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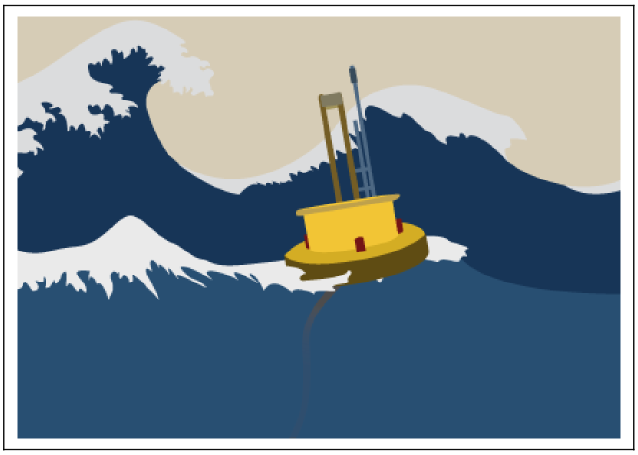

Automated optimisation of a heaving point absorber

A wave energy converter design methodology

Master of Science Thesis

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Gothenburg, Sweden, 2012
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A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

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Abstract

Recent development in energy generation policies around the world has lead to a rejuvenation of the sector of wave energy converters. This study aims at proposing a method of automated optimisation for such a system. The analysed system is a single buoy heaving point absorber with a linear generator as power take off system. The buoy is initially modelled as a cylinder and analysed using potential flow theory for the hydrodynamic motion characteristics. The solution takes into account annuity averaged results as well as the possibility of optimisation of generator damping for each sea state. An automated optimisation routine is set up and used to investigate a number of cases that illustrate the behaviour of the model and the optimisation set up. Verification efforts show good agreement with expected behaviour as well as published results for the various parts of the solution and analysis behave as expected. Further a two degree of freedom model is developed for investigation of surge contribution potential and to illustrate how the model can be applied to a different system.

Keywords: wave power; point absorber; automated optimisation;

Preface

Given the great variety of systems being developed at present as well as the forthcoming demand for energy generation alternatives it is easy to comprehend the need for competence in analysis and design of wave energy devices. This fact has led to the recent start up of a competence centre for wave power devices at Chalmers university of technology in which this thesis is performed.

This thesis is a part of the requirements for the master's degree at Chalmers University of Technology, Göteborg, and has been carried out at the Division of Marine Design, Department of Shipping and Marine Technology, Chalmers University of Technology.

I would like to acknowledge and thank my supervisor, Dr. Claes Eskilsson at the Department of Shipping and Marine Technology, for his enthusiasm regarding renewable energy sources and the geographically far extended help I have been given. I would also like to thank my co-supervisor, Dr.-Ing. Stefan Harries at FRIENDSHIP SYSTEMS Gmbh for giving me the opportunity to work closely with the team in Potsdam as well as for his moral and scientific support. I would naturally also like to extend my sincere gratitude to the team at FRIENDSHIP SYSTEMS for their invaluable help and "gute Stimmung", in particular my fellow students and office mates Sebastian Weickgenannt and Jan Land.

Berlin, May, 2012
Erik Dölerud

Contents

1. Introduction

1.1. Background

The wave energy generation sector is a relatively young one. Proper research and work towards a full scale device that can generate high quality electricity for the grid has only been ongoing since the seventies[1] and with a fairly unstable pace. A few projects are to date in full scale testing, e.g. the Pelamis, the AWS and Seabased's system[1,2,3,8], and many reside on the drawing board, however none has reached a fully commercial system.

There can be no doubt that renewable sources of energy is a must in the years to come. The until now for the industrial development so crucial fossil fuel sources are coming to an end[4] and as prices for energy goes up the incentives for governments and organisations world wide to rid themselves of oversees dependency as well as environmental pollution increases. Wave energy promises perhaps not to be the sole solution to this problem, it has the capability however to do its part in the diverse distributed energy generation infrastructure of the future.

The ocean waves are created as winds blow over the water surface. They accumulate energy from the wind and can thus be seen as a form of concentrated wind energy. The energy contained in a linear surface gravity wave is composed of a kinetic part and a potential part of near equal magnitude[16]. Inside the wave water particles travel in a circular pattern that constitutes the physical representation of this energy transfer[9]. Power in the wave is proportional to the square of both its amplitude and period[17] and for European waters ranges between 2-70kW/m incident wave front length.

Wave energy density in the oceans of the world varies, however the west European countries are exposed to a belt of high energy wave systems due to the relatively stormy weather and the long fetch of the north Atlantic. Leishman & Scobie [18] performed 1975 an estimation of the potential energy generation from wave power in the British islands and concluded that a 1700 miles contour circumventing the islands holds some 500 million megawatt hours, on an annual basis, more than double the combined energy production in the UK at the time. Following some reasoning of efficiencies and consideration of navigational clearways it is estimated that potentially half of the British energy requirements could be met. In a much later study meant to summarize the state of wave power development in the European union in 2002, Clèment et.al. conclude that the potential energy production from wave power in Europe may be in the magnitude of 320GW[17].

Development of wave energy conversion (WEC) systems has been ongoing for the last two centuries. The first patent certificate on wave energy conversion was issued in 1799[16] and more than 1000 patents have since been approved[16]. After the oil crisis in 1973 the research increased substantially. At the University of Edinburgh Stephen S. Salter began his research that would result in the Salter Duck. In Joao Cruz book “Ocean Energy, current status and future perspectives” Salter gives an in depth account to the times of development of the duck in the second chapter of the book[1]. A great deal of politics seem to have caused the funding of the project to have been somewhat intermittent, especially the cost benefit parameters founding decision making for politicians are being questioned by Salter. Further, substantial work has been performed in several countries including Portugal, Ireland, Norway, Sweden, Denmark and The Netherlands[17].

Given the amount of wave energy conversion devices already designed and patented and their diversity with respect to working principles, support structures or intended location it is hard to discuss them all as a single entity. Most authors attempting to give an overview make some sort of categorization of existing designs. Leishman & Scobie [18] makes this categorization into no less than 38 categories, however they are grouped together after what physical characteristic of the waves they utilize as is shown below.

- Variations in surface profile
- Sub-surface pressure variations
- Sub-surface fluid particle motion
- Unidirectional motion of fluid particles in a breaking wave

Johannes Falnes gives a more deducted discussion about various principles for wave energy conversion without attempting any categorization[19]. George Lemonis [16] gives a categorization following the working principle or direction of oscillation of the device as follows.

- Oscillating water column (OWC) devices
- Over topping devices
- Heaving devices
- Pitching devices
- Surging devices

Again as a part of Cruz book [1], Gareth Thomas at the University College Cork gives a categorization more related to the geometry of the device.

- Point absorbers, are devices that are small in relation to the occurring wavelength usually with an axisymmetric geometry
- Attenuators, have one dominant dimension which is meant to coincide with the incident wave direction
- Terminators, similar to Attenuators but intended to receive the waves perpendicular to the dominant direction

This classification is limited to floating devices only and Thomas also suggests the additional qualifier Onshore, Nearshore or Offshore to introduce the intended location of the device.
As mentioned previously there are a number of wave energy converters that have reached full scale testing and a few that are actually connected to the grid as well. The following section

will give descriptions of some successful WEC-systems and at the same time try to explain the main categories, from the previous section.

The LIMPET OWC, is an oscillating water column device. It has been installed in the island Islay off the Scottish coast, directly on the shoreline and can therefore be classified as an Onshore-, Terminator-, OWC-device. It is comprised of an inclined concrete collector tube sitting directly on the bedrock of the coastline. At the back top end of the collector an outlet is connected to a double contra rotating wells turbine. As the water level inside the collector raises and falls with the incident wave fronts through the “communicating pipe” principle, air is forced through the wells turbine in alternating direction driving the turbine and the connected generator assembly. Although the plant has not reached the predicted power generation levels, substantial experiences has been made, the shortcomings explained and research continues [20].

The Wave Dragon is a floating offshore platform that collects water in an elevated reservoir through waves travelling up a ramp. It features long wave collector arms that extend the width of the device as well as a novel kind of hydraulic turbine with low overhead to to convert the hydraulic head of the reservoir water into electricity. The device can be classified as an offshore-, terminator-, over topping system. The wave dragon has been tested in scale during an extended period in Denmark with successful results[21].

The Pelamis Wave energy converter is comprised of several cylindrical segments joined together through hydraulic linkages meant to absorb bending moments and transfer them into hydraulic power. The device is meant to align with the direction of the incident wave front and as the the length spans several wave crests it looks something like a snake moving on top of the wave surface. Parts of the device as well as the entire system has been tested several times in different scales[22] and an economical feasibility study has found the cost of the produced power to potentially lie somewhere in the region of 0.15-0.6€ per kWh[23]. The Pelamis may be categorized as an offshore-, attenuator-, pitching device.

The AWS, or the Archimedes Wave Swing, is a fully submerged device meant to sit on the seafloor. It is comprised of two parts, the base stands on the seafloor while the top moves as the incident wave front alters the pressure on top of the device. Inside, apart from the air chamber exerting pressure on the top, resides a permanent magnet linear generator that converts the relative motion between parts to electricity[24]. This system can be classified as a near shore-, point absorber-, heaving device.

A short background to the achievements of Prof. Mats Leijon and his associates at the Department of Engineering Sciences, Electricity, Uppsala University will be given here. They have been working on a near shore-, point absorber-, heaving device since 2002 named “Lysekilsprojektet” (meaning the Lysekil project) after the main test site. Many papers have been published and contributions have been made in many relevant fields, such as wave climate measurement[25,26], linear motion generator systems[27], hydrodynamic modeling and correlation with measured results[28], economic studies[29], modeling and design and analysis of complete systems with various degree of complexity[5,8]. Their device can best be described as a cylindrical buoy connected to a linear motion permanent magnet generator through a vertical string passing a fully submerged spherical body. The annual average power production at Swedish coastal locations is meant to lie somewhere in the region of 10kW per WEC however the system as a whole is meant to be deployed in farms of many such buoys reaching annual capacities of 10GWh[26]. Such farms will produce many power signals of varying phase and amplitude, technology to collect these signals, condition them and insert them into a power grid is also under development[27]. The project has been chosen as base for this thesis due to its geometrical simplicity as well as the straight forward power take off characteristics.

The difficulties of developing a wave energy converter system are many. Most importantly on a concept level are the following:

- Irregularity in wave climate parameters that the device operates in makes it difficult to achieve high efficiency over a broad range of operational scenarios.
- Structural loading may sometimes exceed 100 times average loading in extreme weather conditions.
- Coupling of irregular slow moving force signal to electrical generator systems operating at much higher frequencies for acceptable efficiencies.

Disregarding the latter two while focusing on hydrodynamic modelling and analysis it is easy to understand the difficulties in getting a holistic view on the performance of the WEC. Clever design alterations may improve ones converter performance in one sea state but reduce it for another, negating the effect. When also realizing the number of parameters and their dependencies one has to work with it may seem as an impossible task. This is where automated optimisation may make a significant contribution. Through proper evaluation of performance, such as the annual average generated power given a scatter diagram of sea states for the current location, parametric modelling and a robust optimisation algorithm the best possible design for the location of interest can be found.

Following a short introduction to optimisation will be given. It is largely based on a book put together by Lothar Birk and Stefan Harries for the 39:th WEGEMT summer school Optimistic, held at the Technical University of Berlin in 2003[30].

Optimisation is in everything an engineer does. Weather he is trying to design an A-frame for a race car, improve the cost efficiency of a production plant or manage a team his task is nearly always to strive for the best possible outcome with respect to some condition of success (often profit on a corporate scale). Consequentially optimisation has been carried out since the dawn of man. Dido, the Phoenician queen, allegedly bought as much land as would fit inside a cowhide upon arrival in Carthage. She then optimized the area of that land by slicing the cow hide in as slender slivers as possible and tying them together to form a long string which could reach around a large piece of land. This has much later become known as the isoperimetric problem. In ancient Greece the same problem was solved by comparing the area of polygons with similar perimeter length and varying number of sides arriving at the conclusion of more sides gives larger area. Thus they could deduce that the greatest area contained within a constant perimeter is described by a circle.

Euler and Lagrange gave the field of optimisation a set of new possibilities in the 1700:s by their works in infinitesimal calculus. It was now possible to look for extremal points in functional equations. In practical engineering tasks optimisation played a small role in the early days (although it can be argued that all design attempts is optimisation) even though Euler in 1727 participated in a competition for finding the "optimum placement, number and height of masts in propelling a sailing vessel". To conduct large scale formal optimisation driven practical design there are two main prerequisites that need to be fulfilled. The understanding of the governing physics behind the problem must have reached a level to allow for set up of the optimisation and computational systems to evaluate the merit function must be available. The last century has seen the development of both these fields within the marine technology sector and today optimisation techniques are used more and more for practical design.

