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PROGRAMME

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CONTENT

PART 1

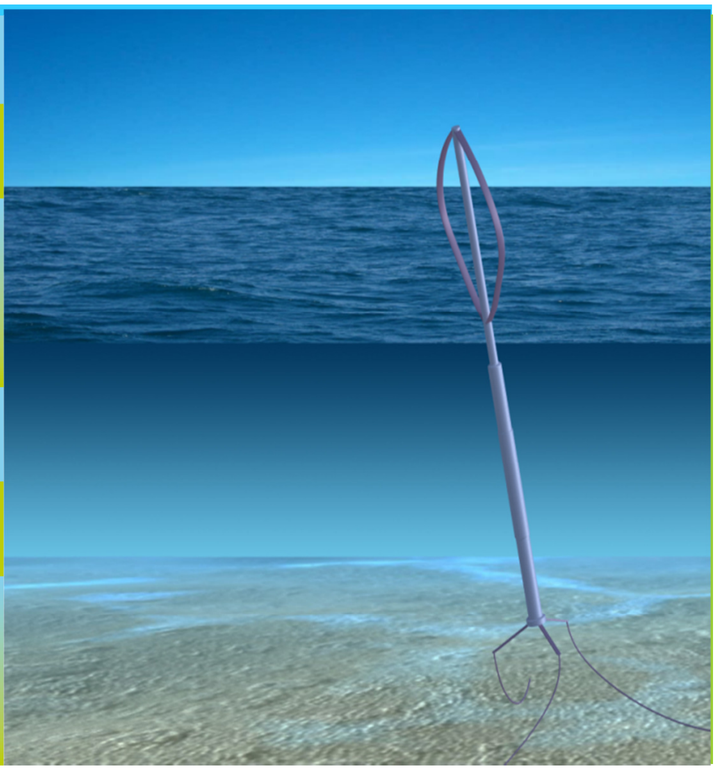
Sizing of a spar-type floating support structure for DeepWind.
Technical report E-0043.

PART 2

Floating spar buoy for the DeepWind concept.
Technical report MT2014 A-008

SIZING OF A SPAR-TYPE FLOATING SUPPORT STRUCTURE FOR DEEPWIND

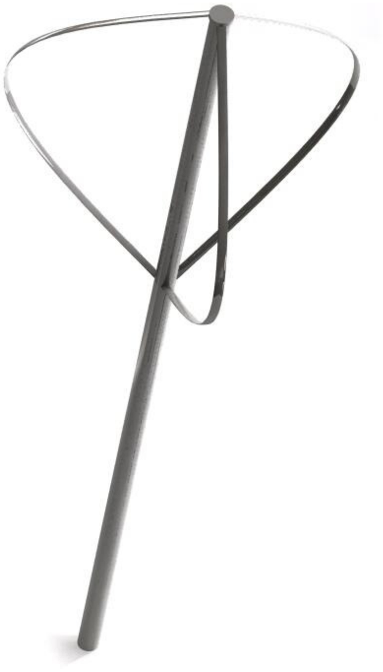
Department of
Wind Energy
E Report 2013



Uwe Schmidt Paulsen

DTU Wind Energy E-0043

November 2013



DTU Wind Energy
Department of Wind Energy

Authors: Uwe Schmidt Paulsen

Title: Sizing of a spar-type floating support structure for DeepWind

Summary (max 2000 characters):

The work describes is a revised work based on the Report RISOE-2614(EN)[1], which originally was carried out for Statoil. The company showed large interest in the VAWT technology for offshore application and expressed the concept of the creation of ideas within offshore (VAWT). Statoil provided the information as background material to DeepWind, a European funded project under FP7 Future Emerging Technologies 2020, and the material has been revised to take into some considerations of this work.

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Preface

This report is a contribution to DeepWind, Fp7 256769 on sizing of a spar-type floating support structure as part of D5.1 in work package 5.

The work describes is a revised work of the Report RISOE-2614(EN)[1] which originally was carried out for Statoil. The company showed large interest in the VAWT technology for offshore application and expressed the concept of the creation of ideas within offshore (VAWT). Beside that Statoil provided the information to DeepWind as background, a European funded project under FP7 Future Emerging Technologies 2020, and the material has been revised to take into some considerations of this work.

The present report focuses on the basic design of existing VAWTs. The knowledge is supported by comprehension of experiences from the literature survey, with emphasis on applications onshore and with objective to translate the technology into offshore applications and answer on why this concept has been chosen. Following key topics have been identified on the floating VAWT designs:

- Foundations (concepts of floating foundations)
- Integration of floating foundations with VAWT rotor
- Design developments/descriptions
- Conceptual modifications from onshore applications

Risø, November 2013

Uwe Schmidt Paulsen

DeepWind Co-ordinator and WP08 leader

Content

Summary

The present report deals with floating wind turbine concepts and why the concept has been selected amongst others to be a candidate for further exploration. A development from the status 2008 is shown and parallels are drawn to present. The emphasis is to consider the integration of vertical axis wind turbine concepts with floating foundations. As such, the report describes concepts without going into too much detail. The considerations made are based on simple calculations and basic judgement. A concept is proposed that differs from existing technology, and which is simple in its basic ideas, but which needs significant development and optimization before a definitive comparison can be made with the existing offshore HAWT technology.

The present overview is taken mainly from RISOE-2614(EN) report[1], and reflects the status as per 2008 and followed up on recent developments.

2. Concepts of floating foundations

2.1 Offshore technology introduction

Offshore technology for wind energy uses different technologies along with size and application concurrent with the development of the substructures. A recent survey on the subject has been performed by NREL[2], from which *Figure 2.1.1* shows a cost estimate comparison of these structures.

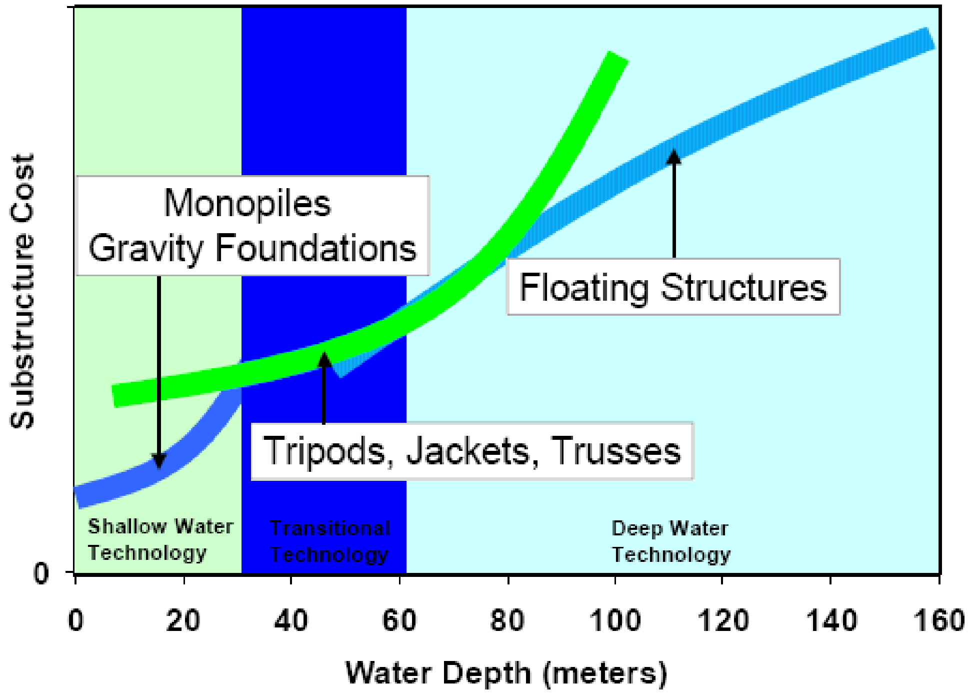

Figure 2.1.1 Cost of offshore wind technology with different water depths, figure from NREL study [2]

Wind turbines (presently horizontal axis wind turbines-HAWTs) are now installed with substructures, using monopole, gravity based or suction bucket technology. These principally possible designs are shown in *Figure 2.1.2*. Foundation types are identified numerically in the figure (from left to right): 1) tripod tower, 2) guyed monopole, 3) full-height jacket (truss), 4) submerged jacket with transition to tube tower , 5) enhanced suction bucket or gravity base; for more deep water; the substructures are transformed into floating substructures as indicated in Figure 2.1.3. It also shows a wide range of floating foundation concepts being currently considered. Foundation types are labelled numerically in the figure (from left to right): 1) semi-submersible Dutch Tri-floater, 2) barge, 3) spar-buoy with two tiers of guy-wires, 4) three-arm mono-hull tension leg platform (TLP), 5) concrete TLP with gravity anchor, and 6) deep water spar.

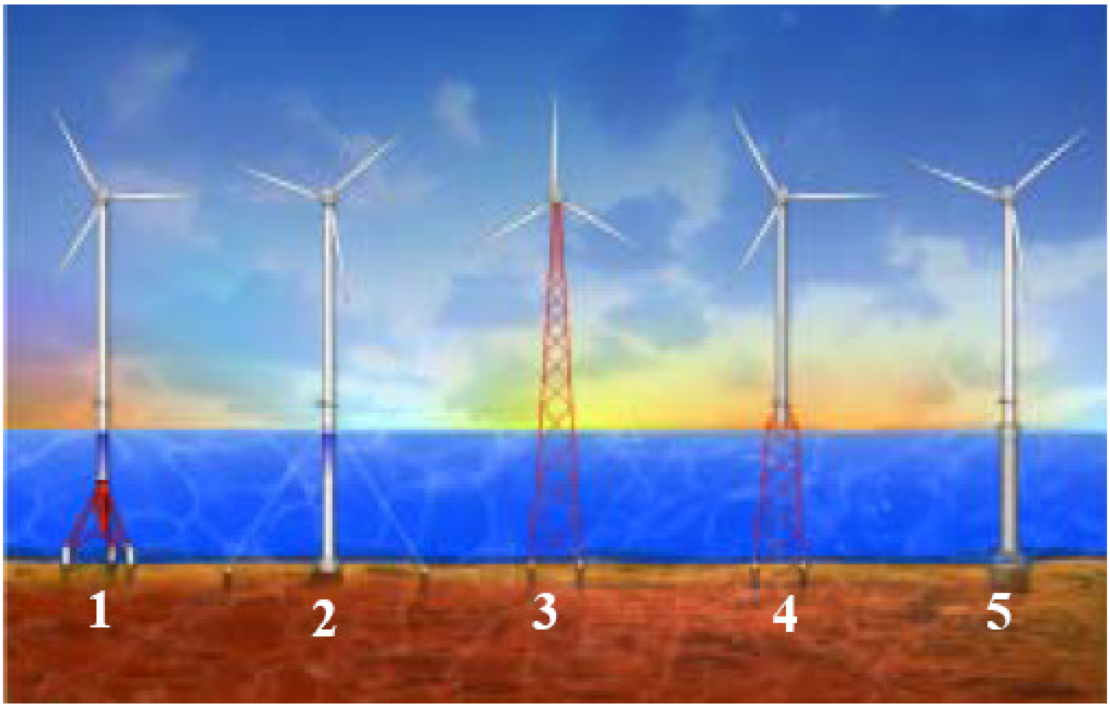

Figure 2.1.2 Transitional substructure technology, figure from NREL study [2]

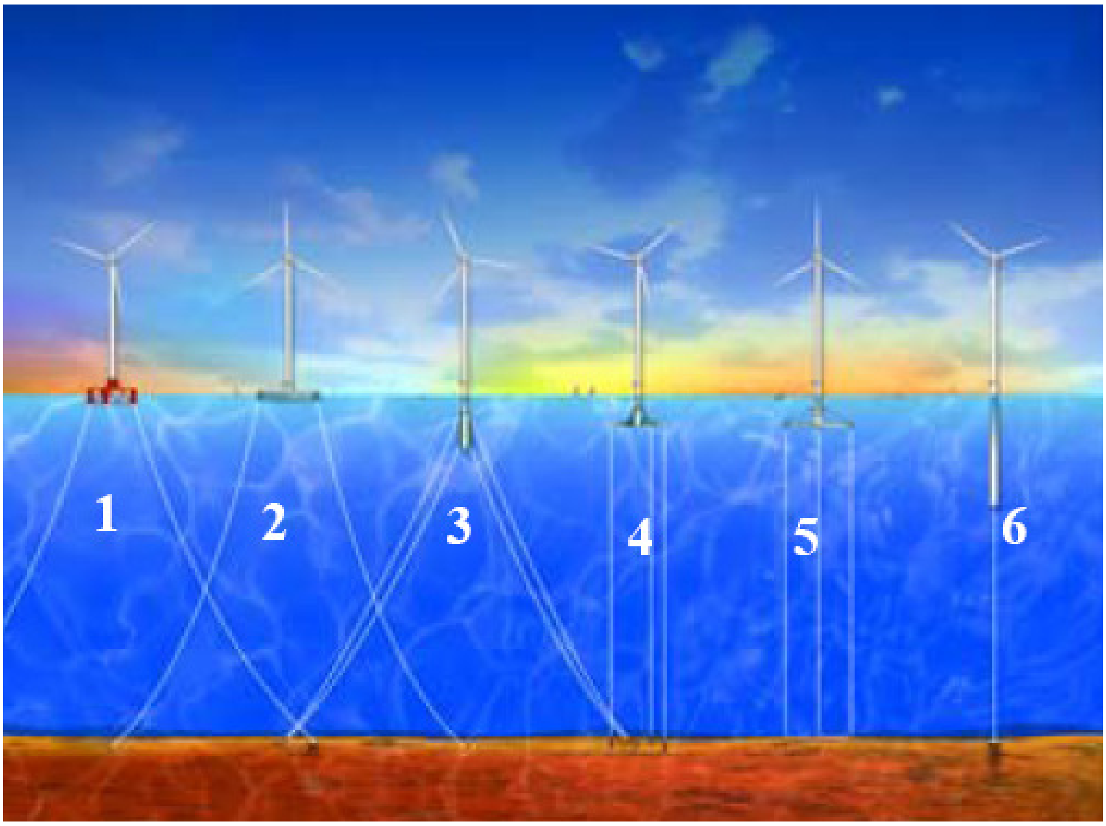

Figure 2.1.3 Floating offshore substructure technology, figure from NREL study [2]

This report deals mainly with the concepts for floating foundations. They are commonly based on point buoyancy and contra-weight on structural members of the entire structure. The report briefly summarizes the two basic principles for designs of offshore technology with HAWT, which still is on the drawing board. The description is further developed for use of VAWT offshore application and evaluated for potential use of this application within this technology. However a semi-submersible design was found which utilizes a VAWT. This concept was developed by EcoPower (and the sister company- Floating Windfarms LLC). The founder of the companies was earlier connected to FloWind Corporation.

There are presently three patents published using HAWTs with floating wind turbine foundation technology: Vestas, HydroStatoil and Sway.

