, and to highlight a few differences between rotating and linear generators. Some system aspects and their effects on generator motion are also introduced. For more details on electromagnetics and generators, see e.g. [36] and [37].

5.1 Rotating and linear generators

The general purpose of generators is to convert mechanical energy to electric energy. Most conventional generators are of the rotating kind, but the system studied in this thesis uses a linear generator. The principles of electric energy conversion do not differ however, and a linear generator consists of the same key components as its rotating sibling. In figure 5.1, a schematic illustration of a rotating and a linear generator can be seen. Both generators have a moving part (the rotor/translator) and a static part (the stator). On the moving part, there are magnets mounted, with alternating magnetic direction. All generators are based on Faraday’s law, which states that a changing magnetic field in a coil will induce an electromotive force $U$ in that coil:

$$U = -N \frac{d\Phi}{dt}.$$  \hspace{1cm} (5.1)

$N$ is the number of coil turns and $\Phi$ is the magnetic flux. The changing magnetic field can come from a motion of the coil, a motion of the magnet or a change of magnetic flux density. In figure 5.1 the magnets are of the permanent kind, but electromagnets can also be used, which allows for control of the magnetic field.

In a rotating generator, $N$ in equation 5.1 remains constant. In a linear generator however, there is a possibility for the moving part (the translator) to leave the static part (the stator), resulting in a decrease of the active area, i.e. the part of the generator that induces voltages. This means that the voltage will drop, and that the dynamics of the generator will change. The impact of such effects will among other things depend on the stator length vs. the translator length, the stroke length of the translator, the equilibrium position for the translator, and the load connected to the generator. Detailed descriptions of the effects become very complicated, for more on this see e.g. [38].
5.2 Generator output

One more important difference between rotating and linear generators is that it is possible to run the former, but not the latter, at constant speed. Since the length of a linear generator is finite, the translator must come to a stop at both ends. This means that the voltage output for linear generators becomes less regular than is possible to achieve in a rotating generator. In fact, the voltage will vary both in amplitude and frequency. If a constant frequency and voltage is required (as is the case for grid connections), this can be handled through power electronics. In such cases, the voltage from one (or several) generators will be rectified and then inverted again, but this time to the grid frequency.

5.3 Electrical system and damping

Depending on how the electrical system is designed, the damping of the generator will vary. When an electrical load is connected to the generator, power will be drawn from it, and the motion of the translator or rotor will change from the no-load case. This change will also affect the dynamics of whatever it is that drives the generator (e.g. a hydro power turbine, a wave power buoy or a wind turbine). The damping in the generator depends both on the value of the connected load and on how the electrical system is set up.

If an ideal generator is connected without rectification to a purely resistive load, the damping will increase with decreasing load impedance $R$. This is due to the fact that for a constant voltage $U$, the current $I$ through the load

![Figure 5.1: A rotating and a linear generator. Illustration by Rafael Waters, from [8].](image-url)
will increase, as will the power $P$, see eq. 5.2 and 5.3. For a set resistive value however, the damping will not change.

\[ U = R \cdot I \quad (5.2) \]

\[ P = \frac{U^2}{R} \quad (5.3) \]

The case becomes somewhat different if the voltage from the generator is rectified. This means that no power is delivered from the system until the induced voltage reaches the voltage on the DC side, see figure 5.2. In other words, the generator is not damped initially. It is only when the induced voltage exceeds the DC voltage that power is delivered, and the generator is dampened. The more power that is delivered, the higher the damping becomes, until the induced voltage again drops below the DC voltage level.

![Figure 5.2: A system using voltage rectification. The generator will be damped when $\bar{U}_{\text{gen}} > U_{\text{DC}}$.](image)

All this means that the choices made on the electrical side of an energy conversion system will have consequences on the mechanics, hydrodynamics, aerodynamics, and any other part involved in the system. The opposite is of course also true.
6. Image Analysis

The purpose of this chapter is to give a brief introduction to the field of digital image analysis, as well as explain some of the methods used. The interested reader may turn to e.g. [39] for a more thorough description.