Optimisation strives to achieve the best possible design of a system. Within shipbuilding a common task is to reduce wave making resistance. In order to perform such an optimisation several functionalities must be present. There must be a way of evaluating the resistance, a way of making decisions whether improvements to the design are being made and there needs to be a way of altering the design input. This can all be done in a manual fashion where the responsible engineer designs a hull shape, evaluates the flow around it, analyses the results, deducts design improvement strategies and finally alters the design in the desired direction. The process has traditionally been carried out with ship model basin trials, which requires the labour intensive process of making a new physical model for each design iteration, or with computational fluid dynamics. While using CFD (computational fluid dynamics) to evaluate resistance the shipbuilder has utilized some sort of surface based CAD (computer aided design) tool for geometrical representation of the hull design.

Modern CAE (computer aided engineering) tools promise to efficiate this entire process by supplying the possibility of connecting all the parts of the optimisation process and automate it. The aim is to allow the computer to alter designs based on results from f.ex. resistance evaluations and let a search algorithm decide in which direction these alterations should progress. Thereby a convergence against the sought after behaviour is achieved. A crucial prerequisite for an automated process is however the existence of a geometric (CAD) model that can easily be altered by the computer. Such a model is achieved by parametric design which is a way of functionally describing the various dimensions of a hull surface and gathering them into higher level entities.

In this study the optimisation process and parametric modelling has been carried out in the CAE environment the FRIENDSHIP-Framework [11].

1.2. Objectives

The primary objective is to establish a method of automatic optimisation of the design of a wave energy converter with respect to its power capture efficiency and develop a test case illustrating this method. Other, secondary, objectives include investigating the behaviour of power generated depending on the various design parameters, investigating the need for design alterations given different locations of deployment of the system and investigate the affect that a continuously optimised generator damping has on the annual energy generation efficiency of the system.

1.3. Methodology

The objective of this thesis as stated in the previous section implies a high level of automation. Automation is defined in Wikipedia as “The act or process of converting the controlling of a machine or device to a more automatic system, such as computer or electronic controls.” [http://en.wiktionary.org/wiki/automation], which correlates well to the objective of this thesis – to turn the design, or dimensioning of the design, of a wave energy converter into a process automatically controlled by a computer.

The dimensioning of a wave energy converter system is a problem with many different challenges. It can be broken down into the following problems and sub problems:

- Analysing the system's behaviour in its intended environment
  - Modelling the system geometry
  - Analysing the system's hydrodynamic behaviour
  - Modelling the system's internal mechanical behaviour
- Analysing power generation behaviour
  - Describing wave climate
  - Modelling power take off
  - Analysing generated power
- Improving the design based on results from analysis
  - Determine an appropriate parameter to alter and the most beneficial direction of change
  - Alter the system model to reflect the intended design change
- Iterate

For each sub problem a computerized method of analysis either exists or can be devised. For example, modelling the system in a fashion that allows for hydrodynamic analysis using available methods as well as allow for rapid geometric design parameter change may be done with fully parametric surface oriented CAD.

The methodology of this study will consequentially be to select an appropriate computerized method for each of the steps represented in the previous bullet list, where no such method exists one will be written and finally to integrate these methods into an optimisation routine that will allow for all methods to exchange data with each other and the routine. This will result in an automatic wave energy converter design optimisation application that will be used to investigate the secondary objectives of this study.

Methods used to solve the sub problems are:

$$\begin{matrix} Friendship\ Framework\left\{\begin{matrix} CAD\left\{\begin{matrix}Modelling\ the\ system\\ Alter\ the\ system\ model\end{matrix}\right\} \\ Design\ engine\left\{\begin{matrix}Select \wedge alter\ parameter\\ Iterate\end{matrix}\right\}\end{matrix}\right\} \\ MAPS - Hydrodynamic\ analysis \\ EOM\ \ power\ evaluation\ code\left\{\begin{matrix}Describing\ wave\ climate\\ Modelling\ internal\ mechanics\\ Modelling\ power\ take\ off\\ Analysing\ generated\ \ power\end{matrix}\right\}\end{matrix}$$

Where the FRIENDSHIP-Framework is a marine industry CAE environment developed by FRIENDSHIP SYSTEMS GmbH in Potsdam Germany [11], MAPS (the Motion Analysis Program Suite) is a novel sea keeping code developed by prof. Wei Qiu at the University of Newfoundland in Canada [13] and the “Equations Of Motion (EOM) power evaluation code” will be written in C++ by the author of this study.

The work flow, as can be seen in figure 1, to achieve the set up is aimed at a continuous increase in complexity of the solution. Initially the outline of the set up is laid out and the basic functions of each part established. The Hydrodynamic evaluation is established and verified and a simple parametric cylindrical shape is analysed. The power evaluation code (EOM code) is written with rudimentary functions. This solution is then continuously expanded to include more functions and a higher order of complexity, such as the surge degree of freedom (DOF) and power take off (PTO) characteristics. The reason for this strategy is to at an early stage be able to detect difficulties in the set up and take action accordingly.

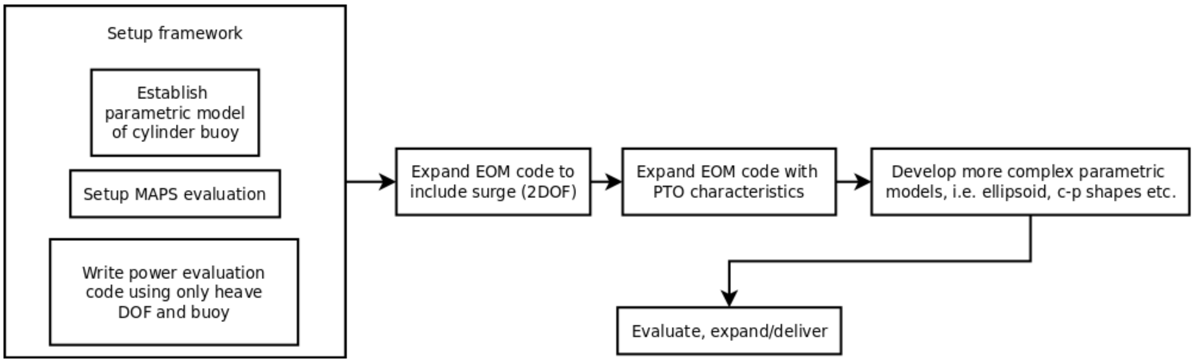

Fig. 1: Flowchart of work plan.

For the hydrodynamic evaluation MAPS uses a potential flow method which takes some assumptions into account, for example it neglects all viscous flow effects. Further the power evaluation is performed mainly in a frequency domain solution which also neglects the non-linear effects of the power take off system. Survivability of wave energy converters is a key factor in the evaluation of their performance, however due to the nature of analysis carried out in this thesis survivability will not be taken into account.

2 Heaving Point Absorber

In this section a detailed description of the analysed system is given which can be seen as a base for the theory and model sections. Uppsala university and Seabased AB in cooperation have developed the design of this particular system. They are conducting extensive research and testing on it outside of Gothenburgh, west Sweden[7,8].

2.1 Description of system

The analysed system is of the type "linear motion heaving point absorber" which basically means that a buoy, in an idealised case, is bobbing up and down along the z-axis of a global Cartesian coordinate system. An illustration of the system configuration is given in figure 2. Further this particular system features a cylindrically shaped floating body as well as a spherical, fully submerged body. These two bodies are attached to each other as well as the on the sea floor standing generator by a vertical line. The generator is of the linear motion type as well meaning that it is composed by a stator in which a translator is linearly oscillating, the electricity is generated through the electromechanical field phenomena that occurs when the alternating poles of the translator are passing the coils of the stator[1].

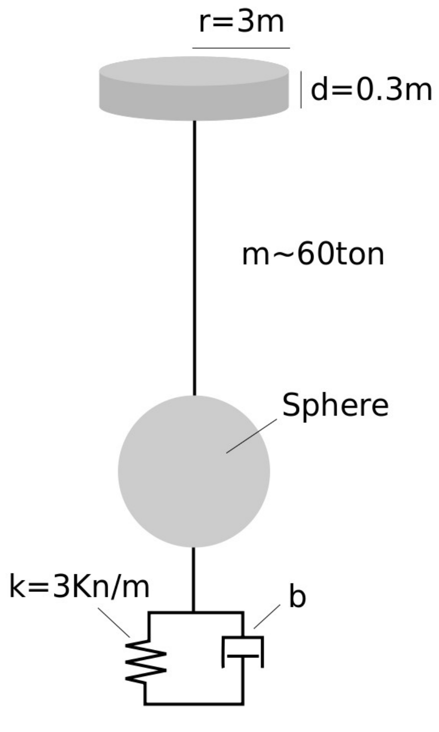

Fig. 2: Heaving point absorber with submerged body.

2.2 System features

The purpose of the floating cylindrical body is obvious, it acts as the energy absorbing body of the system. It also has the purpose of holding the system upright. These two functions are performed by the buoyancy and the induced pressure forces due to water particle movement in the wave front.

The submerged body has neutral buoyancy and is meant to reside on a depth greater than the influence of the wave motion. It has as its main purpose to add inertia to the system, which we know from dynamics is the most efficient way of altering a dynamic, oscillating systems natural frequency. This fact is often used in engineering to reduce vibration by moving the parts natural frequency away from the frequency of the environment. Here it is used to achieved the opposite, move the systems natural frequency closer to resonance for the given sea state[8].

The generators primary task is to convert the motion of the system into electricity. It features a spring which is also used to pre-tension the system (in effect giving it more displacement than the mass) in order to keep the line straight. While generating electricity the translator is moving in and out of the stator, a force counteracting this motion that is proportional to the translators velocity is subjected to the translator from the electromechanical field phenomena that drive the power output. The output energy has the same voltage amplitude and direction as the motion of the system and is therefore not possible to directly connect to the distributing grid. For power conversion and alteration to fit the grid, the Lysekil project team are also designing electrical infrastructure[7] but in this thesis power output is treated as found on the generator terminals.

2.3 Modelling the system

In the previous section we concluded that the generator consists of a spring-damper system. Naturally the translator also has mass why we can treat the generator as a dynamic system according to classic mechanics with a mass, damping and stiffness coefficient. As the rest of the system is modelled to be rigidly attached to the generator, this is one of the main assumptions of this analysis, it follows that the entire system moves in phase and we can simply add the mass of all other components.

We can model also the behaviour of a floating object as a harmonically oscillating dynamic system[9]. The buoyancy force will then act as the returning force, damping is exerted through radiation of energy in the form of waves and we will need to add a mass factor representing the incompressible fluid that has to be accelerated when the body starts to move. This allows us to build up a complete expression that represents the movement of the total system as will be shown in later sections.

The fully submerged spherical body has a constant added mass coefficient, no damping and no hydrostatic stiffness. This follows from the fact that the body is not breaking the surface [8] and its neutral buoyancy. The behaviour of the sphere can therefore conveniently be treated as a pure mass, consisting of the actual and added mass of the sphere, which is exactly its sought after property: to add inertia.

The displacement of the surface piercing cylinder would intuitively be related to the system mass, however due to the pre tension from the generator spring and the possibility to affect the mass by adding or subtracting buoyancy with the submerged sphere it is decoupled from any mass property. This fact is very convenient for analysis since the depth of the buoy can be optimised with full regard to the exciting forces rather than meeting displacement constraints.

For convenience in the later analysis the mass properties are treated as one total mass. Determination of geometric properties like sphere radius is then derived from this mass by subtracting the displacement and solving for radius in the combined expression for sphere displacement and added mass.

3 Theory of modelling and optimisation

3.1 Parametric modelling

Computer Aided Design, or CAD, can be divided into conventional tools, tools with limited parametric capabilities and fully parametric tools. Conventional tools feature abilities to quickly produce drawings from drawn geometry in both two and three dimensions however changes to geometry are made by manually altering individual dimensions. Tools with limited parametric capability typically features the possibility to describe dimensions as a function of other dimensions or parameters. These allow for rapid design alterations however the parametrization is typically limited to the basic geometry manipulation tools that are available. Fully parametric tools typically feature the possibility of creation of fully mathematical interrelationships between entities and revolves around the creation of dependency structures. Fully parametric modelling therefore need to take its origin in which parameters that will control the model and which alterations that need to be investigated. Rather than creating a geometry which is then manipulated this can be said to be centred on the manipulation itself.

The interrelationship between automated optimisation and parametric modelling can not be neglected. Through clever, purpose directed parametrization the number of design variables in an optimisation investigation may be considerably reduced. Thereby reducing the computational cost and convergence time of the optimisation process.

