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Automatic Adjustment of the Floatation Level for Tight-moored Buoy

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Abstract

Automatic Adjustment of the Floatation Level for a Tight-moored Buoy

William Healy Strömgren

This thesis gives examples of different methods of automated adjustment of floatation level for a static moored buoy, an overview of the theories behind water level change and a statistical analysis of the water level changes for Stockholm, Kungsholmsfort and Kungsvik.

Depending on the range and frequency of the water level change different methods of adjustment are recommended. For areas with small changes in sea level the best choice would be no adjustment of the floatation level. Areas that are influenced by moderate tidal ranges should incorporate a system of regulation consisting of a winch, gearbox with a gear ratio of around 10,000:1, 12 V DC motor, 12 V maintenance free battery, air coiled linear generator and a strain gauge. For areas with large tidal ranges the previous system should be complimented with a horizontally mounted spring, inside the buoy, to lessen the loads on the motor.

The statistical analysis found the largest extremes in water level of the three sites to be at Kungsvik and Kungsholmsfort, both exhibiting a range of almost 1.6 m. Kungsvik was the station with the largest daily variations, this is because this is the only station influenced by tidal variations.

Keywords: Static mooring, tight mooring, buoy, linear generator, wave energy converter (WEC), point absorber, sea level change, tides, storm surges.

Referat

Automatisk justering av flytnivån för en statiskt förankrad boj

William Healy Strömgren

Denna rapport ger förslag på olika metoder att automatiskt justera flytläget på en statiskt förankrad boj, en överblick över de processer som styr ändringen av vattennivån och en statisktisk analys på vattennivåförändringarna vid Stockholm, Kungsholmsfort och Kungsvik.

Beroende på vattenivåns variation finns olika metoder för justering. Områden med små variationer av vattennivå lämpar det sig bäst utan någon som helst justering av flytläget. Områden med inte för stora tidvattensförändringar bör justeras med ett system bestående av vinsch, växellåda med en utväxling på 10 000:1, en 12 V DC motor, ett skötselfritt 12 V batteri, en luftlindad linjärgenerator och en trådtöjningsgivare. Områden med stora variationer i tidvatten behöver en avlastning för motorn i form av en fjäder och dämpare. De monteras horizontellt inuti bojen för att skyddas från den yttre miljön.

Den statistiska analysen påvisade de största vattennivåändringarna vid både Kungsviks och Kungsholmsfotrs mätstationer, båda uppvisade ett intervall på 1,6 m mellan minimum och maximum. Kungsvik var den station med de största dagliga variationerna, detta på grund av tidvattnets påverkan i området.

Nyckelord: Statisk förankring, boj, linjär generator, punkt absorbator, vattennivåförändring, tidvatten.

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Preface

A team of scientists, at the Division of Electricity at Uppsala University, are presently investigating the potential in converting the oscillating motion of the sea surface to electricity with the use of linear generators. I was brought into this project through a course on wave power held in the spring of 2004. The possibility of using the ocean as a power source is to me pretty obvious as I have spent quite a bit of time both in and on the sea as a surfer and windsurfer. I jumped at the chance to get involved and was glad to have the possibility to make my mark on the evolution of the wave power systems of tomorrow, but none of this would have been possible without the help of my supervisors.

A big thank you to Hans Bernhoff who has helped me evolve new ideas and found time to help me regardless of his busy schedule. Another big thank you is directed to Mikael Eriksson who has been a great help especially when it comes to the structure of the report, the dynamic properties of the buoy and to help me understand that illustrations are a good thing!

I am very grateful of all the people who have helped me at the Division of Electricity over these past months. I would like to thank Oscar who helped me with the basics of CorelDraw, Thomas who fixed all computer related troubles, Hanna who made my writing process feel like less work and more fun and last but by no means least Olle who helped my understanding of most of the mechanical solutions used in this thesis.

Thank you all!

William Healy Strömgren

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1 INTRODUCTION

Harnessing energy from the sea is not a new idea; in fact Girard & Son submitted the first patent as early as 1799 [1]. Since then a multitude of wave energy converters have been invented but only a few have reached beyond the design stage. At the moment research is being conducted at the Division for Electricity and Lightning Research at Ångström laboratory, Uppsala University, for a wave energy point absorber that is adapted to the vertical movements of the sea surface. By using a linear generator it is possible to directly connect the movement of the buoy to the generator without the need for conversion from linear motion to rotational. Many designs use rotating generators such as in the Pelamis [2] or Sloped IPS wave energy converter [3]. Resources are then spent finding or creating technologies to convert the linear motion, by pumping gas or liquid, to the rotational motion of the generator.

The current setup consists of a surface following buoy that is connected via a static line to the linear generator placed on the seabed. The buoy follows the motion of the waves while the generator is steady on the seafloor [4], see figure 1.1. The system is dependent on a static line of a length equivalent to the buoy lying semi submerged at the long term mean sea level or actual sea level. The vertical movement of the buoy moves the magnetic fields of the alternator through the stator which induces a voltage.

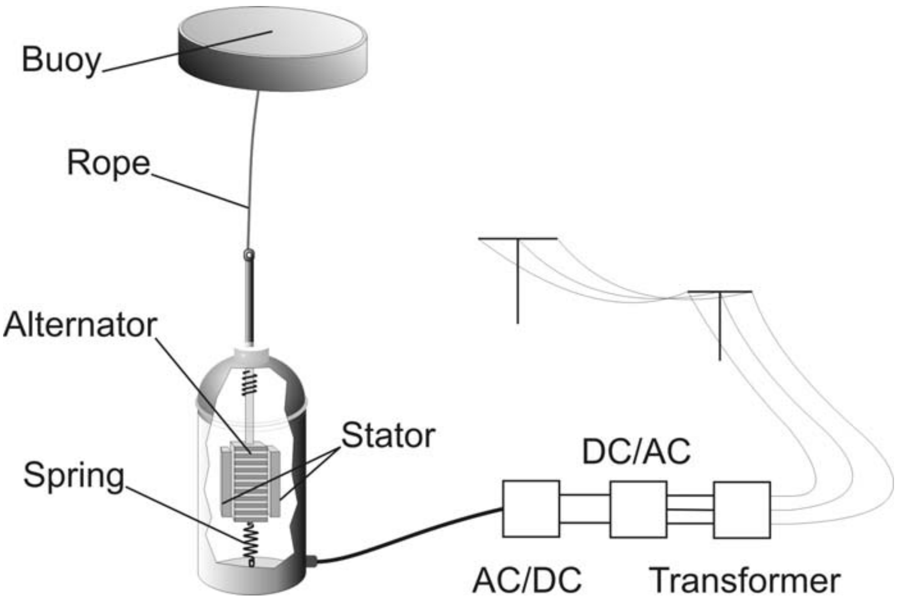

Figure 1.1 *A schematic illustration of the linear generator and its connection to the grid, from ref. [5].*

The idea is that several buoys are placed in a buoy park. They then oscillate individually creating a more stable power level to the grid [6]. All the generators are connected to a central under water hub, before connection the voltage from each generator is rectified to a DC voltage. The DC voltage is then converted to a harmonic AC voltage with an amplitude and frequency similar to the AC-grid used in the country to which the wave energy converter is constructed.

Areas with high energy wave density, such as the Atlantic or Pacific coasts, are suitable for this type of wave energy converter. Significant amounts of energy can also be found in sheltered areas with calmer seas and a steadier wave climate such as the Baltic Sea [6] and the west coast of Sweden. The first prototype is planned to be deployed outside Skaftölandet on the Swedish west coast.

The purpose of this work is to investigate technologies to adjust the floatation of the buoy so that it always floats at a specific level relative the sea surface. Since the line must be kept taut at all times changes in water level will negatively affect the energy absorption. The thesis looks at present technologies and discusses and evaluates possibilities of new ones.

Figure 1.2 gives a brief overview of the problems associated with water level change for the wave energy converter. At actual levels the power plant works fine but when water levels fall too low or rise too high the ability to generate electricity is reduced.

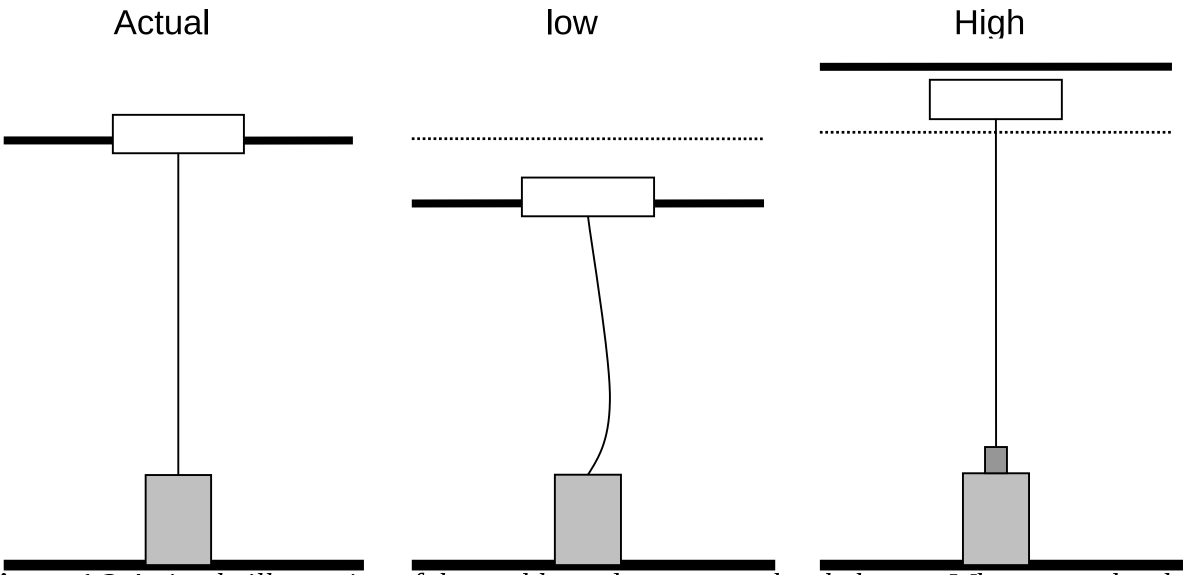

Figure 1.2 *A simple illustration of the problems due to water level change. When water levels fall below normal levels the line goes slack and there occurs a poorer energy conversion. Energy conversion is also lessened when water levels rise too high pulling the alternator to its maximum position and thereby inhibiting normal movement of the alternator.*

A theoretical part explores the reasons behind water level changes and data on the range and frequency of water level changes for the area around Skaftölandet are inspected. The report is concluded with a suggestion of the most suitable adjustment system for Stockholm, Kungsholmsfort and Kungsvik. Kungsvik is the observation site closest to Skaftölandet so most time will be spent on finding an adjustment system for that area.

Note: the encapsulated linear generator situated on the seabed will in this report be referred to as the main generator.

1.1 DESIGN GOALS

The current buoy prototype is a steel construction and is cylindrical in shape with a diameter of 3 meters and a height of 0.8 meters. The buoy would need an internal framework to spread the load and support the different components of the adjustment system, but the current buoy prototype does not contain this.

The main requirements for the device body are that it behaves as an efficient primary energy absorber and exhibits seaworthy characteristics even in storm conditions while still keeping the costs low. Below follows a list of requirements for the floatation adjustment system.

- The buoy has to be able to adjust itself to changing water levels automatically.

- It has to be sturdy enough to cope with the potentially large movements of the buoy.

- The system has to be economically viable.

- The system should be, as much as possible, contained in a water free environment to minimize the effects of corrosion and short-circuiting.

- It should also be light enough to not sink or interfere with the hydrodynamic properties of the buoy[1].

A literature survey has been conducted to find similar working solutions used in practice, however no tight moored systems have been discovered. There are several solutions available for slack line mooring that are used for buoys of the scale being constructed in this project, such as weather buoys, but those methods are not applicable for tight-moored systems, [7], [8].

The linear wave energy converter can be used along many of the coasts around the world, therefore the adjustment system must be able to cope through a wide variety of water level fluctuations. Therefore the design part of the thesis contains systems that can adapt to large variations in sea level even if the adjustment systems for the Swedish coast only need to be designed for relatively small changes in sea level.

Self-reliance is possibly the hardest goal to achieve. If the system is in need of a power source this must be charged in some way. In other words the system must be able to charge a battery from an alternative source that gives a, more or less, continual trickle of current.

Other obvious goals of great importance are creating a simple construction containing few parts and low maintenance. Both these aspects go hand in hand with reducing the long-term operational costs of the wave energy converter.

There are several environmental properties that are desired. The system should as much as possible comply with Swedish environmental law by using the best possible technical solution in regard to safety of people, surroundings and environment[2], MB kap 2 §3 [9]. Especially in constructing a buoy park a MKB (assessment of the environmental consequences) will most likely be needed to receive planning permission. By keeping the individual buoys quiet and environmentally sound it will alleviate the total load of the buoy park.

[1] This was an early criterion but, as will be seen in section 5.2 on hydrodynamics, has no real relevance except for keeping the buoy afloat.
[2] Author’s translation from Swedish

2 CHANGES IN SEA LEVEL

The wave power plant adapted for a linear generator is dependent on a static line running from the main generator to the buoy for optimal energy transformation. Keeping the buoy in a certain vertical floating position is easy to achieve as long as the mean sea surface remains at the same level, but this is often not the case. The oceans of the Earth are constantly changing in size and depth due to variations of short and long term external and internal forces. These changes are made evident by the rise and fall of the sea level, currents and tides. Not all changes are of concern, only the changes of sea level that occur within one year and of a magnitude of more than a few centimetres are of importance to this wave power plant[3].

2.1 LONG TERM CHANGES IN SEA LEVEL

The time span for sea level changes varies from seconds, for waves, to tens of thousands of years, for the movement of tectonic plates. For example movements of tectonic plates create a change in sea level, as does sedimentation and melting of glaciers. These alterations and other long-term causes are divided into separate categories.

Secular change: A non-periodic change of sea level for a specific site over a span of decades. This is often the result of sedimentation, erosion, glacial formation or melting.

Eustatic change: Global volumetric changes caused by thermal expansion or extraction and glacial formation or melting, etc. Similar to secular change but now the sea level change is global instead of site specific.

Isostatic adjustment: An added or removed load over a certain area due to an increase of mass causes an adjustment of the seabed. Load differences usually are a result of eustatic changes. For example the seabed of the Baltic Sea is constantly rising by a few millimetres per year. This is because the landmass used to be covered by a glacier. The bedrock is still adjusting itself to the change in load by slowly rising.

Epeirogenic movement: The uplift or subsidence of large area of continents, usually due to the movement of the seabed [10].

The above listed long term changes in water depth have no influence on the efficiency of the buoy as the time-span vastly exceeds the life span of the structure. Therefore only short-term changes in sea level are of interest, which will be discussed in the following chapters.

2.2 SHORT-TERM CHANGES IN SEA LEVEL

There are several reasons behind short-term changes. In the following sections a brief explanation of the water level changes that have most relevance to this project is given.

[3] It is not yet known how the buoy will be affected by changes in sea level. It could be negatively affected by a 2 cm or by 20 cm, but tests have not yet been carried out on this.

2.2.1 Background

The short-term changes in sea level can be described mathematically. A general representation of the sea level in any part of the world follows:

$$X(t) = Z_0(t) + T(t) + S(t) \qquad (2.2.1\text{-}1)$$

where $Z_0(t)$ is the mean sea level which changes over very long time spans (see sec 2.1 and 2.2.2). T(t) is changes due to tidal fluctuations and S(t) describes the outcome of meteorological effects as well as other factors such as seiches and density changes [11].

S(t) can be broken up further into four specific groups. They are listed below and are described in greater detail later in this report.

- Atmospheric pressure.
- Surface wind stress (storm surges).
- Thermal expansion or extraction.
- Saline concentration changes.

These short-term changes of sea level have a considerable effect on vertical distance between the wave power plants generator and buoy. Therefore a system for adjusting the length of the line must be incorporated to achieve an optimal energy transformation regardless of sea level.

2.2.2 The geiod

The geiod corresponds to the site specific mean water level on any point on Earth. An important factor regarding sea level measurements is to find the actual sea level. This level corresponds to the undisturbed surface of the ocean of which the tides oscillate and is the reference level to which all changes in sea level relate.

The geiod varies around the world depending mainly two factors. First, the local gravitational pull from the Earth due to differences in density deep in the Earth and secondly, the rate of rotation of the Earth round its own axis. An area just south of India in the Indian Ocean contains an area of mass deficiency, which results in regional relatively low-density area. This area has therefore a lower gravitational pull and cannot attract the water with a force equivalent to other areas whereby lowering the sea level by 106 m. An area of high geiod sea levels is found north of Australia resulting in 73 m above global mean level. This is most probably due to density differences in the Earth’s core, but these relationships are not yet fully understood [11].

2.2.3 Astronomical tides

As early as the seventeenth century scientific studies on astronomical tides were conducted. Sir Isaac Newton made it possible to understand tides mathematically with the publication of his *Philosophiae Naturalis Principia Mathematica* in the form of his law of gravitation [12]. Since then tidal predictions have become more and more complex but also much improved. Examples of thorough tidal predictions can be found in [11] and [13] and a short description of harmonic tidal predictions can be found in section 2.2.7.

Several different astronomical factors contribute to the changing sea levels of the Earth. They all increase or decrease the gravitational pull exerted on the oceans of the Earth and cause different tidal patterns according to how they help or counteract each other [11]. The two main categories are diurnal and semi-diurnal tides.

2.2.4 Semi-diurnal

Semidiurnal tides peak twice for every rotation of the Earth, which takes 24 hours and 42 minutes [11]. The peaks are due to the gravitational pull of the Moon on the Earth and the inertia due to the rotation of the Earth-Moon system. The two celestial bodies rotate around a point that is inside the Earth. This point is called the barycentre and refers to the common centre of mass between the two bodies [14].

The force exerted on the Earth by inertia is equal in size and direction on all points of the Earth and is directed away from the Moon [14].

The force due to the gravitational pull from the Moon is dependent on the distance between the Earth and Moon and is directed towards the Moon (see equation 2.2.4-1). Therefore the side of the Earth facing the Moon experiences a stronger gravitational pull than the opposite side [14].

$$F = G\left(\frac{m_1 m_2}{r^2}\right) \tag{2.2.4-1}$$

where

F	is the gravitational force	[N]
G	is the universal gravitational constant (G = 6.673 × 10^{-11})	[N m^2 kg^{-2}]
m_1, m_2	are the masses of the two bodies	[kg]
r	is the distance between the centre of the two bodies	[m]

The gravitational pull and the forces due to inertia are balanced at the centre of the Earth. On the side closest the Moon the gravitational pull is greater than the forces due to inertia. This imbalance produces a tidal bulge on the side closest the Moon. On the opposite side of the Earth the forces due to inertia are greater than the gravitational attraction and therefore cause an imbalance in the other direction. The end result of the two counteracting forces are the two tidal bulges that are represented in figure 2.1.

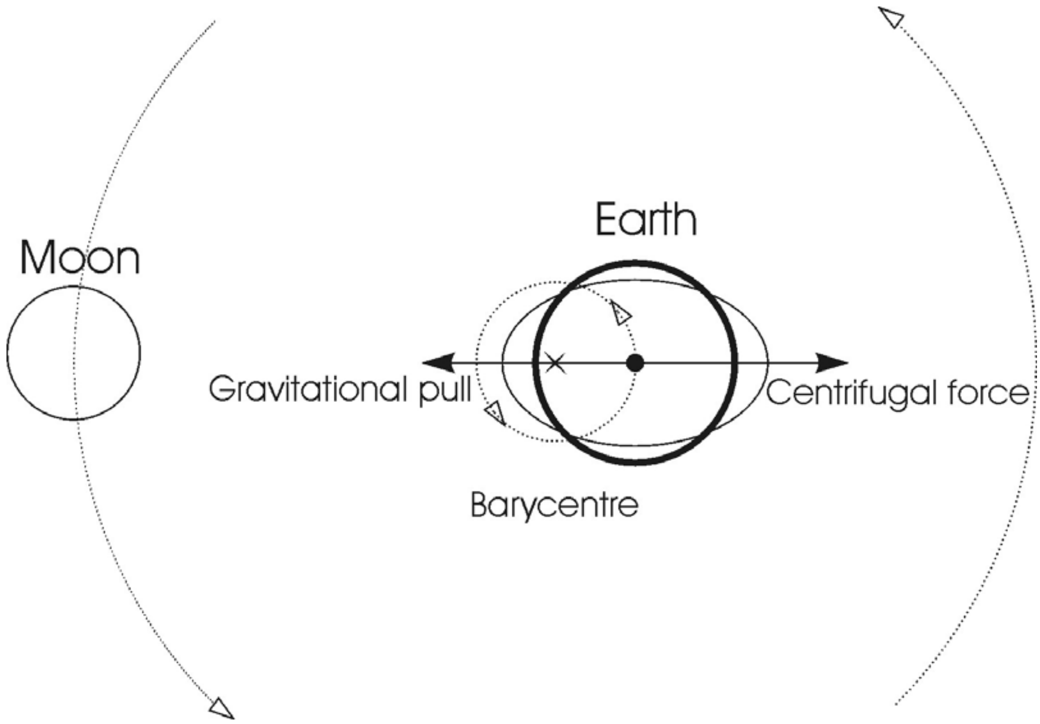

Figure 2.1 *Illustration of the tidal generating forces on Earth. The gravitational pull of the two celestial bodies is balanced by the inertia or centrifugal force. The 'x' marks the location of the barycentre. Both the Earth and Moon rotate around this point. (Figure is not at scale).*

The orbit of the Moon around the Earth is not circular but oval; therefore the distance between them varies regularly over time. The largest distance from the Earth is called apogee and the closest is perigee. The time cycle of this event is 27.55 days [11]. The gravitational pull and the centrifugal force are greatest when the Moon and Earth are close to each other and therefore local maximum tidal levels occur at the event of perigee.