6.1 Working with digital images

Working with digital images means dealing with one or more of the following steps, illustrated in figure 6.1.

- Image capturing
- Image enhancement
- Segmentation
- Feature extraction
- Recognition, classification and interpretation

Depending on the application some steps will be easy and others will be more difficult to control.

![Image Analysis Process](image)

*Figure 6.1: The process of image analysis.*

6.2 Capturing images

In cases where the user has control of the object or environment to be imaged, a lot can be done to improve the image captured. Proper lighting, carefully selected colors, distinctive shapes and uniform background are among the things that can significantly simplify the image handling. Full control is seldom pos-
sible however, and it necessary to deal with imperfect images and artifacts (image defects).

A digital image consists of a number of pixel values, where the value for each pixel represents a gray scale or color intensity, most often in the range [0, 255] (i.e. 8 bit) where higher numbers represent brighter pixels. Color pictures are usually represented as three layer pictures with intensities in red, green, and blue. This is also called RGB color space. The spatial resolution of an image is number of pixels in the vertical and horizontal direction, e.g. 640 \times 480. See an example in figure 6.2. Time series of images also have a temporal resolution, i.e. the number of images per second. Information about

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figures/figure6_2.png}
\caption{A 4 \times 3 grayscale image to the left and a 4 \times 3 color image to the right.}
\end{figure}

an image can be given as a gray level histogram, in which the number of pixels for each intensity is displayed. Studying the histogram can give clues on how to enhance the image. An example of a picture with corresponding histogram can be seen in figure 6.3.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figures/figure6_3.png}
\caption{Gray level image with corresponding histogram.}
\end{figure}

6.3 Enhancing images

Image enhancing can be done either to make the image “better” to the human eye, or to enable the use of different computational tools, or as a combination of both. An example of the former is brightness and contrast adjustment, which means moving or stretching out the histogram. This does not affect the
information in the image, but to the human eye the image may become much clearer. An example of the latter is filtering.

Filtering can among other things be done to sharpen edges, remove noise or smooth out pictures. When filtering, information from a number of neighboring pixels is used to transform the pixel in question. A common neighborhood size is $3 \times 3$, where the center pixel is the one being adjusted. Examples of smoothing filters are mean filters (sets the pixel value to the mean of the neighborhood) and median filters (sets the pixel value to the median in the neighborhood). The latter is good for removing Gaussian (random) noise, without blurring edges. Examples of edge sharpening filters are Laplacian, Roberts and Sobel filters. All these use a combination of first or second order spatial derivatives to enhance edges. In other words, they highlight areas where pixel values change fast. Choosing the proper filter often means a balance between performance and computational time. In paper V, a Canny filter is used. This filter uses a derivative of a Gaussian (smoothing) filter, together with an algorithm to discriminate between stronger or weaker edges, and chose only those weak edges that are connected to strong ones. Using a Canny filter is a slow but efficient process.

6.4 Segmenting images

Once the image has been sufficiently improved, there is often a wish to divide the image into objects and background. One way to do this is thresholding, which means dividing the pixels into two groups; one above and one below some threshold intensity value. The result is a binary picture (every pixel can be represented as either 1 or 0). The histogram can often be used to find a suitable threshold value. If a color picture is available, multiple thresholding can be done, using the information in all three layers of the picture. Another way to segment is to use the edges detected, and try to link them so that objects can be distinguished from background.

6.5 Extracting features

There are a large number of features that can be extracted from images. Since there often are very differing preconditions in each application, this is also a step that likely will require case-specific solutions. There is a large margin for inventive use of the available tools. Among the features that can be extracted are e.g. color, size, shape, compactness, connectivity, number of holes, convexity and texture. The difficult step is often not to find extractable features, but to chose them so that they say something about what you are interested in.
6.6 Identifying, classifying, and interpreting images

Similar to the process of extracting features, this step also requires case-specific solutions and innovative thinking. Furthermore, it is not always easy to determine where feature extraction ends and identifying begins.