An example of parametrics may be given based on a regular hexahedron. Its geometry is fully described by coordinates of each of the eight corner points. This gives a total of 24 parameters that can be altered. If it were to be parametrized with respect to its length, breadth and height the number of parameters have reduced to only three and if it were to be parametrized with respect to volume only, perhaps forming a cube, only one parameter controls the geometry. Naturally we have in the process sacrificed the ability to form some shapes, e.g. shapes with inclined surfaces, however with an appropriate parametrization this can also be achieved. This illustrates the need for purposeful parametrization, to quote Stefan Harries at FRIENDSHIP SYSTEMS: “-The art of parametric modelling lies in finding the balance between the freedom to do everything and the restriction to do only what you really need."

3.2 Optimisation

Optimisation is the strive for the best solution or design. This problem can be formulated something like "Find the set of decision variables D for given parameters P that will minimize/maximize the measure of merit function M(D,P), not violating the constraint C(D,P)" [30], which is very similar to any design methodology problem. An illustration is given in figure 3.

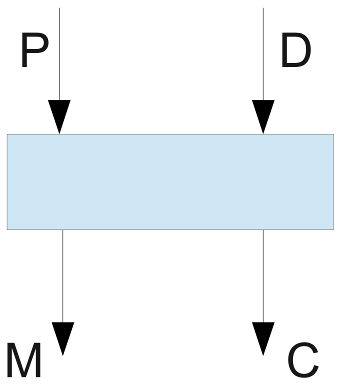

Fig. 3: Optimisation problem illustration.

The terminology is explained as follows:

Design variables - are the variables of the optimisation, they are under control of the optimiser. They can be continuous, discrete or mixed. All design variables, considered as dimensions in an n-dimensional coordinate system, make up the so called design space.
Parameters - are other variable characteristics of the system not under control of the optimiser. Can be deterministic or stochastic however deterministic parameters are most common.
Measure of merit - is the objective function, it is dependent on design variables and parameters. Can be single or multiple objective, often single f.ex. lowest wave making resistance.
Constraint - function dependent on design variables and parameters that define the limit of the design space.

A solution to the optimisation problem exists if the constraints are not conflicting and the measure of merit function is defined in the solution space. This is often fairly simple to check prior to optimising. Further there is one unique solution if the measure of merit function and the feasible solution space are both convex.

There are numerous optimisation methods, some of the most common categories of numerical methods are described here. Methods for unconstrained optimisation are algorithms that simply finds solution extremal points(maxima or minima), they can be divided in search methods, gradient methods, Newton-Raphson methods and higher order methods. Search methods rely only on evaluation of the measure of merit function in the solution space. Direction of convergence is determined by design point variation and comparison of results. Gradient methods determine the direction of fastest convergence through evaluation of the measure of merits first partial derivative in each design variable dimension. Newton-Raphson methods use second order derivatives through evaluation of the so called Hessian matrix with respect to the design variables and finally there are higher order methods however they are quite rarely used.

Solution method is chosen based on requirements of efficiency and reliability. Both of these measures are means of determining how well the optimal solution will be found. Efficiency relates to the computational power, or time, needed to converge upon the solution and reliability indicates the robustness of the algorithm while finding an extrema as well as its ability to ensure it is the global extrema. Efficiency of a method is often a trade off, simpler methods require less computational effort to evaluate one design however often need to evaluate more designs than more complex methods due to their comparatively slow convergence. Higher order methods generally converge after fewer trial points but must evaluate gradients etc. in each point making every design evaluation more intensive. Experience will tell the optimizer which method to use for each application since rules of thumb can not be given in general.

Methods for constrained optimisation include penalty function methods, feasible direction methods and sequential linear/quadratic programming methods. The objective in constrained optimisation is to find the feasible optimum solution, i.e. the point of best measure of merit function that does not violate any constraint criteria.
Penalty function methods - treat the problem like an unconstrained optimisation but adds a penalty term to the merit function. This penalty terms magnitude depend on the proximity to or violation of constraint functions.
Feasible direction methods - whenever a constraint is near, or violated, a new ”feasible direction” is generated upon which the method subjects an unconstrained method.
Sequential linear/quadratic programming - is based on approximation of non-linearities and constrain functions in the vicinity of the current best point. This produces a simplified problem that can be solved quickly for a new best point and a continuous iteration will lead to convergence.

Factors that affect the performance of the method at hand include dimensionality of the problem (i.e. how many design variables there are), starting point location, accuracy criteria (i.e. when has convergence been reached), tuning of the algorithm and naturally computer and software platform. To evaluate the performance of an algorithm the following factors are commonly used: no of trial points required, time to compute one trial point design, time for total convergence and success rate in finding multiple and global optima.

Marine engineering problems in general and shipbuilding problems specifically are often very complex. They tend to have far too many variables and conflicting objectives for direct optimisation to be feasible. Therefore a breakdown of the problem within suitable areas is appropriate, this can be done by defining simplified rules that dictate the interrelationship between different areas of interest and their effect on the total performance of the vessel. An example could be a hull form design problem where design variables would be any free form hull parameters, such as length, curvatures, areas etc. Parameters would be fluid characteristics, set geometrical relations or any other specific entity out of control of the optimizer. The measure of merit function then describes some sort of efficiency for example shaft work done per unit of transported cargo distance, however this is often simplified to e.g. the wave making resistance. Constraints are then the limiting interrelations that define this area of interests correlation to the rest of the vessel design. Constraint criteria may be given with respect to ship stability, ship motion, structural requirements or geometrical limitations (e.g. Panamax dimensions).

3.2.1 Genetic Algorithms

Genetic algorithms (GA) is a relatively new class of optimisation algorithms. It revolves around an idea of mimicking evolution and its way of searching for an optimal organism through “survival of the fittest”. Typically a GA consists of generations of designs where the design variables (DV) of the individuals in each generation is set as combinations of the DV of the previous generations designs based on the performance of these designs. A simplified work flow for a GA may look something like:

1. Generate a generation of n individuals, stochastically covering the design space
2. Evaluate the measure of merit function for each individual
3. Generate a new generation of $n*(1-\alpha)$ individuals based on the fittest individuals of the previous generation. Fill up the rest of the generation with $n*\alpha$ individuals based on stochastic coverage of the design space. α is a probability of mutation factor.
4. Iterate steps 1-3 until convergence criteria are reached.

The primary advantage of this type of algorithm is its robustness. Due to the basis of simple design point evaluation and comparison within the generations these algorithms can handle discontinuous solutions spaces as well as noisy and approximate design point evaluations. Further, due to the stochastic spread of initial and mutated individuals, the design space can be covered well to ensure convergence upon the global extrema. Since each generation consists of several, from each other independent, design points their evaluation is well suited for parallelisation of computation, which promises to reduce time required when computational clusters are available. The disadvantages include large number of individual evaluations as well as relatively computationally intensive evaluation of each generation, both contributing to the computational cost.

GA are also suitable for optimisations with regards to more than one design objective, so called multiple objective optimisation. This is particularly useful when looking at problems with several, complex, contradicting design objectives such as many marine engineering tasks on a higher level than the previously suggested, broken down approach. Rather than looking for one optimal solution multiple objective investigations aim at finding the so called “Pareto

Set" which is a set of solutions consisting of "optimal" compromises of the design objectives in different combinations.

3.2.2 Optimisation methods used in this thesis

The primary objective with the optimisation algorithms used in this thesis has been to illustrate the behaviour of the solution and verify whether the automatic optimisation method works. A short summary of the methods used will here be given:
The Sobol algorithm is a pseudo random deterministic algorithm that is used to sample a design space uniformly while avoiding the cluster effects often seen in true random algorithms[11]. It can be categorized with the unconstrained search methods according to the optimisation theory section discussion as it simply spreads design variables uniformly over the design space and evaluates the measure of merit function for each design. For examining solution behaviour over the design space this algorithm is very useful and it has been used extensively within this work to illustrate generated power with respect to various design variable alterations.

As useful as the Sobol algorithm is, it does not do what the objective of the study aims at namely fully automatic optimisation. For this purpose a T-Search method has been utilised. The name is short for "Tangent Search" implying some sort of evaluation of first order derivatives of the measure of merit function. It works in two steps, initially a number of exploratory evaluations are carried out in the vicinity of the design point along the variable axes. After a successful exploratory phase the descent direction in the best direction can be established and global moves are made. If a constraint is reached in either direction measures are taken to return the solution the feasible design space[11].

NSGA-II, the Non-dominated Sorting Genetic Algorithm for Multi objective optimisation is a genetic algorithm for finding several near optimum solutions along the pareto-front of a multi objective, multi dimensional problem[10,11]. It allows for simultaneous evaluation of a number of solutions in a so called population. The results from the recently evaluated population is then combined in various ways and together with a certain probability for randomisation form the basis of the next generations population.
The NSGA-II is in this thesis mainly used as a benchmark algorithm, to simultaneously produce a large solution space and investigate whether some convergence can be reached. Some attempts were also made to use the NSGA-II for multiple objective optimisation of the 2DOF buoy system.

4. Theory of hydrodynamics and sea state description

In the theory section an overview of the underlying theories used to achieve the model is discussed.

4.1 Hydrodynamics

In order to evaluate the motion of the system and subsequently the produced power it is necessary to be able to estimate the forces and movement induced by the incoming wave surface. This is done by adoption of the so called potential flow method[9]. It is a robust and comprehensive method that has been proven over many years to deliver reliable results in sea keeping problems as well as hull resistance problems considering the wave making resistance.

Potential flow is based on three assumptions, incompressible, inviscid and irrotational flow. These lead to the main governing equation, the Laplace differential equation.

$$\frac{\delta^2 \Phi}{\delta x^2}+\frac{\delta^2 \Phi}{\delta y^2}+\frac{\delta^2 \Phi}{\delta z^2}=0$$

From which velocities and accelerations can be solved directly within the solution domain. To calculate pressure another condition is required, the so called Bernoulli Equation.

$$\frac{\delta \Phi}{\delta t}+\frac{1}{2}(u^2+v^2+w^2)+\frac{p}{\rho}+gh=C$$

Which can be obtained from the Navier-Stokes' Equations using the assumption conditions.

These expressions are solved over a finite domain to achieve a series of field solutions describing the velocity and pressure in each point within the domain space. For the solution to show some meaningful characteristic it is important that we can control boundary conditions of the solution domain as well as the disturbing geometry. This is done using sources and sinks which are basically points in (or outside) the solution domain that radiate potential and it is the superposition of the contribution from all of the sources that gives the solution in each point.

Solving these hydrodynamic field equations will give us information on the forces and moments acting on the body at hand for its current position and velocity in the water. In order to assess characteristics of a floating body in a wavy ocean surface different contributions must be taken into account. A common way of dividing these force contributions is[9]:

- The forces acting on the body held fixed, due to the incident wave front
- The forces acting on the body while forced to oscillate in a flat surface climate
- The mooring forces

The forces acting on the body may be written

$$F_{tot} = F_e + F_r + F_g$$

where F_e is the wave excitation force, F_r the hydrodynamic reaction force and F_g the force due to mooring effects(or as in this thesis generator forces). F_r, the hydrodynamic reaction force, may be described as a linear approximation characterised by three properties, **A** added mass, **B** damping coefficient and **C** hydrostatic stiffness and can therefore be written

$$F_r = -A\ddot{\eta} - B\dot{\eta} - C\eta$$

where η represents the displacement in the current degree of freedom[9].

4.2 Wave theory and sea state description

Waves generated by the wind on the open sea show a seemingly random behaviour. Each wave crest and trough appear to be different from the other and to describe this behaviour mathematically could seem like a challenge. It is however known that all continuous functions on a finite interval can be described by superposition of an adequate number of regular sine and cosine functions. One can obtain a solution for the regular wave components from a wind wave time trace by performing a so called Fourier analysis, which is known from analytical mathematics. The result is a list of amplitudes and frequencies as well as phase angles representing each component. The description of the wavy sea surface can now be said to have been transformed to the frequency domain.

When visualized in a graph this list of component properties is known as a wave spectra. Wave spectra are generally converted to show a continuous energy density function rather than just a list of amplitudes as this allow us to uniformly represent and compare spectra generated from samples with different numbers of components. The recommended number of components is usually said to be 100-200[9]. An exemplary transfer function can be seen in figure 4.