Another astronomical factor contributing to the variations in tide is the declination of the Moon north or south of the Earth's equator. The period for this occurrence is called nodical month and takes 27.12 days [11].This irregularity is the reason behind diurnal tides. Diurnal tides will be explained later in this chapter.

Theoretical gravitational forces would suggest a normal tidal range of less than 2m. Why tidal ranges can reach in excess of 10 m depend on other factors, which will be discussed further in section 2.3.

2.2.5 Diurnal and mixed tides

Most coastal regions experience two high and low tides per lunar day, but there are areas on Earth that experience high and low tides only once per lunar day, these tides are known as diurnal tides. Diurnal tides only occur at certain coastal zones. They arise due to the Moon's declination towards the Earth. Areas such as the northern Gulf of Mexico and the Pacific near east Asia can experience diurnal tides [21].

The maximum declination of the Moon is 23.5°N degrees and 23.5°S of the equator. When the declination of the Moon is greatest, during summer and winter months, the diurnal tides have their largest amplitudes in areas positioned at the same angle from the equator as the Moon. This can be clearly seen if you visualize the Moon rotating around the vertical axis of the Earth in fig. 2.2. The opposite sides of the Earth, point one (1) and point two (2) experience different tidal levels. Point one (1) is at the large daily maximum level while point two (2) is at a much lower tidal level.

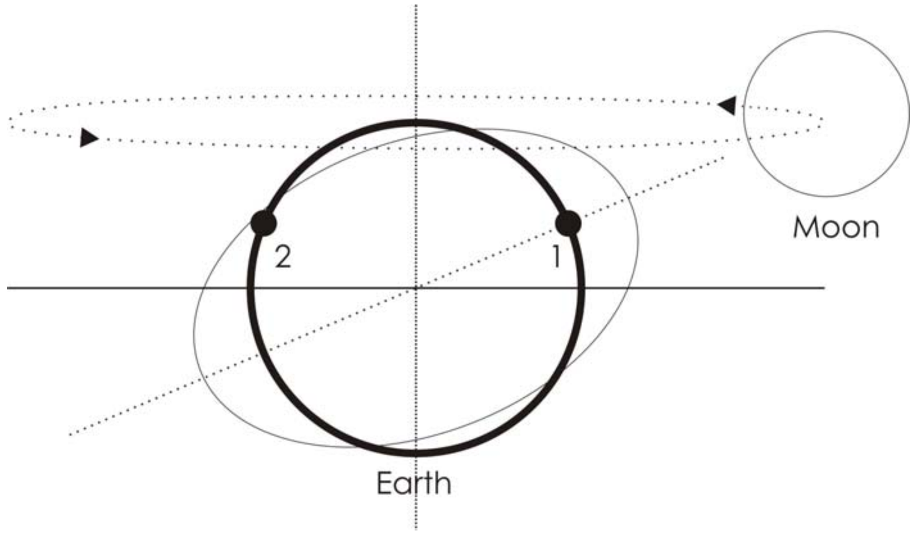

Figure 2.2 *Example of the basis of diurnal tides. Areas that are close to the points are subjected to one accentuated tidal maximum and minimum per day. (Figure is not at scale).*

This is an extreme case were there exists only one maximum for each cycle. There also occur tides in between the two extremes of diurnal and semi-diurnal tides, they are commonly known mixed tides. Mixed tides are the most frequently occurring of the three types of tides. They are characterised by two maxima and minima every 24 h and 42 min. One maximum is greater than the other and one of the minima is lesser then the other. The figure below shows the three different types of tides (figure 2.3).

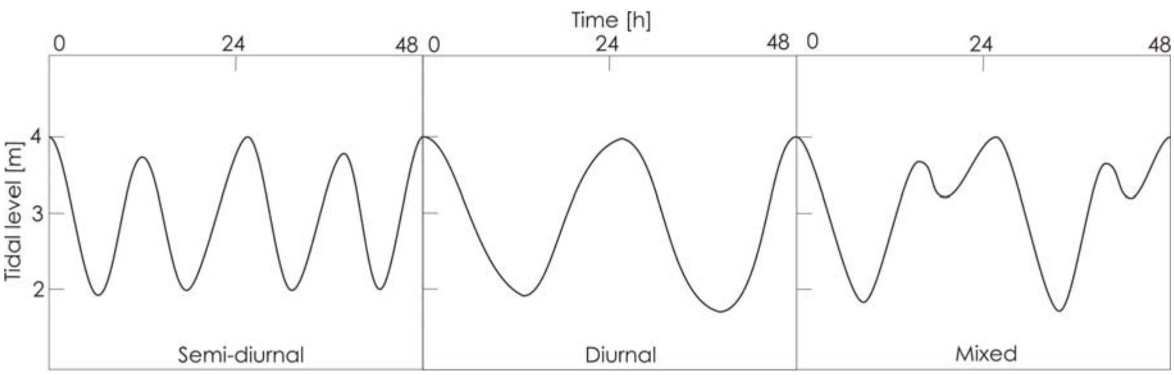

Figure 2.3 *A sketch of the main three types of tide, semi-diurnal, diurnal and mixed tides*

2.2.6 Spring and neap tides

A monthly variation in maximum and minimum tidal ranges can bee seen on most places on the planet. The maximum ranges are called spring tides and are the result of the Moon, sun and Earth being in line, which is known as syzygy, see figure 2.4a. Minimum tidal ranges appear at the half states of the Moon and are called neap tides, see figure 2.4b. [11]

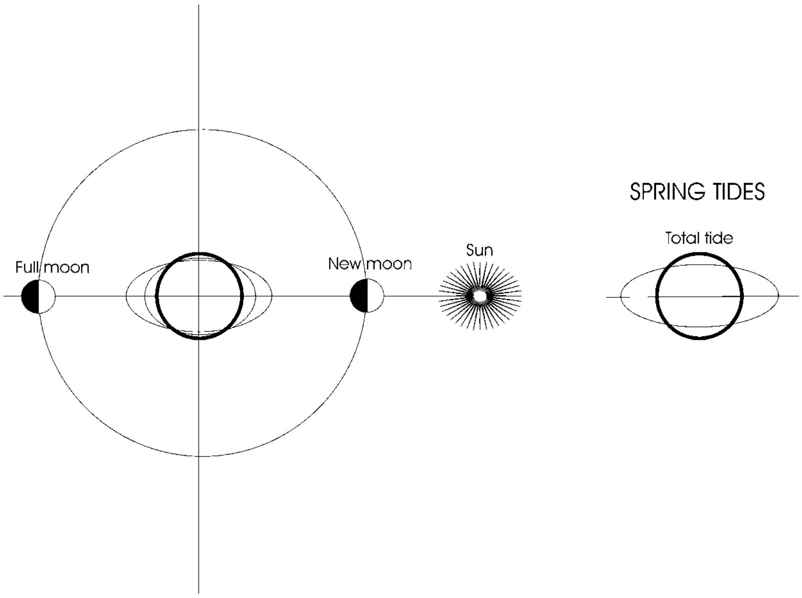

Figure 2.4a *Example of the occurrence of spring tides (figure is not at scale).*

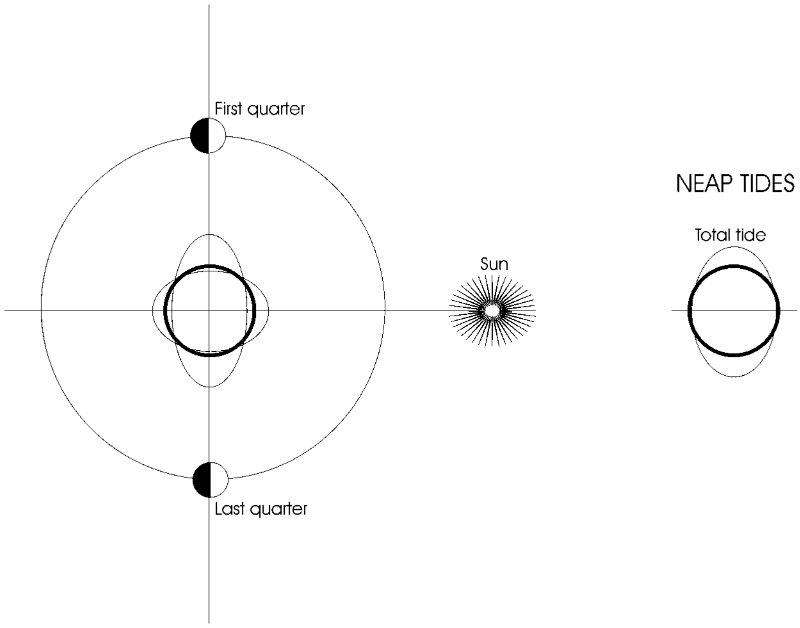

Figure 2.4b *Example of the occurrence of neap tides (figure is not at scale).*

2.2.7 Harmonic Tidal Predictions

The harmonic method is the most usual and satisfactory method for predicting tidal heights. Tides are divided up into different constituents depending on their origin, as described earlier. The different constituents have differing cycle times and effects on the tide depending on the interactions between the relative astronomical motions of the Earth, sun and Moon. As many as 390 components have been identified. Table 2.1 gives an example of different constituents, their symbol, their period and coefficient ratio (tidal power in relation to the constituent of the Moon, $M_2 = 100$) compared to the principal lunar constituent [15].

Table 2.1 *Example of a few tidal components.*

Name of tidal component	Symbol	Period in solar hours	Coefficient ratio (M_2 = 100)
Principal lunar	M_2	12.42	100
Principal solar	S_2	12.00	46.6
Larger lunar elliptic	N_2	12.66	19.2
Luni-solar semi-diurnal	K_2	11.97	12.7
Luni-solar diurnal	K_1	23.93	58.4
Principal lunar diurnal	O_1	25.82	41.5
Principal solar diurnal	P_1	24.07	19.4
Lunar fortnightly	M_f	327.86	17.2
Lunar monthly	M_m	661.30	9.1

The calculated predictions can not by themselves function as an exact tidal gauge. They have to be adapted to the specific location by thorough analysis and data collection of the existing tidal variations. Only then can accurate predictions be made for that specific site. This has to do with the bathymetry of the area, morphology and several other factors that will be discussed in greater detail in the upcoming section. Tables of precise tidal predictions are widely available from many different sources. One of the most popular is published by The United Kingdom Hydrographic Office (UKHO). It is updated every year and is available at their website [16].

2.3 TERRESTRIAL EFFECTS ON TIDES

Tides that are theoretically described by purely astronomical phenomena seldom reach amplitudes of more than 1.5 m, but there are areas were the tidal ranges surpass 10 m [11]. This part of the report discusses different elements that magnify the tidal waves amplitude.

2.3.1 Actual Tides

Theoretical tides and the tides that are measured at a daily basis are seen to differ greatly in size. There are several reasons to why the pure theoretical description of tides cannot predict the actual tidal range of most coastal regions. A list of the major factors contributing to the change in tidal ranges is explained in brief as follows.

- Tides can be described as waves with very long wavelengths propagating around the Earth. They travel from east to west but are hindered by the north-south continental boundaries and therefore rotate around nodical points.

- Tidal waves travel at a speed related to the position of the Moon and the depth of the water (see eq. 2.3.2-1). Because of the huge length of the wave the water depth of the oceans is insufficient for this speed to be sustained and the tidal wave lags behind the Moons position.

- The bathymetry of the oceans, bays and continental shelves can create resonance through natural oscillations causing regional magnification and reduction of the tides.

- The rotation of the Earth affects the tide in the same way as the Coriolis effect forces weather systems to rotate causing the tidal flows to rotate anti-clockwise in the northern hemisphere and clockwise south of the equator.

- The gravitational field of the Earth is, among other factors, dependent on the distribution of mass around the Earth. When the tidal wave travels the Earth it changes this mass distribution and thereby also the gravitational field of the Earth, which in turn changes the size of the tidal wave.

2.3.2 Sea depth changes

Tidal waves and waves in general are affected by changes in water depth. The speed of a long wave is proportionate to the square root of the depth of water beneath it [17].

$$c = \sqrt{gD} \qquad \text{Shallow-water phase velocity} \qquad (2.3.2\text{-}1)$$

where

c	is the speed of the wave	[m s^{-1}]
g	is the acceleration of gravity	[m s^{-2}]
D	is depth of the water	[m]

For example; if the wave is travelling in water with a depth of 1000 m and then reaches a continental shelf with a depth of 100 m, the speed of the wave will decelerate from 99 m/s to 31 m/s. To compensate for the change in speed the wavelength shortens and the amplitude rises. In reality a part of the energy of the wave disappears through friction, reflection and turbulence due to the sudden change in depth.

2.3.3 Resonance

When a tidal wave hits a shore it rebounds back out to sea. Some energy is lost in the reflection, which can be seen as the amplitude of the rebounding wave diminish, but the wavelength of the wave is conserved. This motion can be described with two almost identical tidal waves travelling in opposite directions. By superpositioning these two waves a resulting wave is found with a larger maximum amplitude than the two parts. In fact the amplitude is the sum of both the single waves. This can be shown mathematically with the linear theory of ocean surface waves for two dimensions with the waves travelling in the *x*-direction [18].

$$\zeta = a\sin(kx - \omega t) \qquad (2.3.3\text{-}1)$$

with

$$\omega = 2\pi f = \frac{2\pi}{T} \qquad (2.3.3\text{-}2)$$

and

$$k = \frac{2\pi}{L} \qquad (2.3.3\text{-}3)$$

where

ζ	is the sea-surface elevation	[m]
ω	is the wave frequency	[rad s^{-1}]
f	is the frequency	[Hz]
k	is wave number	[m^{-1}]
L	is the wavelength	[m]

Linear equations can be superpositioned as follows:

$$f(a+b) = f(a) + f(b) \tag{2.3.3-4}$$

The equations for an incoming wave and outgoing wave can be written as:

$$\zeta_i = a_1 \sin(kx - \omega t) \tag{2.3.3-5}$$

$$\zeta_o = a_2 \sin(kx + \omega t) \tag{2.3.3-6}$$

The result of this simple example is a standing wave with maximum amplitude which is the sum of the two separate amplitudes.

$$\zeta_{res} = (a_1 + a_2)\sin(kx) \tag{2.3.3-7}$$

The result is the total tidal range from a tidal wave rebounding on the continent. Figure 2.4 shows how this would look in theory with a wave rebounding with half the amplitude of the incoming wave.

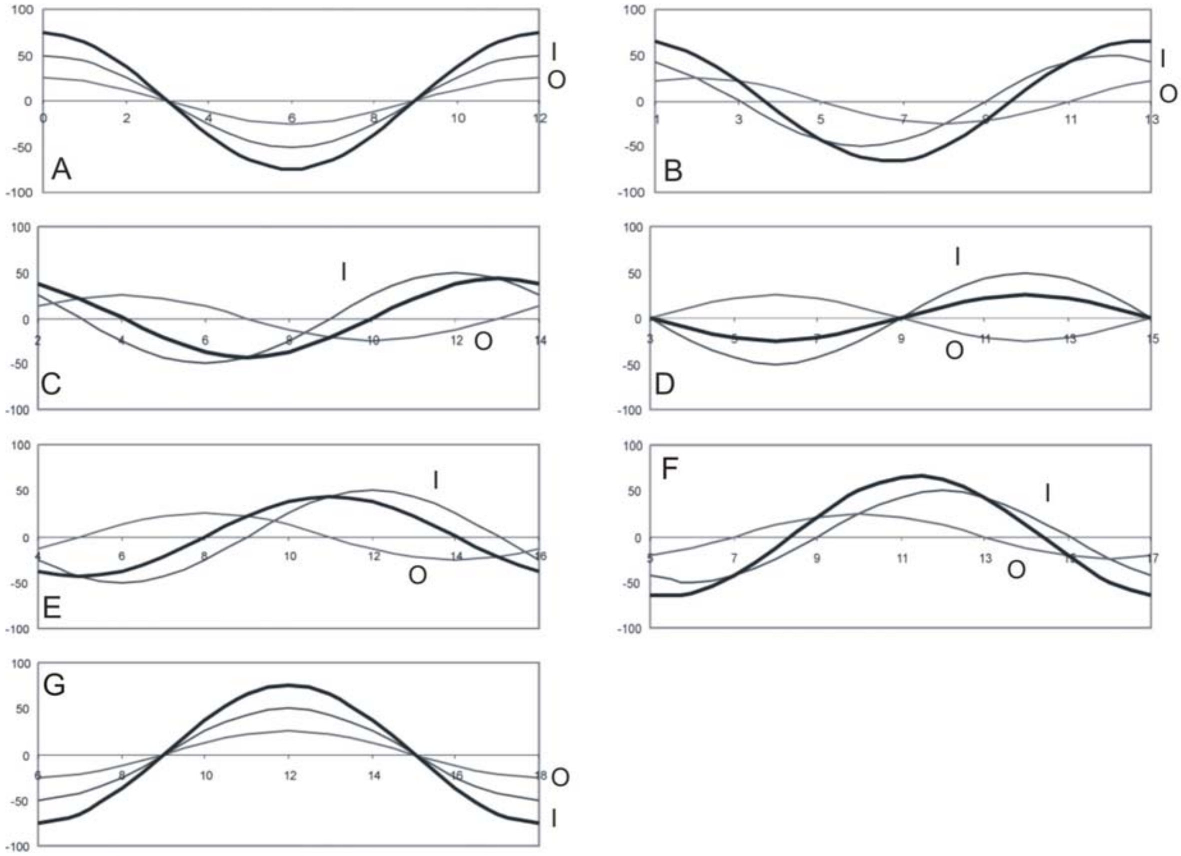

Figure 2.4 *A graphical representation of a rebounding wave over time. The figure should be read from A to G. The left side of each frame represents the shore. The incoming (I) wave is moving to the left and has an amplitude of 50 cm. It hits the shore which is represented by the left side of each frame and rebounds. The rebounding or outgoing wave (O) is travelling to the right with half the amplitude of the incoming wave, 25 cm. The bold line represents the resulting wave. The x-axis depicts the arrival time of the different parts of the incoming wave in relation to frame 1.*

2.3.4 Effects from a rotating Earth

A tidal wave moving across the Earth's surface is subjected to forces accredited from the Earth's movement. These geostrophic forces cause a deflection of the tidal currents towards the right of the direction of motion in the northern hemisphere. On an open ocean this would result in rotating tidal patterns, yet because of the continents this motion is hindered and there develops a build-up of water on the coasts. This build-up of water can be seen as a wave and is known as the Kelvin wave.

These Kelvin waves rotate around certain points called amphidromes. Amphidromes have no tidal range contribution from the Kelvin wave part of the tidal whole. The location of such nodes depends mainly on tidal wavelengths, bathymetry and coast morphology [11].

2.3.5 The influence of continental shelves on tides

Tides near the coasts often have much larger amplitudes than the tides out in the oceans. This has much to do with the change in depth when the tidal wave travels onto the continental shelves. The more shallow areas cause the tidal wavelength to shorten and at the same time the amplitude to increase. The friction from the seabed increases which is the main contributor to energy losses.

Continental shelves have the same influence on the Kelvin waves size and the resonance from basins resulting in a marked change in tidal ranges.

2.3.6 Bay of Fundy

Tidal ranges differ immensely depending on morphology of the coast and seabed. An extreme example of this can be found at the Bay of Fundy in Nova Scotia. At the mouth of the bay the tidal range is 3.5 meters but at the head the tide reaches a maximum of 15.4 meters. The large tidal ranges are considered to be caused mainly by the resonance of the semi-diurnal component with the oscillation of the basin. In addition, as the bay is cone shaped, the water moving into it is forced upwards as the bay continually narrows. It can be added that the diurnal astronomical constituent in this area is not much more pronounced than the tidal variations of 50-60 cm that occur in the oceans [19].

2.4 METEOROLOGICAL EFFECTS

All changes to the sea level that cannot be attributed to tidal variations are said to be surge effects. These are also known as non-tidal components or meteorological residuals. There are two different factors that contribute to surge effects, atmospheric pressure and wind related effects.

2.4.1 Atmospheric pressure

The differences in atmospheric pressure have a major effect on the sea level. An area of high pressure will act as a weight on the ocean surface depressing it and therefore lowering the sea level beneath it. A low-pressure system will act in the opposite manor and cause a rise in sea level. This is known as the inverted barometer effect and can be mathematically described as follows [11].

$$\Delta\zeta = -\frac{\Delta P_A}{\rho g} \qquad (2.4.1\text{-}1)$$

where

$\Delta\zeta$	is sea level change relative to the mean sea level	[cm]
ΔP_A	is change in atmospheric pressure relative to mean	[mbar]
ρ	is density of sea water[4]	[kg m^{-3}]
g	is the acceleration of gravity [5]	[m s^{-2}]

Example:
Seawater density (ρ): = 1026 kg m^{-3}
Acceleration of gravity (g): = 9.82 m s^{-2}

$$\Rightarrow \Delta\zeta = -0.993\Delta P_A$$

[4] Depends on the temperature and salinity of the water
[5] Varies depending on location

The sea level sinks by about 1 cm for every increase of 1 mbar of atmospheric pressure as theoretically presented above. Because the oceans are slow to adjust to this change the pressure system has time to move before the effect has fully developed. More importantly this adaptation to the change in pressure becomes relatively small in the more influential effect of wind stress.