2.2 The Hywind concept

The Hywind floating wind turbine concept [3] was developed by HydroStatoil(now Statoil) with an overall object to provide a technically sound solution for offshore wind power energy production at large scales. The cost ambition for Statoil is to provide a demonstration of the concept competitive with near shore wind farms. The floating wind turbine concept is intended in its first steps as a demonstration project with 2-3MW capacity, with a midterm objective to provide energy for platforms with a typically total load of 100 MW. As a long term potential vision, a comparison was made of the natural gas from Ormen Lange with its predicted production of 125 TWh/year for 20 years with a Hywind windfarm, which for the same amount can be produced from a Hywind windfarm with a size of 20 x 40 square miles. The Hywind concept, *Figure 2.2.1* shows a sectional cut of the submerged part (left picture), and the technical combination of anchor and wind turbine (right picture).

Figure 2.2.1 The floating offshore windmill, from Statoil web site [3]

The concept is basically consisting of a concrete or steel cylinder with ballast and a base case which is 120m deep. The anchor lines positions the floating foundation at water depth of 100-700 m. The capacity is designed for 2-5 MW wind turbines, which allows for a yearly energy capture of 22GWh. In order to achieve satisfactory fatigue strengths in the steel tower, and to keep low fabrication and installation cost, a deep buoy (SPAR) has been designed with low dynamic response compared to the displacement, combined with a 3 point anchoring system with low cost components and installation cost. Furthermore the anchors are shown to balance any remaining torque in the substructure.

With a 3.6 MW wind turbine the height of the construction is according to wind turbine specifications and information on the Hywind concept complying with a length of 103m plus 120 m for the submerged part, in total 223m. The structure height above sea level as well as submerged may be equal as a rule of thumb that is near 240 m of length from blade tip to anchor point.
The fabrication, completion and testing is intended to take place in sheltered waters with this setup. The active control of the wind turbine (pitch and yaw) allows limited turbine motion when operating. Model testing has been made at Norwegian R&D institute Sintef Marintek's ocean basin laboratory in Trondheim, allowing for a 100 year wave.

The innovative cost-efficient anchor concept resulted in an array layout of a 5 times 12 turbine array as shown in *Figure 2.2.2*.

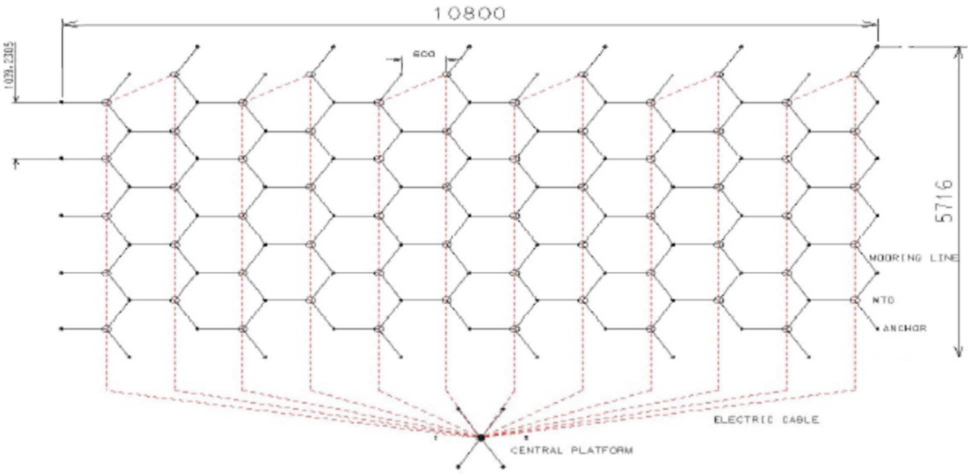

Figure 2.2.2 Layout of the offshore floating platforms in a 5x12 array, figure from Statoil web site[3]

2.3 The Sway concept

This concept[4] is as the Hywind concept intended for operation with HAWTs. The main difference from the Hywind concept is that the single tension leg going to the sea bed suction foundation is considerably in tension providing an excessive downward force well above the combined action of buoyancy and thrust by the structure. Another difference is that the downwind wind turbine yaw arrangement is put at the bottom of the floating foundation part towards the anchor point, see *Figure 2.3.1*. The tower is de-loaded by means of stays attached to the tower top and extending via a support further into the submerged part. The concept has a patented control system providing equilibrium between structure motion and active thrust control.

The concept has been designed as a 5MW project presently capable of using commercial offshore HAWT wind turbines such as Multibrid or RePower. The SWAY system is a floating foundation capable of supporting a 5MW wind turbine in water depths from 80m to more than 300m. The dimension of the structure is such that the ballast pulls the structure down to 100m depth. Furthermore the design is constructed to withstand a 100-year wave of maximum 30m height. With this 5MW wind turbine the following estimate of height is obtained:

Tower height: minimum	60 m
Rotor diameter:	116 m
Blade length:	58 m
Transition zone for wave:	30 m
Submerged part:	100 m
Total foundation part length:	190 m

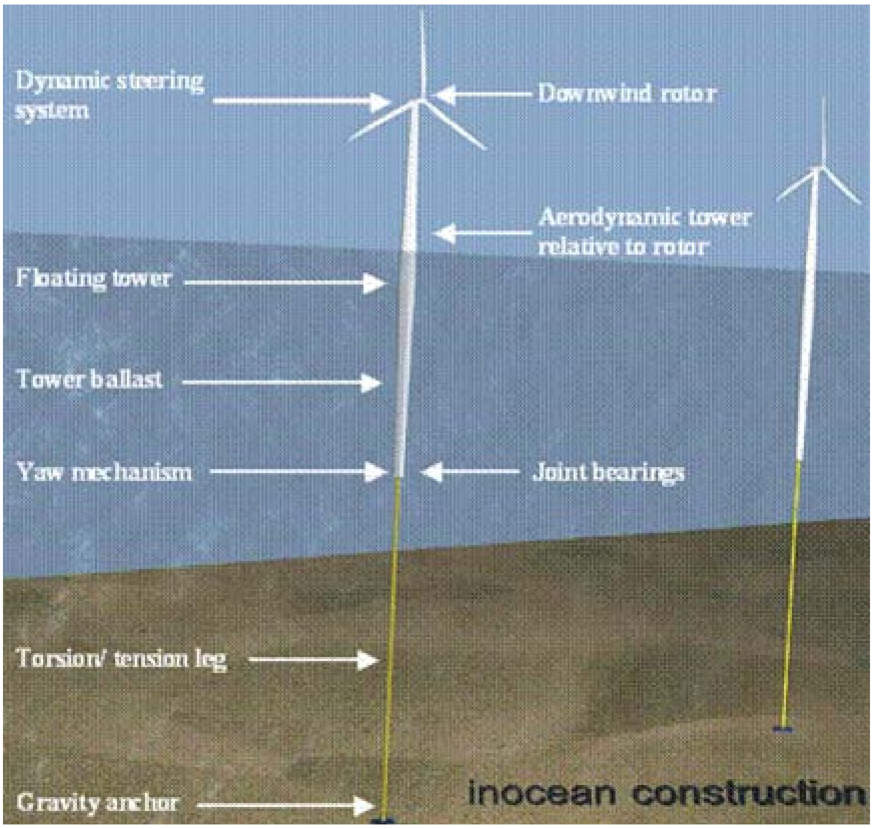

Figure 2.3.1The Sway concept, figure from Sway web site [4]

2.4 The EcoPower concept

One floating offshore VAWT wind turbine concept was found on the internet. EcoPower describes their floating wind turbines as ‘soft’ wind turbines on submerged floating platforms. As from the EcoPower web site [5], these ‘soft’ wind turbines are claimed to:

- cost less to manufacture
- can be placed on floating platforms to harness the strong wind at sea, over shallow as well as deep waters
- can be towed to and anchored at the offshore wind farm sites, and avoid the high costs of offshore foundations and installation
- can be towed back to shipyards for repairs and maintenance avoiding the danger and high costs of offshore repairs and maintenance.

The EcoPowers concept is shown in *Figure 2.4.1*.

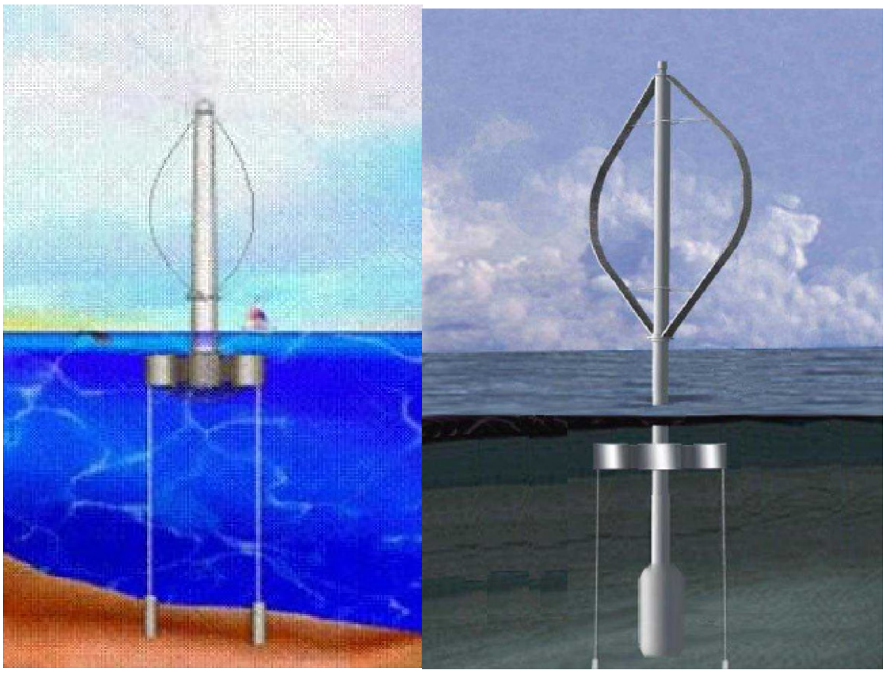

Figure 2.4.1 EcoPower concept, pictures form EcoPower web site [5] indicating EcoPower's on-going conceptual development over time (from left to right)

2.5 Hybrid concepts

The meaning with this is to emphasize on merging the known VAWT concepts from onshore applications with floating foundation as shown in the preceding paragraph; i.e. to show a concept which is mix of an existing VAWT rotor and the support structure of the HYWIND or SWAY foundations.

In order to have this principle to work, the self-supporting main rotor has to rotate over the main part of the foundation as for the HYWIND or SWAY concepts.

A VAWT rotor on either of these floating foundations would benefit on:

- wind direction insensitivity
- floating platform suitable for water depths as intended originally for both projects with HAWTs
- easy transportation and erection operations
- manufacture at shore possibilities and assembly of small parts to integrate entities

- ready to use concepts for motion and power control
- well-engineered concepts and adapted rules on the floating part due to extensive research and development by the companies
- possible use of concrete towers and foundations
- minimum steel material consumption due to well-engineered structure

The possibilities of the self-supported rotor configuration lie within the vertical axis wind turbine rotor family, in particular the Darrieus rotors and the Giromill (H-type) rotors. The most proven VAWT rotor configurations lies within the Darrieus design, i.e. Pioneer (Fokker), Alcoa, FloWind, Sandia, Chinook (Sustainable Energy), Dermond or VawtPower Inc. DAF Indall, Eole.

The main bearings for VAWTs with the HYWIND concept are placed either at the height coincident with the thrust centre as in the case with Pioneer concept, or just in close proximity beneath the lower blade assembly joint (Sandia, VawtPower). In both cases the loads on the bearings are significant due to axial (thrust), radial loads(weight) and bending at the base, and it is judged that the size of the bearings is big and costly (roughly 10-5% of rotor diameter) in order to overcome the loads, compared to HAWTs. (As a rule of thumb for horizontal axis wind turbines, a rotor shaft has a diameter of 1% of the rotor diameter).

The conversion of mechanical power into electrical power is made at the last stage of the drive train just above the non-rotating foundation. Traditionally the combination of gearbox and generator has been widely used on HAWTs. It would probably be more interesting to use permanent magnet direct drive generators in this concept in terms of O&M and weight in this offshore concept.

The SWAY concept with its tension tube going to the suction foundation at the sea bed is a possible technical approach for substituting the horizontal axis rotor with a vertical axis rotor, but in this case without the stays. The SWAY concept is designed for its yaw bearing at the bottom of the floating foundation, and allows for slow rate yawing. In this application it shall be designed to transform the full rotor torque via the anchoring part.

2.6 Floating concepts-status 2013

Several commercial companies have developed floating offshore projects, such as [1]Statoil, [2]Sway, [3]BlueH, [4]WindFloat, [5]Ecopower, [6]Nova and [7]Nenuphar. The last three use a vertical-axis rotor, but they are based on basically onshore technology, where the foundation is fixed compared to the rotor. They are shown in *Figure* ***2.6.1***. A different floating offshore and tilting

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[1] http://www.statoil.com/en/TechnologyInnovation /NewEnergy/RenewablePowerProduction/Onshore/Pages/Karmoy.aspx

2 http://www.sway.no/

3 http://www.bluehgroup.com/

4 http://www.principlepowerinc.com/products/windfloat.html

5 http://www.ecopowerusa.com/floatingTurbine.html

6 http://www.nova-project.co.uk/

7 Nenuphar Executive summary, Charles Smadja June 2009

serpentine turbine has been patented by [8]SELSAM. On the very flexible shaft an array of propeller like rotors deflects the shaft like a Palm-tree in a strong wind.

The concept behind DeepWind was presented in [9]*A Novel Floating Offshore Wind Turbine Concept*. In the article the main features are described of the concept. In contrast to SELSAM this concept does not have a non-rotating generator casing linked to a floating universal joint. The rotors of Nenuphar and Nova use bearings above sea to sustain the rotor, which due to the reaction forces require large bearings. This goes also for the Eccopower and Selsam systems, which use a bearing (and floating) device surrounding the rotating shaft in sea level. An overview of the on-going offshore wind power plants are shown in *Table 1* for comparison. The grouping is barge, TPL, and spar type of floating devices. In the meantime, the Nova project has been cancelled.

A hybrid [11] , which consists of the ½ part rotor, based on the former Flowind VAWT and mounted on a barge, has been analysed conceptually.