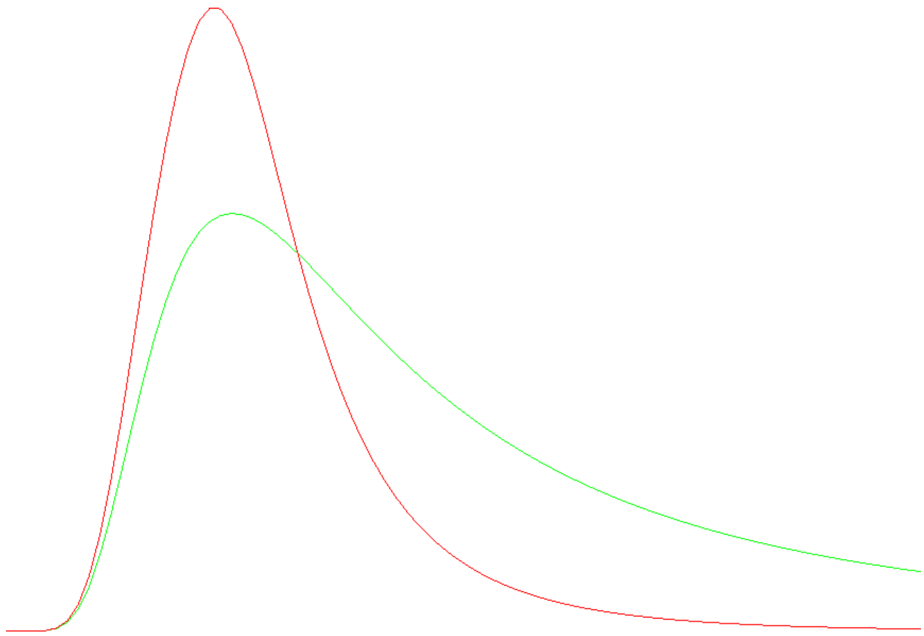

Fig. 4: Transfer function example illustration, magnitude vs frequency.

The idea of having a uniform way of representing sea states is very useful since it allows us to describe conditions in an area of the ocean without measuring it. There are several analytical functions that have been developed to describe the shape of wave spectra given a number of parameters. The mostly used spectral function in this thesis is the Bretschneider spectra which uses significant wave height and the average period to fully describe the sea state. There are several formulations of this spectral function, one example is

$$S_b = \frac{5}{16} \frac{\omega_m^4}{\omega^5} H_s^2 e^{\frac{-5\omega_m^4}{4\omega^4}}$$

which instead of the average period uses the modal frequency (ω_m) together with the significant wave height (H_s). Other spectral functions include the single parameter Pierson Moskowitz spectra and the five parameter JONSWAP.

5 Theory of motion in waves and power prediction

5.1 Equations of motion

The equations of motion for a 1 DOF heaving body can be written [9]

$$M\ddot{z} = F_r + F_e + F_g$$

where F_r is the hydrodynamic restoring forces acting on the body, F_e the exciting forces acting on the body as a result of the wave and F_g is the forces acting on the body from the mooring system (here denoted as $Force_{generator}$).

$$F_r = -a_{33}\ddot{z} - b_{33}\dot{z} - c_{33}z$$

where a_{33}, b_{33} & c_{33} are the added mass, radiated damping and stiffness coefficients respectively.
The exciting force is in the literature given on the form

$$F_e = (a_{33}\ddot{\zeta} + b_{33}\dot{\zeta} + c_{33}\zeta)e^{-kT}$$

where ς is the vertical position of a water surface particle in relation to the still water surface, k is the wave number and T the draught. This is known as the Froude-Krylov force and it is based on a number of assumptions, namely that the cross section of the body is rectangular with a flat horizontal bottom, the small body assumption and the wave is not distorted by the presence of the body.

The MAPS calculation, however, provides us with the hydrodynamic coefficients as well as the exciting force amplitude and phase lag as a function of frequency, why we can adopt the denotation as follows

$$F_e(\omega) = |F_e(\omega)| e^{<F_e(\omega)}$$

Where the < indicates the argument of complex number on polar form. The generator force needs to be modelled in some way. The following model has been adopted

$$F_g = -m\ddot{z} - b\dot{z} - kz$$

where m is the translator mass, k the stiffness of the springs "holding down" the translator according to figure 5 and $b\dot{z}$ represents the electromotive force, E_{mf}, that is subjected to the translator due to power take off [2].

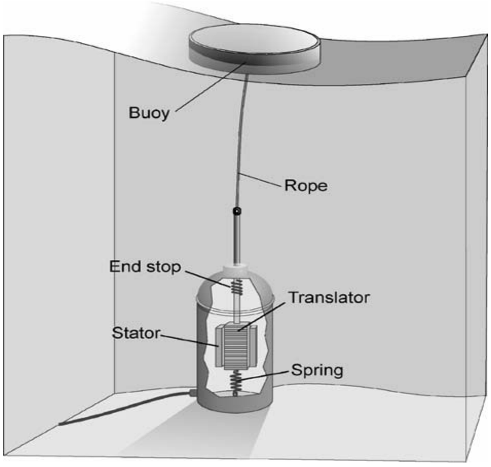

Fig. 5: Wave Energy Converter (WEC) with linear generator, from [8]

Assuming that F_g is linear we can now express the equation of motion like

$$M\ddot{z} = -a_{33}\ddot{z} - b_{33}\dot{z} - c_{33}z - m\ddot{z} - b\dot{z} - kz + F_e$$
$$\rightarrow (M + m + a_{33})\ddot{z} + (b + b_{33})\dot{z} + (k + c_{33})z = F_e$$

which can then be Laplace transformed into

$$(M + m + a_{33})s^2 Z + (b + b_{33})sZ + (k + c_{33})Z = F_e$$

where s is the complex variable. Now, solve for Z (the position in the Laplace plane)

$$Z = \frac{F_e}{(M + m + a_{33})s^2 + (b + b_{33})s + (k + c_{33})}$$

and transform into the frequency plane with

$$s = i\omega$$

yielding

$$Z = \frac{F_e}{(k + c_{33}) - (M + m + a_{33})\omega^2 + i\omega(b + b_{33})}$$

Since we are now in the frequency plane we may write

$$Z(\omega) = \frac{F_e(\omega)}{(k + c_{33}(\omega)) - (M + m + a_{33}(\omega))\omega^2 + i\omega(b + b_{33}(\omega))}$$

which equals

$$Z(\omega)=\frac{|F_e(\omega)|e^{<F_e(\omega)}}{(k+c_{33}(\omega))-(M+m+a_{33}(\omega))\omega^2+i\omega(b+b_{33}(\omega))}$$

given previous discussion on excitation forces. The complex transfer function from wave motion to heave motion is finally given by

$$T_{c_{heave}}(\omega)=Z(\omega)=\frac{|F_e(\omega)|e^{<F_e(\omega)}}{(k+c_{33}(\omega))-(M+m+a_{33}(\omega))\omega^2+i\omega(b+b_{33}(\omega))}$$

which contains the amplitude as well as phase lag behavioural information. To obtain amplification and phase shift one simply performs

$$RAO_{heave}(\omega)=|T_{c_{heave}}(\omega)|$$
$$phase\,shift(\omega)=<(T_{c_{heave}}(\omega))$$

5.2 Power evaluation

The generator coefficient b represent characteristics of the generator according to[1]

$$b\dot{z}=E_{mf}=\frac{2\pi}{w_p}\psi_{pm}N\dot{z}$$

where w_p is the "pole pitch", a fixed distance, N is the fixed number of coil turns and ψ_{pm} is the "permanent magnet induced flux per pole". We know from mechanics that power equals force times velocity, which in this case translates as

$$P=E_{mf}\dot{z}$$

this however would then equal

$$P=b\dot{z}^2$$

which is a non-linear operation that can not be performed in the frequency domain.

The motion spectrum of the floating body can easily be obtained by

$$S_{heave}(\omega)=|T_{c_{heave}}(\omega)|^2 S_b(\omega)$$

where S_b represents the wave spectra. In order to obtain the power generated by the system from this motion description we need to transfer back to the time domain according to previous discussion. This is done by incorporating an Inverse Fourier Transformation which basically superposes the components of the spectral formulation over a finite interval to form the real, time domain motion[12].

Once the motion time trace is available we can find the average power by the following expression:

$$\overline{P}=\frac{1}{T}\int_0^T b\,\dot{z}^2\,dt$$

It is norm in the wave energy generation sector to express the efficiency of a device in the so called "power capture ratio" entity. It is generated power normalized by the incident wave front energy flux according to

$$P_{cr}=\frac{\overline{P}}{2\mathrm{rJ}}$$

where 2r represents the characteristic beam of the device, for a cylinder two times the radius, and J is the incident energy flux which may be given by [8]

$$J=\frac{\rho g^2}{64\pi}T_e H_s^2$$

where T_e is the energy period and H_s the significant wave height.

6 Model

In this section a detailed description of the current model is given. The theory is linked to the actual problem formulations in this thesis and an orientation on the practical set up is presented.

6.1 Overall solution set up and the functionalities of the FRIENDSHIP-Framework

The sought after parameter for this set up is the power capture ratio of the current design, either for a single sea state formulation or as an annual average to indicate the overall efficiency in long term energy generation for a specific location. To achieve this single value a number of steps need to be taken as follows

- The geometry of the current design needs to be generated
- The hydrodynamic characteristics of this geometry must be evaluated
- A sea state must be described in form of a wave spectra
- Power take off characteristics must be taken into account
- A transfer function must be formed given the hydrodynamic properties, and the PTO characteristics
- Given this transfer function and the sea state description the motion of the system can be evaluated
- And finally from the motion and the characteristics of the power take off the generated power can be calculated as well as the power capture ratio

This will give us the ability to analyse the model for one design at the time, making educated guesses as to which design aspects to alter and in what direction to improve the design. In order to achieve an automated optimisation process we must connect the ends of the model in some way. The FRIENDSHIP-Framework is in this thesis utilised to perform just that task. It has the ability to initiate design variable alterations that propagate into an altered geometry as well as ordering the necessary calculations from external software applications to evaluate the power capture ratio for the altered design. Once produced this result is read into the framework and fed into the driving optimisation algorithm. It analyses the result and based on this and previously given results estimate the appropriate direction of convergence for the model and produces a new set of updated design variables. Thus the model has formed an effective loop that automatically searches for a given optimum criterion.

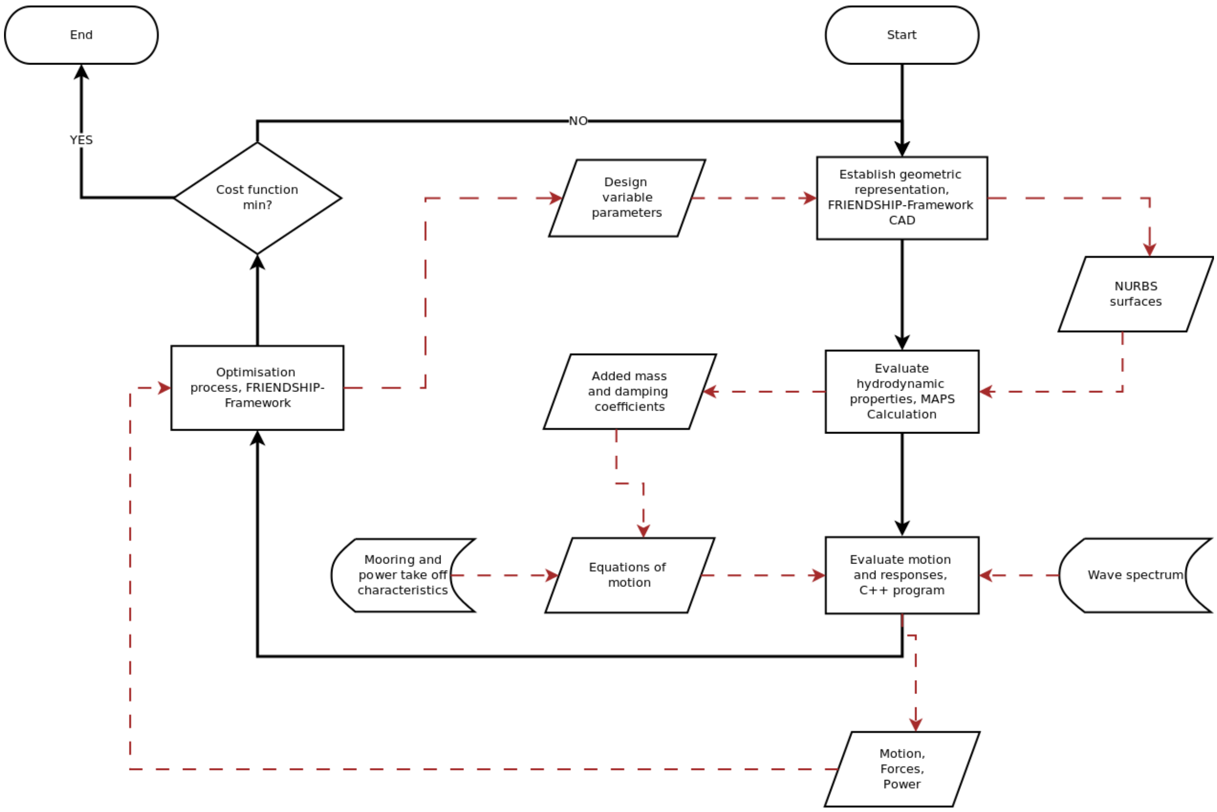

Fig. 6: Optimisation loop flow chart.