There are areas where the sea level varies by up to 20 cm over the span of a year. Certain weather types usually dominate these areas over a long time period. For example, low pressure systems dominate the area around Iceland during the winter months and therefore raise the sea level by an average of 12 cm. The Asian and North American coasts are subjected to annual sea-level variations of up to 16 cm [19].

2.4.2 Wind stress- surges

Winds are the result of differences in atmospheric pressure. They affect the sea through frictional forces that express themselves as waves, currents and changes in sea level. A widely used expression of extreme cases of the wind effect is storm surge.

Depending on the wind direction of the storm, relative the coast, the surge is called either positive or negative surge. A positive surge raises sea levels while negative surges lower [19].

When two layers of fluid are in contact the faster moving fluid transfers energy and momentum to the slower moving fluid. In this case the wind causes a drag along the sea surface and creates a movement of water that results in waves and eventually a change in sea level. With prevailing onshore winds the water is pushed towards the coast and a sloping water level is created. The highest levels are at the coast and the water level drops further from the coast. The largest changes in water level can be found when strong winds blow over shallow areas.

As a general rule, the drag of the wind on the sea surface is given by [11]:

$$\tau = C_D \rho_A U_{10}^2 \qquad (2.4.2\text{-}1)$$

where

τ	is wind stress	[kg m^{-1} s^{-2}]
C_D	is the drag coefficient[6]	[dimensionless]
ρ_A	is air density	[kg m^{-3}]
U_{10}	is wind speed[7]	[m s^{-1}]

A simplified version of reality can give an example of how this affects water levels. For wind blowing in a shallow and narrow channel steady-state conditions arise when the effect of wind stress is balanced by the inequality of the pressure gradient. This change in sea level can be described mathematically through the degree of slope of the sea surface [11].

[6] Varies depending on the roughness of the water i.e. wave height
[7] Measured 10 m above the surface

$$\alpha = \frac{C_D \rho_A U_{10}^2}{g\rho D} \qquad (2.4.2\text{-}2)$$

where

α	is the slope of the sea surface	
D	is depth of the water	[m]
ρ	is the density of sea water	[kg m^{-3}]

2.4.3 Ekman transport

There have been observations of sea level change close to shore when strong winds have been blowing parallel to the shoreline. One explanation of this occurrence has to do with the Coriolis effect. When water is dragged along with the wind it does not follow the direction of the wind but travels at a 45 degree angle to the wind at the surface. The angle relative the wind increases with increased depth. The result is a mean transport of water to the right for the northern hemisphere. This results in an increase of sea level when the coast is to the right of the wind direction and a decrease if the coast is to the left. The opposite is true when on the southern hemisphere. Illustrations of the movement of the water in an Ekman spiral and the resulting effects are presented in figures 2.5a & b [20].

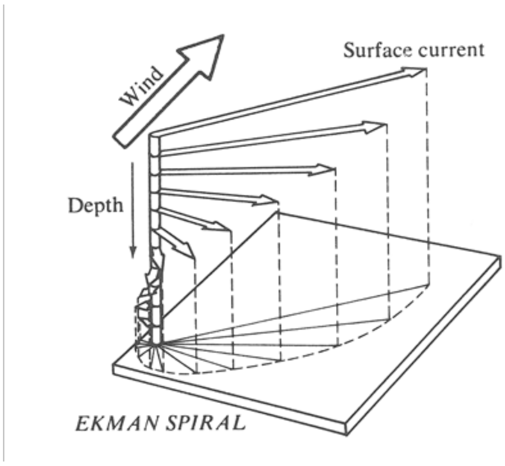

Figure 2.5a *Illustration of the motion of the water at different depths in the Ekman spiral for the northern hemisphere. τ_w is the direction of the wind. The result is a water transport to the right. [21].*

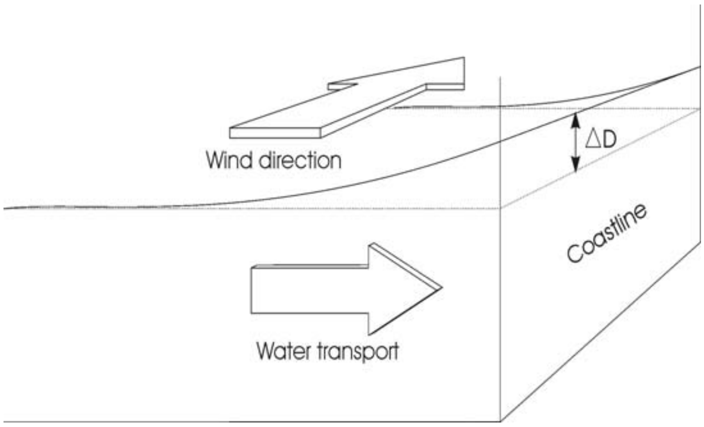

Figure 2.5b *Example of the resulting change in sea level close to shore due to the Ekman spiral. ΔD is the change of water level from windless conditions. The resulting mean movement of water transport is perpendicular to the wind direction.*

2.5 SEICHES

Certain areas with special characteristics can produce regular oscillations that are not directly due to tidal or meteorological effects. These fluctuations are usually rhythmical and can vary in time span from a few minutes to an hour or more. They are seldom more than a few centimetres unless triggered by an unusually large surge such as a tsunami. Seiches arise from the morphology of the local area. If the area is connected to the ocean by a narrow continental shelf an oscillation can occur in this area resulting in a fluctuation of sea level that is superimposed onto the normal variations, figure 2.6 gives an example of this.

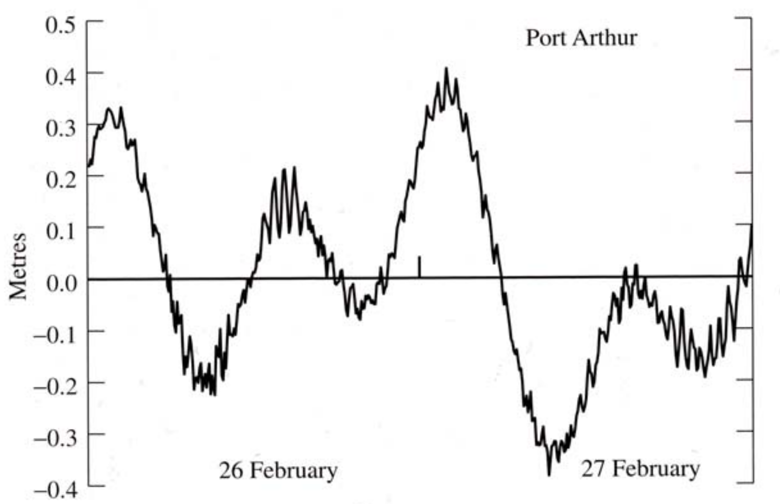

Figure 2.6 *Seiches with a time interval of twenty minutes are superpositioned on top of the mixed tide at Port Arthur, Tasmania, Australia [11].*

2.6 TSUNAMIS

Although well known, sea level changes due to tsunamis are rare. Tsunamis are generally triggered by seismic or other geological events and can give large sudden changes in sea level causing flooding and chaos. Because of their rareness and short time span tsunamis are not considered to be a sea level change that the buoy needs to be corrected for.

2.7 WATER DENSITY

The density of water in the oceans varies mainly with temperature and salinity. The changes in sea level due to variations in density are usually smaller than both the tidal and meteorological effects, but do carry importance in certain areas. There is also a small amount of variation due to compression, but this is so slight that it is hard to discern from other factors.

2.7.1 Temperature

Changes in temperature mostly occur at the surface, as this is where solar activity takes place. The product being heating, cooling and evaporation which all contribute in some way to density changes of the water. Precipitation can also have an effect on the temperature of the upper layer of the ocean. Water is most dense at 4 °C, above and below that temperature the density decreases until it reaches its respective boiling and freezing points. Figure 2.7 shows the variation of water density with temperature.

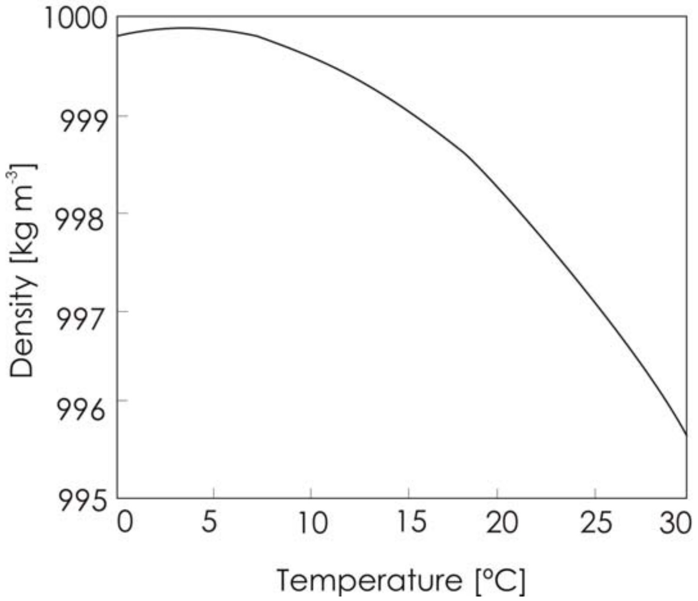

Figure 2.7 *Water densities at different temperatures. Maximum density is reached at 4 °C.*

The average range of sea level change due to temperature changes is 11 cm. This average is from data collected at stations all around the world and is therefore a global average. Although sea level changes seldom reach heights of more than 15 cm there have been accounts of ranges reaching 25 cm north of the Bermudas and in the Sea of Japan. Polar and equatorial regions show little variation in density due to thermal effects. [19]

2.7.2 Salinity

The amount of dissolved salt in the sea has a linear relation to the density of the water (see figure 2.8), the higher the salinity the higher the density [22]. Not much data is available on the affects of fluctuation in haline concentration on the sea water level. However it seems that sea levels rarely differ more than 5 cm due to this effect, but there are a few regions that show considerable fluctuations. The sea level in some areas of the Bay of Bengal have been measured to vary 41 cm due to changes in salinity alone [19].

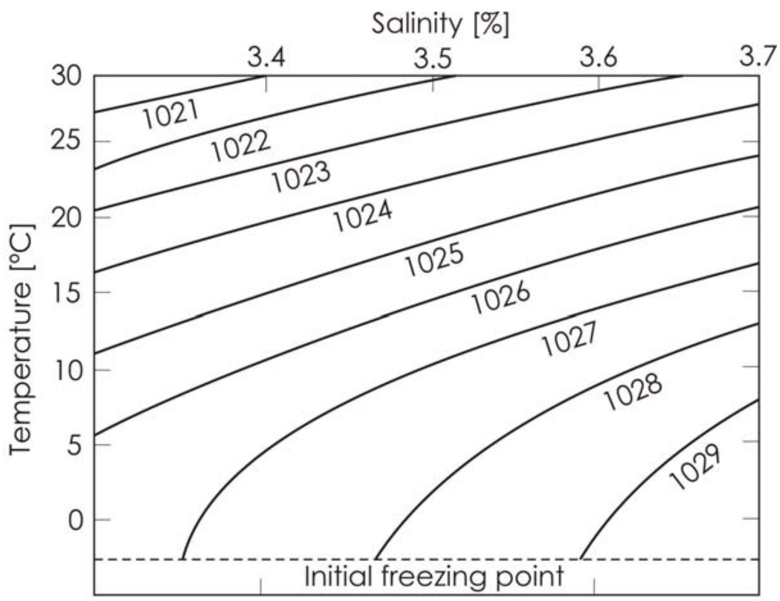

Figure 2.8 *Water density [kg m^{-3}] at different degrees of salinity and varying water temperature [21].*

3 OBSERVATION SITES

The buoy and the components thereof, all have an optimal size and energy output that has to be selected for the system to work properly. These properties are all directly dependent on the change in water level. If water levels were to change very often more power and sturdier components would be needed to cope with the more variable conditions. Therefore information on water level change for different areas is of importance for the design of the adjustment system.

Water level variations are site specific. To give an example of the differences that can be expected between sites three locations around the Swedish coast were selected, Kungsvik, Kungsholmsfort and Stockholm (figure 3.1).

The water level data was collected by SMHI, The Swedish Meteorological and Hydrological Institute, and was measured every hour for all three stations. No other sites have been analysed because at this stage of the project the focus is laid on the deployment site of prototype, Skaftölandet, which is close to the observation site of Kungsvik.

Figure 3.1 *Location of the three Swedish water level observation sites.*

3.1 STOCKHOLM

Stockholm is situated almost in the middle of the western side of the Baltic Sea. The Baltic Sea acts like a seesaw with the Stockholm area as a node. When atmospheric pressure systems pass by one end of the Baltic they do not only affect the area of the Baltic sea in their near vicinity but also the water level on the other end causing an opposite reaction to the sea level [11]. For example if a low-pressure system travels over the northern Baltic Sea area the water levels of this region will rise. The water added that creates this rise is withdrawn from southern regions causing a lowering of these water levels. Therefore as Stockholm is in the middle of the seesaw this site is not much affected by passing weather systems. In addition to this the area has very small tidal fluctuations due to its connection to open oceans.

As can be seen in figure 3.1 the water level observation site is placed inside the Stockholm archipelago. This will cause further dampening of the water level changes due to the frictional losses that the water is subjected to when passing through the archipelago.

In summary the Stockholm site is not subjected to large variations in sea level. This can be clearly seen in Appendix I. Out of the three sites this one has the smallest water level fluctuations, which is also seen in the data collected in table 3.1 and in the histogram in figure 3.2.

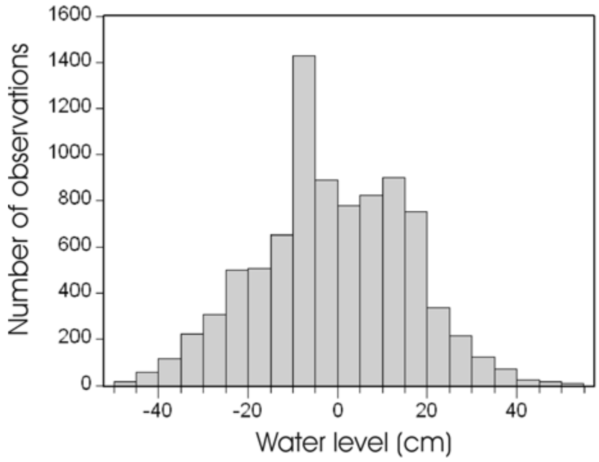

Figure 3.2 *Histogram of the hourly water level of Stockholm 2003.*

3.2 KUNGSHOLMSFORT

Kungholmsfort was chosen because of its closeness to the southern part of the Baltic Sea. The tidal properties in this area are similar to those in Stockholm but exaggerated. The main difference between these two sites is the location on the Baltic seesaw. Kungsholmsfort is near one end of the seesaw so is therefore greater affected from passing weather systems than Stockholm.

As predicted the sea level chart (Appendix II) for Kungsholmsfort exhibits larger fluctuations, of sea level, and a larger standard deviation, over the span of one year, than Stockholm.

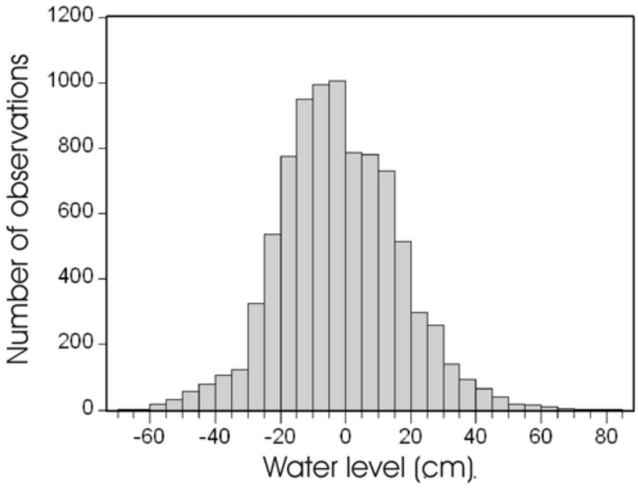

Figure 3.3 *Histogram of the hourly water levels for Kungsholmsfort 2003.*

3.3 KUNGSVIK

Kungsvik is the most northern water level measuring site on the Swedish west coast. Here the predominant factor in sea level change is due to tides. On average there is a bi-daily maximum tidal variation of around 40 cm (see Appendix III). The remaining fluctuations are almost solely due to changes in atmospheric pressure as weather fronts pass by.

Analysing the chart for Kungsvik it is apparent that the daily variations are a lot more frequent and have larger amplitude than for the east-coast sites. Statistically this site has the largest standard deviation of all the sites. More statistical information can be found in table 3.1.

The reason why the data from Kungsvik is from 1995, and not 2003 as for Stholm an Kungsholmsfort, is that March of that year was witness to maximum tidal levels stemming from the alignment of the Moon and the sun together with the Moons perigee. The idea was to see how large the largest tidal ranges were and to be able to construct the buoy to cope with them as well. Identifying these maxima is not trivial as passing storms have a greater influence on the total change in water level than the difference in tidal maxima and minima.

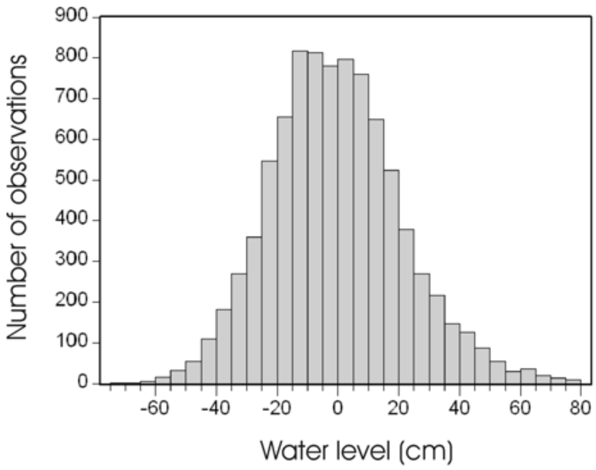

Figure 3.4 *Histogram of Kungsviks hourly water level for 1995.*

Table 3.1 *Comparison of the different observation sites.*

	Stockholm 2003	Kungsholmsfort 2003	Kungsvik 1995
Position [latitude]	N 59° 19’	N 56° 06’	N 59° 00’
Position [longitude]	E 18° 05’	E 15° 35’	E 11° 08’
Mean water level[8] [cm]	-1.51	-2.53	-1.09
Standard deviation [cm]	16.68	18.38	21.69
95 % interval [cm]	-34.20 / +31.18	-38.55 / +33.49	-43.60 / +41.42
95 % interval range [cm]	65.38	72.09	85.02
Max / Min [cm]	-48 / +54	-66 / +84	-79 / +74
Total range [cm]	102	150	153

[8] The mean water level is compared to a specific pre-set reference level.

4 ELECTRICAL ADJUSTMENT SYSTEMS

Because of the changes in water level described in chapter 2 the buoy will need a system to adjust the length of line running from the buoy to the main generator, this to ensure that the buoy will follow the water level changes that are due to tidal and meteorological phenomenon. An electrical adjustment system is one way of overcoming these problems.

The electrical system includes motor, battery, regulator, charger and drum or winch. A motor drives the winch. The battery acts as an energy source to drive the motor. The speed of the motor is geared very slow, which has two advantages. The first and most important is that it relieves the load on the motor allowing for a weaker motor to be used and secondly, because of the slow speed, it gives a gentle adjustment of the line lessening forces due to sudden stops and starts. A sensor measures the water level, an I-regulator[9] calculates the mean water level by averaging out the waves and adjusts the level of floatation of the buoy to an optimal one.

The electrical system is the most straightforward solution to adjusting the length of line. It can also be seen as the system that almost all other solutions stem from.

4.1 DESIGN RESTRICTIONS

A few design restrictions have been set. The system has to be independent of the main generator encapsulation and no power lines are to be drawn from the main generator to the buoy.

4.2 MEASURING THE FLOATATION LEVEL

There are considerable changes of water level for both the east and west coasts of Sweden, as shown in the previous chapters. To design a buoy that accurately adjusts itself to the appropriate water level it is vital to know the water depth or at which level the buoy is floating.

There exist a large number of sensors that can be applied to measure the flotation level of the buoy both directly or indirectly. They all have inherent drawbacks and advantages. The main problems are most likely arise in rough sea states when the buoy will be moving a lot both vertically and horizontally.

4.2.1 Float gauges

Float gauges were the standard method of measuring and automatically recording sea levels before methods with higher accuracy became more available. The system consists of a tube with a small hole in the bottom to let water in. A float is connected by wires and weights and lies on the surface of water inside the tube. The level of the float is registered automatically and gives the momentary water level. The hole in the bottom of the tube is of a size so the speed of the water entering the tube is slow to ensure passing waves do not register as water level change.