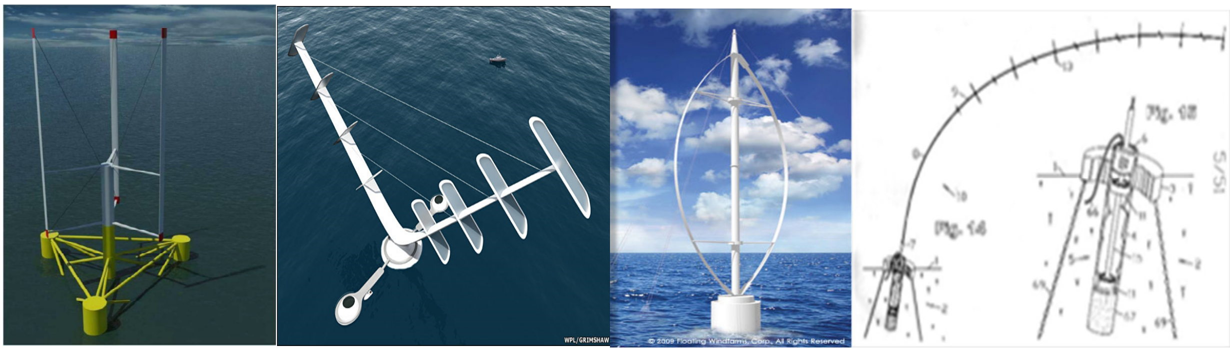

Figure 2.6.1 From Left to Right: Nenuphar (F), NOVA (UK), EccoPower (USA), Selsam(USA)

Table 1 Overview of offshore wind power projects

Project Name	Partner Leader	Status and target of the of project	Platform	Rotor
DeepWind	Risø	Paper/ Academic	SPAR (rotating)	VAWT
HyWind (Skaare, et al., 2007)[1]	Statoil, NO	Demonstration / Commercial	SPAR	HAWT
MIT/NREL TLP (Jonkman, 2007)	MIT/NREL, US	Paper/ Academic	TLP	HAWT
JAPANESE (Ushiyama, Zechi, & Miura, 2004)	JOIA (Japan Ocean Industries Association)	Paper and Prototype / academic and commercial	SPAR	HAWT
BLUEH[3]	BLUEH, UK	Prototype/ Commercial	TLP	HAWT

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8 http://www.selsam.com/

[9] Paper presented at EWEC2009, Marseille. Vita L, Paulsen US, Pedersen TF, Madsen HA, Rasmussen F

VERTIWIND[7]	Technip, FR	Paper /Commercial	TLP	VAWT
Nova [6] **(Cillu et al, 2012)**	Cranfield University, UK	Paper/ Commercial	Barge	VAWT
SeaTwirl[10]	Gothenburg University, Se	Demonstration	SPAR (rotating)	VAWT
FAWT-S/FAWT-C[11] **(Hiromichi Akimoto et al 2011)**	Daejaen University KO	Paper	SPAR-barge hybrid (rotating)	VAWT
ITI Energy barge **(Jonkman, 2007)**	Glasgow University, UK	Paper/ Academic	Barge (squared semi-submerged platform)	HAWT
WindFloat[12]	Principle Power, US	Paper /Commercial	Barge (tri-floater jacket)	HAWT
WindSea[13]	Statkraft, NO	Paper /Commercial	Barge (tri-floater jacket)	HAWT
Sway[2]	Sway, No	Demonstration/ Commercial	Spar	HAWT

3. Design development

3.1 Concept considerations

A new design concept has been proposed and is different compared to the existing floating designs described in the previous chapter.

The principle of the proposed design is an integration of a vertical axis wind turbine rotor with a floating and rotating foundation. The advantages of this concept are:

- a slender 2/3-bladed, self-supporting Darrieus rotor
- the bearings to support the rotor are made up of the floating and rotating foundation
- the heavy parts of transmission system can be put at the lowest level
- the only bearing necessary is a bottom bearing that transfers rotor thrust and rotor torque to anchor parts
- the floating system is simple and has to be manufactured from a limited number of components.
- Transportation and maintenance costs of the device(s) shall be low
- The concept has inherent up scaling features(rotor and carrier)

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[10] www.seatwirl.com

[11] Environ. Res. Lett. **6** (2011) 044017 (6pp)

[12] http://www.principlepowerinc.com/products/windfloat.html

[13] http://www.windsea.com

- Extending the rotor shaft into the water and adding buoyancy capability into the shaft, the water is working as a rolling bearing and damping the dynamic effects of the bending moment on the turbine.
- Dynamic stability of the system, stability of the structure and of the motion (translational and rotational)

A sketch of the proposed design is shown in *Figure 3.1.1*. The principles of the proposed design are described in the following chapters.

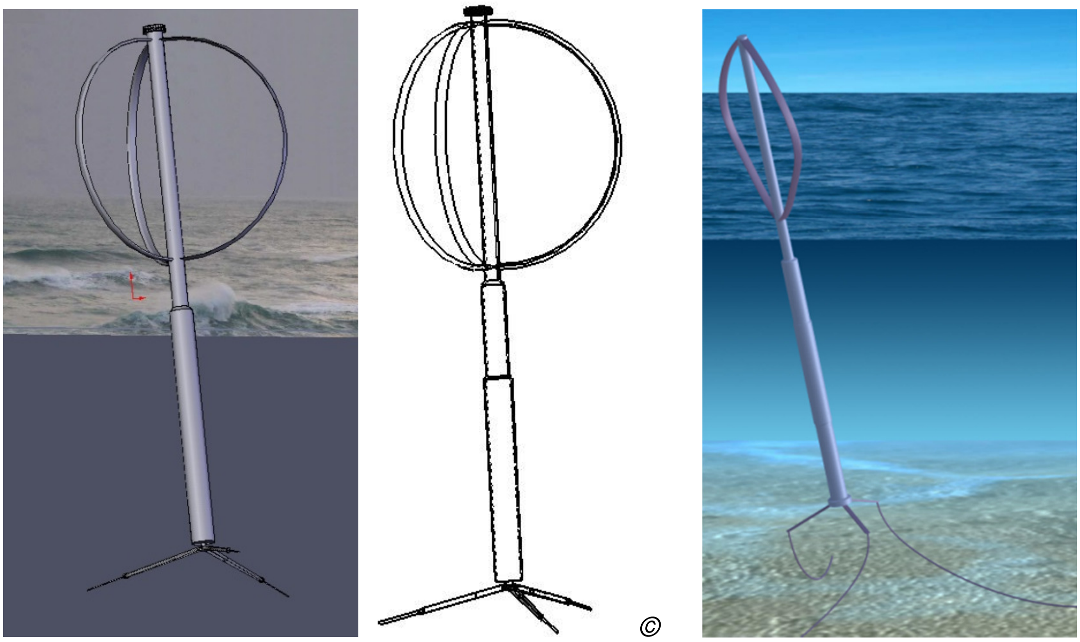

Figure 3.1.1 Sketches of proposed design with integrated rotor and rotating foundation

The carrier which supports these design constraints is of spar type(e.g. symmetrical). As the shaft is integrated as the carrying (and floating) device, the bottle like structure needs a device which absorbs the forces and moments. As a consequence of this, the torque and the thrust from the rotor are transmitted through the substructure to the bottom of the structure. The substructure is anchored to the sea bed with tensioned wires. The forces are transferred through these wires. To take the torque two or more rigid arms are necessary. For deeper water, a floating and mooring system is used. For a floating VAWT, water brakes can be integrated into the submerged part and hence used as over speeding protection. The system can consist of drag devices, deploying from the rotating submerged foundation in case of over speeding conditions.

The DeepWind rotor and the foundation can be towed to the site. A two-bladed rotor, the whole structure, without counterweight, can float and lay horizontally on the water line. Counterweight can be gradually added, to tilt down the turbine. In case that the generator is mounted inside the foundation, it can be inserted from the top of the structure. This is a typical installation in O&G industry and it would be more favourable than for HAWTs, because the lower weight at the top of the tower would reduce the bending moment on the structure during the procedure.

In the present phase O&M aspects are speculative I nature. No experiences are made with the emerging technology in the offshore sector. One aspect deals with the marine growth on the submerged part. Because this growth is associated with photosynthesis developing in the upper layers of the water, there will be a need for 1) procedures to remove the materials, 2) material coatings that prevent marine growth. However this will not be investigated in this phase of the project.

In conclusion, a wind turbine of vertical-axis technology, possessing symmetrical structural features along a vertical direction, is integrated with a highly symmetrical spar buoy and extending deep into the water for proving buoyancy to carry the total weight. The spar buoy is acting as an oversize and hollow rotor shaft for the wind turbine with a generator placed at the bottom of the tube. The design has a low centre of mass and features a high stability in sea.

3.2 Concept Revision

As mentioned in the report, the different carrying devices show a rating in terms of performance from carrier and operations. The DeepWind concept is intended to have following features:

- The rotor is a 2 bladed vertical-axis self-supporting rotor which operates independent on the wind direction and hence independent on the structural coupling between turbine and wave-wind excited loads. The carrier design is not be linked to any preferred damping(e.g. the design is of symmetrical nature)
- The carrying (floating) device is intended to operate in water depths of more than 100 m and to be more long than wide for less cost

3.3 Rotor design (Darrieus)

The VAWT rotor that has been chosen as the most appropriate for the design is the Darrieus rotor. In terms of simplicity, efficiency and costs this rotor type has shown the best performance of VAWT rotor in wind farms in California[6]. A substantial amount of tools for design and optimization for this rotor type and a large database on experience is available. In the selection of the number of blades and the height to diameter ratio several factors have to be taken into account: efficiency, loads, production, transportation, installation.

3.4 Tubular support structure

The wind turbine rotor support structure has in the past been tubular for most designs. In this case the tubular structure is continued all through the construction. The tubular support structure should be considered in three parts:

1. the wind turbine rotor tube,
2. the surface transition tube
3. the foundation tube.

The wind turbine rotor tube should be self-supporting and light, made of steel or aluminium. It shall be able to transfer all the loads from the wind turbine blades to the surface transition tube. The surface transition tube shall transfer the loads from the wind turbine rotor and the loads from waves to the foundation tube. It should preferably be made of steel. The foundation tube shall transfer the loads to the water and to the anchor parts. The foundation tube shall also give the main buoyancy and stability support to the whole construction. It can preferably be made of pre-stressed concrete or steel.

The support structure rotating in the water has some losses due to friction in the water. Meanwhile, this friction is quite small compared to the power of the wind turbine rotor, even if the foundation surface is fouled with sea animals or sea plants.

The long tubular support structure may be used as an elevator shaft for access to the generator and other parts in the bottom. A crane in the top can pull components up and sink them on the outside of the tube.

3.5 Surface transition part

The surface transition tube is the connection between the wind turbine rotor and the foundation. It has the role of taking care of wave loads and of wave splashing. The rotor blades should not hit the water and the surface transition tube should therefore extend 17m above the sea surface. It should also extend 6m below sea surface to take wave loads. These lengths have been provided by Statoil[7]. The surface transition tube should also be able to support some buoyancy because of the basic principle of the design of the wind turbine where the rotor thrust is absorbed in the bottom of the construction. Because the thrust will be absorbed by anchor cables that are tilted relative to horizontal, a vertical reaction component will have to be counteracted by buoyancy in the surface transition tube. As the tubular support structure will both tilt and sink a little under loading the surface transition tube must be optimised to keep the rotor blades free from water. On the other hand, the lower parts of a Darrieus rotor are rotating at slow speed in contrast to a HAWT rotor where tips hitting the water would be disastrous.

3.6 Buoyancy and counter weight of foundation part

The foundation part has to support the main buoyancy part of the whole construction, including the anchoring parts, and it also has to stabilize the construction, so that the tilt of the rotor during loading is kept within acceptable limits. The buoyancy and stabilization is provided by a buoyancy part and a counter weight part. The buoyancy should be positioned as high as possible and the counter weight as low as possible in the foundation. The buoyancy can be provided by the tube itself but could also be added in a tubular chamber on the upper part of the foundation. The buoyancy is provided in water on a submerged body and it is the difference between the vertical component of pressure force on its underside and the vertical component of pressure force on its upper side; therefore it will provide about one ton of buoyancy per cubic meter of displaced volume.

The counter weight should be provided in the bottom of the foundation. It shall be cheap, heavy and stable when fixed. It may be put in the middle and bottom of the foundation, but there may also be made a broader tubular section in the bottom for the counter weight.

The buoyancy and counter weight controls stability and tilt of the construction, but it may also be used to reduce the foundation depth. If, specifically the wind turbine concept is intended for shallow waters, the buoyancy and counter weight can be increased, while keeping stabilization and tilt at the same level.

3.7 Bearing and generator part

The rotor has one bearing construction positioned at the bottom of the rotor. The bearing construction has two purposes, 1)to transfer thrust and 2) to balance rotor torque from the rotating foundation to the anchor parts. The bearing construction is a critical part. It must be kept free of water with an appropriate sealing. Sealing technologies known from ships and submarines must be used to cope with this part. Maintenance is also difficult and should be considered specifically.

The generator has two tasks. One task is to start the Darrieus rotor when wind is high enough for power production. The other task is to generate power. The generator is mounted at the bottom of the construction where its weight has the highest impact on balance, and it may be combined with the shaft in different ways. Figure 3.7.1 shows four configuration principles for mounting and operation of the generator. In the leftmost configuration the generator is mounted inside the foundation and the shaft is going through the bottom to connect to the anchor part. The generator may be separated from the shaft, which is then supported by separate bearings. The power cable must in this case be lead through the shaft to the anchor part. The generator may be taken out through the foundation tube using this as an elevator shaft. The second configuration shows the generator mounted on the outside of the bottom of the foundation. In this case the generator is also transferring the thrust and rotor torque to the anchor parts. The power cable is also in this case led through the shaft. The advantage in this case is that the generator relatively easy can be dismantled and lifted to the surface for repair and maintenance. The third configuration shows the generator mounted on the anchor part. In this case the power cable may be lead through the generator housing. The generator shaft just has to be connected to the bottom of the rotor. The last configuration shows a configuration where only the shaft is mounted in the bottom while the generator is split into two generators mounted in two turbine gondolas. The turbine gondolas each have a turbine directly connected to the generator shaft, and through the water flow due to the rotation they convert the rotor power to electricity.

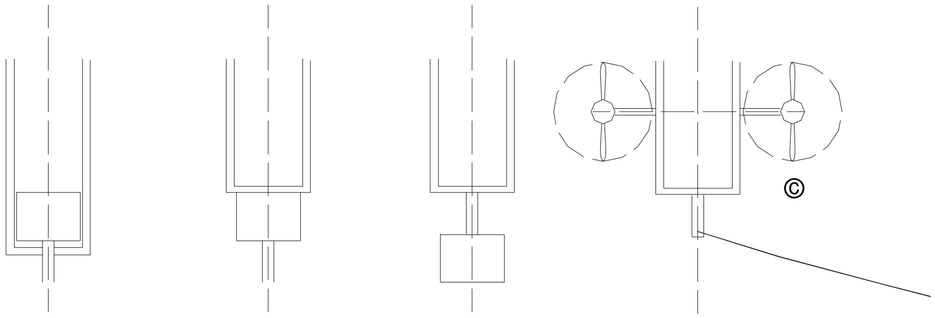

Figure 3.7.1 Principles for mounting of generator

Whatever generator configuration is used the generator and shaft must be designed specifically to their purpose and operational and environmental conditions. The generator may be considered as a component operating under deep sea conditions and be designed to operate under varying water pressure conditions. This may be achieved by adjusting the pressure inside the generator to the outside water pressure, thereby avoiding sealing problems.