As a concrete example, it is difficult to tell coniferous trees and flowering trees apart in an aerial picture by just looking at the color of the trees. However, using a combination of the signature in the infrared region and a texture measurement, the two kinds of trees can easily be distinguished. In such a way, the fraction of coniferous to flowering trees in a region can be extracted from an image (provided the use of an infrared sensitive camera).

There are many more ways to classify objects, but in summary, the task of identifying, classifying, and interpreting images is often a question of finding the relevant features, and using the right number of uncorrelated features.
Part III:
Experimental work

In this part, the articles that this thesis is based on are summarized, and the experimental setup at Klammerskär is explained in detail. The finishing chapters discuss the work done, and elaborate on work still to come.
7. Summary of Papers

This thesis is based on five papers, presented in their full length at the end. Here, a short summary is given, to enable some discussion of the work as a whole, and on possible future work. Papers I–III give a comprehensive background to the Lysekil project, and present some results acquired along the way. Papers IV and V present more specific wave energy research performed by the author.

**PAPER I**

The Conversion of Wave Motions to Electricity Using a Grid-Oriented Approach

In this paper, the main ideas behind the Lysekil project are introduced, together with a short summary of the process of carrying out the project. Compared to paper II and III, the focus is here more on what philosophies led to the chosen system, than detailed descriptions of the technology.

The author contributed in a major revision of this paper and took part in the submission process.

This paper is published in *IEEE Power & Energy Magazine*, volume 7, issue 1, 2009.

**PAPER II**

Wave Energy from the North Sea: Experiences from the Lysekil Research Site

A very thorough description of the Lysekil project can be found in this paper, both on the technology used and the process of installing the first WEC. The paper covers all parts of the project: from a brief introduction of wave energy projects around the world to describing the properties of the Lysekil research site and the results on wave characteristics, electrical systems, absorption and environmental impact.

The author contributed with the text regarding the observation tower, as well as the actual installation of the tower, and coordinated the texts from the other authors.
This paper is published in *Surveys in Geophysics* 29:221–240, 2008.

**PAPER III**

The Lysekil Wave Power Project: Status Update

This paper presents a more brief, but slightly more up to date description of the status of the Lysekil project, as compared to paper II. A lot of the material in this paper is covered in paper II as well, but the focus here is more on the work performed by the author, i.e. the effect of varying water levels and the installation of the observation system.

The author performed most of the writing of this paper, based on the information given by the people who had carried out the experiments within each field. The work of installing the observation tower mentioned in section 4.6 was also carried out by the author.

This conference paper is published in *Proceedings of the 10th World Renewable Energy Conference* and was orally presented by the author in Glasgow, UK, in July 2008.

**PAPER IV**

On the Influence of Water Levels on Wave Power Absorption: Experimental Results

Since the generator of the WEC has a finite stroke, it is reasonable to assume that the WEC performance is dependent on the equilibrium position of the translator. In this article, absorbed energy has been matched against water levels and incoming wave energy, to investigate if there is a correlation between changing water levels and changing absorption values for the WEC system. It is found that the correlation exists, if sea states with low wave height and little water level deviation are excluded. The effect is most noticeable for water level deviations of more than 25 cm. Such data points correspond to approximately 15% of the set. The conclusion is that water level variations do not seem to constitute a big problem at the Lysekil research site.

Most of the work on this paper was performed by the author. Rafael Waters contributed with figure 1 and performed the computer analysis that lead to the values for absorption.

This paper has been submitted to *IEEE Journal of Oceanic Engineering* in October of 2008.
Paper V

Tracking a Wave Power Buoy Using a Network Camera - System Analysis and First Results

Since the summer of 2008, a camera system has been operational at Klammer-skär, south of the Lysekil research site. In this paper, the process of designing and installing this system is described, and an analysis is made of the first series of pictures from the camera. The wave power buoy has been photographed during operation, and using image analysis on these pictures, buoy motions have been extracted. The values (±0.5 m maximum vertical motion) correspond fairly well to what would be expected based on the sea state during the image sequence ($H_{m0} = 0.82$ m). The strengths and weaknesses of the system are analyzed in the paper, concluding that some work remains on quantifying the accuracy, and synchronizing the images to the measurements of voltages in the linear generator. In general the system has worked well.