To relieve the problems due to biological fouling copper is often used around the narrow opening. In areas were icing is a problem a small amount of kerosene, or any other type of

[9] An integrating regulator.

anti-icing agent with a lower density than water, can be used to keep the water in the tube ice free. [11]

The main reason why this measuring system will encounter difficulties is that it is dependent on the float not hitting the sides of the tube. For this reason alone it seems an unsuitable choice for the buoy.

4.2.2 Acoustic tide gauges

Acoustic tide gauges have more or less replaced the float gauges as instruments for measuring the water level of coasts around the world. They work by sending out a sound wave and timing its return. The time is directly proportional to the distance to the sea floor, consequently accurate measurements of the depth of water can be made. The gauge is sensitive to changes in atmospheric pressure and air temperature so corrections for these factors must be made. This means that the acoustic gauge has to be supplemented with a thermometer and a barometer so that adjustments to the calculation of the distance to the seabed can be made.

Except for problems due to change of temperature and pressure there also occur questions of the reliability of the system in rough conditions when there is a lot of air mixed into the upper layer of the sea. Large amounts of white-water will most probably interfere with the speed of the sound pulse through the water giving false readings of the actual depth. There may be ways to overcome this, such as installing a pipe that travels down from underneath the buoy. This will create a passage of still water for the pulse to travel through even if the surrounding water is aerated.

The pulses are measured continuously and a mean water level calculated over a predetermined time span. To save battery power it might be worth considering letting the acoustic tide gauge take measurements for five minutes every half hour and then adjust the level of floatation if needed.

4.2.3 GPS

Global positioning is used particularly with offshore buoys. When measuring with a GPS system the most important factor is accuracy. Standard handheld systems often have an accuracy of a few meters which is inadequate for the wanted system. To reach the accuracies needed for measuring the water level change a reference GPS system is needed. This consists of a reference station placed on land and a GPS antenna attached to the buoy. By using this method a vertical accuracy of 20 mm can be achieved [23].

By averaging out the waves an accuracy of a couple of centimetres can be possible for the GPS, but this only gives the level of the buoy, not the sea surface. Therefore a slack line moored buoy with a GPS antenna must be used to measure the actual water level and relay that information to the tight moored buoy.

In the long term the floatation level of buoy may be disturbed by leakage or biofouling, this will then negatively influence the reading of the GPS even with the slack lined buoy. Another negative aspect is that a lightning bolt could strike the antenna and knock out all internal electrical components.

4.2.4 Hydro-pressure sensor

A hydro-pressure sensor can be fitted underneath the buoy. Its function is to measure the depth of which the underside of the buoy is relative to the sea surface, thereby allowing for adjustments of the floatation level of the buoy. This solution should be fairly cheap as pressure sensors are widely available. The main drawbacks would be its efficiency in rough water states where there is a lot of white-water or long term problems such as biological fouling. This would effectively hinder the sensor from working properly.

A hydro-pressure sensor could, alternatively, be fitted to the seabed and then relay information of the water level to several buoys via a radio transmitter. Positive aspects are fewer sensors but the downside is the lack of control of the individual buoys floating level. There would also be no way of telling if one or more of the buoys were in a suboptimal vertical position.

Both solutions using the hydro-pressure sensor are dependent on averaging out the short term water level change that is concurrent with passing waves. This is done by incorporating a I-integrator to the hydro-pressure sensor.

4.2.5 Strain gauge

A strain gauge can be used in several different ways on the buoy. The important aspect is to find a location that relays the stresses resulting from the depth at which the buoy is floating. The deeper the buoy lies in the water the more force will be exerted on the line and buoy structure.

A strain gauge can be placed somewhere on the line between the buoy and main generator on the seabed. The sensor will give feedback on the pull from the buoy, the mean water level will be calculated and adjustments can be made. Because the strain gauge has to be active during the whole range of water level variations it must be placed far enough down the line so that it will not be ravelled up together with the line on the drum and then loose all usefulness. There is also the question of pre-stretching the line. If the line has not yet been properly stretched before-hand the strain gauge will, over time, start relaying false information on the loads that the line is subjected to.

Another alternative would be to mount the strain gauge to the axle that takes up the loads from the drum. It could also be placed somewhere on the framework that supports the axle and drum. The advantage of this positioning is that the gauge is mounted inside of the buoy protecting it from the harsh marine conditions.

4.2.6 Tide poles

Harbour entrances often have tide poles or engraved levels on their walls to help ships know the water level and be able to pass without incidents. This will be difficult to adapt for the buoy because there is no stable reference point to install the indicator on.

4.3 DRUM

The drum is used to wind the line in and out. Many aspects of the drum can be adjusted but the most important is the diameter. The diameter will affect the speed of the line and the torque exerted on the axel and gearbox. A small diameter gives a faster rotational velocity if the line speed is to be kept constant. It also results in a smaller amount of torque exerted on the drum and drum-axel.

The negative side to a small diameter is that the line will travel several times around the drum and rub against itself when wound in and out, raising the possibility of breakage due to wear and tear. One solution may be to add a length of chain the first few meters. This will give a slight increase of weight but a much tougher solution where the line is subjected to most stress. There are many marine solutions regarding anchor chains that are applicable to the buoy.

The drum should be mounted directly to the axle. The axle in its turn is connected to the buoy on both sides by ball bearings that take up the loads exerted on the line and allow for a smooth rotation of the drum. The entry points of the axle into the buoy are the only places where the hull of the buoy is not sealed so a watertight sealing of the ingoing axle is adamant for the longevity of the buoy. As most boats have propeller-shafts this technology should be easy to adapt to this project.

4.4 MOTOR

The main criterion for the motor is that it has to be driven by a 12 volt DC car battery. A second aspect is that it has to be powerful enough to retract a fully submerged buoy with a volume of about 5.65 m^3, which is the equivalent to a force of roughly 51 kN for the steel buoy. This force is calculated for calm salt water sea states (see equation 6.1.1-3). The actual forces exerted on the line are greater due to hydrodynamical properties of the buoy (see sec 6.2). Different electrical motors have different characteristics depending on the type of motor. There are mainly three types of motors.

The brush-type motor is the simplest form of DC-motor and is often the choice when working with speeds of less than 5,000 rpm. They can be run without sensors or electronics, which is not the case for brushless motors. The brushless system is preferred when working over large speed intervals and at high speeds up to at least 60,000 rpm. The downside of brushless motors is the higher price and complexity of the system compared to a brush-type. There also exist linear motors, but as they are not applicable to this system there is no need to delve deeper into how they work [24].

The motor used in this application has no need for high rotational speeds or control over a wide range of operational speeds, so the obvious choice would be brush-type DC motor. This also happens to be the most economical choice.

The motor should also be both reversible and include a locking mechanism. Reversible so that it can wind the line both in and out. The locking mechanism is to ensure that the drum and line stay in position once the buoy has been adjusted.

The power of the motor will be chosen according to the characteristics of the gearbox, drum and line speed. The idea is to use as small amount of power as possible so that charging the battery will not become a major problem. The less power used by the system the better.

4.5 GEARBOX

The gearbox is essential if an unassisted motor is to be used to drive the system. Two benefits are derived from the use of a gearbox; the power needed to drive the motor is lessened and the rotational speed of the drum is lowered. How large this change is depends on the gear ratio of the gearbox.

Choice and design of the gearbox is very important as the system will most likely have a gear ratio of something in the region of 10,000:1. At these gear ratios efficiency can be a problem while choosing the right gearing method for the gearbox. For example worm gears have low efficiency but are relatively small in size compared to normal spur gears and are therefore not desirable for this project.

Other factors to consider are the weight and the size of the gearbox. The size of the gearbox is limited only by the space inside the buoy. The total weight of the gearbox is a balance between the efficiency of the system and the efficiency of the buoy at different weights, which at present is an unknown factor.

4.6 BATTERY

A couple of important aspects of chargeable batteries must be taken into account when charging. Most batteries have an upper limit to how large current can be used for charging. This maximum charge current is roughly 30 % of the capacity of the battery in Ah. For example a battery with the capacity of 100 Ah should not be charged with a current stronger than 30 A. It should be added that if the charging current is uneven the batteries lifespan could be shortened. Both these factors of course vary with what type and make of battery is chosen but are of importance when choosing the most adequate battery [25].

4.7 CHARGING

Charging the battery is one of the more essential aspects of the system. One method would be to divert a small part of the energy generated by the linear generator to directly drive the motor when needed. This would be an almost unnoticeable part of the total energy generated, but because of design restrictions a power line from the generator to the buoy is not allowed. Therefore some passive charging device is needed.

Even though the design restrictions do not allow for power to be taken from the main generator this solution would mean fewer parts. It would also give the opportunity to disregard the charger. If this direct drive were possible a transformer would be needed to convert the voltage to a usable 12 or 24 Volt level. Complications would arise when diverting the power from the generator to the buoy. The current idea is to connect several generators to one hub where the electricity is transformed to usable levels. If the, above mentioned, method was to be used a power line from the hub to every buoy must be incorporated. This causes problems as the power lines must cope with the changing water levels and the harsh marine environment.

4.7.1 DC motor

The DC motor used for controlling the length of line to the buoy could additionally be used as a generator. By allowing a small amount of movement of the drum a rotation of the motor can be produced. Through a gearbox with a gearratio of 1:10,000 the movement is magnified

10,000 times. In theory this means that a 1mm movement of the line is equal to 10 m travel of the DC motor. Of course there are large losses in gearing up a system like this but if the technical problems are overcome a very simple system is the result.

Problems can arise due to the aforementioned gearing problem, mainly because such a small variation of change on the level of the buoy creates large rotational speeds of the generator. If, for example, the drum rotates at 1 rpm (line speed of 1m/s and a drum diameter of 0.3 m) and the gear ratio is set to 1:10,000 that would equal a rotational speed of the motor of 10,000 rpm. The motor for driving the drum would preferably be a brush-type motor. Brush-type motors have an upper rotational speed limit of 5,000 rpm, and would therefore be inappropriate for charging the battery. A brushless motor would in this case be a better choice.

A problem that occurs when gearing up a system is that any play between the gearbox and the motor or drum will be magnified 10,000 times. For example if the adjustment system were subjected to some wear and tear, which is very likely in this constantly moving environment, a play of 1 mm could be expected. If this play is from the drum to the gearbox it would equate to 10 meters of play on the other side of the gearbox!

Another negative aspect would be the lifetime of the motor and the gearbox. As the motor would now be in use for every passing wave the operational time for it would in practice be more or less continous. This would shorten the lifetime of motor and gearbox considerably. In non-charge mode the motor would only be in use approximately 10 minutes per day[10] instead of the 1,440 minutes per day it would be in use if it functioned as a charger.

Because of these problems the idea of using the DC motor as a charger is disregarded.

4.7.2 Solar cell panels

Solar panels could be an alternative for charging the battery, but the main problem is the lack of light during the winter months, especially December and January. So the sizes of the panels have to be designed to cope with low-light conditions.

In a marine environment the solar panels are subjected to harsh conditions such as waves, wind and ice (during winter). By mounting the panels vertically problems such as covering due to ice and snow are kept to a minimum. Of course there will be periods of snow and ice covering the panels but these periods should not be longer than a few weeks and under this time the system should work adequately on battery power alone. Angling the panels in this manor comes at a cost because the efficiency is diminished during summer months when the sun is in its highest position. Fortunately, during the summer months, the energy levels radiating from the sun are high and so is the number of daylight hours, so this should not be a problem. The most important factor must be to set the angle of the panels so that they are efficient during the low light and low energy conditions of the winter months.

Vertically mounted solar cells give a better angle during the low solar energy months of winter. If the panels are to be placed vertically there is a need for at least three panels, pointing in different directions, to ensure that energy is generated regardless of which way the buoy is facing.

[10] This is for an adjustment level of 10 cm at a speed of 10 cm/min in the region around Kungsvik.

4.7.3 Tubular linear generator

An air-coiled tubular linear generator could be used as a charger. The steady trickle of energy due to the motion of the buoy should be sufficient to charge the 12 V DC battery. Calculations have been made to calculate the dimensions of the linear generator to charge the battery. Even when constructing a 5 W generator, which is approximately 5 times the needed power, the generator was very small. Due to the assumption of no losses in the analytical approach the theoretical size of the generator becomes very small. Instead it may be better to calculate the needed voltage and physically construct a tubular linear generator from that criterion.

There is also the possibility of having several smaller linear generators set at different angles to produce a more constant current to the battery. Depending on the major motions of the buoy the generator should be mounted either horizontally or vertically. If placed vertically the preferred position would be to one side of the buoy to maximize the speed of travel for the air-coiled linear generator.

4.7.4 Wind generator

It is possible to mount a wind driven generator on top of each buoy to generate the electricity needed to charge the battery. The main drawback of the wind generator is the question of the structural durability of it during high seas. One large breaking wave would probably be sufficient to snap the blades off the wind generator. Problems also arise when the wings of the wind generator act as a sail and tilt the buoy and thereby affect its hydrodynamical properties. Since the wind generator sticks up out of the buoy it is susceptible to lightning strikes.

5 NON-ELECTRICAL ADJUSTMENT

There are several possible alternatives of using a construction that is free from electronics and therefore of a power source. Most of these choices can be used together with the standard electrical system discussed in chapter 3.

5.1 NULL ALTERNATIVE

The null alternative is to have no adjustment of the length of line at all. The line is connected directly to the underside of the buoy. The benefit of this is simplicity. No moving parts means virtually nothing can go wrong or break. The major negative aspect is that the system is thought to be less effective when water levels rise or fall below certain limits. How much the buoy will be affected is not yet known, but this is an extremely important aspect when choosing the correct solution. Because of the simplicity of the null alternative it is always the better choice in areas where water levels do not vary much as the maintenance and construction costs are, in comparison, very low.

The choice between the null alternative and others is made by calculating how large the financial losses are, in generated electricity, when the buoy is not at an optimum floating level. Until this correlation is known only a rough estimate can be made when choosing between the null alternative and other solutions.

5.2 SPRINGS

When using springs in the construction it is important to be familiar with of their properties. The springs mentioned below all have a linear dependency between force and retraction length. This means the force of retraction from the spring will differ depending on how far it is stretched or compressed.

The reason for incorporating springs is to have a balance at normal water levels, that is to say the buoy should float at the correct level with the help of the spring. As soon as the water levels change the spring will automatically retract or lengthen. The force exerted on the drum from the spring is constant for a certain predetermined floating level, but as the length of the spring changes so does also its force on the drum. Therefore, even if a spring is considered an adequate solution, a motor must be incorporated to counteract the excess forces when the spring is stretched or compressed beyond certain limits.

The point of the spring is to lessen the power needs of adjusting the lines length. The spring is to take up most of the force from the buoyancy of the buoy. For a semi submerged buoy the spring must be able to withstand a force of about 25 kN. If a solution including springs is chosen it would be advantageous to use the same contact that was chosen for the main generator springs Stefan Musslinder at Lessjöfors AB [26].

To fully counteract the pull from the main generator the springs in the buoy should have similar load characteristics to the springs mounted in the main generator, but there are a few differences such as load repetitions and travel.

The amount of load repetitions on the springs mounted inside the buoy are considerably less than for the springs mounted on the main generator. This is fairly obvious as the springs inside the buoy would only move for the long-term changes in sea level and the springs for the main generator move for every passing wave. The travel of the springs should be adjusted for the specific area in which the buoy is situated. Some areas have larger tidal ranges than others and springs should be chosen so that they can assist in almost the full range of water level variation.

All the spring solutions are dependent on a locking device to keep the line and buoy static as the waves pass by. This locking device can either be a switch that locks the springs in place or a dampener with a large time constant that gives a slow dampening to eradicate the effects of passing waves. The speed of the adjustments then has to be adjusted so that it is not faster than the speed of the dampeners. On the other hand the dampeners should not be so slow that they hinder the adjustment.

The main problems with all the spring-loaded buoys are the effects due to the weight increase. The buoy has a certain volume and therefore a maximum amount of buoyancy. If a buoy with an adjustment system containing springs was to be deployed in an area with a large range in water level variation it may be necessary to include relatively long springs. The weight of these springs may be, together with the other components such as a gearbox and motor, heavier than what the buoy is capable to keep afloat. In this case a larger buoy with more buoyancy is needed to carry the heavy internal adjustment system.

5.2.1 Drum mounted spring

To avoid large stresses on the motor and winch a pre-loaded torsion spring is inserted into the winch cylinder. The idea is to balance the force from the generator so that the pre-loaded spring adjusts the buoy to a more effective level. The spring is locked into position when no adjustments are made.

5.2.2 Vertical spring

This system incorporates a vertically loaded spring to alleviate the forces exerted on the motor. This leads to a design change of the buoy because the spring needs to be able to travel the same distance as the maximum water level change, which is about 1.5 meters (see fig 5.1). The spring would in this case stick out of the buoy by as much as 2 meters.

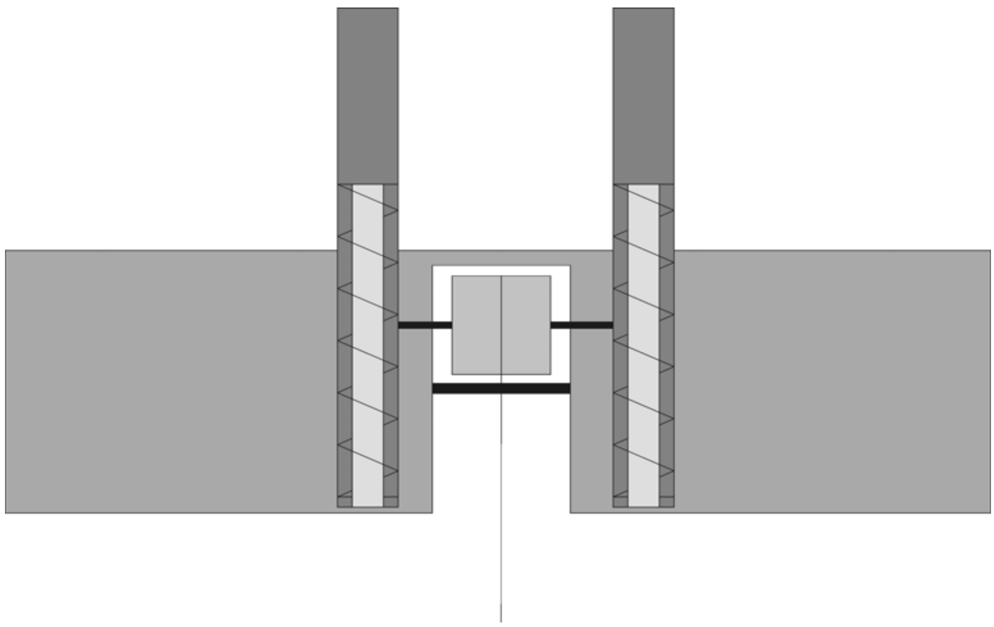

Figure 5.1 *A hollow buoy with guide wheel and dual vertical springs. The light grey inside the springs represent the dampeners. (Side view).*

5.2.3 Horizontal spring

A system where the spring is placed horizontally inside the buoy will ensure a construction without the need of redesigning the form of the buoy. The length of the spring would then be restricted by the size of the buoy. A more reasonable maximum length for the spring would be 2 m. This is perfectly adequate for most situations around the Swedish coast, but for areas with a greater range in sea level a pulley-tack system could be incorporated to make it possible to use a shorter spring. If for example a 2:1 pulley-tack system is used a 4 m change in sea level could be absorbed by a 2 m long spring. Of course this would also mean a doubling of the forces and therefore a spring of twice the stiffness would be needed (fig 5.2).

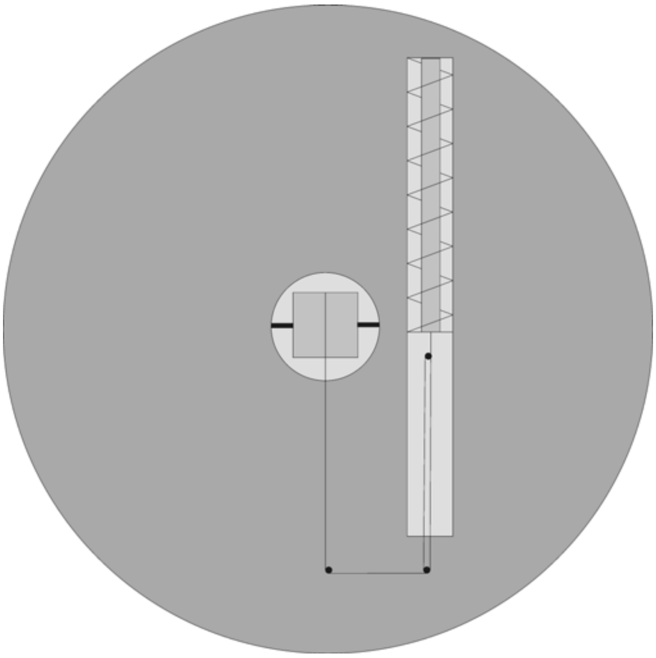

Figure 5.2 *A hollow buoy with horizontal spring and pulley-tack system. The darker tube inside of the spring is the dampener. (Top view).*

5.3 COUNTERBALANCE

The purpose of a counterbalance is to relieve the loads on the motor. This method is used in elevators to facilitate the incorporation of a motor with a low power output.

5.3.1 Simple counterbalance

The counter-weight hangs on the opposite side of cylinder giving the winch neutral rotational force. This gives the possibility of using a low powered motor to drive the winch/cylinder.