3.8 Anchoring part

The anchoring part connects the wind turbine rotor with the sea bed foundations. Both the thrust and rotor torque must be transmitted through the anchoring part. The thrust is easily taken up by reaction forces in the anchor chains, while the rotor torque must be transmitted through torque arms connected to the anchor chains. The torque arms must be adequately long to transfer the torque in critical situations and avoid being pulled around with the foundation. With a pre-tensioned guy wire connected to the anchor chain the pre-tensioned guy wires react with elastic forces due to movements, hereby increasing systems damping considerably.

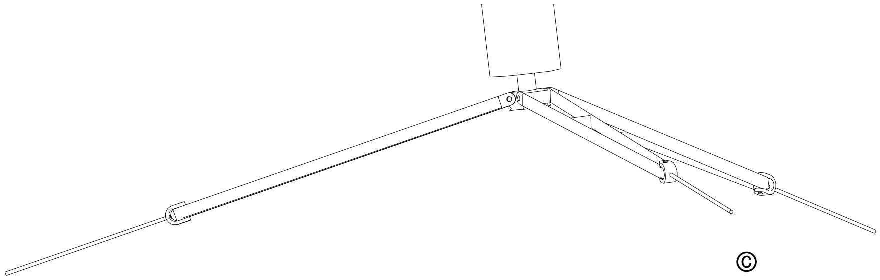

Figure 3.8.1 Arrangement of torque arms on the anchoring part

A favourable configuration of anchor chains is to connect three anchor chains to the torque arms in one end and to connect them to sea bed foundations in the other end, see Figure 3.8.1. In a wind farm configuration these sea bed foundations each connect to three wind turbines, like the Hywind concept[3]. A mass attached to each cable may contribute to control a proper transmission of the reaction forces to the sea bed foundation.

3.9 Counter rotating drag device

A special configuration of the anchoring/generator parts is a counter rotating drag device as shown in Figure 3.9.1. In this configuration the rotating drag device is connected to the rotor of the generator and rotates at a slow rotational speed while developing drag that counteracts the rotor torque. In this case the rotating foundation has to be connected to the anchoring part through another shaft going through the middle of the rotor shaft to the drag device.

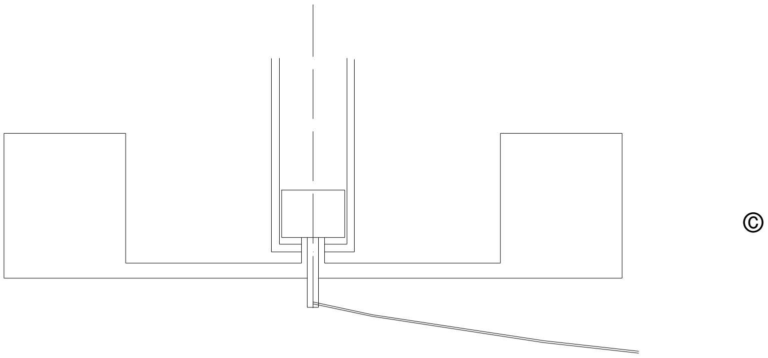

Figure 3.9.1 Counter rotating drag device that transfers rotor torque to the water

The advantage of this configuration is that the rotor torque does not need to be transferred through torque arms of the anchoring part. The anchor chains can be directly connected to the centre shaft. A disadvantage is that the configuration generates a power loss. The power loss is in the order of the rotational speed of the drag device to the rotational speed of the wind turbine rotor.

If we designate the wind power with $0.5\rho A U^3 C_P$, and for equilibrium conditions the water opposes with a power of $\eta N 0.5\rho_w A_w U_w{}^3 C_w$, a relation between U and U_w (which is identical to ωR of the undersea panel) and the ratio in the following is called λ, which can be derived as:

$$\lambda = \sqrt[3]{\eta N (\frac{\rho_w}{\rho})(\frac{A_w}{A})(\frac{C_w}{C_P})}$$

Figure 3.9.2 shows the efficiency of the panel for different number of panels of equal size.

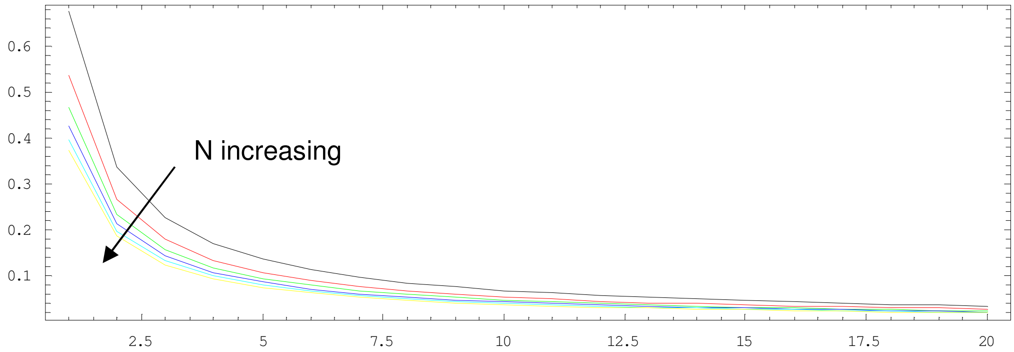

Figure 3.9.2 (U,Uλ^{-1}) for various number of panels N at an efficiency η of 60%

3.10 Water brake as safety device

Most wind turbines need safety devices to be deployed during over-speeding conditions. Pitch regulated wind turbine use their pitching system to stop the rotor. Stall regulated wind turbines as the Darrieus wind turbines proposed in this concept need air brakes; we propose water brakes, because the efficiency of water brakes compared to air brakes is much higher, see Figure 3.10.1. Only small drag devices are needed to generate high drag because the density of water is about thousand times larger than the density of air. Another idea for a safety system developed during the near to real test carried out on the 1 kW demonstrator in Roskilde fjord. Waves were sometimes too high compared to design conditions, which resulted in a slamming of the wave on the blades. The rotor speed dropped instantaneously during the impact.

So the idea came up to 'sink' the turbine with intent, by letting water at the bottom enter and in this way drag down the structure until the water hits the blade roots.

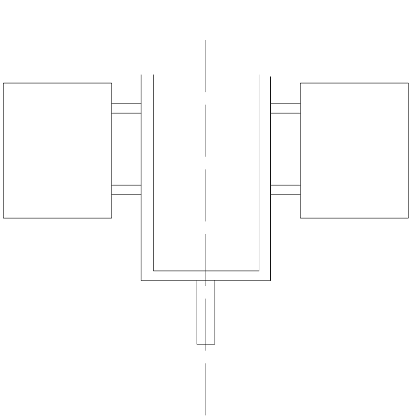

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Figure 3.10.1 Sketch showing drag devices deployed from the rotating foundation to counteract the rotor power as a safety device

4. Rotor and floater designs

In this chapter some design considerations and their cost consequences will be made to study the Darrieus wind turbine concept, based on simplistic assumptions for the rotor and for the design of the floater in non-wavy sea conditions. There will be made some consideration to optimize it and some realistic examples will be shown. This analysis is based on a multiple stream tube 2D model, developed at Risø. The simulations are based on simulations for a 1MW wind turbine, with simple tube geometry for the floater.

4.1 Assumptions

The rated wind speed for determination of the nominal power has been considered to be 13-15m/s as supported by literature 8, 9]. A wind shear profile was used in the model with a roughness constant of z_0 =0.0001 (up to 10m/s) and 0.01 (for wind speeds above 10m/s). The reference wind speed is considered at the equator of the wind turbine (the horizontal mid plane of the rotor).

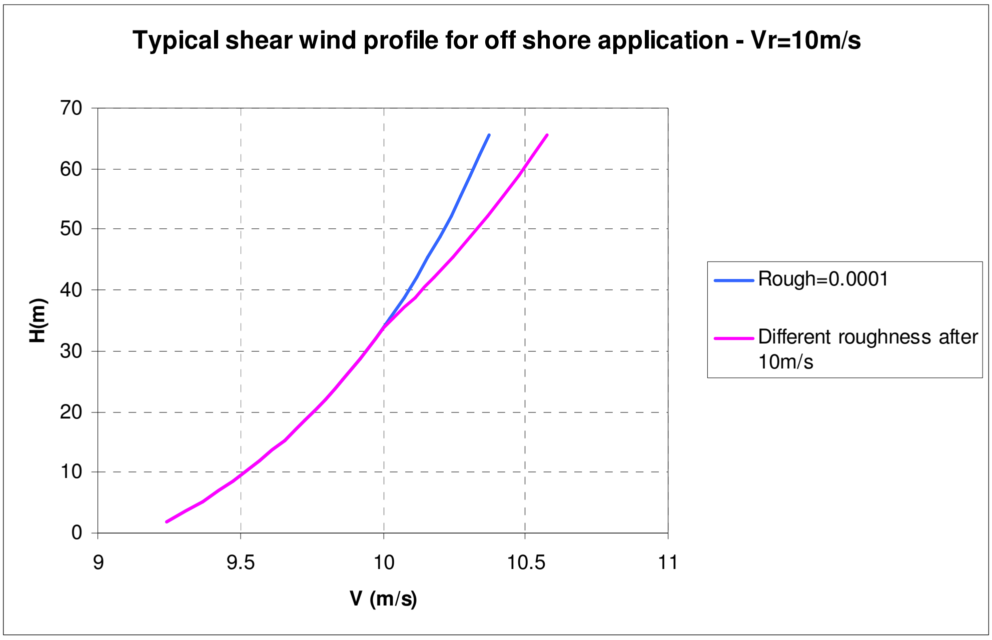

Figure 4.1.1 Wind Shear profile

The wind direction is not considered in the study because the turbine is wind direction insensitive. Furthermore, waves are not considered.

The applied assumptions are very simplistic; the wind shear profile is more adequately described as a function of turbulence intensity, averaging time(other than 600s), and height in a dependency as shown in Figure 4.1.2 from data derived at Statfjord(No)[12]:

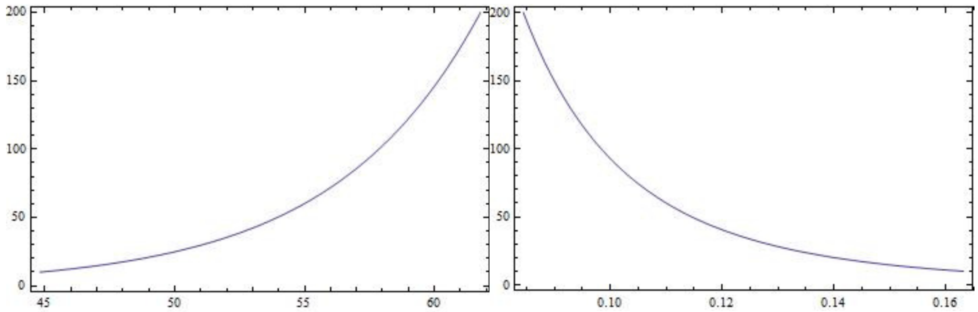

Figure 4.1.2 Left: Wind Shear profile turbulence and Right: Wind shear mean wind speed[12]

The solidity (s=Nc/R) of the wind turbine was fixed at 0.15, where the number of blades (N) was three. The swept area was fixed at 2019 m^2, according to chosen rated wind speed. The study and optimization of the structure are based on the basic principles of forces, sketched in *Figure. 4.1.3*:

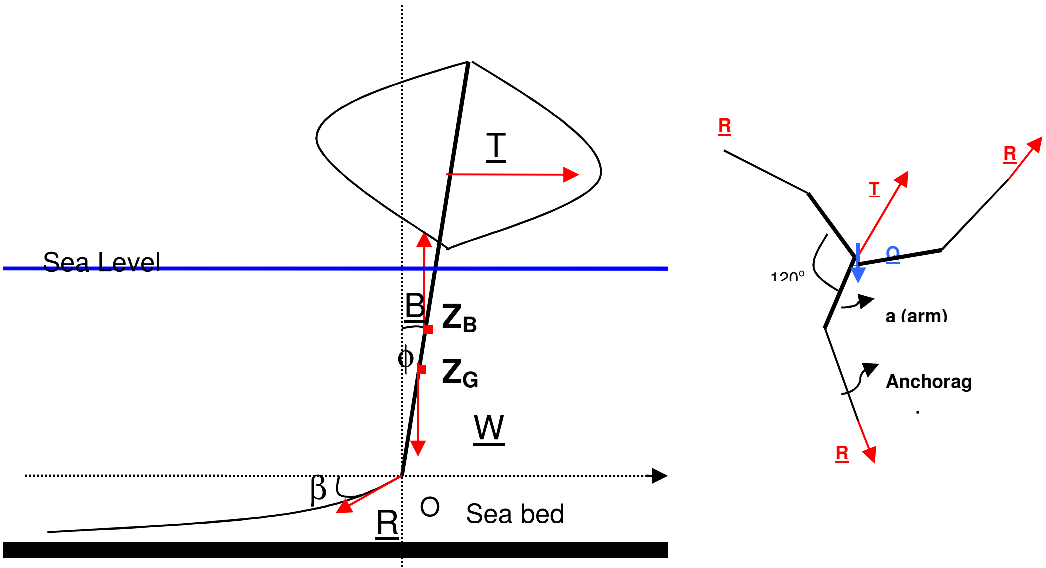

Figure. 4.1.3 Scheme of the forces by lateral and top view.

The symbols being used are:
T is the thrust of the turbine at the rate conditions;
B is the buoyancy of the underwater part of the structure;
W is the weight of all the structure;
R is the reaction force of the cable;
Q is the rated torque of the turbine;
Z_G is vertical coordinate of the center of gravity of the all structure;
Z_B is vertical coordinate of the center of the buoyancy of the underwater structure;
β is the angle between the wires and the turbine;
ϕ is the angle between the rotor and the vertical;

a is the arm of the force that has to equilibrate the torque.

Other symbols being used in the analysis are:
r is External radius of the rotor tube;
r_i is Internal radius of the rotor tube;
R is Radius of the rotor;
h is Height of the rotor(55 m);
ρ is h/R;
s is Solidity is Nc/R;
c is Chord;
N is Number of blades;
L is Length of a blade;
H is Height of the foundation structure;
H_0 is Distance between the bottom of the blade and the sea level(17 m);
H_1 is Height of the first part of the structure underwater that is been considered subjected to the bending moment due to the thrust is6m;
H_{TOT} is Total height of the structure;
H_{som} is Height of the underwater part of the structure;
H_w is Depth of the water;
Z_w is Height of the wires, measured from the sea bed;
L_w is Length of the wires;
A is Form parameter in cable design
p is Specific load vertically
σ is Bending stress
σ_{LF} is Ultimative material stress
I is Quadratic moment of inertia
y is Ordinate axis perpendicular on the tube axis
M_1 is Bending moment on the rotor;
M_2 is Bending moment at the sea level;
M_3 is Bending Moment on the bottom of the surface tube;
V_r is Reference speed, considerate at the center of the rotor.