Figure 6 illustrates the functional flow of the overall model. Black solid lines represent flow of functionality where's red dashed lines flow of information.

To achieve these different functionalities three different software applications are used. The FRIENDSHIP-Framework drives the design alterations based on evaluated results as well as generate the parametric CAD geometry. The hydrodynamic evaluation is performed by a potential flow code called MAPS, the Motion Analysis Program Suite and the rest of the model namely motion prediction and power evaluation is carried out in a standalone C++ application that was developed for this thesis by the author.

The FRIENDSHIP-Framework also controls the overall process, administers the data transfers between each application and initiates their executables in the appropriate sequence. This tight integration of external software into a Framework model is made possible by the ability to read and write ASCII files that are used as containers for the data transfer between the different stages. These text files can then be passed as arguments to executable codes that have been written to handle this form of input.

6.2 Geometric models

Two parametric geometric models have been developed for investigations in this thesis. One cylinder shape has been used for verification purposes and to act as a simple initial model to work with while achieving the solution.

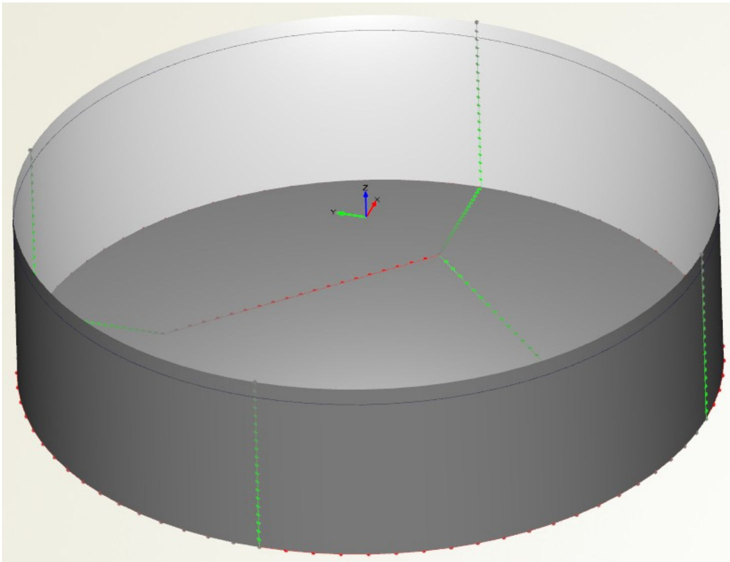

Fig. 7: Geometric model of cylindrical buoy.

It is composed of nine surfaces, four ruled surfaces in the mantle and five coons patch surfaces in the bottom. It has coinciding surface parameters meaning that the u-v resolution is matching over all surface boundaries. Further the size of the bottom centre square surface can be controlled as a fraction of the radius. This set up was found to be working well with the MAPS code for square sizes ~0.63 times the radius (from centre of bottom to corner of square). It is parametrised by the radius and the depth below the water line, which can be seen as a thin line close to the top of the mantle surface in figure 7.

An elliptic-like shaped buoy model has also been developed for the purpose of investigating possible benefits of a non unity length over width ratio. Further it also has the ability to take a cone-like shape, in order to investigate effects of differing displacement depth concentration effects. It is parametrised by four variables, namely the half width, depth, length ratio and bottom ratio where the latter represents the characteristic radius of the bottom as a fraction of the top.

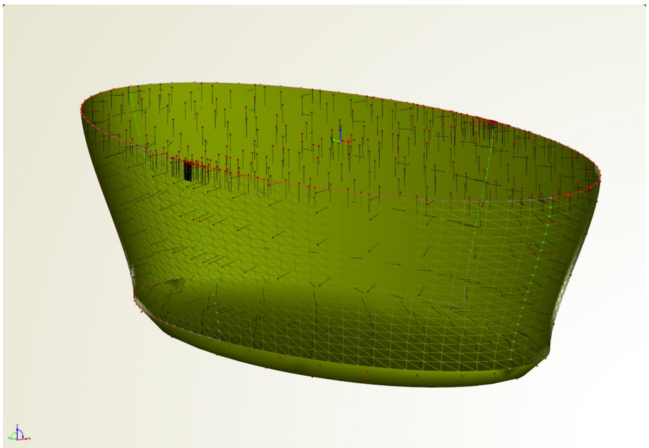

Fig. 8: Geometric model of elliptic buoy with MAPS Gauss point distribution.

The main application for this model, which can be seen it figure 8, is the 2DOF model analysis as it is believed that these geometry alterations have negligible effect in the purely heaving case.

6.3 MAPS

The Motion Analysis Program Suite is a potential flow sea keeping code based on a novel panel free method developed by prof. Wei Qiu and associates at the Memorial University of Newfoundland, Canada [13]. It has the ability to produce comprehensive sea keeping characteristic data for the given geometry such as response amplitude operators, hydrodynamic motion coefficients and exciting forces.

MAPS is based on potential flow theory but differs from the widely used panel method on several accounts. It is claimed that the main sources of error for the panel method lies in

- The discretisation of the geometry,
- The assumption of constant source strength over these discretised panels,
- The evaluation of the singular terms in the integral equation and
- The evaluation of the free surface Green function

MAPS uses a so called “panel free” method that suggests improvements on the first three sources of error. For geometry description NURBS (Non-Uniform Rational B-Spline) are used which allows for a fully mathematical interpretation of the input geometry. The integral equations are then discretised globally over the geometry using Gaussian quadratures which eliminates the need for panel wise source strength distribution. Further Qiu et. al have been able to remove the singularity due to the Rankine term in the Green-function[13].

The MAPS computation is controlled by a number of variables, most notable are perhaps the surface data and the Gaussian-point distribution control parameters. Extensive work was carried out to ensure tolerable error levels by convergence analysis depending on these gaussian-point parameters as well as surface configuration modifications. A thorough description of the verification work is given in section 7.

6.4 Power evaluation code

The power evaluation code has been written by the author of this thesis, in cooperation with the programmers at FRIENDSHIP SYSTEMS GmbH, in the language of C++. A functional flow chart overview of the computations is given in figure 9. The steps taken in the computation are described mathematically in the theory, an outline will be given here.

Hydrodynamic behaviour data is read from a MAPS output file along with the power take off parameters from a configuration file generated in the FRIENDSHIP-Framework. Given this data the complex transfer function is formed which holds information on the systems response to an incoming wave motion in terms of amplification and phase shift.
A set of spectral parameters are also read in combination with information on which spectral function should be use for the sea state description. This data is used to form the wave spectra density function. The spectral function is element wise multiplied with the transfer function to obtain the motion spectrum description of the systems motion in the frequency domain.

To describe the systems real time domain motion an Inverse Fast Fourier Transform algorithm is used [12]. It takes information on each regular component of the motion spectra and predicts the superposition of these over a length equal to the period of the longest wave length. A resolution of 60k data points for one time trace is used.

Finally to asses the generated average power over this time trace a summation of step wise differentials multiplied with the generator damping coefficient is divided with the longest period, see the theory section 5.2.

Results from the computation is obtained from the power prediction, the real time motion as well as the incident energy flux as calculated from the spectral parameters.

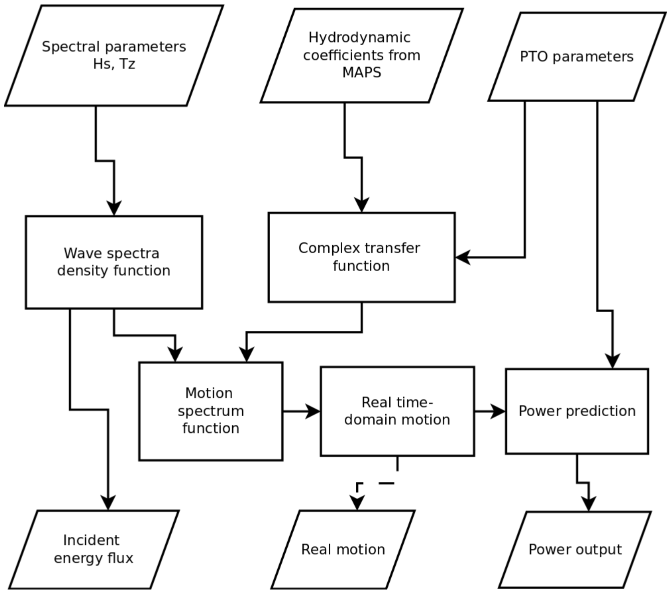

Fig. 9: Power evaluation code, functional flowchart.

Apart from the above given functionalities the code is also able to perform the following features.

- Read MAPS output files and adapt the calculation to the in MAPS used frequency discretisation.
- Estimate the average energy generation over any number of sea states.
- Read generator characteristics from a configuration file generated in the FRIENDSHIP-Framework.
- Option of local optimisation of generator damping with respect to energy generation for each sea state.

This section describes the workings of the 1DOF power evaluation code. The code has also been extended to include surge motion, making it a 2DOF version. The main difference is the formulation of the transfer functions which in the 2DOF case is a series of equations forming the equations of motion in each direction with respect taken to the influence of the other, according to:

$$T_{c1}=\frac{|F_{e1}|e^{<F_{e1}}S-|F_{e3}|e^{<F_{e3}}Q}{PS-QR}$$

$$T_{c3}=\frac{|F_{e3}|e^{<F_{e3}}P-|F_{e1}|e^{<F_{e1}}R}{PS-QR}$$

where

$$P=k_1+c_{11}-(M+m_1+a_{11})\omega^2+(b_1+b_{11})\omega$$

$$Q=c_{13}-a_{13}\omega^2+b_{13}$$

$$R=c_{31}-a_{31}\omega^2+b_{31}$$

$$S=k_3+c_{33}-(M+m_3+a_{33})\omega^2+(b_3+b_{33})\omega$$

for further reference see Principles of Naval Architecture [14]. The following evaluations in the 2DOF version are similar to the 1DOF but occur in two instances. The final power is a superposition of the contribution from each degree of freedom, thereby simulating a wave energy device according to figure 10.

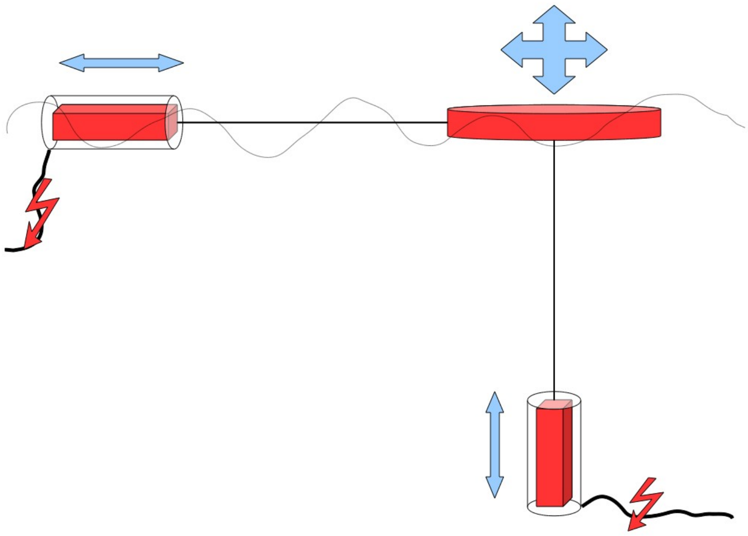

Fig. 10: 2DOF WEC

It must be noted that this is a relatively unrealistic WEC design with many difficult design challenges beyond the scope of this study. The 2DOF model serves the purpose of illustration how integration of other WEC systems can be done as well as investigate the potential for surge motion energy extraction.

7. Verification

In order to verify that the solution is producing results of satisfactory accuracy it is important to perform some sort of verification study. Due to the many collaborating processes in this model several such studies has been carried out.

7.1 MAPS

Comparison of results obtained from the cylindrical model was compared to published results from the constructors of MAPS [13] as well as Newman[15]. Table 1 shows acceptable agreement for the dimensionless added mass coefficients.