Problems to consider are the entanglement and chaffing of the line and the possibility weight sinking the buoy if the buoy were to spring a leak. Another factor would be resonance due the oscillation of the sea. At certain frequencies a pendulum motion could occur that would hinder the wanted motion of the buoy.

5.3.2 Guided counterbalance

To counteract the problems due to line abrasion a hollow cylindrical weight can be used. It would let the up-going line travel through the cylinder with guide wheels and thus reduce the chances of abrasion through friction (fig 5.3). Problems could arise due to biological growth around the guide wheels and the hollow. It would also mean a more complex design and construction.

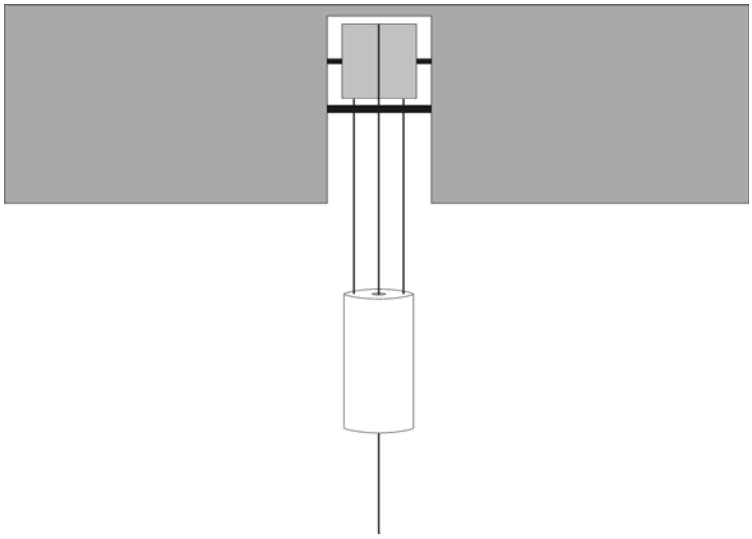

Figure 5.3 *Hollow buoy with guide wheel and guided counterbalance. (Side view).*

5.3.3 Railed counterbalance

Incorporating a guidance system can lessen the resonance (pendulum) problems may arise from the hanging counterbalance. This consists of at least two bars that are attached underneath the buoy, on which the weight travels up and down. This is to ensure that the weight only travels vertically (figure 5.4).

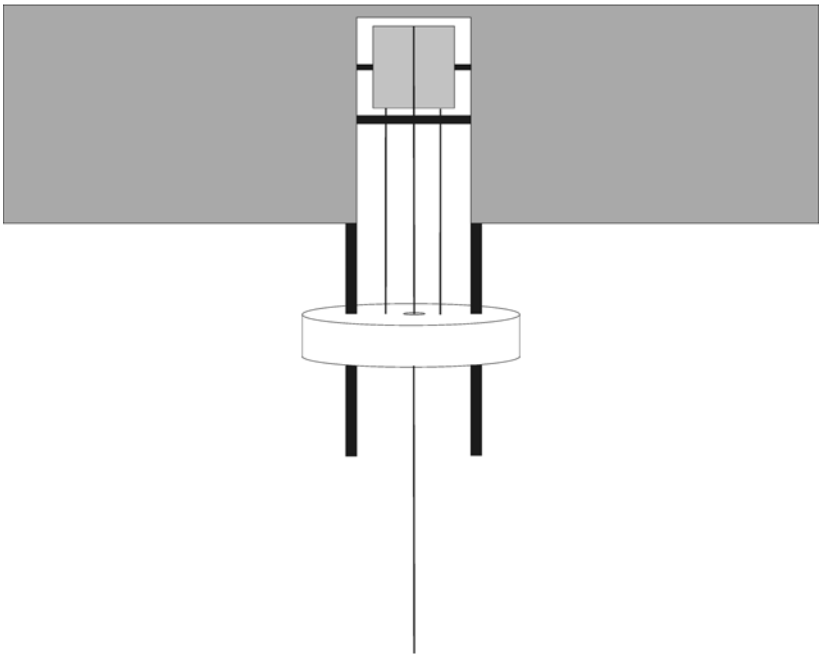

Figure 5.4 *A hollow buoy with guide wheel and railed counterbalance. (Side view).*

The downsides are increased weight, a more complex buoy design and the possibility of more biological build-up, which in the long term may hinder the weight to travel smoothly. Another problem could stem from the weight being lifted at a skew angle causing it to jam on the guide pole. Having the weight fitted with rollers would counteract this dilemma.

5.3.4 Floatation counterbalance

Instead of a weight an underwater buoy is used to create the pull needed to counter balance the main generator on the seabed. The lift created by the new buoy will probably not be adequate so a system of pulleys and tacks are needed to increase the lifting force of the buoy. The main advantage of this is that the system as a whole will weigh considerably less than one incorporating a weight, but because of hydrodynamical effects (section 6.2) this gain will not make such a difference to the system as a whole.

This system is rather complicated as it contains many parts. Entangling as well as biofouling are problems that could cause concern. A solution to the problem of entaglement is adding a rotation point. This would allow the whole pulley/tack system and buoy to rotate independently of the linear generator.

5.4 SELF-ADJUSTING BUOY

The possibility to design and construct a system without the need for electricity should be advantageous. It would allow for a way to avoid the many parts required for the battery powered motor-gearbox system.

The approach to solving this problem lies in the two major changes of the sea level. The main motion is the short term change in sea level with passing waves. This is harnessed and converted into electricity by the buoy and main generator. The other movement is the mean change of sea level that the buoy should be adjusted for. Theoretically it should be possible to use a small part of the energy from the passing waves and store it so that it can be used for adjusting the floatation level of the buoy. An important factor to consider is that the energy taken from the waves is also possible energy for the main generator so the energy conversion for the adjustment system has to be kept to a minimum.

Hydraulics could be a solution to this. By incorporating a spring mounted hydraulic pump it is possible to utilise a small part of the energy from the passing waves. The rise and fall of the hydraulic system, with the passing waves, adds pressure to a pressure chamber. A hydraulic motor could then use the stored energy for adjusting the floatation level of the buoy.

5.5 BUOY BASE DESIGN

The buoy itself is subject to several design choices. The form of the base of the buoy can be changed to help in the construction of the winch-system. The current buoy prototypes have, as stated earlier, a cylindrical shape with a diameter of 3 meters and a height of 0.8 meters.

5.5.1 Closed

A completely sealed buoy has the advantage of keeping the winch components safe and dry from the outer elements. The difficulty is in finding a watertight seal were the line travels linearly through the base of the buoy. The main generator utilises this method for the stators movement in and out of the rotor. A Bachelor of Science thesis in Mechanical Engineering by Sven Karlström [27] evaluates different methods for this type of linear motion sealing.

The problem with most of the linear solutions is the complex system and the frictional losses that occur because of the watertight sealing. Most systems are dependent on o-rings that glide along a shaft that enters the generator. In the case of this project the shaft would travel into the buoy by at least a meter to adjust for largest changes in sea level. Because the buoy is only 0.8 m thick it would mean a major design change of the buoy. Considering that the drum still needs to be incorporated into the sealed buoy the thickness of the buoy would need to be equal to the length of shaft and the diameter of the drum. This adds up to around 1.5 m, depending on the diameter of the drum, almost twice the thickness of the current design. This is quite a large sacrifice considering other options have simpler solutions and do not require such a major design change of the buoy.

It should be possible to incorporate a flexible rubber tube that works as a bellow following the lines movement in and out of the buoy. One end of the tube would be attached to the underside of the buoy and the other end further down the line so that the full range of the buoy can still be utilised. This will create a watertight sealing for the buoy. It is expected that because of the slow and infrequent movement of the line there should not be too much problem with durability.

5.5.2 Open base -small opening

The simplest idea is to have a closed buoy with a small hole that lets the line out. This ring should have diameter slightly larger than the lines diameter. Biological fouling will be hindered by the line by rubbing against the inside of the ring.

5.5.3 Open base -large opening

A buoy with an open base lessens the chance of disturbing the lines passage out of the buoy. Instead biological fouling could reach the inside walls of the buoy giving it a greater weight and possibly interfering with the drum or winch. How far the biological growth will reach is difficult to judge, but it can be compared to a drinking-glass turned upside down and submerged in water. When moving the glass from side to side only small amounts of water rise to levels that could interfere with the drum. The time that the inside of the buoy, high up where the drum is attached, is wet should be too small to allow any type of biological build-up.

The organisms are dependent on seawater to grow, so if the periods between wetting are too long they have no chance of sustaining growth. The smaller the diameter of the hole is the smaller the chance of wetting and therefore biological fouling, but a smaller diameter also increases the chance of the line chafing against the buoy. By rounding the edges of the opening the problem will be alleviated, although construction will be more complicated.

The size and shape of the hollow is important. The first aspect to take into account is the fact that the line will drop more or less vertically from one side of the drum. The line should be connected via the centre of effort to minimize tilting the buoy. This means that the drum must be placed asymmetrically in the hollow to allow for the lines movement when the buoy is being pushed around by the waves. In other words the line must be centred in the buoy meaning the drum is placed to one side as is shown in figure 5.5.

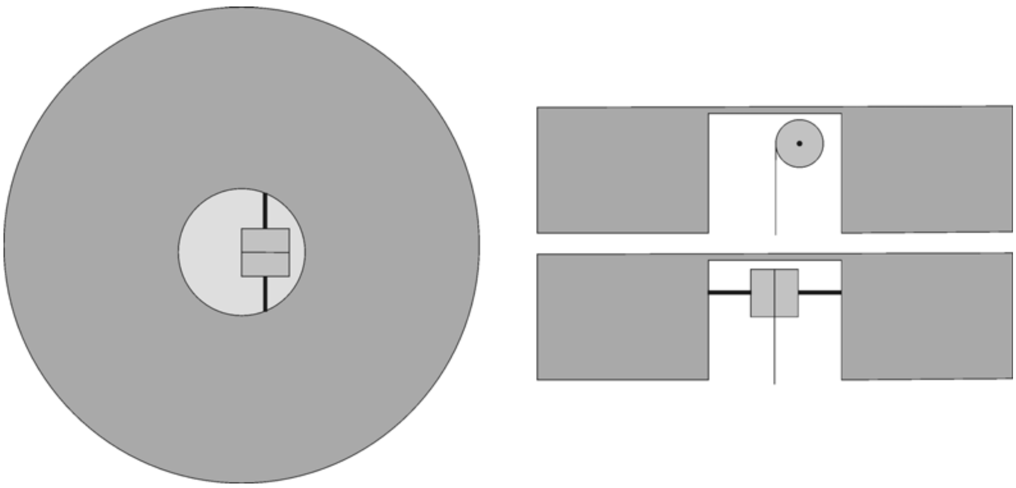

Figure 5.5 *A hollow buoy with large opening. The drum is placed asymmetrically inside the buoy to allow for the line to be centred. Clockwise from left: view of the buoy from above, view from the side and view from the front.*

One way to overcome the symmetry problem would be to add a guide wheel just beneath the drum. The guide wheel will centre the forces, primarily making it easier to construct a balanced buoy. Another positive aspect of this is that now the hollow can be made narrower, lessening the chance of biological matter climbing the inner walls, see figure 5.6.

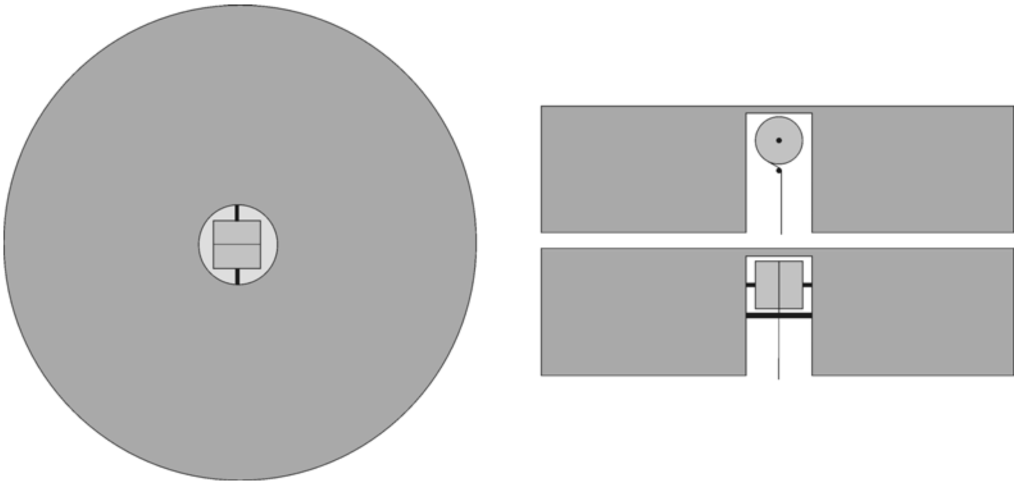

Figure 5.6 *A hollow buoy with guide wheel. Here the drum is centred in the buoy allowing for a smaller diameter of the inner hollow. A guide wheel is added to steer the line into a central position. Clockwise from left: view of the buoy from above, view from the side and view from the front.*

It is important that the buoy is symmetrical in shape so that no matter which direction it is facing the hydrodynamic properties are equal. A circular shape ensures that the rope has the same distance to all sides and there are no corners in which it can get trapped and chafe against. A negative side is the potentially more complex construction than the alternative without a guide wheel.

A square or rectangular shape is easier to construct, but the shape would also mean a slightly more complicated anticipation of the movement of the line against the buoy. It should be added that the hydrodynamic properties will differ slightly depending on which way the buoy faces.

A cone shaped hollow could possibly increase the chances of a dry drum and lessen the likelihood of the line rubbing against the side of the buoy. (Fig 5.7)

Figure 5.7 *A buoy with cone shaped hollow and guide wheel. The cone shape is to lessen the chances of damage to the line. Clockwise from left: view of the buoy from above, view from the side and view from the front.*

5.5.4 Open base -raised head

A raised buoy head could relieve the potential problem of biological fouling. It would increase the distance from the winch system to the sea. The downside of this is a more complicated design shape of the buoy. (Figure 5.8)

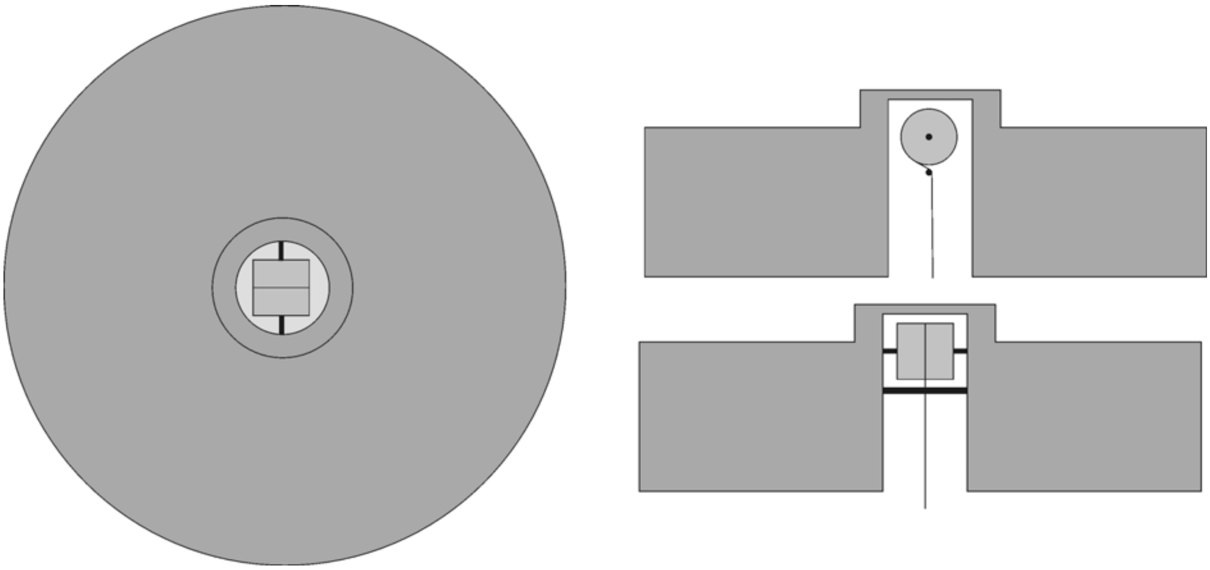

Figure 5.8 *A hollow buoy with a raised head and guide wheel. The raised head increases the distance between the drum and the water surface. This is to decrease the chances of wetting and biofouling of the moving parts. Clockwise from left: view of the buoy from above, view from the side and view from the front.*

5.5.5 Placement of adjustment system

There are several choices for the placement of the adjustment system. The natural and most obvious solution would be to install everything inside the buoy. This has several benefits such as keeping all machine parts in a watertight environment and an easy place to access for maintenance. Because the parts are located in the buoy near the surface there is no need for deep-sea divers to dive down to large depths for maintenance work, instead the buoy can be detached at the surface and lifted onto a boat or ship where the service can be carried out.

The only serious drawback is that the apparatus is then situated at the sea surface where the system will be under greatest stress from the surrounding environment. By attaching the adjustment system somewhere on the line to the main generator it would then be in a calmer environment. The deeper it is placed the lesser are the forces from the waves. On the other hand it would mean constructing a completely watertight casing that could withstand the pressures at those depths. This solution seems unnecessarily complicated for both construction and maintenance reasons.

When placing sensitive instruments in the buoy it would be preferable to situate them fairly high or in watertight casings in the case of the buoy springing a leak, it would ensure that the buoy would still function when water filled, at least for a while.

5.5.6 Discarded solutions

During the process of finding a system for automatically adjusting the floatation level of the buoy several less acceptable systems or system parts have been discarded.

Sailboats sometimes have drag-generators that are pulled behind the boat. The drag generator consists of a propeller that is connected to a generator and enough electricity is generated to charge the onboard battery. Beacause the lateral motions of the buoy are unknown and the propeller most probably has to been cleared of debris often this idea was discarded.

Many wrist watches have a self-winding mechanism. They utilise the movement of the arm to wind the clockwork. The technology behind this may be applicable to this project.

It is possible to combine different technologies that compliment each other. For example solar cells work well during the summer when the solar energy is high but are inefficient during winter months. The linear tubular generator works well during the winter when storms pass the Swedish coast but do not generate much electricity during the summer months when the wave climate is low. If both of these were combined they would compliment each other well, giving a more constant charge to the battery.

6 BUOY CONSTRUCTION

Here follows a brief explanation of the formulas used to calculate, among other things, the power needs for the adjustment system of the buoy.

6.1 THEORY

Once the frequency of the adjustments is known calculations can be done to predict the amount of power needed to operate the machinery. Formulas for the calculations have been included in an Excel spreadsheet for easy adjustment of the parameters. Below follows the main formulas used in the calculation sheet.

6.1.1 Formulas

A short explanation of each included parameter and the equation used follows.

Buoy volume

$$V_b = \pi \left(\frac{D}{2} \right)^2 H \qquad [\mathrm{m}^3] \qquad (6.1.1\text{-}1)$$

where

D	is diameter of the cylindrical buoy	[m]
H	is height of the buoy	[m]

Weight of cylindrically shaped buoy (dry and empty)

$$W_b = \rho_b dD(\pi H + \pi \frac{D}{2} + 2H) \qquad [\mathrm{kg}] \qquad (6.1.1\text{-}2)$$

where

ρ_b	is the density of the buoy material (7800 kg/m^3 for steel [28])	[kg m^{-3}]
d	is the thickness of buoy material	[m]

Force exerted on line from fully submerged buoy, calm sea state

$$F_{\max} = g(V_b \rho_w - W_b) \qquad [\mathrm{N}] \qquad (6.1.1\text{-}3)$$

where

g	is the acceleration of gravity (9.81 m/s^2 is used for calculations [28])	[m s^{-2}]
ρ_w	is the density of seawater (1026 kg/m^3 is used for calculations [19])	[kg m^{-3}]

Torque exerted on drum axel and gearbox from fully submerged buoy, calm sea state

$$M = Fr_d \qquad \text{[Nm]} \qquad (6.1.1\text{-}4)$$

where

r_d is the radius of the drum [m]

Maximum power needed for adjustment, calm sea state

$$P = F_{\max} v \qquad \text{[W]} \qquad (6.1.1\text{-}5)$$

where

v is the speed of adjustment [m s^{-1}]

Amount of work, calm sea state

$$W = n_l P_{eff} T \qquad \text{[Wh]} \qquad (6.1.1\text{-}6)$$

where

n_l is the number of retracting adjustments per day
P_{eff} is the predicted power with efficiency included [W]
T is the time the motor is in use [h]

6.2 HYDRODYNAMICS

The geometry of the buoy plays an important part in the interaction between the buoy and the waves. By making some assumptions to the Navier Stokes equation, a linear theory for the hydrodynamics is obtained. Because of the linearity, the forces at work can be split into two parts. One part is the force acting on a non-moving buoy when a wave is passing, this is called excitation force. The other is how a bobbing buoy is affected by the water.

The second component is called radiation impedance, which can be seen as a dampening force. This impedance is separated into two different parts. The first is known as radiation resistance. Radiation resistance can be seen as the waves created by a buoy bobbing in still water. The second element is the added mass, this part contains the water movement created under the buoy when it accelerates through the water.