Except from being able to resist the aerodynamic loads the Darrieus rotor part has to be as light as possible in order to reduce dynamic loads and to increase stability of the construction. Some simple assumptions are made for a basic dimensioning of the construction. The only loads considered are the aerodynamic loads (the full thrust) and the gravity. The cycle components of the loads and other additional loads are not considered. For a full analysis of the wind turbine concept all loads must be included in detail, such as aerodynamic loads, gravity loads, dynamic loads, wave loads, starting loads, etc.

To have a simple scheme for the structural analysis we take into account simple beams, with homogeneous material and a safety factor SF of 2:

$$SF = 2 = \frac{\sigma_{LF}}{\sigma} \text{ with } \sigma = \frac{M \cdot y}{I}, \text{ y=R, } I = \frac{\pi\left(r^4 - r_i^4\right)}{4},$$

r external radius and r_i internal radius of the structure. The bending moment M is calculated in 3 positions (bottom of Darrieus rotor, at sea level and 6m below sea level) giving M1, M2 and M3:

$$M_1 = T \cdot \frac{h}{2} \; ; \quad M_2 = T \cdot \left(\frac{h}{2} + H_0 \right) ; \quad M_3 = T \cdot \left(\frac{h}{2} + H_0 + H_1 \right)$$

The bending moment distribution is shown in *Figure 4.1.4*.

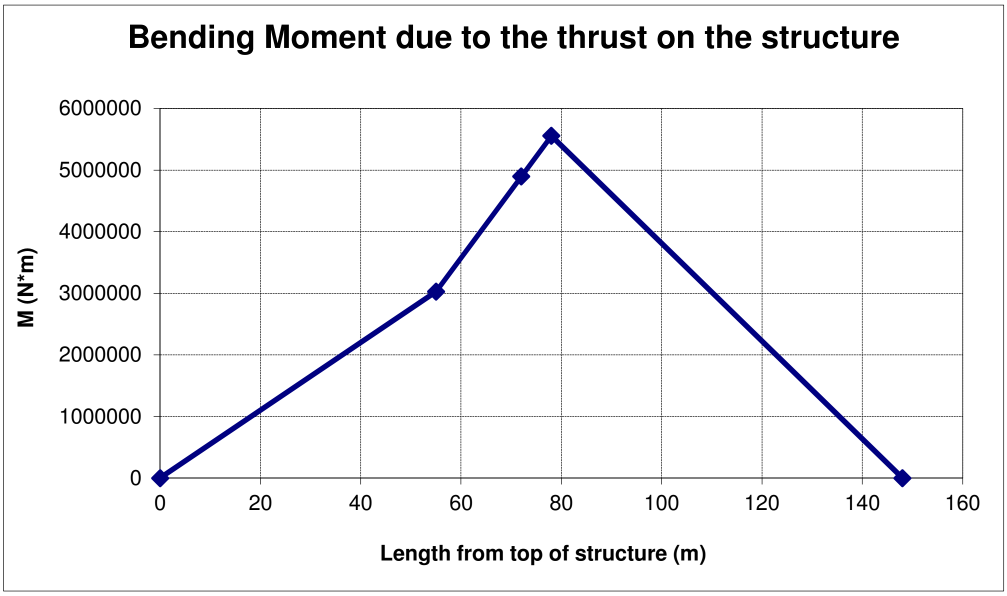

Figure 4.1.4 Bending moment, due to the thrust, on the tubular structure. M_1 corresponds to 55m, M_2 to 72m and M_3 to 78m (revise text in figure)

The underwater part of the structure has to assure the necessary buoyancy and counterweight to the structure to keep it in balance under all circumstances. A static equilibrium is considered at the rated power condition. The tilting angle of the structure ϕ is dependent on the thrust of the rotor T at the centre of the Darrieus rotor and on the buoyancy B in the centre of buoyancy Z_B and total mass W at the centre of gravity Z_G.:

$$\tan(\phi) = \frac{T \cdot (H_{TOT} - \frac{h}{2})}{(W \cdot Z_G - B \cdot Z_B)}$$

For the equilibrium a value of Z_B greater then Z_G is required. The maximum value of the tilting angle Φ is considered to be constrained to about 20°.
The balance of the vertical forces on the construction is dependent on the thrust, the weight, the buoyancy and the angle of attachment of anchor wires to the construction:

$$T \cdot \tan(\beta) = B - W$$

Concerning anchorage a model based on the "statics of the cables" [10] has been considered. The shape of the wires is hyperbolic and the length and height of the cables are linked to the factor $A = T / p$ where T is the horizontal thrust on the wire and p is the specific vertical load.

To ensure the equilibrium an extra weight has to be added to the specific weight of the cable, as shown in the HYWIND project design (Figure 2.2.1) [3,7].

4.2 Optimization of the Darrieus rotor

A first analysis has been made regarding the relative height to diameter ratio for fixed swept area of the rotor. The parameter being used is $\rho = h/R$, where h is height of the Darrieus rotor and R is radius of the rotor, see *Figure. 4.1.3*

A maximum Cp value is obtained for value of ρ close to 3. At the same time for decreasing ρ values the peak of the curve is shifted to the right to higher wind speeds. It is useful to note that to fix the value of the solidity s it has been necessary to change the value of the chord c to keep swept area constant.

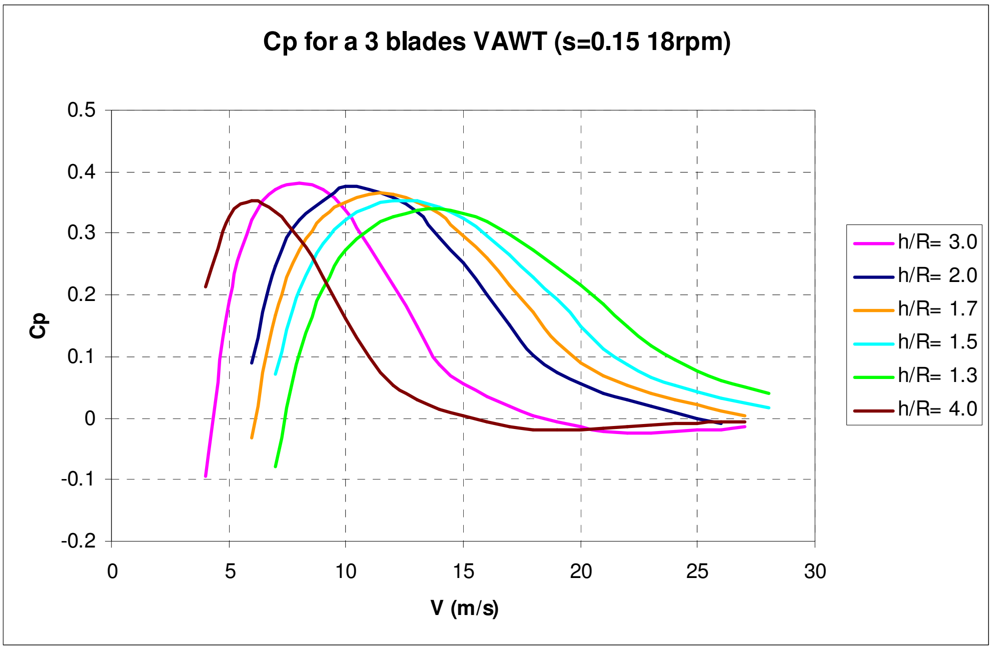

Figure 4.2.1 Cp vs wind speed with different ratio h/R

Considering a size of 1MW for the VAWT and analysing the configurations for values of ρ equal to 1.7, 2.0 and 3.0, the geometry and the necessary rotor speed are shown in Table 2.

Table 2 Dimensions of a VAWT for different ratios of h/R (solidity, rated power and swept area are fixed)

ρ	Height (m)	Rotor radius (m)	Chord (m)	Rated rotor speed (rpm)	Rated power (kW)
1.7	44.34	34.1	1.49	14.8	1002
2	55	27.5	1.35	18.5	1003
3	67.36	22.45	1.12	23.5	1002

The power curves of the three rotor configurations of Table 2 are shown in Figure 4.2.2. The graph shows how similar the power curves are for the configurations with ρ equal to 2 or 3;

while for ρ equal to 1.7 the curve is shifted to the right (higher values of wind speed). It is interesting to note that in considering other rotor sizes the heights of the rotor will change and so will the different wind speeds in the higher part of the rotor. The structural loads will also change because the arm of the thrust will change.

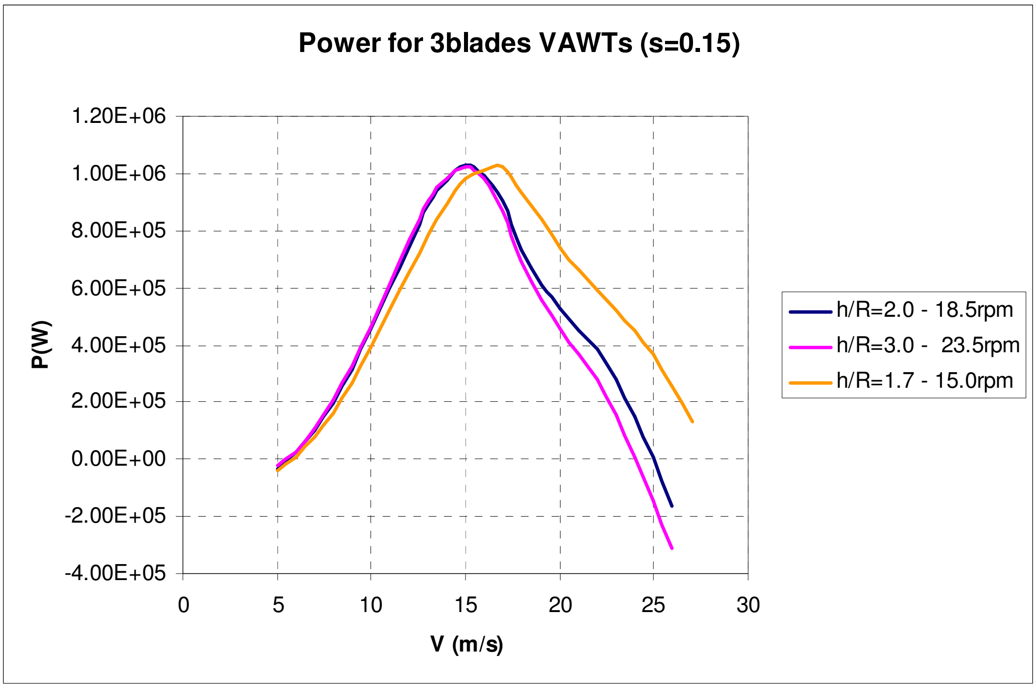

Figure 4.2.2 Power vs wind speed for different ratio h/R

To facilitate the choice of the best rotor geometry, the length of the blade has also been considered as a main factor in the blade costs. It is clear from Figure 4.2.3 that the minimum length of blades is obtained for ratio ρ of 2, or in other words when rotor height is equal to rotor diameter.

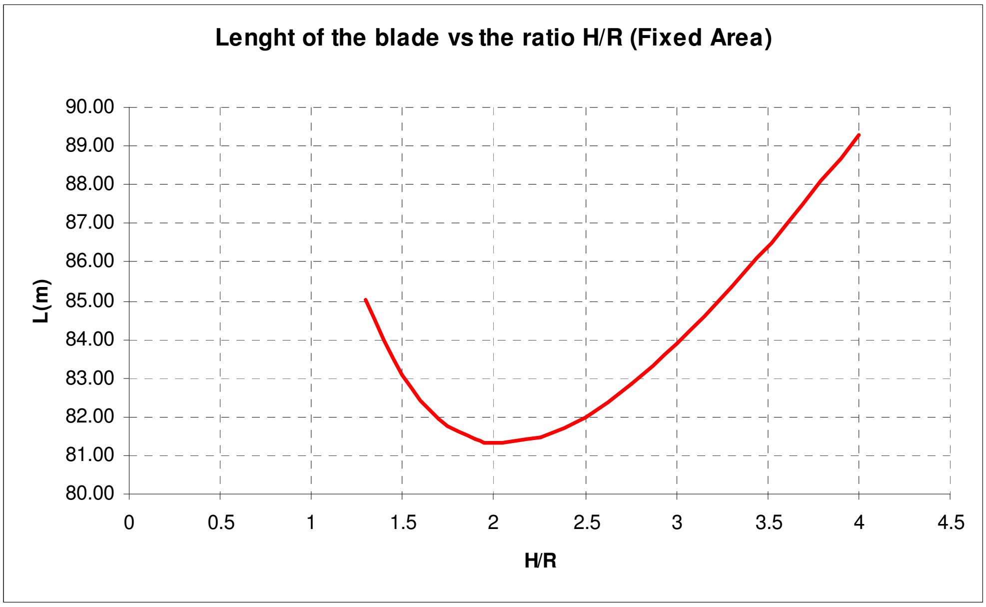

Figure 4.2.3 Length of one blade for different ratio h/R (different chords are considered to keep solidity fixed while swept area and rated power are also fixed)

An interesting aspect of the three configurations is to look at the specific power, the power per blade length P/L, as seen in *Figure 4.2.4*.

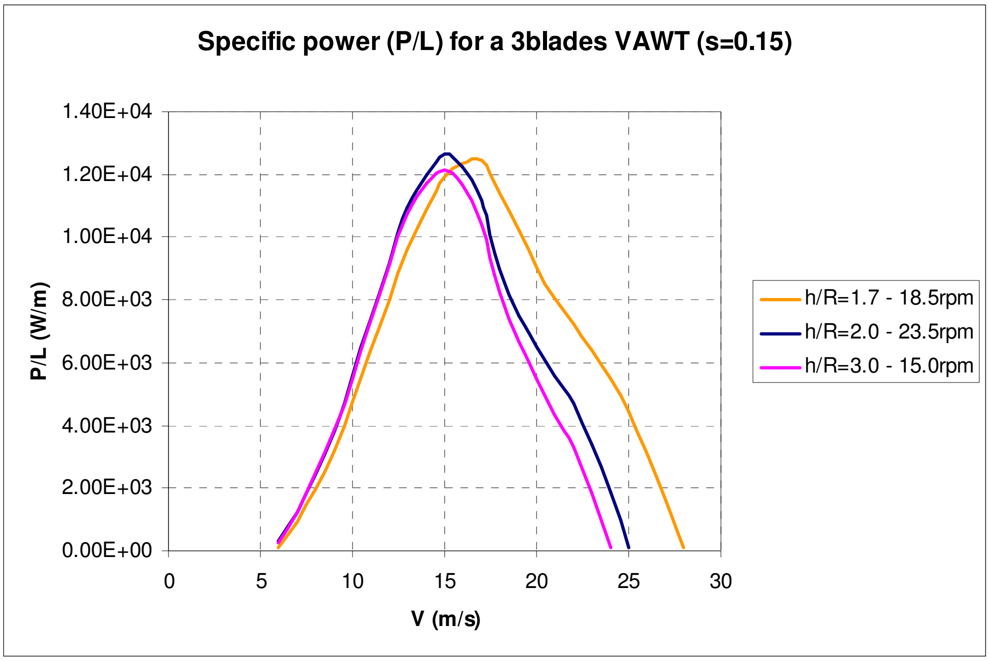

Figure 4.2.4 Specific Power (P over blade length) vs wind speed at different ratio h/r.