The author performed most of the work in this paper.

This conference paper is accepted for publication in the peer-reviewed Proceedings of the 28th International Conference on Offshore Mechanics and Arctic Engineering and will be orally presented by the author in Honolulu, USA, in June 2009.
8. The Station at Klammerskär

The work on the observation station at Klammerskär (see the sea chart on page 2.3) was started in 2006. Since the installation of the tower, the system has gradually been expanded and improved. This chapter gives a more detailed description of the station, as compared to the one found in the papers.

8.1 Tower setup

The tower is 12 meters high, and is placed on a concrete foundation of about one meters height. The height of Klammerskär above the ocean surface is an additional meter, meaning that the total height of the tower is around 14 meters. Figure 8.1 shows a sketch and a picture of the tower, with descriptions of what equipment is installed at what height.

At an early stage, it was planned for the batteries and electrical control system to be placed at the foot of the tower. However, the winter storms of 2007–2008 destroyed some of the first installed equipment, as well as the lower part of the ladder. It became clear that the forces from the waves were too great for any equipment to survive at that height. The conclusion was drawn that although the base of the tower itself was in good shape, all additional equipment needed to be placed at least four meters up in the tower to be able to survive.

8.2 Electrical system

The electrical system supplying the camera and communication equipment with energy runs at 12 V DC, and consists of two 110 Ah batteries and two 85 W solar cell panels, controlled by a charge regulator. A circuit diagram of the system can be seen in figure 8.2. The system is connected to ground through a copper wire drawn from the tower into the ocean.

8.3 Camera output

The height of the camera determines the angle at which the buoy is photographed. In figure 8.3, taken from paper V, the geometry of the imaging system vs. the geometry of the physical setup is shown. The camera is at point
A, at the height \( h \), and the equilibrium point for the buoy is at point B, at a distance \( d \) from the camera. The angle \( \alpha \) describes the difference between the two coordinate systems \( xyz \) and \( x'y'z' \). In the \( xyz \)-system the \( y \)-axis coincides with the direction for the force of gravity, and is perpendicular to the undisturbed ocean surface. This direction is shifted \( \alpha \) degrees from the \( y' \)-direction, which is the vertical axis in an acquired image, whose frame is represented by the dashed rectangle surrounding point B. At Klammerskär the angle \( \alpha \) is found through \( \alpha = \arctan \frac{h}{d} = \arctan \frac{14}{300} \approx 2.7^\circ \).

The accuracy of the approximations made in paper V (e.g. that the motion of the buoy in the \( y \)-direction can be described by the motion in the \( y' \)-direction of the projected buoy in the image) depends on \( \alpha \) being small. For greater values of \( \alpha \), it would be easier to study buoy motions in the \( xz \)-plane, but more difficult to study motions in the \( y \)-direction.

8.4 Working with the images
After acquisition, the images from Klammerskär have been adjusted so that motion data could be extracted. In figure 8.4, an original buoy picture is dis-
played to the left, and the resulting image after thresholding to the right. In the middle there is a picture where the contrast has been enhanced using a combination of the information in the red and blue layer, see details in paper V. From the binary picture to the right, position data can be extracted for e.g. the center of the imaged buoy. The motion of such a point from one image to the next is then used to describe the real buoy motion.