A large buoy radius will cause a large added mass, the forces due to added mass increase quickly. In figure 6.1 it can be seen that the added mass for a 1.5 m buoy radius is 5 – 10 tons depending on wave number. A mathematical explanation can be found in Falnes book, “Ocean Waves and Oscillating Systems” [29].

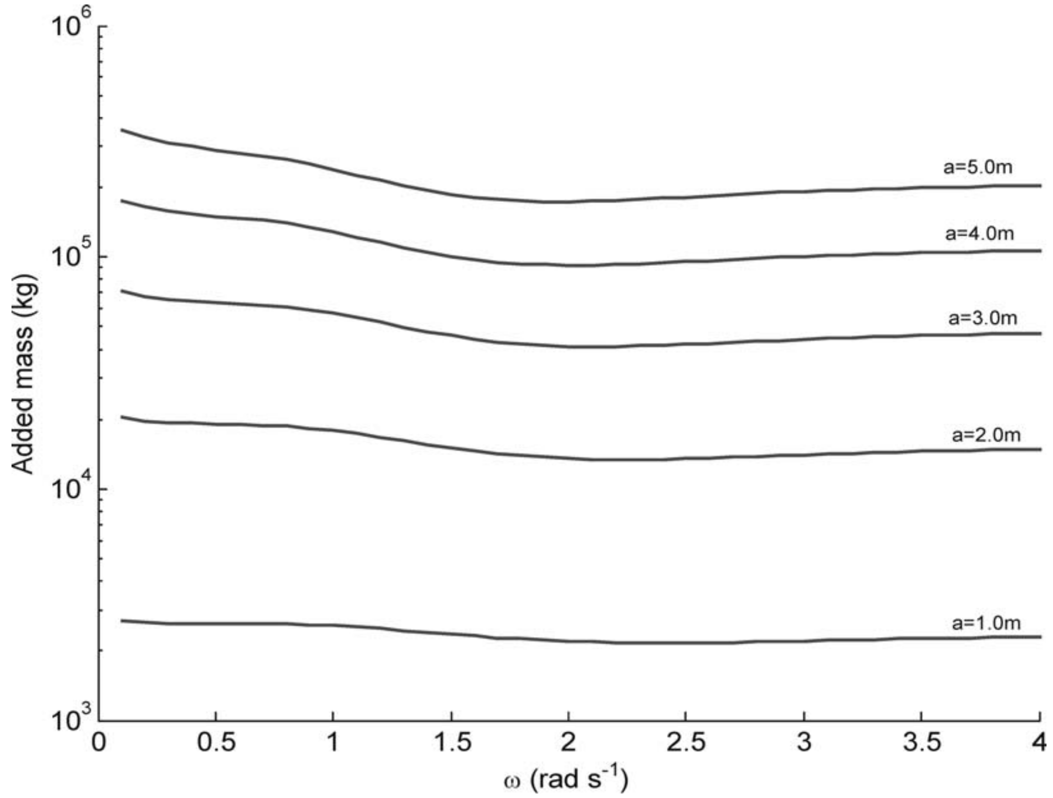

Figure 6.1 *Change in added mass with radius of buoy (a) and angular wave frequency. Added mass increases with increasing radius. Draft (amount of buoy under the water line) is 1.5 m and the water depth is 23 m. Courtesy of supervisor Mikael Eriksson, previously unpublished)*

In reality this means that the weight of the buoy has less and less influence on the dynamic properties of the buoy as the diameter increases. Consequently, keeping weight down for the system has no real relevance for the vertical movement of the buoy. The only upper limit for the weight of the system is that it must not sink the buoy or pull it under a certain floating level.

6.3 CALCULATION METHODS

The number of adjustments and the statistical level of confidence for the range of adjustments of the water level are of the utmost importance when designing the buoy adjustment system. These were calculated by collecting and processing data on sea level change from three different stations; Stockholm, Kungsholmfort and Kungsvik. The data was supplied by SMHI. More information on the sites can be found in chapter 3.

Two aspects define the number of adjustments; the amplitude and frequency of water level change and the set limit of water level change before an adjustment is made. The latter is decided by calculating the optimal floating level for the buoy. At present there is no simple way of doing this. A mathematical model of the hydrodynamic properties of the buoy is in the process of being constructed by Mikael Eriksson [30], but when this is completed is not presently known. Meanwhile the calculation sheets and programs in this report dealing with energy consumption have been designed to be as flexible as possible so that they can cope with any level of adjustment.

6.3.1 Simulation of adjustments

Matlab was used to calculate the number of adjustments that are expected over a certain period of time. The program code can be found in Appendix IV. It is designed in such a way that users only have to include ΔH as a separate file, named "A.txt", and define the adjustment level[11]. This information is enough for the program to makes its computations. It will return the amount of adjustments in both up and down directions and the total amount of adjustments. An example of the total amount of adjustments needed for different levels of adjustment for Kungsvik can be found in figures 9.1 a-d.

The program is somewhat dependent on high-resolution data. This is to ensure that quick changes in water level are not lost in between the data sets. For most coastal regions around the world data on water levels are recorded continually and can usually be acquired through governmental agencies with adequately high resolution, such as NOAA, SMHI, and the UK METOffice. Data from NOAA is freely available from their homepage www.noaa.org

6.3.2 Power requirements of the electrical adjustment system

The power requirements of the electrical adjustment system are an important factor for this project. The system has to have low power consumption so that charging will not become a too large problem. A slower speed is justified because of its lower power[12], but there is also a lower limit of how slow the line can be adjusted and this is the fastest speed of sea level change. It was found to be 26 cm/hour and at measuring site Kungsholmfort.

Calculations of the power needed to submerge the buoy, the gear ratio to reach certain speeds and how the diameter of the drum affected these parameters were made in an Excel sheet. The calculation sheet is constructed so that by varying certain key parameters, such as up-haul velocity, drum diameter, buoy size and total efficiency, information about the needed power, gear ratio and average work on a daily basis will be returned.

Because the losses due to a suboptimal floating level are unknown both the MatLab program and Excel calculation sheets have been constructed as flexible as possible to cope with any type of adjustment level.

6.3.3 Gearbox

One end of the gearbox should be mounted directly to the axel of the drum with the motor mounted on the other. In this setup the gearbox takes up most of the forces exerted on the line and buoy. The torque exerted on the ingoing axel to the gearbox is dependent on the drum on which the line is rolled in. By varying the diameter of the drum the load on the gearbox varies, but also the speed of the line. A smaller diameter will give a slower speed but also a reduction of the load on the gearbox.

[11] ΔH is how much the water level has changed since the previous measurement took place.
[12] Equation (5.1.1-5): $P = F\,v$

6.3.4 Battery

Vartas Blue Dynamic is constructed for marine machines such as motorboats and sailboats and is completely maintenance free. It has an energy content of 40 – 100 Ah depending on battery size [[31]].

Appendix VI contains a brief calculation of the maximum time of use for the system if run on a battery that is not connected to a charger. This is from a fully charged new battery of 40 Ah. The average number of adjustments was calculated to be 338. This is of course a rough estimate and is assuming a linear decrease of the battery-life, optimal temperature and constant voltage and amperage.

An average year at Kungsvik would equate to a total of 2730 adjustments in either direction, which would mean the battery on its own would allow for 45 days of continual usage. The system is then working at 100 % efficiency and the only power drain is from the motor, no electronics are involved. If this efficiency was instead halved the number of days without charging would decrease to 22.

There are batteries built especially for solar systems. The main difference between these batteries and regular ones are that there is an automatic protection against deep discharge. The battery will seldom drop below 20 % of its capacity. This is to ensure that problems due to a fully discharged battery are avoided. This type of battery would be of interest for this project as the system would be sensitive to a full battery discharge.

6.3.5 Wind powered generator

A wind generator could be fixed to the buoy. A fairly small wind power generator that is built for marine conditions has been used for calculations and a detailed specification of it can be found in reference [32]. It has an average daily output of 1200 Wh at a wind speed of 5.4 m/s. An average wind speed of that magnitude may be possible for Kungsvik, but the actual average wind speed for the site is not known. In any case the generated power is more then enough for the adjustment system.

6.3.6 Solar cell panels

Solar cell panels are a possible solution to recharging the electrical adjustment systems battery. The main problem is sustaining a reliable charge voltage for the winter moths when solar energy levels are low for Sweden. The monthly average for the area around Skaftölandet for December is 8 kWh/m^2 [33]. This equates to a daily power average of around 260 Wh/m^2.

By comparing the cheapest marine solar panels from different manufacturers, an efficiency of about 9 % was calculated [34] [35]. On a winter day near Skaftölandet a 1 m^2 horizontal solarpanel would produced on average 23 Wh. Given that the power needs of the electrical adjustment system is 9 Wh it would be adequate with a solar panel of about 0.5 m^2.

To increase the efficiency of the solar panels it would be preferable to angle them so that they face the sun thereby increasing the energy uptake. How much this increases the efficiency is not known but a doubling would not be too unlikely.

During the summer months solar energy is not a problem as solar energy levels are high. For example the monthly average for June is 170 kWh/m^2. This gives a daily average of almost 5 kWh which comfortably covers the power needs of the electrical adjustment system.

It must be added that the power generated will be used to charge the battery. The battery used for calculations has a capacity of 40 Ah. A fully charged 40 Ah battery would last for 22 days before full discharge, as stated in the previous calculation example. So even in the situations when the cloud cover is greater than usual the battery would still be able to run the adjustment system without recharging for some time.

7 EVALUATION

The following chapters present an evaluation of the different adjustment systems and there components.

7.1 COMPONENTS COSTS

Only a few of the parts have quoted prices. They are listed below.

Solar Cell Panels
A panel that is 0.5 m^2 would cost 5 550 SEK including taxes [34] [35]. Each buoy would need to be fitted with three of these amounting to 16 650 SEK for every buoy. If this price was determined to be affordable there is also the question of theft.

Wind powered generator
This specific wind generator, Sunwind WG503 Marin, costs 9 000.00 SEK. [36]

Reference GPS
Finding a reference GPS with separate antenna for less than $15,000 (at an exchange rate of 1 US Dollar = 6.87 SEK [37] which equates to 103 021.50 SEK) was difficult. With the precision needed prices will be high [38], [23].

Motor and Gearbox
Olaf Ylisuvantu [39] estimated a price of 35 000 SEK for the motor and gearbox. This is seen as a maximum price and has not been compared to other manufacturers.

7.2 CONCEPT MATRIX

A concept matrix is used to get a quick comparison between the different solutions. This only gives a superficial comparison as the criterias can only be better or worse than a specific solution. There is no weighing of variables or grading of how much better one solution is to another. Here follows an example of the weak points of the concept matrix. Let’s say there are two concepts that are to be compared. The only difference between them is that one of them is slightly more expensive, bigger and heavier than the other. In return it is a lot more robust with a much longer lifetime. By comparing the two alternatives the system that is lighter, smaller and cheaper scores higher even though the other is the better choice. Therefore the concept matrix should only be used in conjuncture with the discussion following it.

Three concept matrices will be presented; one for methods of regulating the floatation level of the buoy, another for the different methods for charging the battery and finally one for measuring the buoys floatation level.

7.2.1 Automatic regulation of the floatation level

Table 7.1 *A concept matrix for three different versions of the automatic regulation of the floatation level. A positive sign indicates that the specific criterion fares better than for the Reference Concept. A zero indicates that it is equal and a negative means worse than the reference. The sum is the total points gained from comparison. The alternative with the highest sum should be the most suitable. The standard technology, which is referred as Concept 1 or electrical adjustment system, consists of a motor, gearbox, water level measurement, device charge system and battery.*

Technology / Criterion	Standard (Reference, Concept 1, section 4)	Standard with spring (Concept 2, section 4 & 5.2)	Standard with counter-balance (Concept 3, section 4 & 5.3)	Null-alternative (Concept 4, section 4 & 5.1)
Price	0	-	-	+
Complexity	0	-	-	+
Durability	0	-	-	+
Weight	0	-	-	+
Reliability	0	-	-	+
Following changes of water level	0	0	0	-
Power needs	0	+	+	+
Σ	0	-4	-4	+5

7.2.1.1 Evaluation of concept matrix 7.2.1

As stated earlier the concept matrix must be read in conjuncture with the discussion. This is very obvious in the case of the different buoy alternatives. It is evident that the null-alternative is vastly superior to any other system, but it fails on one very critical point. It can’t adjust to varying water levels. It may be unfair to include the null-alternative as the main theme of the report is to find a way of adjusting the floatation level of the buoy, on the other hand, it is of great importance to evaluate if there is a need for adjustments at all.

If instead the choice falls between the first three alternatives it seems that the reference system is the best choice. This is in fact only partly true. If power requirements become high, as is the case for areas with large changes in water level, the need for an assisting spring will out-weigh the disadvantages of a heavier and more complex system. What does not show in the concept matrix are the differences between Concept 1 and Concept 2. Concept 1 is most likely a better choice due to the more complex and heavier solution that Concept 2 offers.

7.2.2 Charging

Table 7.2 *A concept matrix for the different alternatives of charging the battery. A positive sign indicates that the specific criterion fairs better than for the Reference Concept. A zero indicates that it is equal and a negative means worse than the reference. The sum is the total points gained from comparison. The alternative with the highest sum should be the most suitable.*

Technology Criterion	Air coiled linear generator (Reference, Concept 1, section 4.7.3)	Solar panels (Concept 2, section 4.7.2)	Wind power (Concept 3, section 4.7.4)	DC motor (Concept 4, section 4.7.1)
Price	0	-	-	-
Complexity	0	+	+	-
Durability	0	-	-	-
Internal/external	0	-	-	0
Σ	0	-2	-2	-3

7.2.2.1 Evaluation of concept matrix 7.2.2

The results of the concept matrix are clear; the best choice would be to use a linear generator to charge the battery. Because the air coiled linear generator can be placed inside of the buoy it is kept protected from the outer elements. This has large benefits when it comes to durability. The only negative aspect of the linear generator is that there exist no off-the-shelf products so it will have to be built and assembled from the separate parts. This should not be a problem as the division of Electricity and Lightning research are at the forefront of linear generator research. The other concept that can be internally constructed is the DC motor. This system would be the most complex of all as it sets very high standards on the gearbox (see section 4.7.1).

Of the two remaining alternatives, solar panels and wind generator, the choice would fall on the solar panels. Although the wind generator produces by far the most energy [32] there are questions on its survivability in storm conditions. The generator is designed to cope with winds of up to 50 m/s but how it would fair against 8 meter high breaking waves is unknown. The blades are made of carbon-fibre and the body has been adapted to marine conditions but that does not prove that it could withstand the force of large breaking waves. On the other hand the solar panels are a concern during the winter months when energy levels are low.

7.2.3 Measuring floatation level

Table 7.3 *A concept matrix for the different alternatives of measuring the buoys floatation level. A positive sign indicates that the specific criterion fairs better than for the Reference Concept. A zero indicates that it is equal and a negative means worse than the reference. The sum is the total points gained from comparison. The alternative with the highest sum should be the most suitable.*

Technology / Criterion	Strain gauge (Reference, Concept 1, section 4.2.5)	GPS (Concept 2, section 4.2.3)	Acoustic tide gauge (Concept 3, section 4.2.2)	Hydro-pressure sensor (Concept 4, section 4.2.4)	Float Gauge (Concept 5, section 4.2.1)
Price	0	-	-	+	+
Complexity	0	+	-	-	-
Durability	0	-	-	0	+
Internal / external	0	-	0	-	-
Adaptability	0	+	-	-	-
Maintenance	0	-	-	0	-
Reliability	0	0	+	-	-
Σ	0	-2	-4	-3	-3

7.2.3.1 Evaluation of concept matrix 7.3

The strain gauge is the best solution for measuring the flotation level of the buoy as long as it is placed on a part of the buoy where the forces are originated from the pull of the line. Because the strain gauge can be placed internally it is protected from the outer elements and probably in need of less maintenance. The main negative aspect of the strain gauge is that it doesn't directly measure the water level. Instead it measures the water levels influence on the buoy. If the buoy would gain weight from biofouling this would interfere with the floatation level but not show up on the strain gauge.

The GPS has very good accuracy but has to be placed externally so that signals can be received and sent to the reference station. The biggest drawback is the price of the system, at around $17,000 it must be deemed to be to expensive to incorporate in the buoy. On the other hand if a cheaper version can be found the GPS would be a good alternative as it is very exact in pinpointing the location of the buoy. Information on the lateral movements of the buoy could also be collected by the GPS system.

Acoustic tidal gauges are sensitive to changes in the waters density. Therefore temperature, salinity and pressure change have to be measured to receive precise readings.

The hydro-pressure gauge may be difficult to implement into the system for several reasons. In section 4.2.4 two alternatives on how to use the pressure gauge were laid forth. The first was to attach it to the underside of the buoy. The second was to place one on the seabed and relay the information on the sea depth to the buoy. In the first case there are questions on if the accuracy of the depth gauge is sensitive enough near the surface. During rough sea states the surface water contains a lot of air bubbles, these will interfere with the precision of the hydro-pressure gauges. The pressure gauges that have been studied all have an upper limit of around 0.5 meters water depth or more before they relay correct information on depth.

The second alternative lacks information on both accuracy and how to relay the information. There seems to be no technology today that does this, if there were this transmitter would need a power source. Therefore this concept is disregarded.

7.3 RESULTS

To determine the power needs of the electrical adjustment system information on how many adjustments that take place over a certain period of time is required. By using the matlab code found in Appendix V and the water level data collected by SMHI the following number of adjustments were needed for the measuring site at Kungsvik for each month of 1995.

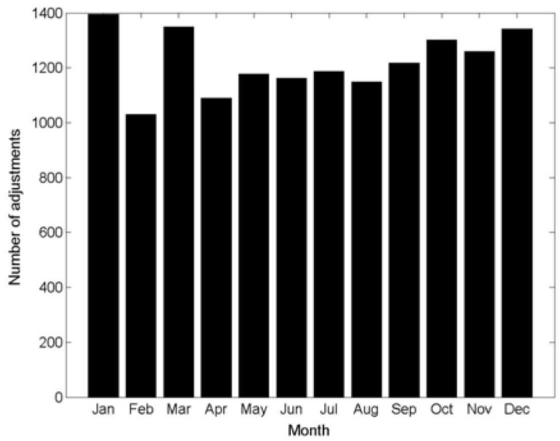

Figure 7.1 a *Number of adjustments for each month during 1995 at Kungsvik. The adjustments take place every 2.5 cm change of water level.*

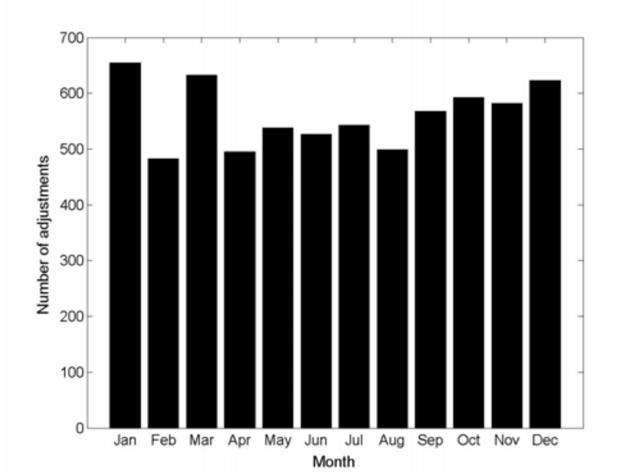

Figure 7.1 b *Number of adjustments for each month during 1995 at Kungsvik. The adjustments take place every 5 cm change of water level.*

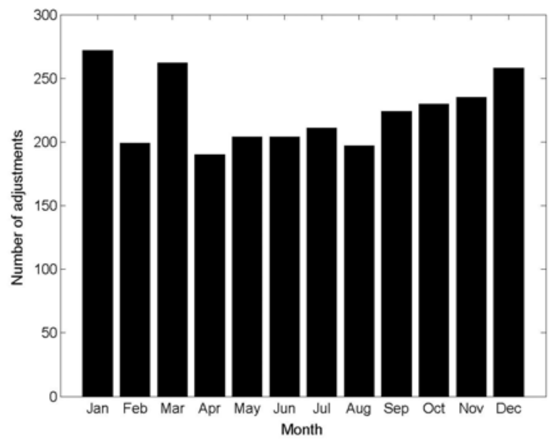

Figure 7.1 c *Number of adjustments for each month during 1995 at Kungsvik. The adjustments take place every 10 cm change of water level.*

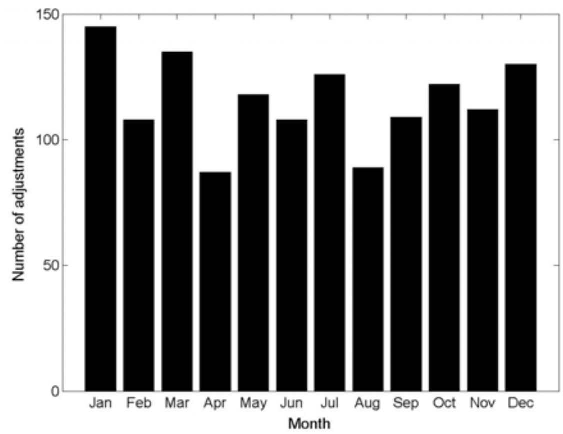

Figure 7.1 d *Number of adjustments for each month during 1995 at Kungsvik. The adjustments take place every 15 cm change of water level.*

The suggested system for adjusting the floatation level in this report is the one consisting of a drum, gearbox, 12 V DC motor, 12V battery, tubular linear generator and a strain gauge acting as regulator. Although the choice has been made on which system is the most adequate for the buoy several components of this system can be varied for differing results. A series of graphs have been constructed for better understanding of the relations between the different components and to alleviate the difficulties when choosing gear ratios, drum diameter and adjustment levels.