Another aspect of the three configurations is that the thrust is changing with the configuration (h/R and rotor speed) as shown in Figure 4.2.5.

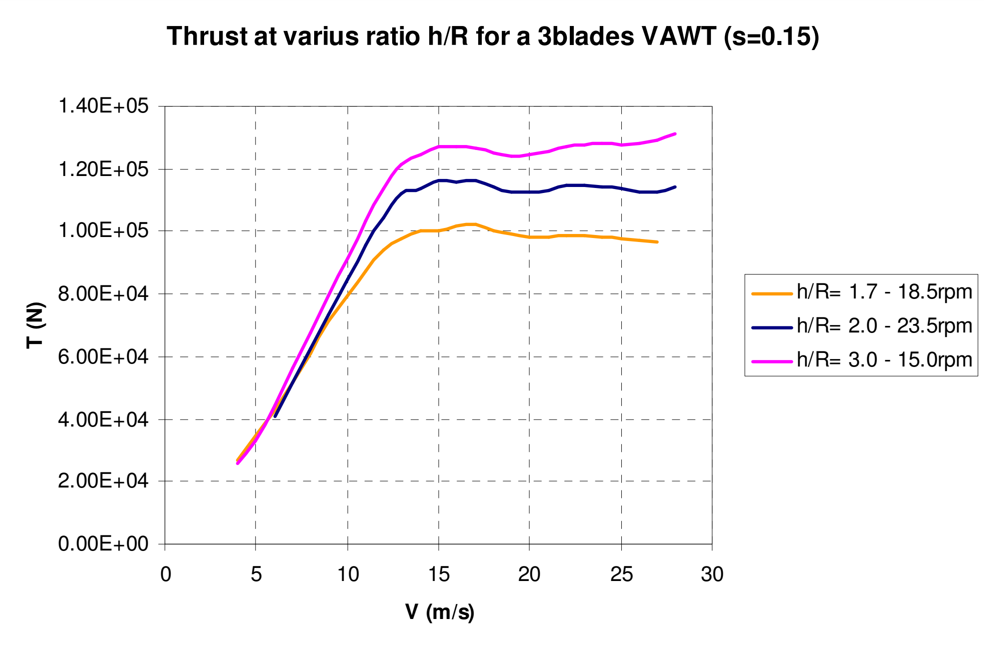

Figure 4.2.5 Thrust at different ratio h/R

The specific power in the relevant wind speed range 6-14m/s seems to be very similar for the height to radius ratios of 2 and 3, while the thrust seems to be significantly higher for the height to radius ratio of 3 compared to 2. This indicates that the height to radius ratio should be selected as 2. This is also supported by the fact that the blade length is the shortest possible for the given swept area. The height to radius of 2 configurations therefore seems to be an optimum for a 1 MW Darrieus wind turbine from this simple analysis.

4.3 Performance and efficiency at varying rotational speed

The sensitivity to rotational speed of the configuration with height to diameter ratio of one is investigated by calculating the performance for 5 different rotational speeds. The power curves are shown in Figure 4.3.1. The corresponding efficiencies, rotor torques and thrusts are shown in Figure 4.3.2, Figure 4.3.3, and *Figure 4.3.4*, respectively.

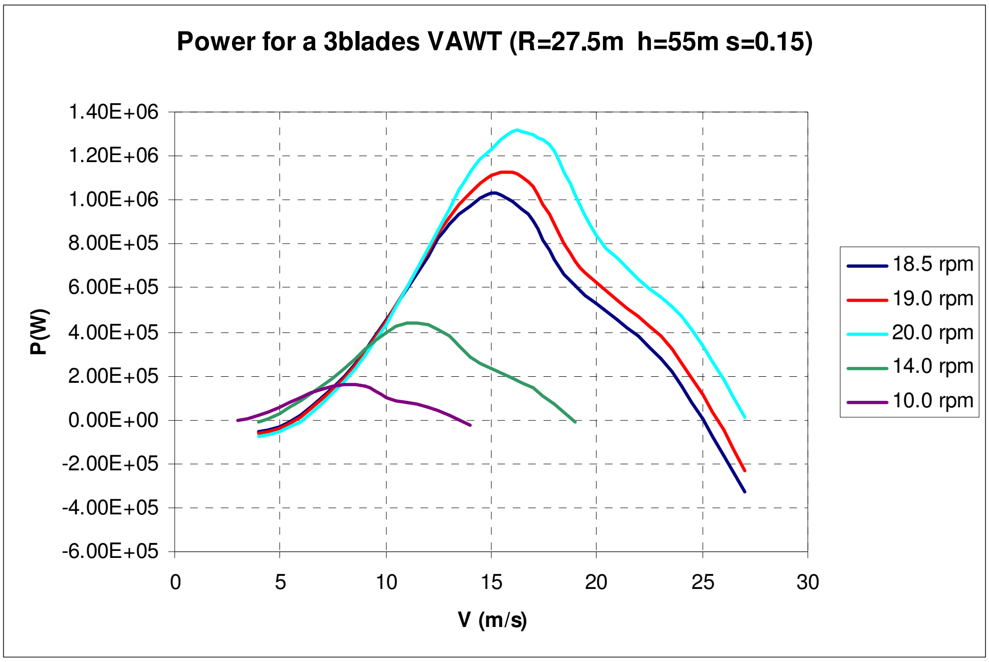

Figure 4.3.1 Power vs wind speed at different rotor speed.

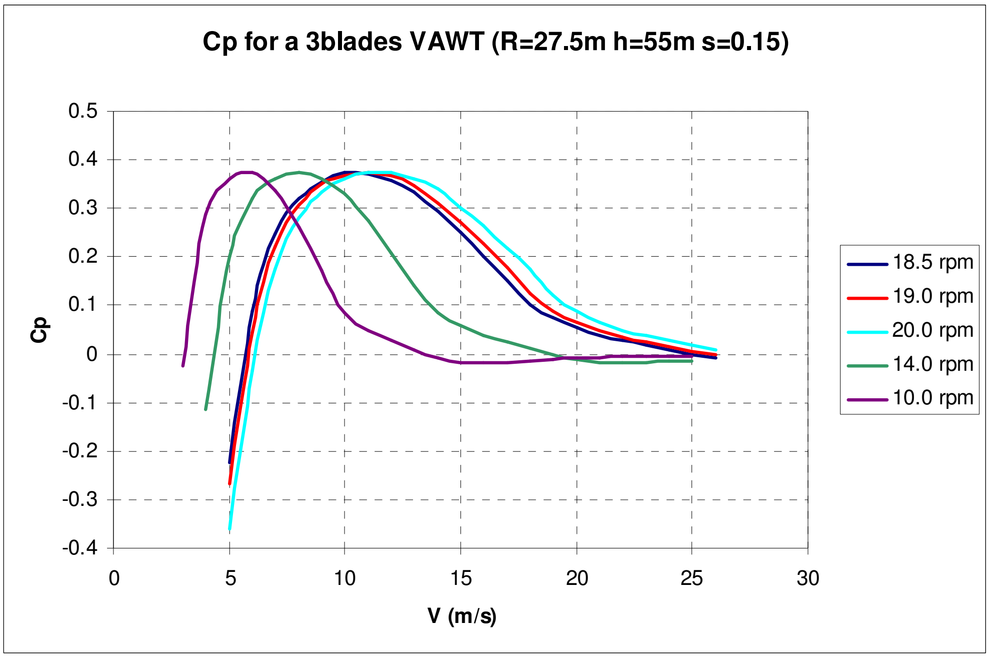

Figure 4.3.2 Cp vs wind speed at different rotor speed.

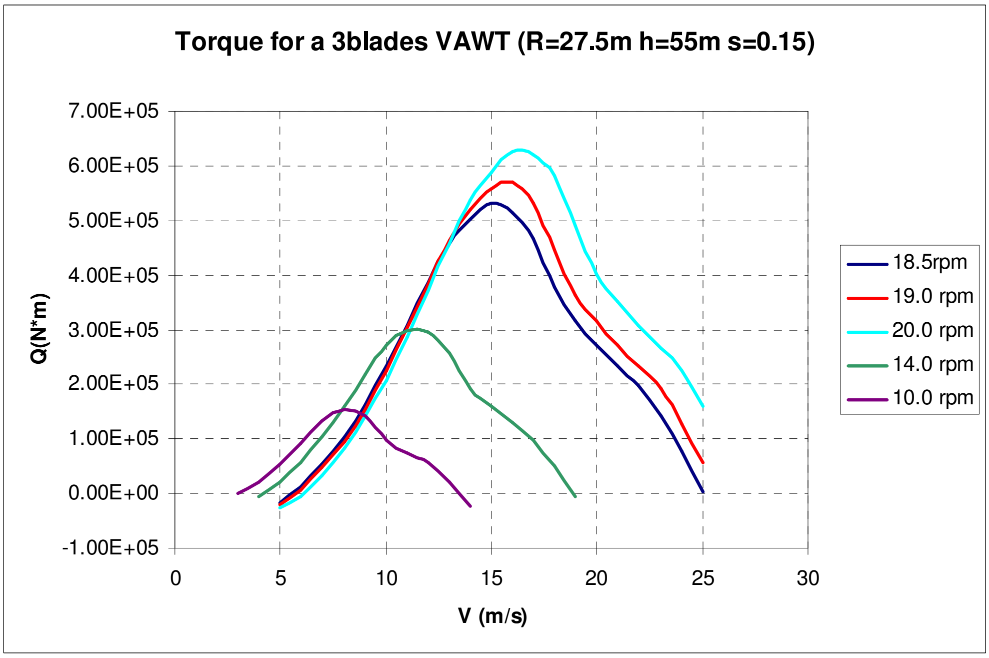

Figure 4.3.3 Torque vs wind speed at different rotor speed.

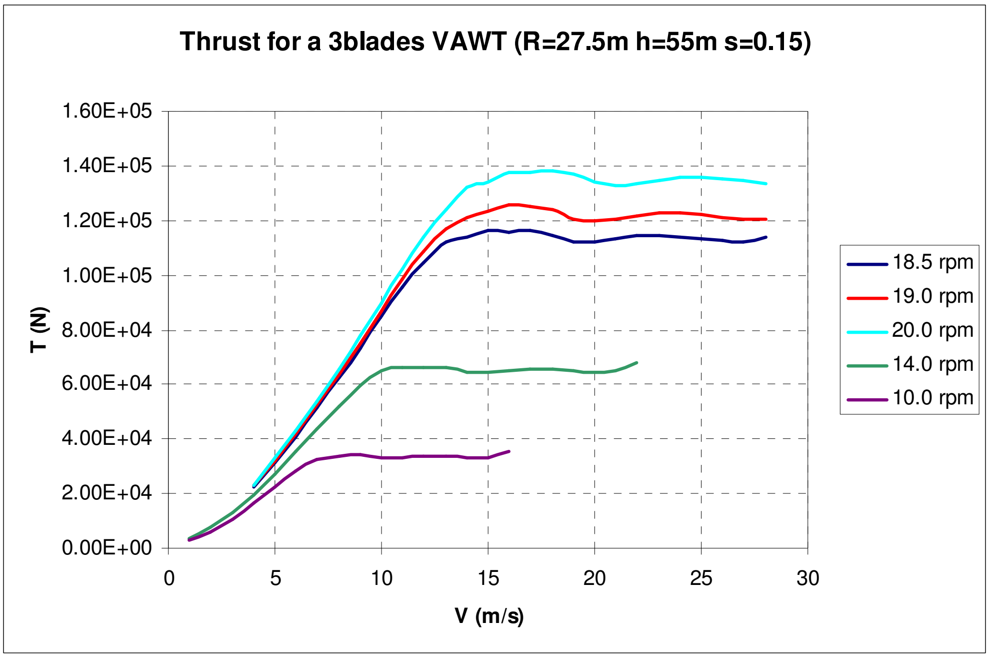

Figure 4.3.4 Thrust vs wind speed at different rotor speed.

It should be noted how the rotor speed does influence the C_P values in the wind speed range 5-10 m/s significantly by varying rotational speed while maximum C_P is almost constant. This analysis in particular seems to suggest the use of a multi speed generator to optimize the performance.

4.4 Tube structure and anchor wires

Many solutions are available for production of a tubular structure for floating off shore wind turbine as described in the preceding chapter. The potential materials that can be used are assumed to be aluminium, steel and concrete, as summarized in Table 3.

Table 3 Specification of potential tube materials for off shore VAWTs

	Density (Kg/m^3)	$\square_{LF}$ (MPa)	Tube parts
Aluminium	2800	110	Rotor
Steel	7700	320	All
Concrete	2500	40**	All

** Ultimate force of tension cables; 279 kN

The main dimensions for the structure, and the potential structure materials, are shown below (the drawing proportions are not real).

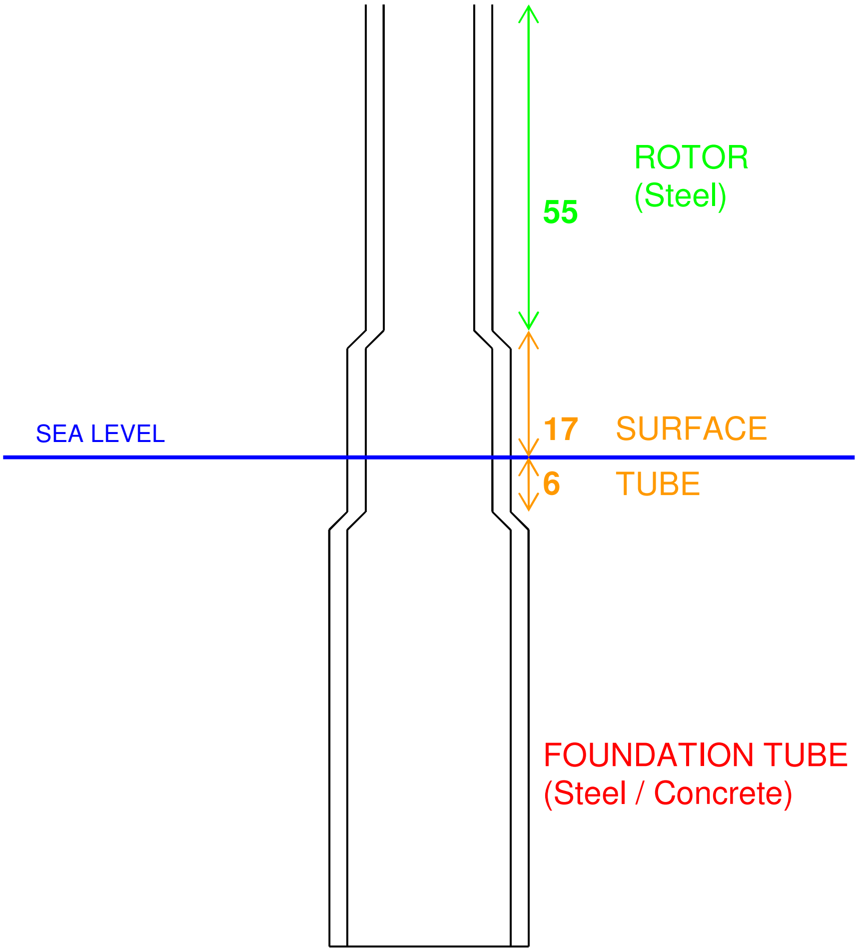

Figure 4.4.1 General concept of the tubular structure.