8.5 Limits of the system
For high waves, the buoy may become partially or entirely hidden from the camera, in the wave through. Figure 8.5 shows two pictures taken in October
2008. In the left picture the buoy is visible, whereas in the right picture, taken two seconds later, a wave crest shields the buoy from the camera. The antenna on the buoy is visible, though not very clearly. The significant wave height for the period in question was 1.5 m. For sea states where it becomes likely that the buoy will be shielded by the waves, the system will not work well with the present setup. However, there is a possibility to install markers on the buoy to make it more visible, see more on this in chapter 10.
9. Discussion and Conclusions

This being a licentiate thesis, the work presented still displays a certain degree of disparateness. During future work the different themes will become more interlaced, and discussing the results as a whole will be more fruitful. There are however already quite a few connections between the different fields under study. For instance, if the optical system can be further developed, it will be possible to increase the quality of future verifications of water level impacts. This can be done by using one more step in the chain of analysis; i.e. not only studying the correlation between water levels and absorption, but also quantifying the buoy movements and in detail explaining the chain of events from waves to buoy to generator. Using a fixed measurement system (in comparison to e.g. accelerometers in the buoy) can also allow for comparisons of absolute buoy motions over longer periods of time, since the system will not have the drifting errors associated with systems that integrate a signal of acceleration. This means that it can become possible to study buoy motions at different times, not only in terms of the quantity of motion, but also around which equilibrium point the motion takes place (which depends e.g. on shifting water levels).

Regarding the results presented in the articles, they have been discussed in each publication, but a brief summary and some concluding comments are given here. Figure 9.1 is taken from paper IV and shows energy absorption values $\sigma$ for L1, for different water levels $w$, after exclusion of data points with very low wave height or small water level deviation (see details in paper IV). The energy absorption decreases as the water levels deviate from the mean level, as expected. Each value of $w$ displays a lot of values for $\sigma$. This is because energy absorption is also dependent on other factors, such as e.g. significant wave height and energy period. It can be seen that as $|w|$ grows, the lowest values for $\sigma$ tend to zero. The lowest values for $\sigma$ approximately reach zero somewhere between $w = -20 \text{ cm}$ and $w = -30 \text{ cm}$. For $w > 0$ there are fewer data points, but the trend is similar. Because of this, it was suggested in paper IV that $|w| = 25 \text{ cm}$ is a descriptive value for the sensitivity of the WEC system to water level changes. It can however be added that the value probably is more fitting for water levels below average than above average. 25 cm should be seen as a very approximate value, but illustrates the point that water level changes do not seem to constitute a big problem at the Lysekil research site, since $|w| < 25 \text{ cm}$ for 84.8% of the measurement period.
Choosing to use a standard (though sophisticated) network camera for buoy observation has meant balancing some pros and cons. The flexibility of the system has enabled the measurements of buoy motion, without hindering the general observations of the park. On the other hand, the accuracy of the measurements would have been improved if the system had incorporated a fixed camera (i.e. without zooming and panning capabilities) with higher resolution. It is however not yet possible to fully quantify the accuracy of the system, so it remains to be seen how large of a problem this is. Using the results presented in paper V, it is possible to say some things about the quality and quantity of buoy motion. Figures 9.2 and 9.3, taken from paper V, shows the motion of the buoy in the vertical and horizontal direction (perpendicular to the wave crest), gathered from the acquired images. The significant wave height at the time was $H_{m0} = 0.82 \text{ m}$. The vertical and horizontal motions are of the same magnitude (approximately $\pm 0.5 \text{ m}$), but the vertical motion displays a somewhat more regular periodicity. The period for the vertical motion is approximately four seconds (15 peaks can be seen in the 60 seconds covered in figure 9.2). Looking at (the unsynchronized) voltage data for the time in question (not published), it can be seen that the average number of peaks during one minute corresponds fairly well to the results from the images. This means that although the temporal resolution is low, it is likely high enough to capture the dominating motion. Nonetheless, achieving a better temporal resolution is a priority, as well as synchronizing voltage measurements and image collection.
9.1 Conclusions

There is a correlation between water level and energy absorption values for L1, such that the absorption decreases when the water levels deviate from average. The effect is noticeable for the whole range of water level values, but is not very prominent for deviations smaller than 25 cm. The designed observation system can double as a motion tracking system, although some work re-
mains on quantifying the accuracy of the measurements. For the studied time period, the measured motions correspond fairly well to the significant wave height. There are several options for increasing the availability and accuracy of the system.
10. Future Work

The results in paper IV and V have indicated some important steps to be taken, and in the coming years, work will be done primarily in three areas:

- Improvements on the measurement systems, including synchronizing of different systems.
- Improvements on the conditions for the measuring station, with focus on higher availability.
- More detailed analysis of acquired data.