Possibly the most important aspect is to identify the predetermined limit for adjustments. Depending on the predetermined limit for adjustments the power needs of the electrical adjustment system will vary. This is because a small adjustment level would mean the buoy would adjust floatation level more often than if this level were set higher. How large this variation is depends on location (see figure 9.2). For example if the adjustment level was set to 5 cm for all three stations there is more energy to be saved by changing the adjustment level at Kungsvik than at the east coast stations.

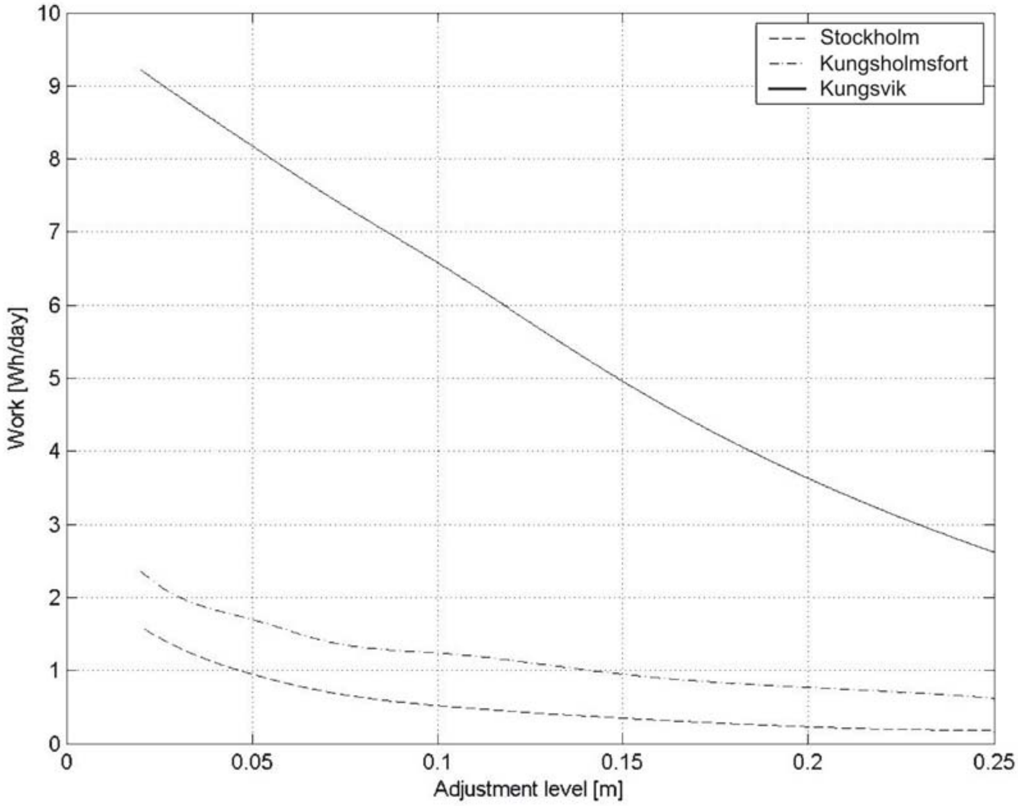

Figure 7.2 *The graph shows how the power need of the regulation system for the buoy varies depending on the predetermined limit of adjustment for the three locations; Stockholm, Kungsholmsfort and Kungsvik. The work per day is the average work derived from the total work over one calendar year.*

When calculating the work only decrease in the water level has been taken into account. This is because only when the buoy is being pulled deeper into the water is there any actual work being carried out.

During major storms it may become useful to detract the buoy beneath the sea surface to a safer environment to ensure that it is not subjected to the harsh surface conditions. If this is to be possible the system must be designed to cope with maximum loads on the motor and gearbox. Therefore calculations contain a maximum force of a fully submerged buoy in calm sea states giving an overestimation of the total mean force needed for the system.

The diameter of the drum affects several aspects that will be decisive for the adjustment system. The torque exerted on the axle and gearbox is directly influenced by the diameter of the drum. Figure 7.3 shows the relation of the torque and drum diameter at two different forces on the line. Fmax is a fully submerged buoy and Fmean is the force on the line from a semi-submerged buoy.

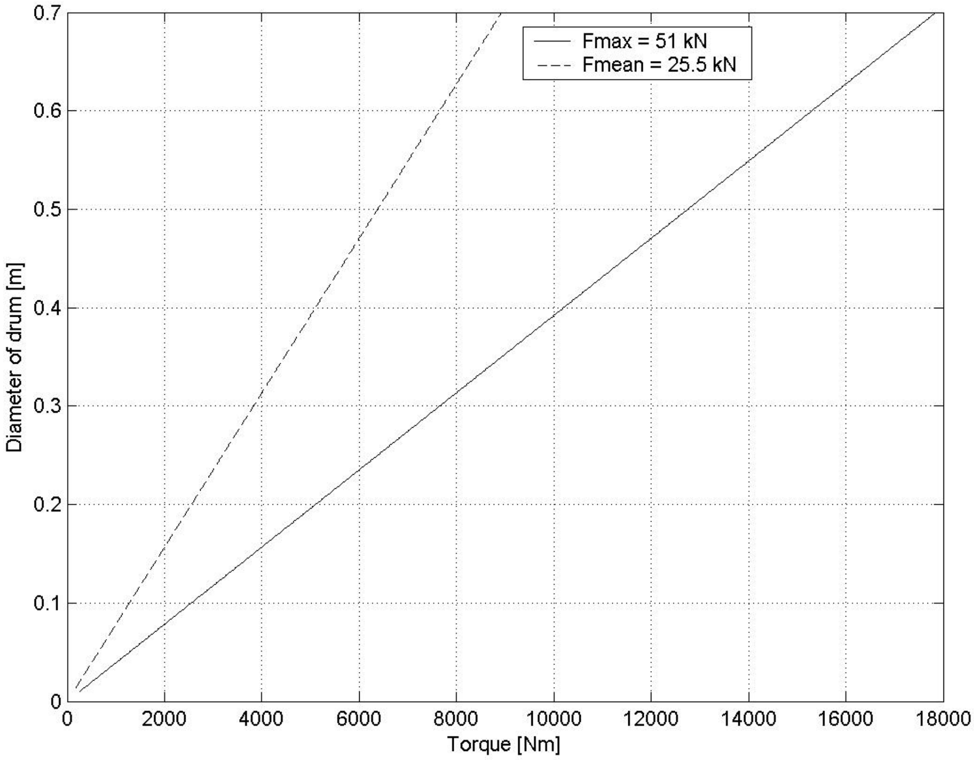

Figure 7.3 *The influence of the drum diameter on the torque exerted on the drum axle. Fmax and Fmean are both calculated from 5.1.1-3*

Figure 7.4 shows the drum diameters influence on the gear ratio at different up-haul velocities. It is clearly seen that at slow up-haul speeds with a large diameter drum the gear ratio will be high. Incorporating a gearbox with a high gear ratio increases the efficiency losses. For example a gearbox with a gear ratio of 10,000:1 has a stated efficiency loss of around 10 % [39]. The specifications for this set-up can be found in appendix VII.

The other factor that determines the diameter of the drum is the flexibility of the line. If the line is stiff it may not be possible to coil it around the drum. On the other hand the last couple of meters could be substituted for a type of line with more flexibility such as chain. This would then allow for a smaller diameter and ultimately a less cumbersome gearbox. The choice of chain for the last couple of meters also had the benefit of being more durable to the possible wear and tear due to chaffing.

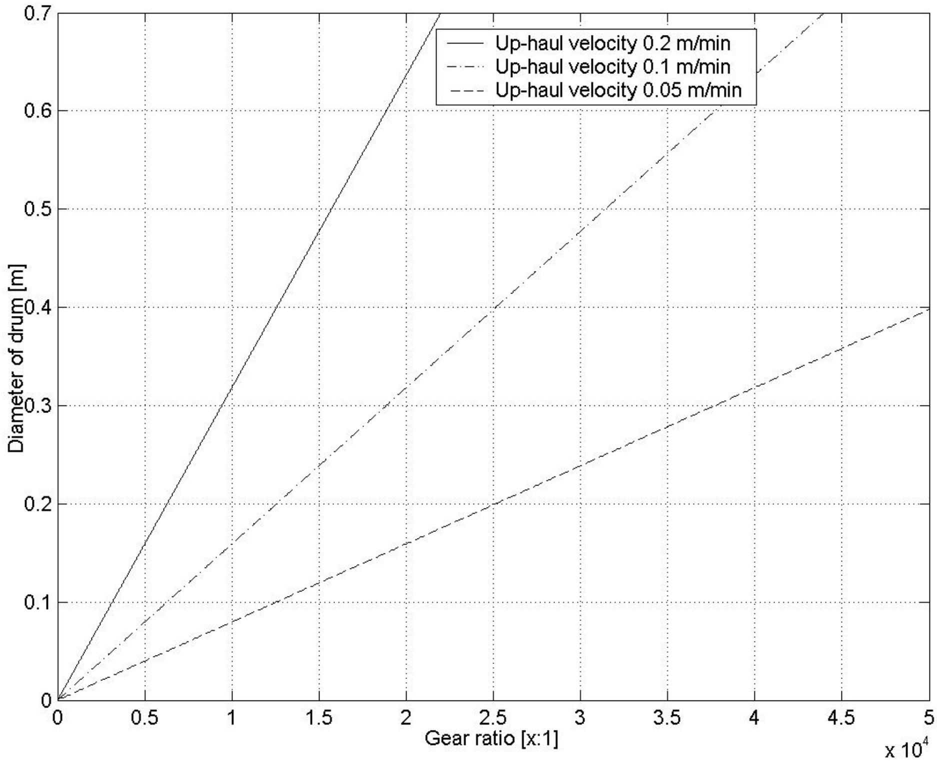

Figure 7.4 *The influence of the drum diameter on the gear ratio of the electrical system.*

Figure 7.5 contains the same variables as in figure 7.4 but now with log scale and gear ratio describing the velocity of the up-haul. In both these figures it easy to discern that a drum with small diameter is important in keeping the gear ratio low.

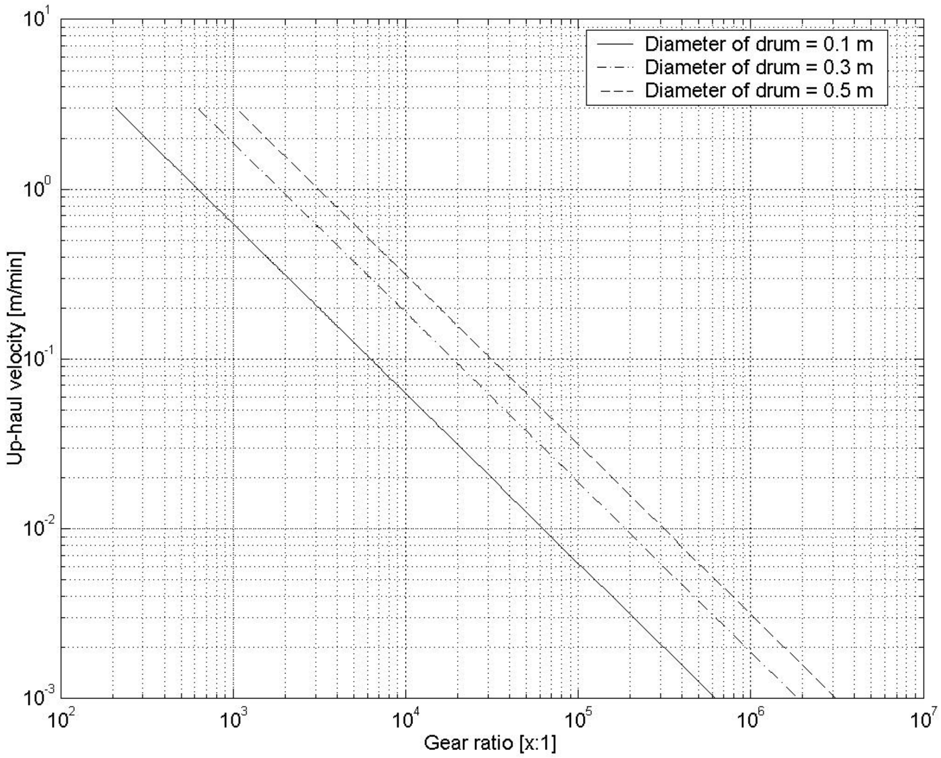

Figure 7.5 *The variation of the gear ratio on up-haul velocity at different drum diameters. This is with a motor working at 2000 rpm.*

The up-haul velocity will influence the choice of motor. A faster up-haul velocity creates the need for a more powerful motor. Because the rotational speed of the motor is constant at 2000 rpm the gear ratio will instead vary with the change in wanted up-haul velocity as seen in figure 7.6. The operational speed of the up-haul are limited, from above, by the power of the motor and the lower limit by the how fast the water levels can change. The maximum power of the motor is determined by the amount of electricity available for charging and the lower limit, the fastest change in water level, was found to be 26 cm/h or 0.0043 m/min.

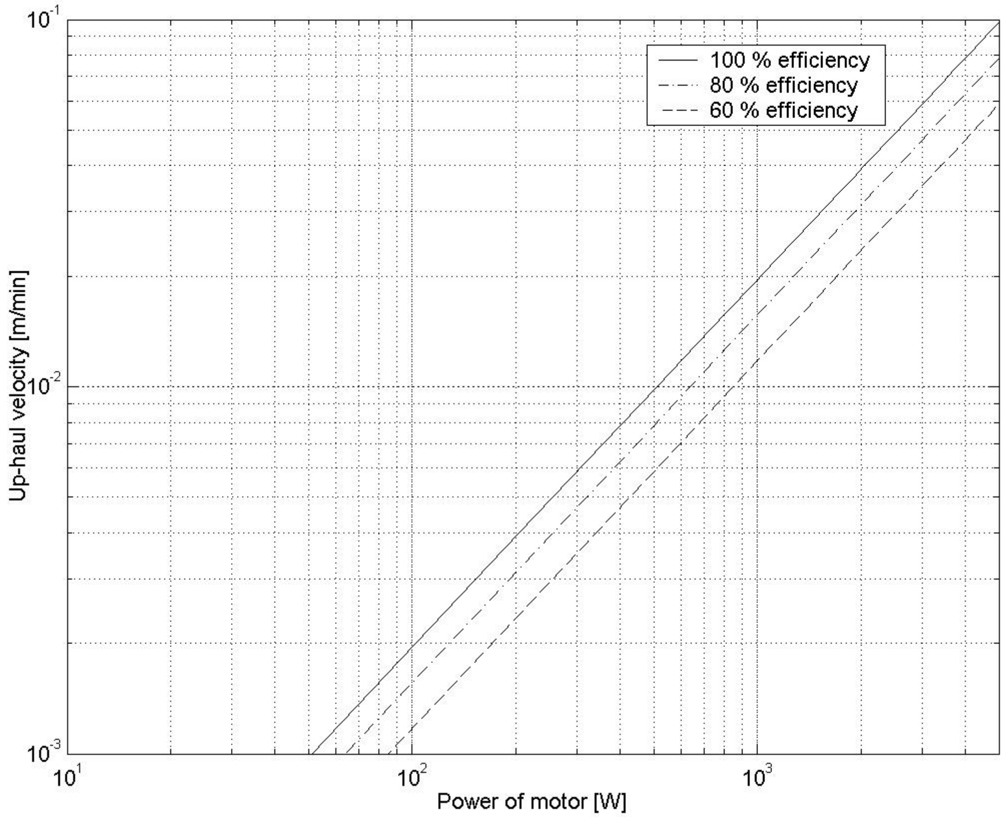

Figure 7.6 *Description of the up-haul velocities influence on the choice of motor at different efficiencies.*

It must be added that all these curves are the result of the equations presented in section 6.1.1 in the form of an Excel spreadsheet constructed by the author. By changing the up-haul velocity, the diameter of the drum and the efficiency of the system it is possible to see how the power needs of the system, gear ratio and total work for the three sites vary.

7.4 DISCUSSION

No studies have been made on how the wave energy converter reacts to the buoy floating at a suboptimal level. In fact there is not even information or knowledge about what floating level is optimal.

Changes in adjustment level can not be drawn purely from the sites water level. Wave height is also very important. Large seas with big waves will still let the rotor of the main generator travel its whole length even if the floating level is not where it is supposed to be.

The greatest changes in sea level around the Swedish coasts are mostly due to meteorological effects. For the east coast this is definitely true as the area is almost completely devoid of tidal constituents. Because of the dominating meteorological effects there are a few factors to consider when looking at the sea level change. The sea level responds to pressure changes of the atmosphere and to wind effects that push water away or towards the coast, as discussed previously in chapter 2.4. Both these events occur when large pressure systems are moving across the area.

To give an example how the weather systems can alleviate the problems due to water level change the site and prototype built for Skaftölandet is used. The site is influenced by both tidal and meteorological fluctuations in water level. The buoy prototype has an alternator length of 1.6 meters which means that below or above this limit the main generator does not produce electricity. A simplified depiction of the main generator can be found in diagram 1.1.

If a low-pressure system with high westerly winds was to pass across Sweden travelling from west to east it would push ahead a lot of water. When this water reaches the coast there will be a marked increase in water level on the west coast. There will also be a marked increase in wave height because of the high winds. As the stator length of the first prototype wave energy converter is approximately 1.6 m and the significant wave height considerably larger the energy transformation will still be at a maximum as the stator travels its whole length even though the buoy is not floating at its wanted level. The buoy will be completely submerged when the wave peak passes but as the trough is so low the stator will most likely reach its lower limit.

When the same low-pressure system, with prevailing westerly winds, crosses over to the east coast the low atmospheric pressure will raise the sea level but at the same time the westerly winds will push the water away from the coast lowering the sea level. The two factors working against each other would most probably result in a lowering of sea level. This is because the change in atmospheric pressure takes longer time to influence the water level than the effects from wind stress. Because the wind is now blowing from land over sea the fetch is very small and therefore also the wave height, which ultimately means there isn’t much energy to convert. As long as the sea level change is not too large the relatively small waves will still be converted into electricity since their amplitude is smaller than the stator length.

A similar situation occurs under high-pressure situations. If a very stable high-pressure system was to pass Scandinavia the water levels would drop and so would the significant wave height because of the lack of wind, which is usually the case in conjuncture with high-pressure situations. Under these conditions wave height is so small that the energy losses are relatively small if compared to the total energy available over the year.

All these situations must be evaluated and tested before a conclusion can be drawn whether the null alternative should be chosen or not. The best way of doing this is setting up two buoys in the same area but not too close, making sure they do not shadow energy from each other. One of the buoys includes a system for regulating the floating level and the other one does not. The difference in produced electricity is the direct result of null alternatives buoy losses due to suboptimal floating levels.

By combining wave data and data on mean water levels it can be possible to calculate the effects of the water level change and change in wave climate. Figure 7.7 gives a rough idea of how the results may look. The figure demonstrates the possible affect of the weather conditions on the range of the stator. The three parallel lines are the mean, maximum and minimum levels of the stator. The bold line represents the mean water level which the buoy should adjust for. The wave climate follows this curve and is represented by the spiked curve. The illustration shows that only during times of atmospheric high pressure would the main generator not be producing the expected amount of electricity. At all other times the wave climate lies inside the range of the stator.

The diagram in fig. 7.7 illustrates a possible scenario. A more realistic graph should not be difficult to emulate with real values. Data on water level can be collected from most countries and data on significant wave heights is also readily available, but not as extensively as for water levels. The most important aspect is to find data with matching time-series.

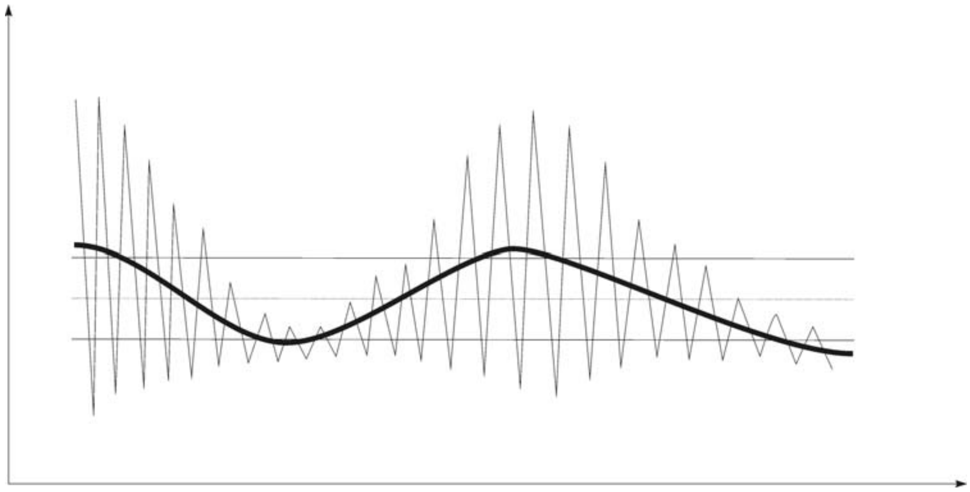

Figure 7.7 *The figure shows the varying wave climate during different mean water levels. When the bold line peaks it corresponds to a low pressure system. They are associated with strong winds and large wave amplitudes. The bold line falls to low levels when high pressure systems settle in the area. They are accompanied by light winds and low wave amplitudes. The y-axis is time and the x-axis is the momentary water level. The dotted line represents the annual mean water level. The two lines running parallel are the alternators maximum and minimum position. The bold line corresponds to the variation of mean water level. The oscillating line represents the wave peaks and troughs for a certain significant wave height.*

It is not yet known if the adjustment system acts as if static when winding the line. Most likely there will be small amount of motion in the adjustment because of passing waves. The question is whether this motion is so large that it would affect the wave energy absorber negatively. If it turns out that energy is absorbed by the up-haul system it would be necessary to have a faster adjustment speed so that the energy losses will be kept small. This will then necessitate a more powerful motor and more charging.