KR	Obtained results	Newman	Qiu et.al
0.050	2.458	2.470	2.467
0.100	2.425	2.438	2.432
0.200	2.274	2.286	2.283
0.400	1.955	1.968	1.965
0.600	1.731	1.745	1.742
0.800	1.595	1.608	1.605
1.000	1.520	1.533	1.529
1.200	1.484	1.497	1.492
1.400	1.474	1.485	1.480
1.600	1.478	1.486	1.482
1.800	1.489	1.497	1.492
2.000	1.505	1.514	1.507
2.500	1.547	1.556	1.547
3.000	1.583	1.584	1.591
4.000	1.630	1.636	1.634

Table 1: Comparison of obtained results to published results as well as theory

KR is a dimensionless value for assessing the correct frequency based on the wave number in deep water and the radius of the cylindrical buoy. A slight discrepancy can be seen between acquired values and values given by Qiu et. al. In an ideal case all three columns would be identical, the discrepancy between Newman and Qiu is best explained by the approximations introduced by the panel free method [13] and the discrepancy between acquired values and Qiu may be explained by differing geometry modelling techniques.

7.2 Power evaluation code

It was initially meant to verify the code using the generated power but due to in-availability of the spectral information used in the published results this could not be done. Instead verification of the transfer function was carried out. In the published results transfer functions for three cases of submerged spheres is presented and the good agreement can be seen in figure 11.

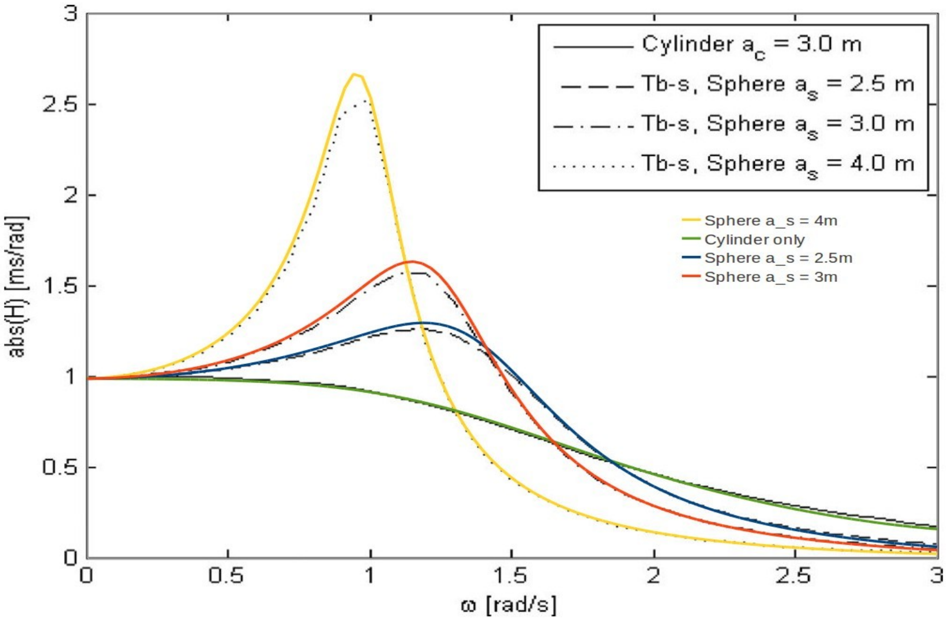

Fig. 11: Comparison of transfer function to published results from [8].

Coloured lines are obtained results for each respective case and grey lines are published results from [8]. The discrepancy can be explained by usage of differing techniques for modelling and hydrodynamic analysis, however the error is small.

8. Results

In this section results from investigations will be presented.

8.1 Benchmark experiment

The initial investigation is meant to enlighten the behaviour of the 1DOF model as well as verify that results point in a similar direction as published results [8]. It has been carried out in three steps and consist mainly of two-dimensional Sobol investigations. The reason for this is the possibility of intuitive visualisation in a three-dimensional plot which allows understanding of the solution behaviour in form of a topographical surface. The following steps were taken

- Two-dimensional investigation of radius and depth vs PCR using generator characteristics as suggested in published results.
- As previous step but for several different total mass values of the system, to find the best performing geometric model somewhat independent of the generator characteristics.
- Choice of best performing geometric model
- Two-dimensional Sobol investigation of total mass and generator damping vs PCR using chosen geometric model and generator spring stiffness from published results.
- As previous step but three-dimensional Sobol investigation of total mass, generator damping and spring stiffness.
- Two-dimensional T-Search of total mass and generator damping using chosen geometric model and spring stiffness from published results.

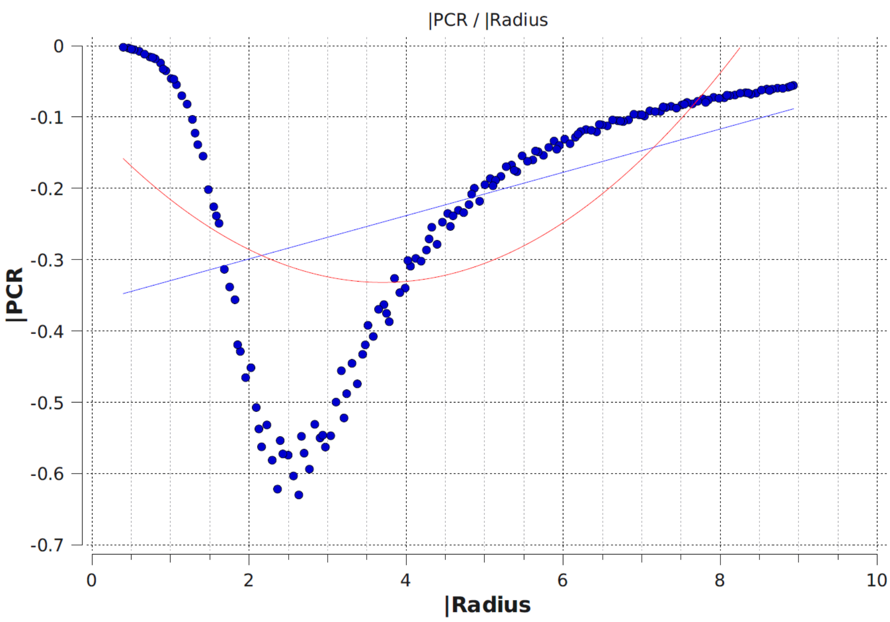

Fig. 12: PCR/Radius, total mass 105ton, gen damp 60kNs/m, spring stiffness 3kN/m. Thin blue and red lines are linear and polynomial regression lines respectively.

Figures 12,14-15 clearly show the characteristic of dependency on radius for the power capture ratio as well as put it beyond all doubt that there is a clearly defined optimum. Further they are meant to relay the dependency of the generator characteristics on the behaviour. We can see a similar behaviour for all three graphs however with a vertical and horizontal shift depending on the difference in total mass.

Figure 13 shows the behaviour of the model when configured similarly to an investigative case in Engstrom et.al. 2009 [8] where the optimum damping is derived for the system with a total mass of 105ton, radius 3 and depth 0.3.

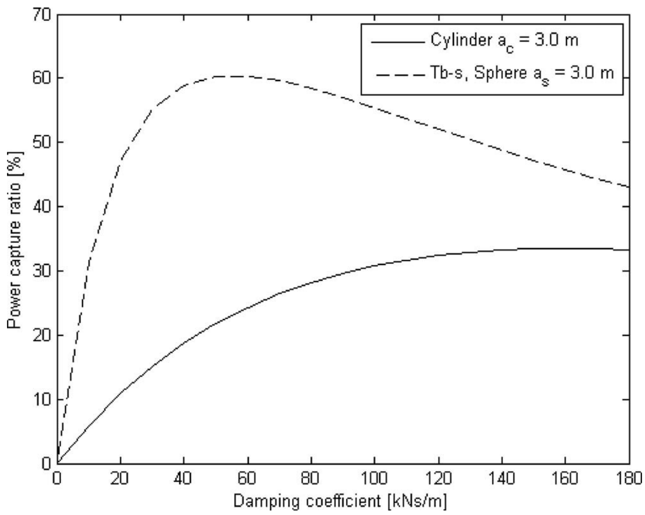

Fig. 13: From Engstrom et.al. 2009[8] showing the selection of 60kNs/m as the optimum generator damping for this specific set up

Obtained results shows clearly a similar behaviour to published results with a PCR very close to 60% for the corresponding configuration. Thereby it can be argued, in combination with findings in section seven, that the model is behaving as expected and that there is a strong effect on the efficiency from even small changes in radius.

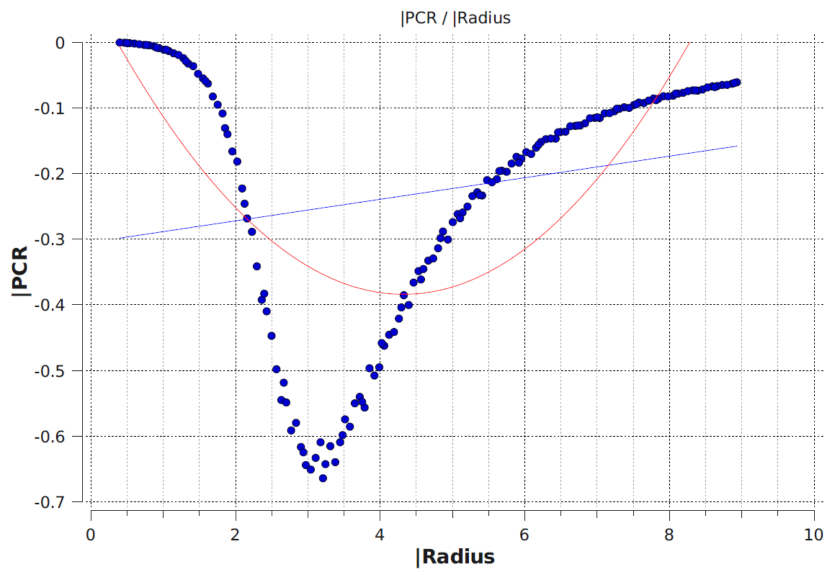

Fig. 14: PCR/Radius, total mass 214ton, gen damp 60kNs/m, spring stiffness 3kN/m.

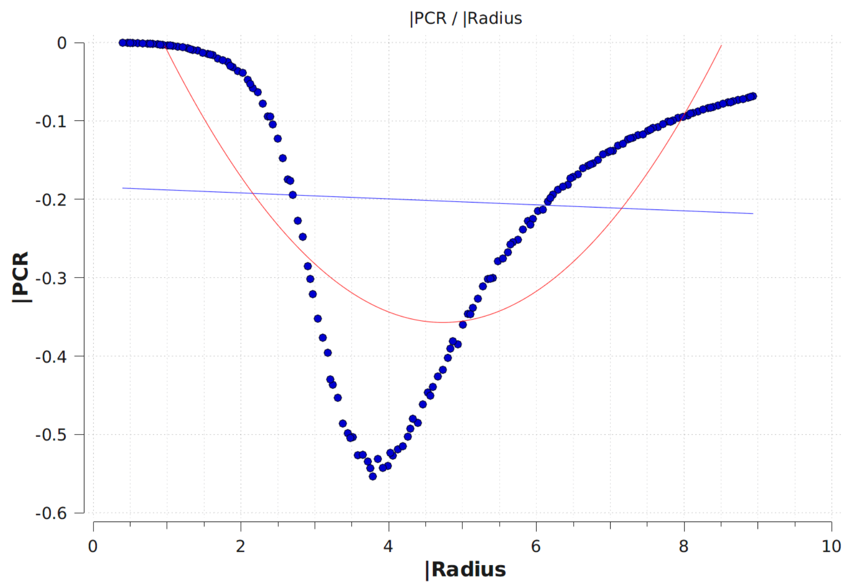

Fig. 15: PCR/Radius, total mass 368ton, gen damp 60kNs/m, spring stiffness 3kN/m

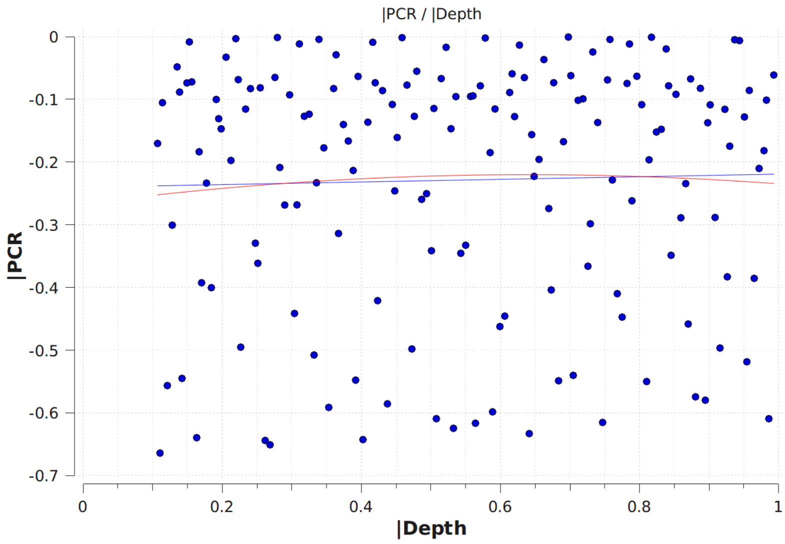

Fig. 16: PCR/Depth, total mass 368ton, gen damp 60kNs/m, spring stiffness 3kN/m

Figure 16 shows the influence from depth on the solution. There is a weak yet distinct tendency for decreased depth of the floating body to benefit the power capture ratio. This is an expected behaviour as it follows from wave theory that the energy content in the wave decreases with depth[9].