When it comes to improving the measurements, the two most important steps will be to increase the temporal resolution of the camera, and to synchronize the images with other systems. This will allow for the necessary verifications of system accuracy, and will also enable more detailed studies of buoy motion. Furthermore, installing markers on present and future wave buoys may become necessary. Such markers will significantly simplify the image analysis, and make it possible to extract more exact motion data.

As is described in paper V, due to the failure of the first installed wind turbine in the tower, there have been some problems of the energy system at Klammerskär. To increase the availability of the camera, a new wind turbine will be installed during 2009, along with a timer for the system, ensuring that the system is only turned on during the bright hours of the day. In this way, the available energy will come to better use.

In the early spring of 2009 L2, L3 and the substation were deployed. When they are fully operational, they will be interconnected, and the substation will be connected to Klammerskär, see figure 10.1. L1, L2 and L3 are placed about 20 meters apart in such a way that they can be individually monitored by the camera, at approximately equal distance. The connection between the substation and Klammerskär will enable faster communication with the camera than the present wireless system. There is also a possibility to connect the energy system on Klammerskär with the energy system in the substation, thereby allowing the wind turbine at Klammerskär to charge the batteries in the substation. This will mean increased redundancy of both systems.

As more and more data becomes available possibilities arise for more complex analysis. For instance, in the future it may become possible to link detailed data on buoy motion to detailed data on translator movements. That means it will be possible to quantify in detail “how much” of the buoy motion is transferred to the translator, for different sea states. Comparing such data
from different buoys will also answer questions on the impact of buoy shapes, and can contribute to validating hydrodynamical models. There is also a lot that can be done with the data already available. For longer time series of images, for example, it is possible to calculate wave spectras based on buoy motions, and compare these to the ones from the wave measuring buoy.

This information and further measurements can be used to solve both practical problems (e.g. *is it likely that the rotation of the buoy about the vertical axis will cause problems in the steel wire connecting the buoy to the generator?*), problems of optimization (e.g. *is the vertical motion of the buoy of the right magnitude as compared to the maximum stroke of the generator translator? Should the buoy be smaller/bigger?*) and problems of theoretical verification (e.g. *does the buoy absorb the predicted amount of energy?*).
11. Svensk sammanfattning


En mätstation har också installerats på närbelägna Härmanö, och en observationsstation på Klammerskäret söder om experimentplatsen.


De resultat som uppnåtts visar att det finns ett samband mellan vattenstånd och energiabsorption för L1 under den studerade perioden. När vattenståndet avviker från medelnivån sjunker också energiabsorptionen. Detta är inte oväntat, eftersom den linjära generatorn har en ändlig slaglängd. Effekten är tydligast för vattennivåavvikelser på mer än 25 cm, och är bara observerbar för de fall då antingen våghöjd eller vattennivåavvikelse är stor.

Observationssystemet har fungerat väl, och den data över bojrörelser (vertikal rörelse i spannet ±0.5 m) som extraherats stämmer tämligen väl överens med data över signifikant våghöjd ($H_{m0} = 0.82$ m) för mätperioden. En ännu opublicerad verifiering mot spänningsdata från generatorn antyder också att systemet lyckats fånga den dominerande bojrörelsen. Systemet lider dock av låg temporal upplösning (ca 1 bild/sekund), och är ännu inte synkroniserat med övriga mätsystem på experimentplatsen. Att åtgärda dessa två problem har hög prioritet i framtiden.


Till alla på avdelningen för elektricitetslära: tack för allt roligt samarbete, diskussioner, inspiration, allmän hjälp, fikaprat, musicerande, disputationsfester, fredagsöl, Basic Cooking, Orsaskidande och roliga konferenser. Jag trivs med att komma till jobbet varje dag och det är inte så lite er förtjänst.
Sist men inte minst: till min familj och Magdalena, tack för stöd, kärlek och glädje!
References