The statistical analysis of the three sites showed a large difference between extreme water levels and the levels in which 95 % of the variations took place. Table 3.1 shows that the span for extreme water level change for Kungsvik in 1995 was 153 cm while 95 % of the time the water level lay inside a range of 85 cm. It may therefore be unnecessary to accommodate an adjustment range that covers the whole span of water level change. By only adjusting for the 95 % range energy can be saved and when applying solutions incorporating springs and dampeners shorter components can be used.

7.5 CONCLUSION

No studies have been carried out on how the wave energy converter responds to the buoy floating at a suboptimal level. There is not even knowledge or information about what floating level is most advantageous for energy absorption. Therefore the most adequate system is hard to define.

The different variations of adjustment system for a tight moored buoy make it quite a complicated task to choose the most satisfactory version of system for the wave energy converter. Presently the most likely system is the system incorporating a drum, motor, gearbox, battery, charger and regulator. A counterbalance or spring should only be necessary in the case of large power needs. The spring seems the least complicated, because of fewer parts and that it can be placed inside the buoy. Especially the horizontally mounted spring is found to be most applicable without making large design changes of the buoys shape and size.

The null alternative is the best alternative when looking at longevity and economical viability. It contains virtually no parts and is almost completely maintenance free. The problem is in knowing when the costs for maintenance and construction precede the losses in produced electricity. That being the losses in produced electricity when the buoy is not floating at an optimal level. At the present moment this is an unknown factor.

In conclusion; the best system for adjusting the floatation level depends on the situation of the specific site. How to choose a buoy according to site can at the moment only be done by rough estimations, when the prototype is deployed more will be learnt on how the buoy behaves in a sea climate. Hopefully then the most advantageous alternative may be chosen when selecting from the alternatives presented in this report.

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[34] Hhttp://www.sunwind.se/sidor/bat.htmlH 2004-12-13

[35] Hhttp://www.ampair.com/htdocs/sunware.htmH 2004-12-13

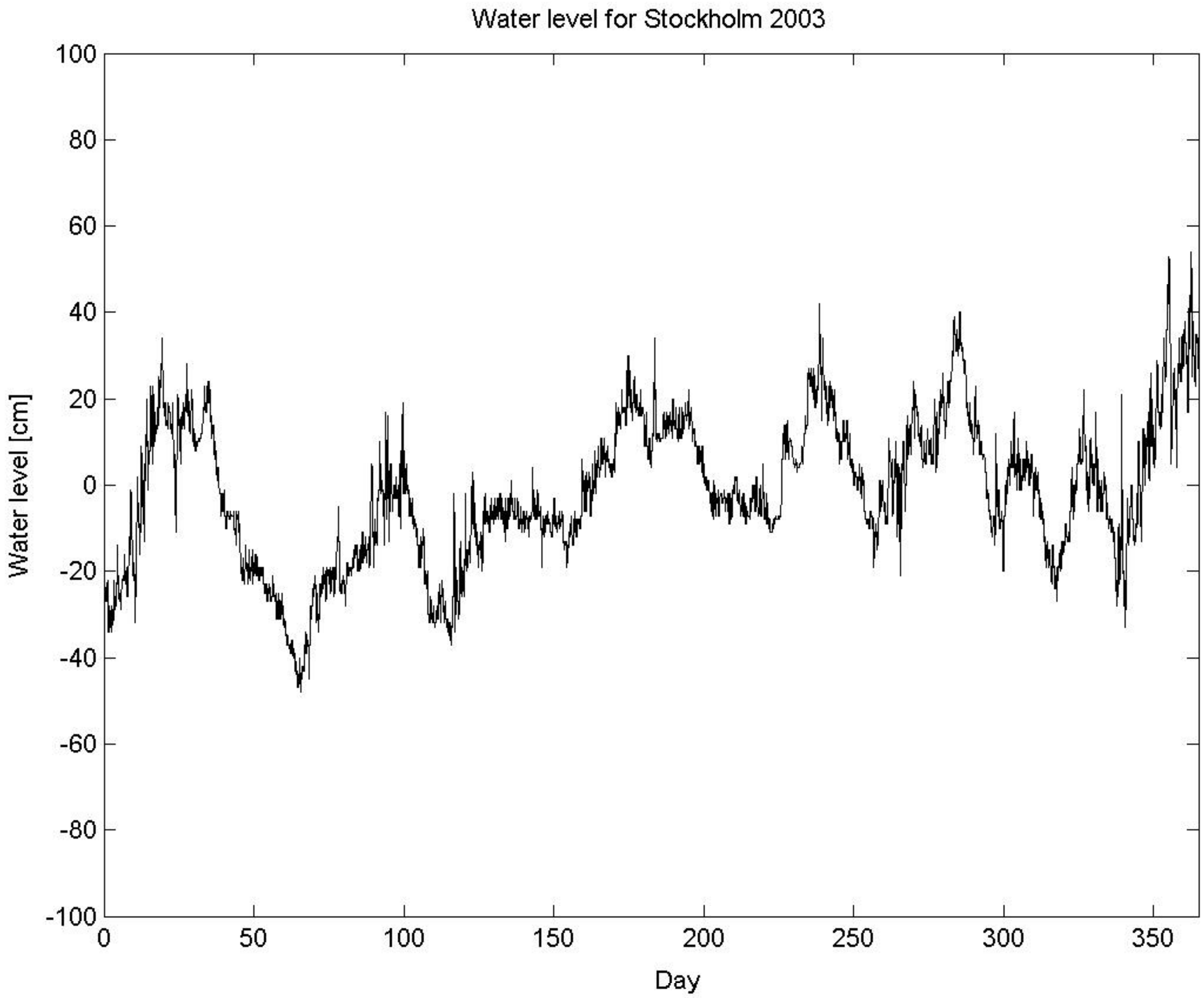
[36] Hhttp://www.marlec.co.uk/products/prods/rut503.htmH 2004-12-13

[37] http://Hwww.forex.seH 2005-02-17

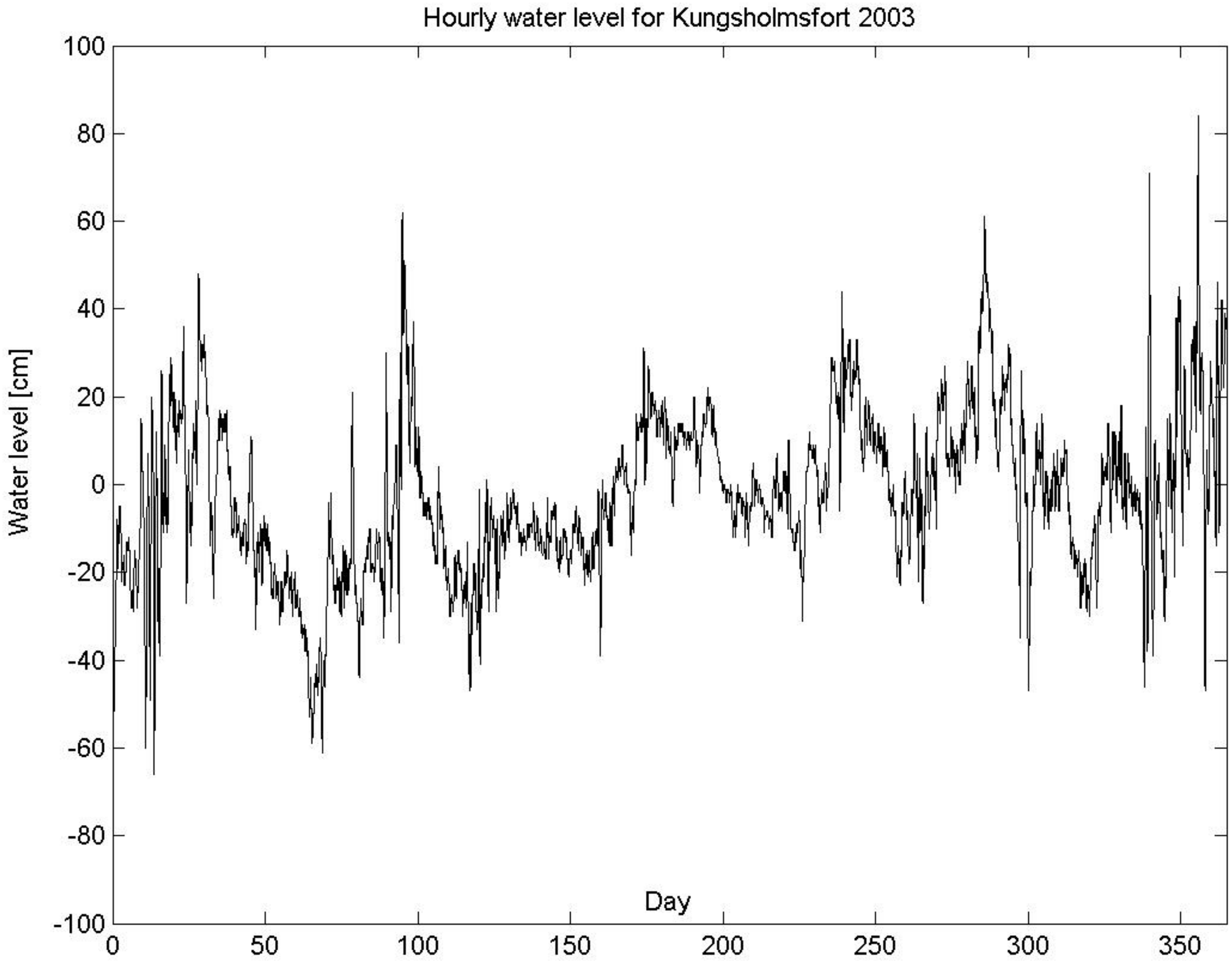
[38] Hhttp://www.prairie.mb.ca/pdf/cornerpost_brochure.pdfH 2005-02-10

[39] Olaf Ylisuvanto, STM Sweden AB, Holaf@stmsweden.seH, 2005-01-27

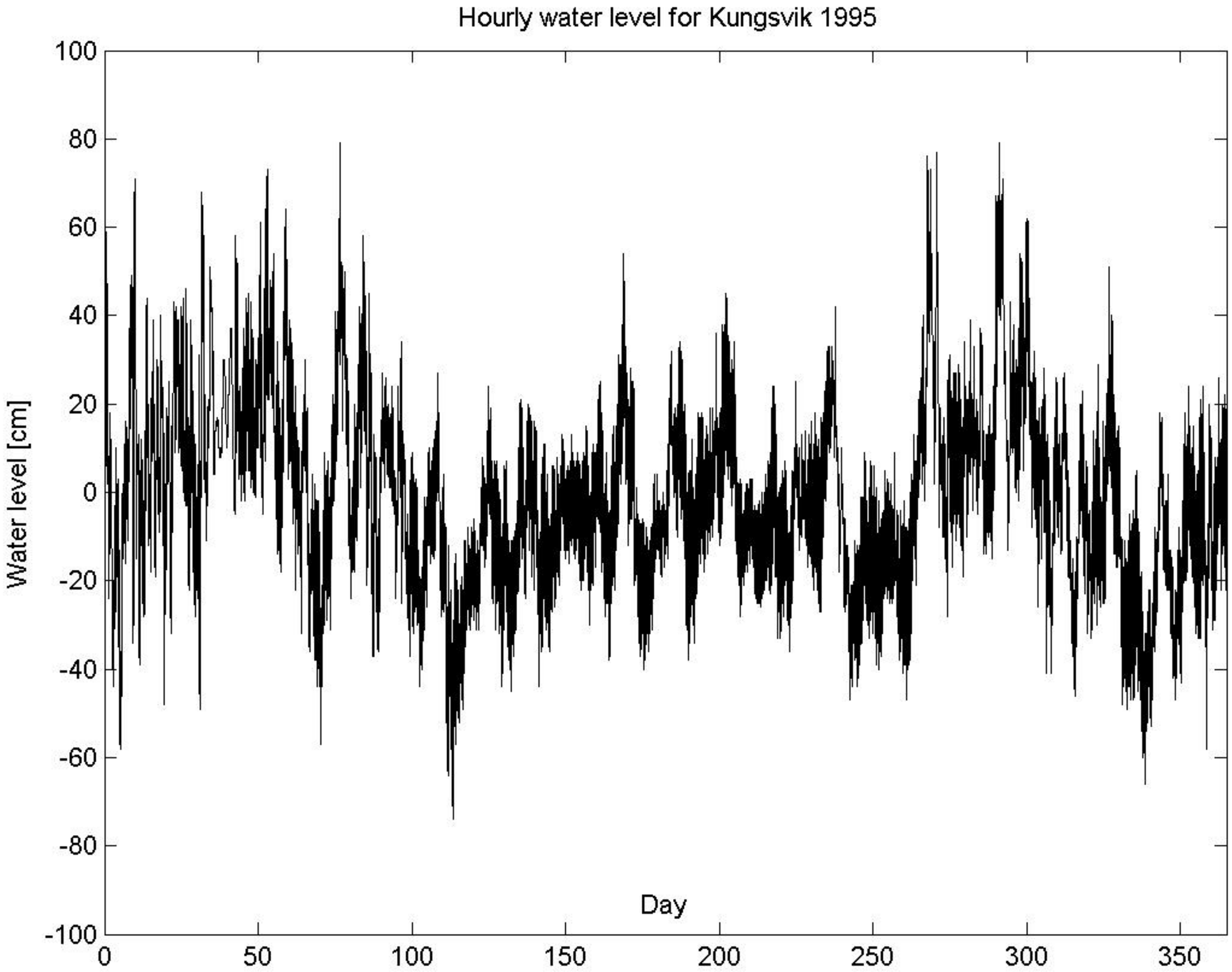
Appendix I-IV


Water level for Stockholm 2003
Water level [cm]
Day
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
50
100
150
200
250
300
350

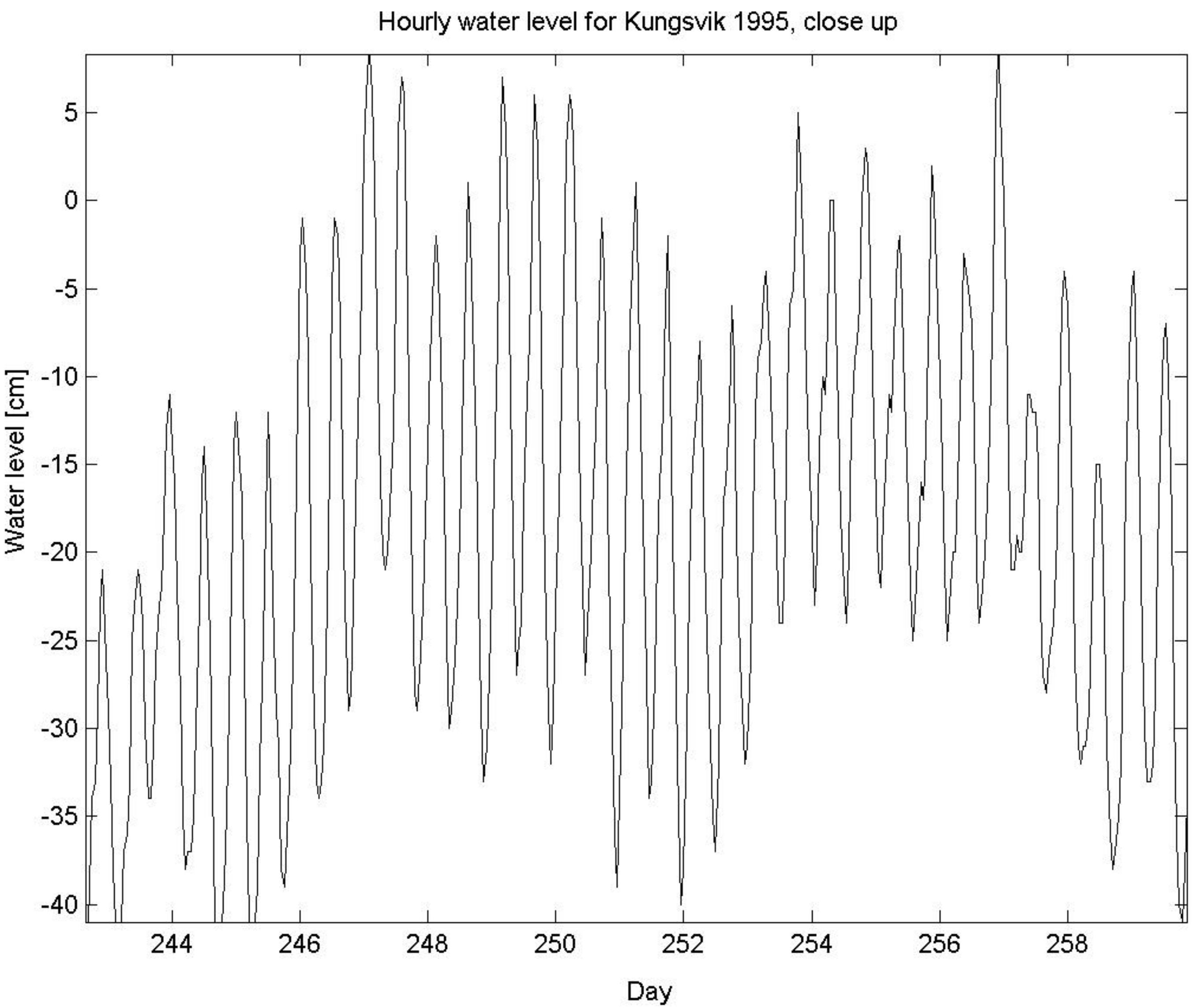
b


Hourly water level for Kungsholmsfort 2003
Water level [cm]
Day
100
80
60
40
20
0
-20
-40
-60
-80
-100
0
50
100
150
200
250
300
350

c


Hourly water level for Kungsvik 1995
Water level [cm]
100
80
60
40
20
0
-20
-40
-60
-80
-100
Day
0
50
100
150
200
250
300
350

d



Hourly water level for Kungsvik 1995, close up
Water level [cm]
5
0
-5
-10
-15
-20
-25
-30
-35
-40
244
246
248
250
252
254
256
258
Day

e

Appendix V

Below is a presentation of the MatLab code that calculates the amount of adjustments done for a vector of data.

```
%--------

clear
load A.txt;

level = input('After how many centimetres change in sea level do you want an adjustment to take
place? ');

rest = 0; raise = 0; raise1 = 0; lower = 0; lower1 = 0;

for (n = 1:1:length (A))
    BIN(n) = A(n) + rest;

    if (BIN(n) >= level)
        rest = mod(BIN(n),level);
        raise1 = (BIN(n) - rest) ./ level;
        raise = raise + raise1;

    elseif (BIN(n) <= -level)
        rest = mod(BIN(n),-level);
        lower1 = (BIN(n) - rest) ./ level;
        lower = lower - lower1;

    else
        rest = BIN(n);
    end
end
raise
lower

%--------
```

Appendix VI

Calculation of the expected lifetime of the battery at Kungsvik.

Batteries Voltage:
$U = 12$ V

Up-haul speed:
$v = 0.0033$ m s^{-1}

Level of adjustment:
$\Delta H = 0.1$ m

Time for adjustment:
$t = 0.00833$ h

Maximum force:
$F_{max} = 51$ kN

Power needed:
$P = F * v = 51{,}000 * 0.0033 = 170.0$ W

Current:
$I = P/U = 14.17$ A

Battery life:
$BL = 40$ Ah

Number of adjustments:
$n = BL/(I*t) = 338$

Appendix VII Component Specifications

This part of the report contains the specifications for some of the products that have been used for calculations. Other products can be found by following the links that are included in the reference list.

Gearbox and motor at 1:10000 gear ratio

This solution was quoted by Olaf Ylisuvanto at STM Sweden AB [39].

Working with a drum with a diameter of 16 cm.

GSM Industrial gearbox type:
RXO3-806-C-660,6-PAM80G-M1
Gear ratio: 660,6:1
Torque: 7600 Nm constant
Max torque: 15200 Nm (momentary)
Outgoing axel diameter: 80H7 mm

Mounted with a:

STM spur gear motor type:
AMF32/2-DC-0,12-2000-IEC63B5
Gearratio: 14,5:1
Output axle speed: 137,9 rpm
Torque 8,1 Nm
Motor type: Creusen DC, 0.18 kW, 2000 rpm
Total resulting torque for this combination is 7600 Nm at 0.21 rpm. For short intervals the torque can be doubled.