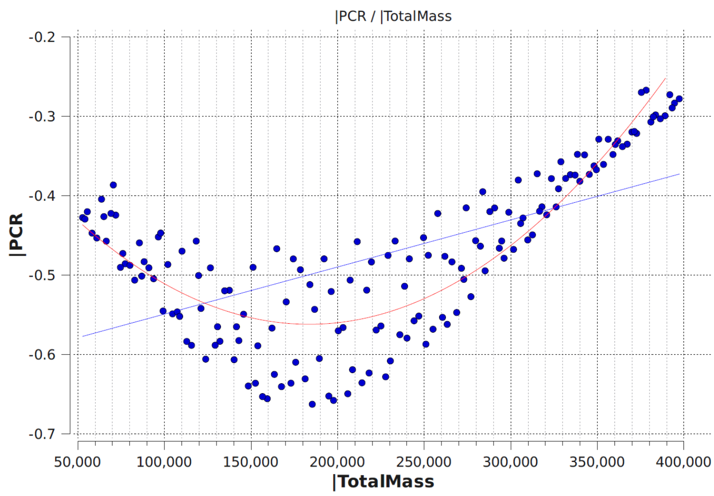

Fig. 17: PCR/TotalMass, Radius 2,97m, Depth 0,27m, spring stiffness 3kN/m

Figure 17 shows the dependency of mass on the system behaviour with a distinct optima to be found around 180ton for the chosen system configuration. The following figure 18 shows the dependency on generator damping coefficient, also here with a clear optima to be found around 60kNs/m further verifying against findings in [8]. These two figures are the result of the same investigation with damping and mass as two variables for the solution, therefore one can imagine the solution to be a surface viewed through the side and end of a box respectively.

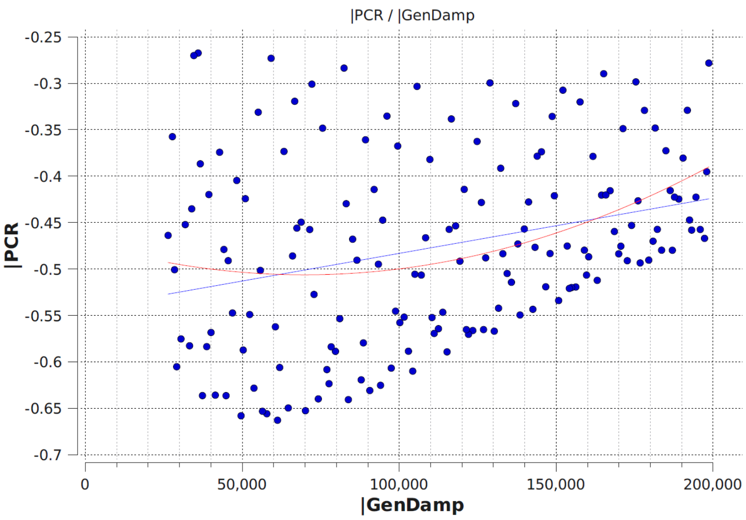

Fig. 18: PCR/GenDamp, Radius 2,97m, Depth 0,27m, spring stiffness 3kN/m

Figure 19 shows PCR as point colour depending on mass and generator damping as well as spring stiffness. It can be concluded from this figure that the spring stiffness has little effect on the efficiency of the system. Also the spring stiffness is subject to hard constraints from other over all design related problems which should therefore be left to dictate this parameter.

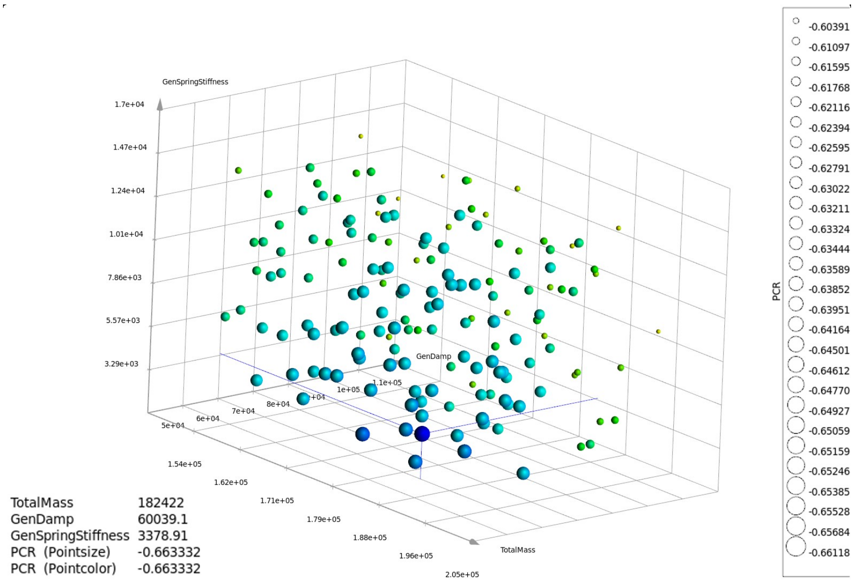

Fig. 19: PCR/Totalmass, GenDamp and SpringStiffness. PCR represented by colour and point size.

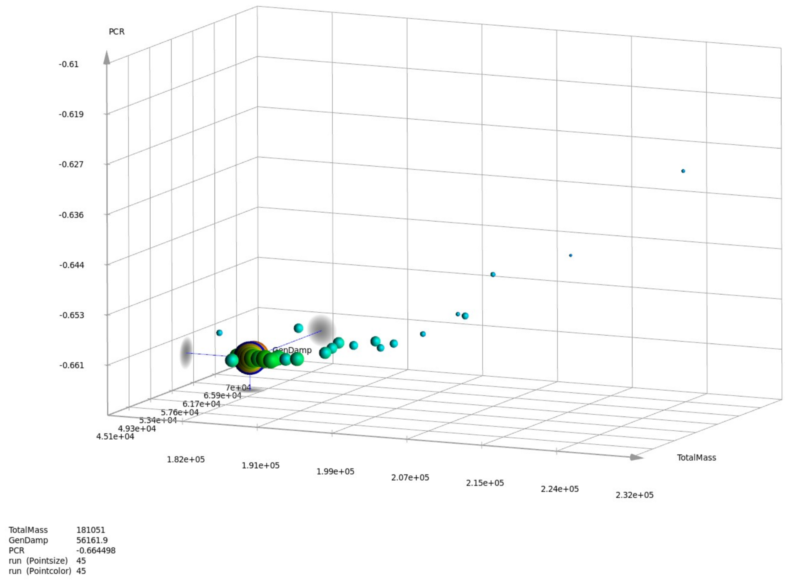

Fig. 20: T-Search progress in two dimensions, point size and colour represents solution run number.

Figure 20 shows the results of a T-Search automated optimisation run subjected to the chosen geometric model with total mass and generator damping as its variables. The point size indicates the run number meaning that the larger the point is the later it has been generated. A clearly converging behaviour can be seen as all the large dots cluster around the optimum point. These T-Search findings also conclude the design estimation for this experiment, following are the final parameters compared to published results in table 2.

	PCR	Radius	Depth	TotalMass	GenDamp	SpringStiff
Experiment	0.66	2.97m	0.26m	181000kg	56000Ns/m	3kN/m
Published	0.59	3	0.3	105000kg	60000Ns/m	3kN/m

Table 2: Comparison of verification experiment results to published results

8.2 Annuity and damping optimisation investigation

An investigation was carried out with the purpose of illustrating generated power differences of the 1DOF system between the single sea state case, a scatter diagram case representing one years sea environment and the same as the latter but with the generator damping locally optimised for each sea state.

The Investigation was carried out as a Sobol investigation in two dimensions altering radius and depth of the floating body but keeping the generator characteristics constant as optimised in the benchmark investigation. The scatter diagram was generated from sea state data given by Engstrom et.al. [8] that have been measured on location in Lysekil. It comprises ten components.

The results can be seen in figure 21 which indicates the single sea state to reach the most efficient energy conversion. This is not surprising as the generator characteristics chosen have been optimised for that particular sea state. As expected the system performs less well given a varying sea state, a near 20% efficiency drop can be seen for the optimal geometry in the Lysekil scatter diagram case. There is also a shift in optimal geometry with a radius reduction of nearly 0.5m. When optimising the generator damping however the efficiency can be recovered somewhat although with an even further shift in optimal radius.

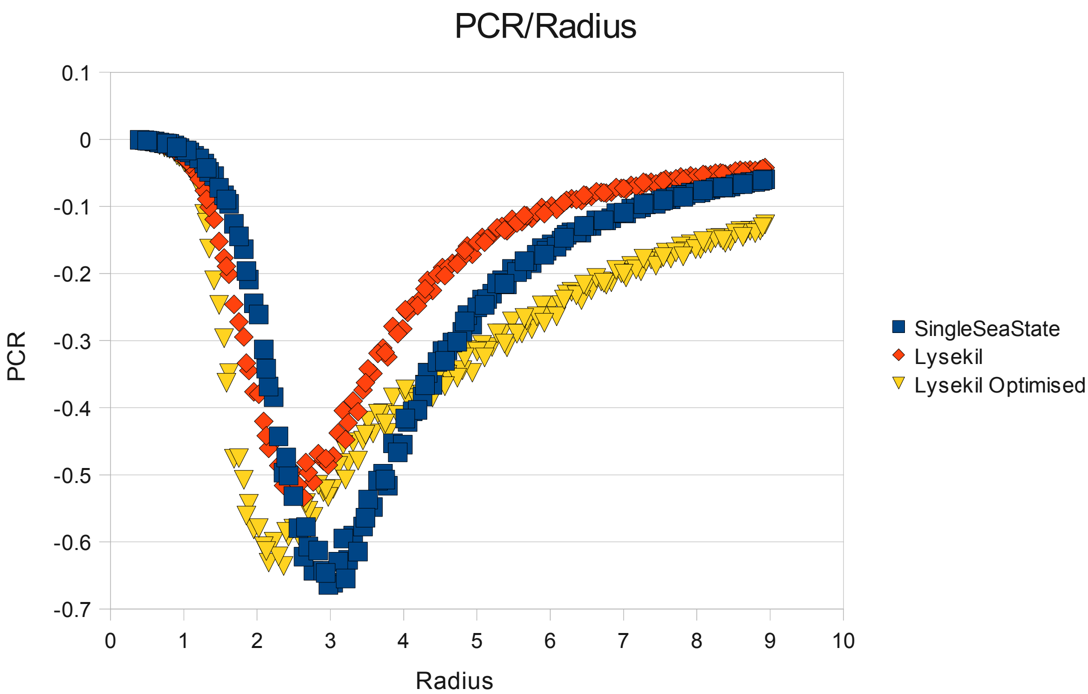

Fig. 21: PCR over Radius for single sea state, annual scatter diagram and annual scatter diagram with locally optimised generator damping.

8.3 Investigation of performance in various locations

This investigation is meant to illustrate the impact on performance with alternating locations. Scatter diagram information, from the Swedish Meteorological and Hydrological Institute publication “Vågor I svenska hav”[31], has been used for five different locations in the Baltic sea. The results in figure 22 shows a small yet distinct difference in performance for the various locations with an optimal pcr of around 0.5 for Finngrundet and ca 0.55 for Vaderoarna.