The height of the Darrieus rotor of the 1MW wind turbine has been fixed in the precedent paragraph to 55m. The surface tube dimensions have been determined to be 23 m (6m underwater).
The minimum internal radius has to be enough to ensure the space for the generator. In the dimension phase some limitation has to be considered: for the construction tilting angle a maximum value of about 20 degrees has been decided and the dimensions of the rotor and surface tubes are simply dimensioned to resist the bending moments graphed in Figure 4.1.4. Having fixed these dimensions, the realizable solutions with different height of the foundation tube are shown in Figure 4.4.2 .

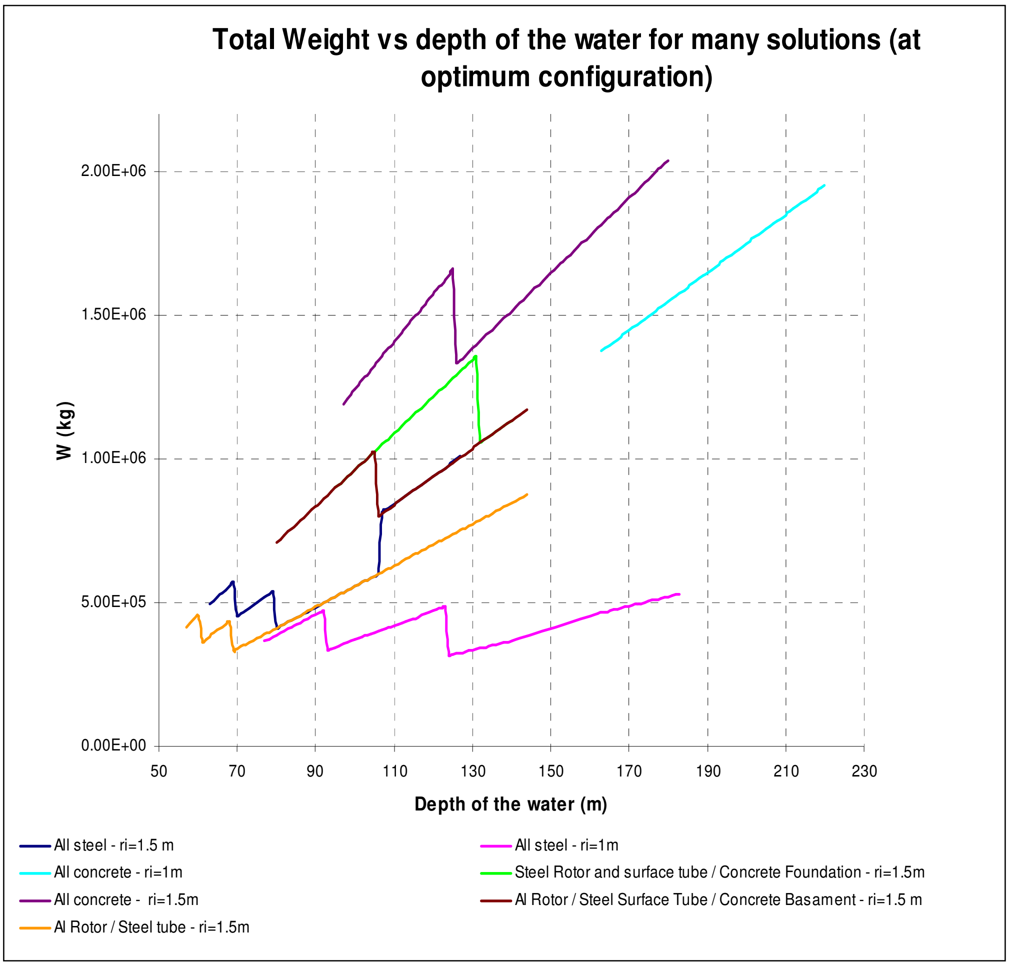

Figure 4.4.2 Total weight vs depth of the water for different tubes and different materials

The weight of the total structure was analyzed for different materials and foundation tube heights. Other alternative solutions, as an aluminum rotor, are graphed too. The most interesting area seems to be for water depth of 60-70 m (foundation tube of 40- 50 m). ”All steel” structure seems to give the best result. Using the aluminum for the rotor, it is possible to save some more weight. The concrete seems to be useful for deeper water and bigger wind turbine sizes.

In Figure 4.4.3 it was analysed how the anchorage angle β influences on the counter weight to keep the construction in equilibrium. The anchorage angle seems to have no influence for deep water and very long constructions. A reduction of the counter weight is instead visible for the smaller construction when the angle increases. However, the percentage of variation of the counterweight is rather negligible.

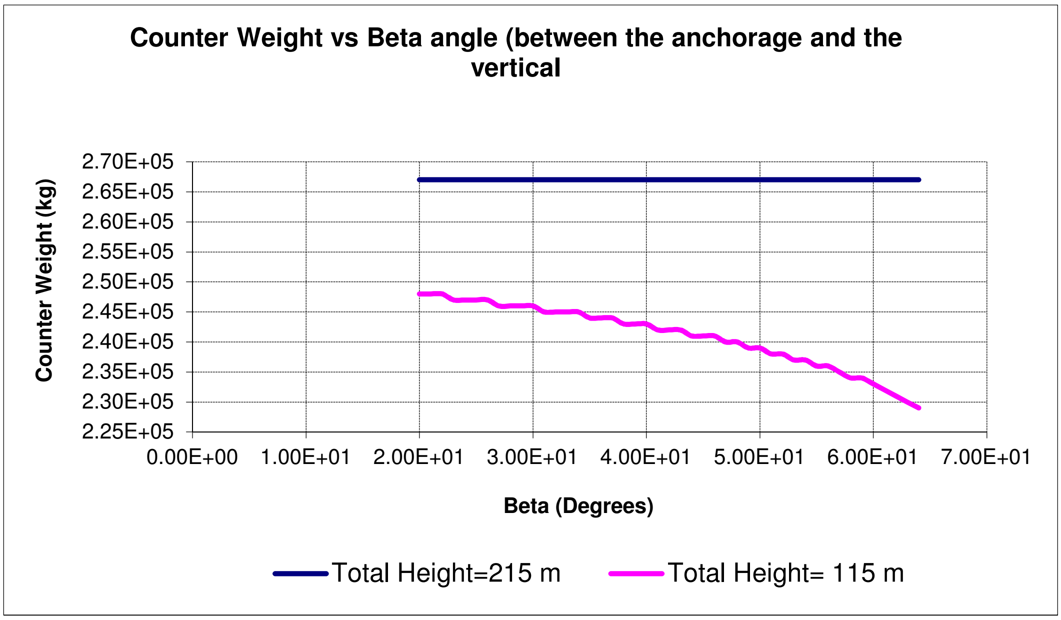

Figure 4.4.3 Counter Weight vs beta angle (angle between the tube and the anchorage wires)

It is reasonable to have an anchorage angle around 40 degrees, in order to have a height of the anchorage wires of 20 meters from the sea bed and with a length of the wires of about 55 m to reach the sea bed and an extra weight of 150kg per meter of wire. An optimization of the”all steel” structure may be possible for water depths form about 70m and down. The concrete structure may be possible from 100m water depth and down.

Figure 4.4.4 shows two possible but different configurations of a 1MW wind turbine concept. The left one is based on steel for all the three tubes. The right one is based on two upper steel tubes and a concrete foundation.

Figure 4.4.4 Drawing of the two main concepts: a. “all steel structure” b. steel structure with concrete foundation

5. Systems and infrastructure

5.1 Production and manufacture of parts

Production and manufacture must be based as much as possible on existing technologies, which are known from the wind industry today. Meanwhile, some technologies are new, and will need research, development and testing.

The integrated steel rotor tube and rotating steel foundation could be based on existing steel tower technology for HAWT wind turbines. The sub-sea part should have a surface protection corresponding to ships. The efficient manufacture of the tube is highly depending on the basic raw material dimensions. It is likely that big ship yard companies efficiently can use huge equipment for forming and welding plates larger than the presently customary 12000x1550mm, 14000x700mm units.

The blades should be made of pulltruded fibre glass or extruded aluminium alloy. The pulltruded fibre glass blades can be substantially improved by development and testing, so that they can be optimized for the purpose in comparison with existing knowledge. In principle, the industry can make pulltruded fibre glass blades up to blade profile chords of more than 10 meter. In principle, the length of the blades can be made indefinitely long. The fibres within the profile can be optimized for bending and torsional strength to suit the specific design needs. Extruded aluminium blade profiles cannot be made in one peace (Hydro Aluminium 40m length). The profiles then have to be assembled to full blade lengths. The profile sections cannot be made in full chord length either (Hydro Aluminium 0.40m wide). This means that parts have to be connected to full chord (i.e. friction welding by Hydro Aluminium), and blade sections must be connected with fittings.

The shaping of the blades may be omitted if a high height to diameter ratio is selected for the Darrieus rotor. In this case the blades may be pre-stressed during installation by simply pulling the blade ends towards each other until they can be mounted on the rotor tube fittings. The blades may also be pre-bent into the Troposkien shape or whatever shape is selected. This is standard procedure for aluminium blades for Darrieus rotors of height to diameter ratios of about one. Alternatively, the blades may be extruded or pulltruded in upper and lower blade profile sections, which are connected after bending in the right blade shape.

The shaft of the wind turbine is a part that needs development and testing. Especially the sealing problem should be considered and a satisfactory solution be found. The sealing must be efficient at the water depth of the bottom of the rotor.

The generator for the wind turbine could be based on a regular gearbox and generator. Alternative converters, consisting of permanent magnetized generators (neodymium or equivalent magnets) and maglev technology with completion electronics (inverter, rectifier) could turn today’s converters into efficient generators. Research and development is on-going with a high industrial focus. The offshore environment may inject some challenges on the technology. These converters have in common that they have low friction, modular mounting and electrically more efficient.

The counterweight for the construction is intended to be put at the bottom section. For the present design where the tilt of the whole construction may be up to 20º the counterweight needs to be fixed at the bottom tube section. If the counterweight is applied on the inside it has to be taken down through the rotor shaft, and it must have space enough in the bottom and still leave sufficient room for the shaft and the generator. The lifting of the counterweight could be done with a crane mounted at the top of the rotor, but it then has to be lifted to the top first before going down the rotor shaft. An alternative position of the counterweight is on the outside. One solution could be to let concrete parts down from a sea vessel into a streamlined basket surrounding the bottom tube.

5.2 Installation

The installation of the construction on an offshore site could be made in different ways. The whole wind turbine could be assembled at a manufacturing site with sufficient sea depth, and then be towed to the site for fixing to the sea bed foundations.

Another possibility is to tow the long rotor in horizontal position to the site and to tilt it into vertical position on site. Afterwards blades and generator are installed by the use of a crane at the top of the rotor.

The sea bed foundations, anchor chains and anchor parts with torque arms should be mounted before the wind turbines are towed to the site. When the wind turbines are in place, the anchor parts are lifted and mounted to the wind turbines.

5.3 Operation and maintenance

Operation of the system may be very simple. The only parameter that should be controlled is the rotational speed. No control of blade pitching or yawing is needed as for HAWT's. When the wind is too weak for power production the rotor is stopped. When the wind is sufficiently high the rotor shall be started by using the generator in motor mode, and when sufficient rotational speed is reached it switches to generator mode. A wind sensor could be positioned at the top platform to assist the control system. This sensor could be a sonic anemometer. This sensor would rotate with the rotor, and it would be able to give more values than the wind speed. The wind direction would vary with a sinus function, which would indicate the rotational speed. The vertical wind component would also vary with the sinus function, indicating the tilt angle because the wind flow inclination angle is zero in average offshore.

When the wind speed catches up the rotor speed may be reduced to reduce power. The calculations of the Darrieus rotor shown in an earlier chapter, meanwhile, indicate that at constant rotational speed the power is reduced after stall, and the thrust is kept constant. With a constant thrust the tilt of the rotor shaft will also be constant. A tilt sensor may be used to indicate the thrust force and to control rotational speed such that the thrust and tilt angle do not exceed certain values. Accelerometers may also be mounted to detect waves.

In case the grid is disconnected the generator should bring the rotor to a stop. The absorbed energy should be dumped into resistors that are cooled by the sea water. In case the generator is not able to keep the rotational speed low enough the water brake shall be deployed automatically.

Regular maintenance of the rotor could be made by entering the rotor at the top platform from a helicopter. This is significantly easier than on a HAWT because the blades do not obstruct the helicopter blades. The blades and blade connections to the rotor could be made by lowering personnel from the top platform. The maintenance on the inside of the rotor could be made by lowering personnel down through the shaft to the bottom. If the generator is a multi-pole generator it should be made big enough, so that personnel can pass through the rotor to inspect the generator and to inspect the bottom shaft bearings. The sealing of the shaft may be very difficult to inspect and maintain, but methods for this are comparable to inspect and maintain the shafts of ships and submarines.

In case the generator is mounted on the outside the bottom of the rotor, maintenance is only possible by dismantling the component from the rotor and anchor parts and lift it to a vessel at sea level. Here, the watertight and sealed component can be opened and inspected. In this case it makes sense to develop a very robust and reliable component. On the other hand this may be the only component of the whole construction that needs to be developed significantly. The generation of electrical power with new PM technology is promising with low O&M costs.

6. Costs

A rough 2008 cost estimate of the concept of an integrated Darrieus rotor with a floating and rotating foundation have been made and compared to present offshore HAWT installations. In comparing costs, the gross prices for basic materials have been acquired from manufacturers, suppliers and public databases. The materials considered are ranging between pre-tensioned concrete, steel, aluminium and GRP.