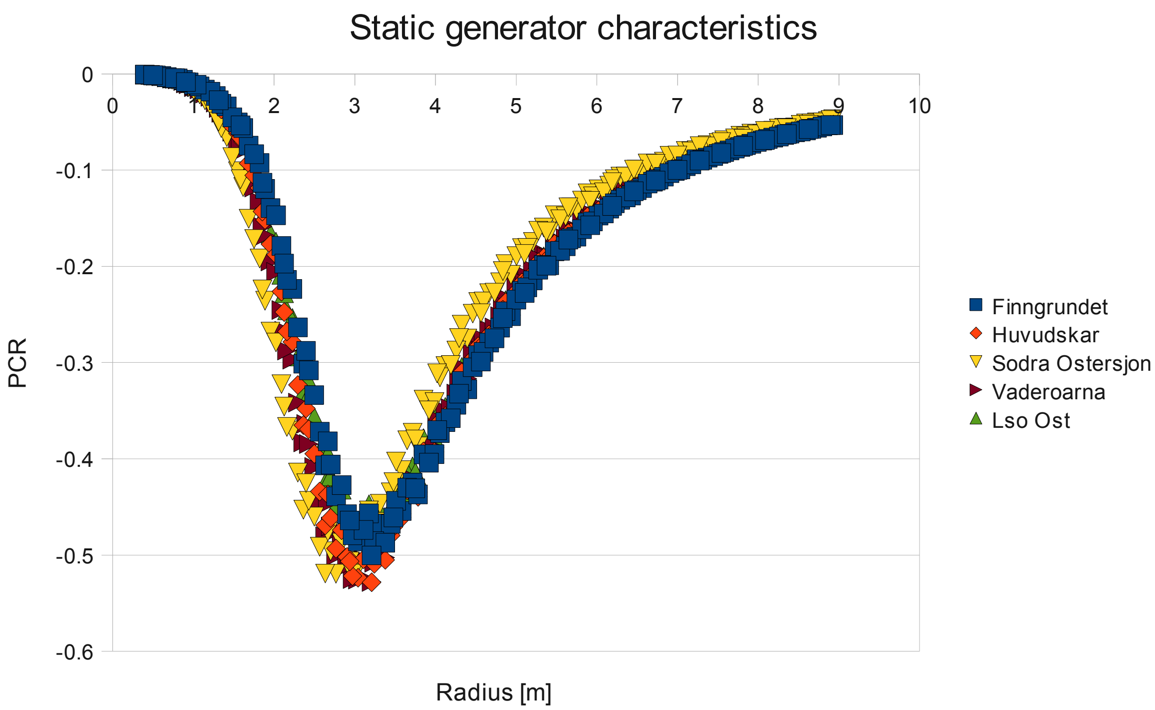

Fig. 22: PCR over Radius for five different locations in the Baltic sea using static generator characteristics.

Figure 23 shows a similar set of results however with the generator damping continuously optimised. The difference in PCR is actually slightly larger between locations in this case ranging from 0.52 to 0.59.

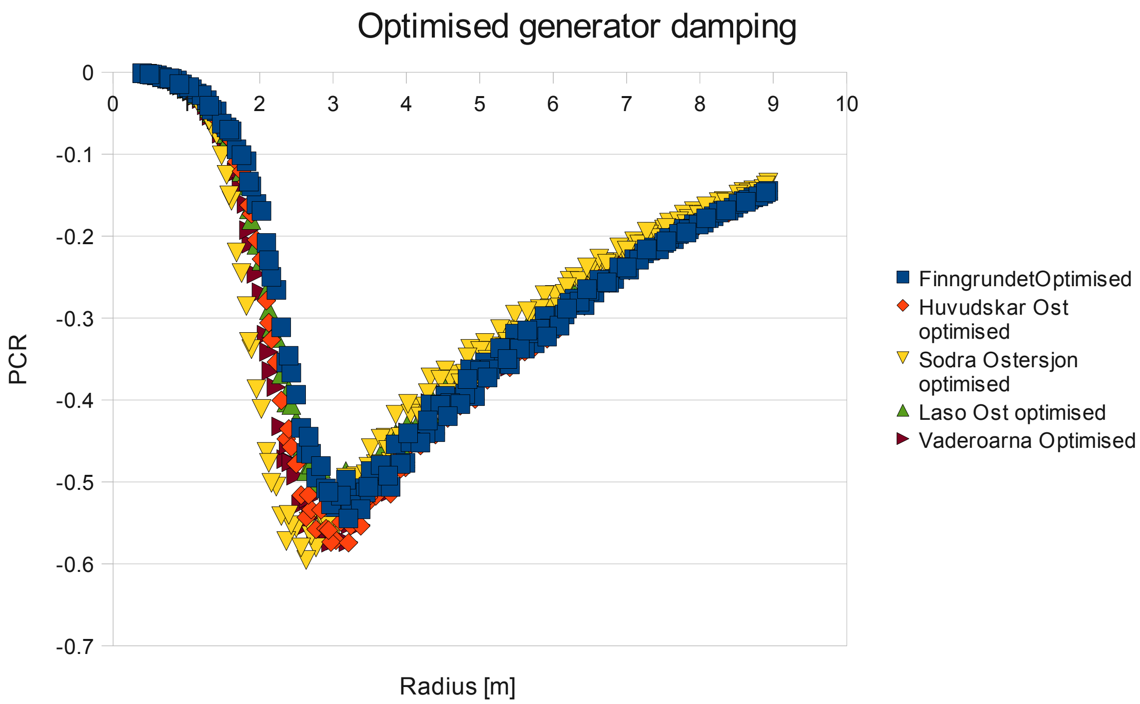

Fig. 23: PCR over Radius for five different locations in the Baltic sea using locally optimised generator characteristics.

8.4 2DOF Basic behaviour investigation

A basic investigation of characteristics of the 2DOF buoy was carried out. In order to limit the number of variable parameters and to save time it was decided to only attempt an investigation of the effects of the length- and bottom ratio parameters. A Sobol investigation was used with the design space spanning 0.5<LR<2, 0.5<BR<1, which had previously been found as practical limits for the MAPS analysis. This parametrisation of the 2DOF buoy leaves the geometric model with constant displacement and frontal surface in the entire design space and was carried out in order to investigate the significance of the surge DOF contribution as well as displacement depth concentration effects.

The main particulars of the system were taken from the initial 2DOF investigation with a half width of 3m, similar generator characteristics in heave direction and a depth of 3m as well in order to produce a significant frontal surface. The surge direction generator characteristics were set to 3kN spring stiffness, 75kNs/m damping and only the approximated buoy mass, as they were found by a fast initial optimisation run.

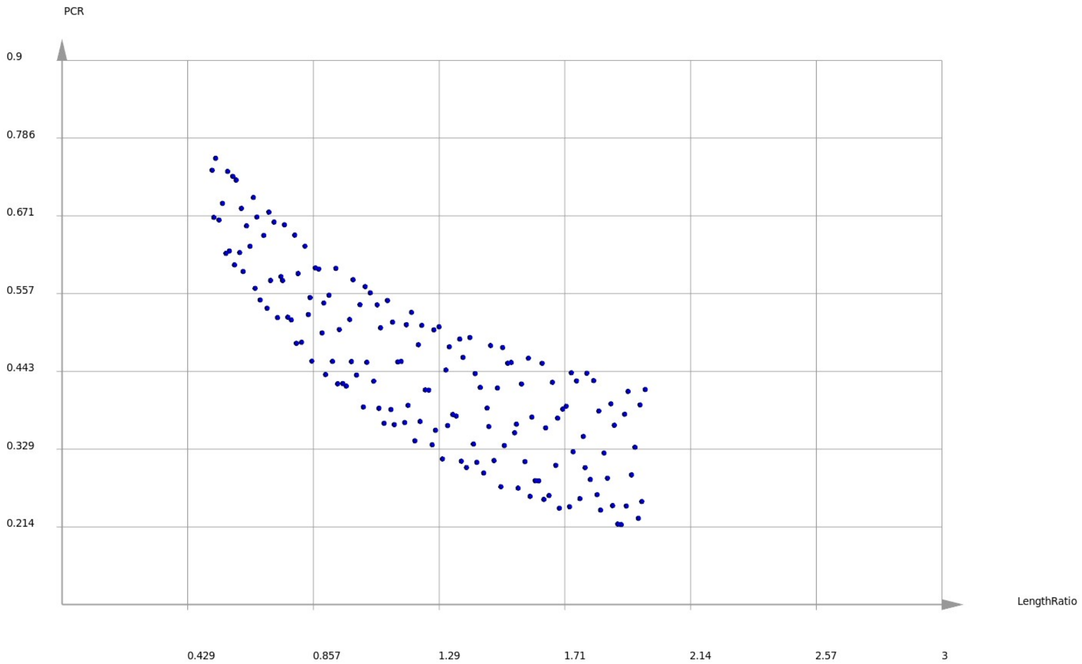

Fig. 24: PCR over length ratio (length over width) of the 2DOF buoy system

Results indicate a reduction in efficiency for lower LR i.e. a wider buoy. This result is logical when considering the formulation of the power capture ratio, as a wider geometry will lead to a greater denominator and a reduction in PCR. This does however not correspond to a decrease in power production, in fact a wider buoy has a greater contribution from surge with near constant heave power and therefore a larger power production in total. Figure 24 shows PCR over length ratio when using a constant radius for the incident wave front energy expression, an analogy to captured power but also a measure of efficiency with respect to over all particulars.

Further it was concluded, as can be seen in figure 25, that bottom ratio variations deviating from the vertical wall case will reduce the overall efficiency of the system.

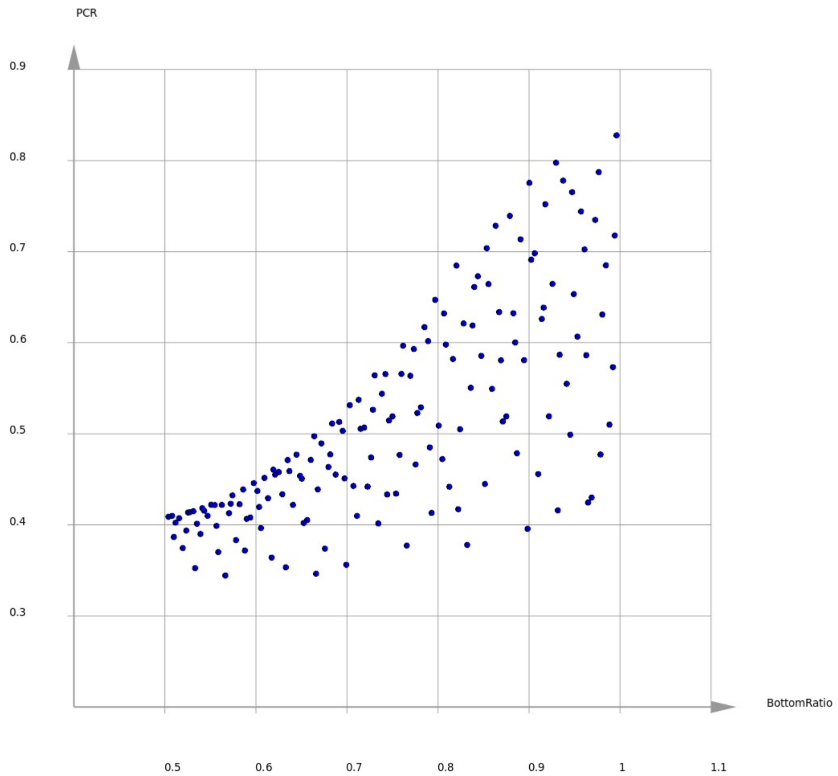

Fig. 25: PCR over bottom ratio (radius of bottom over radius of top ellipses)

9. Summary, conclusions and future work

An automatic optimisation method capable of design of wave energy converters have been established and verified. Several investigatory cases have been used to illustrate the method as well as behaviour of the analysed system in different operating conditions.

From the results it can be concluded, with respect to sensitivity of the parameters, that a proper radius for this particular WEC and sea state is crucial. Depth of the buoy makes a distinct difference however the change is small and this may be subject to other design restrictions. Mass and damping of the system are equally important with respect to PTO characteristics while spring stiffness has little effect on over all efficiency and should be decided by other factors. The benefit of continuously optimised damping in a climate of changing sea states is in the region of 10% which is also the benefit of optimising WEC design for each location in the Baltic sea.

MAPS has been found to be a suitable solver for automated optimisation due to its acceptance of rather large geometry variations without need for "re-configuration" as well as the fact that it uses NURBS as in-data, common out-data for parametric modelling software. Its accuracy has been found to compare with other, more established methods.Further the modularity of the solution allows for fairly straight forward implementation of other WEC analysis codes by mathematical modelling and re-writing of the EOM power evaluation code.

The FRIENDSHIP-Framework was found to simplify establishment of the model. Its capabilities for custom integration of any software that can be run in batch and communicate via csv or xml files contribute to the modularity of the model. MAPS and FRIENDSHIP-Framework in combination promises to be a powerful set up as they both revolve around mathematically described surfaces and can therefore communicate lossless. Further the no-frills optimisation features of the Framework supply capabilities otherwise cumbersome to establish.

Future work should be focused on implementation of other WEC:s possibly using more advanced motion analysis methods, including non-linear behaviour etc.

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