For pre-tensioned concrete, the cost estimate is made for offshore structures based on gliding. It includes rates for varying and shift working hours, cost for forms, pre-tensioning, insurance and social addition cost.

For aluminium and GRP the cost of processed materials has been provided by interviewing a manufacturer of GRP pulltrusions (Fibreline) and a manufacturer of aluminium alloy extrusions (Hydro Aluminium).

For the costs of steel parts, information from the World Stainless Steel Prices by MEPS (Management Engineering & Production Services) was acquired [11]. The cost is based on hot rolled plates with minimum 13 mm thickness of grade 304.

The materials cost is shown in Table 4.

Table 4 Cost of materials

MATERIAL	€/KG
Concrete:	0.3
Steel:	3.3
Aluminium:	6.2
GRP:	5.4

Estimated costs of the rotor blades, the rotor tube, the transition tube and the bottom tube are based on the raw cost estimates of the materials. The cost of a 1MW multi-pole PM generator including frequency converter and control system is estimated at 0.2 million €, which in comparison with latest developments is 20% too high. The costs of the anchoring part, including the torque arms, is estimated at 0.1 million €. Additional to these costs is estimated costs of production and manufacture of 50%.

Costs on electric cables, anchor cables, anchor cable weights and sea bed foundations are not included in this cost estimate. Costs for commissioning the turbine at the offshore site as a turn-key project, e.g. site exploration and assessment, transportation of parts, installation and electrical works, development (engineering, permits, and technical costs for going offshore) and insurance are not considered either. It is however likely that these costs are not that diverging from conditions far from shore a HAWT is installed under.

The two configurations of the wind turbine concept considered are both using a rotor with GRP rotor blades and a steel rotor tube. The transition tube between the rotor and the rotating bottom tube foundation is also a steel tube in both cases. The two configurations only differ in the bottom tube. One uses concrete, the other steel.

The cost estimate of the concrete bottom tube configuration is 1.2 M€ and the cost estimate of the steel bottom tube configuration is 1.4 million €.

A rough estimate of the cost of present offshore HAWT power plant, established between 2001-2009 is in average 2.3 million € per MW installed[14], and as new projects in 2009 at a cost of 2.79M€/MW . For this the wind turbine itself is 1 million € per MW. The projection is uncertain, however this trend of wind turbine installations cost has been subject to Danish public contests seeking to promote projects which can perform 30% cost reductions compared to 2009 ratings. If we assume the cost of a competitive offshore HAWT power plant to be 2.0M€/MW, there is a significant difference in comparing the costs of present HAWT offshore wind power and the present concept. The cost of the wind turbine of the present concept of 1.4 M€(steel) is less than the costs of present HAWT wind turbines of 2.0M€/MW.
The sea bed foundations of the present concept are different (cost are lower on materials, but installation at deep sea conditions are uncertain at the moment). Anyway, these sea bed foundations only have to transmit the thrust force of the rotor to the sea bed, and can be deployed as mooring lines with large masses at one end dumped into sea. They do not have to transfer the bending moment due to the thrust which HAWTs installed directly on the sea bed have to do. The sea bed foundations for the present concept are therefore potentially cheaper than existing mono piles.

The above considerations are to be revised for inclusion of other cost factors, such as inclusion of larger production units, and inclusions of other probable costs due to effects from waves on the materials strength. Material costs on raw materials are assumed equal from the time of analysis (2008) to present.

6.1 Outlook

The cost analysis has been carried out on a rotor with 3 blades and a solidity of 0.15. If the solidity is kept constant, and blade number decreased to 2, the chord has to increase accordingly. That implies for the present assumption of using a 2 bladed version, that the chord is increased approximately 50%, which will give an increase in cost of the rotor-on the other hand the blade number reduction (as given as a scale of that two 3-bladed units will represent three 2- bladed rotors) will tend towards a more favourable cost mix. All in all, based on the present analysis, the concept has a cost advantage of 1.4/2.0. This corresponds to a 30% less cost over existing installed offshore wind turbines.

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[14] Offshore Wind Power: Experiences, Potential and key issues for Deployment (Morthorst et all, Risø 2009)

At this stage of analysis, caution has to be applied: The details of the rotor, the floater construction and the integration of the generator on the floater will require a detailed study of the structure, and in order to guaranty to be able to endure 10, 20 or more years of operation, with the given load cases, erection, service overhaul etc.

7. Extension of the analysis for 5MW design

7.1 Extension

The above considerations have been extended to include the analysis of a 5 MW design, which is based on a 3 bladed Darrieus turbine, and to parameterize the underwater tube parts into 4 sections and variable length and with different materials. The rotor is described in the following graphs in the same way as before:

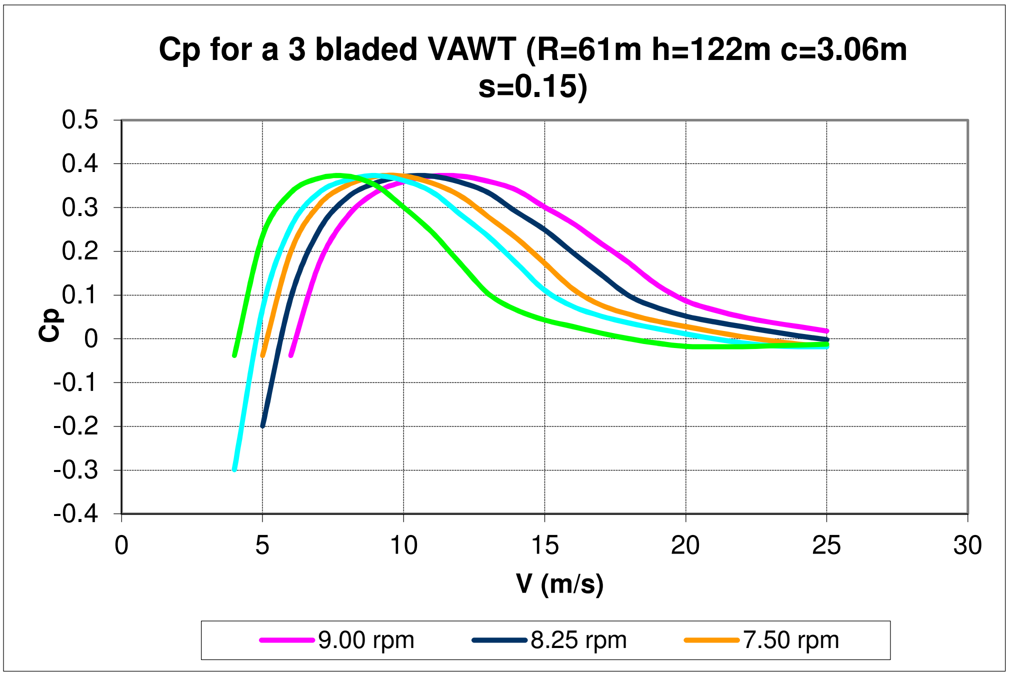

Figure 7.1.1 Rotor efficiency for different rpm

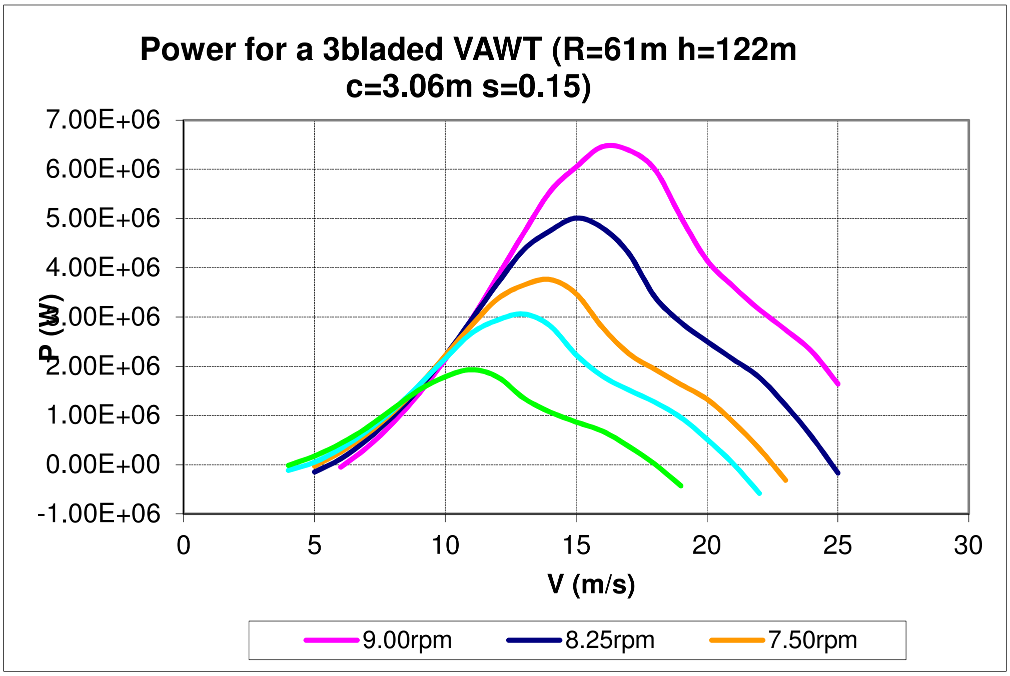

Figure 7.1.2 Rotor power for different rpm

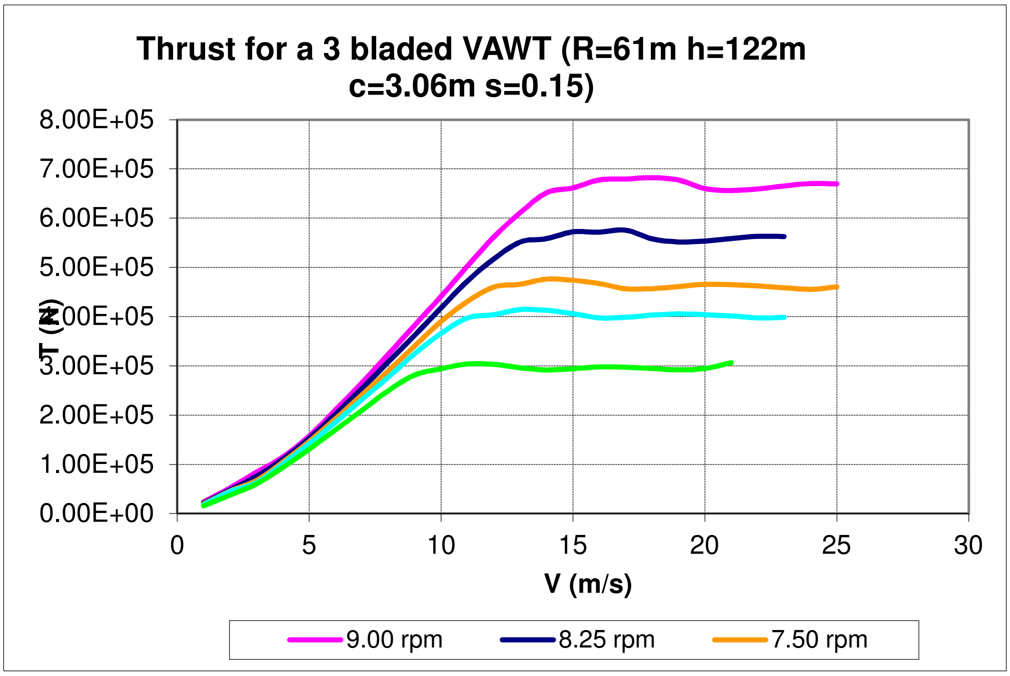

Figure 7.1.3 Rotor thrust for different rpm

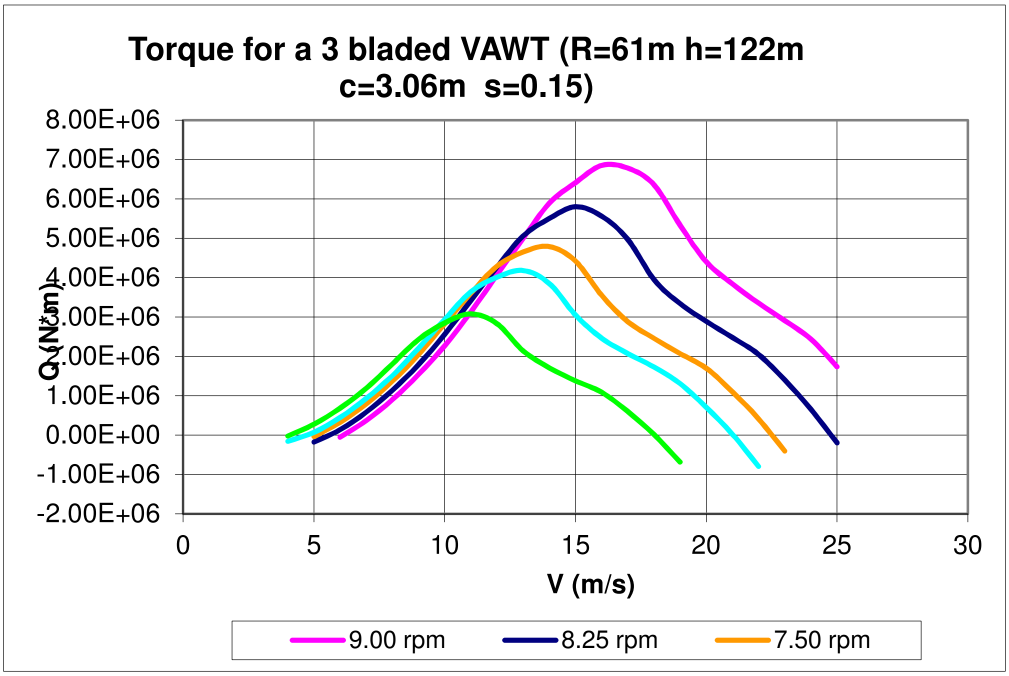

Figure 7.1.4 Rotor torque for different rpm

The following wind turbine has been chosen with the characteristics:

Table 5 3-bladed, 5 MW rotor design

Rated Power [MW]	5
Radius at equator [m]	61
Rotor height [m]	122
Blade chord[m]	3.06
Solidity Nc/R	0.15
Shaft speed [rpm]	8.25
Thrust [kN]	560

The floater is now investigated on the ability how much material is sufficient to carry the rotor, and following graphs show the masses and the costs associated with different diameter of the tube part and materials type chosen.

The all steel tube consists of 4 sections of steel, with thickness of 0.02 m at each section, and an outer diameter at the sections corresponding to 3.74m, 4.24m, 4.44m and 4.44m.

The first graph shows that the all steel tube of 108 m (a number result from the 1st baseline design iteration) is less costly for a design with tube diameter of 3.74m. This choice is also the least massive with 2000 T and that the weight of the tube alone is around 500 T, the ballast 1090 T and that the cost for this particular design is 1.96M€. The ballast is assumed to be 0.3 €/kg.

Tube Cost M€	Ballast Cost M€	Total Costs M€
1.630	0.326	**1.956**

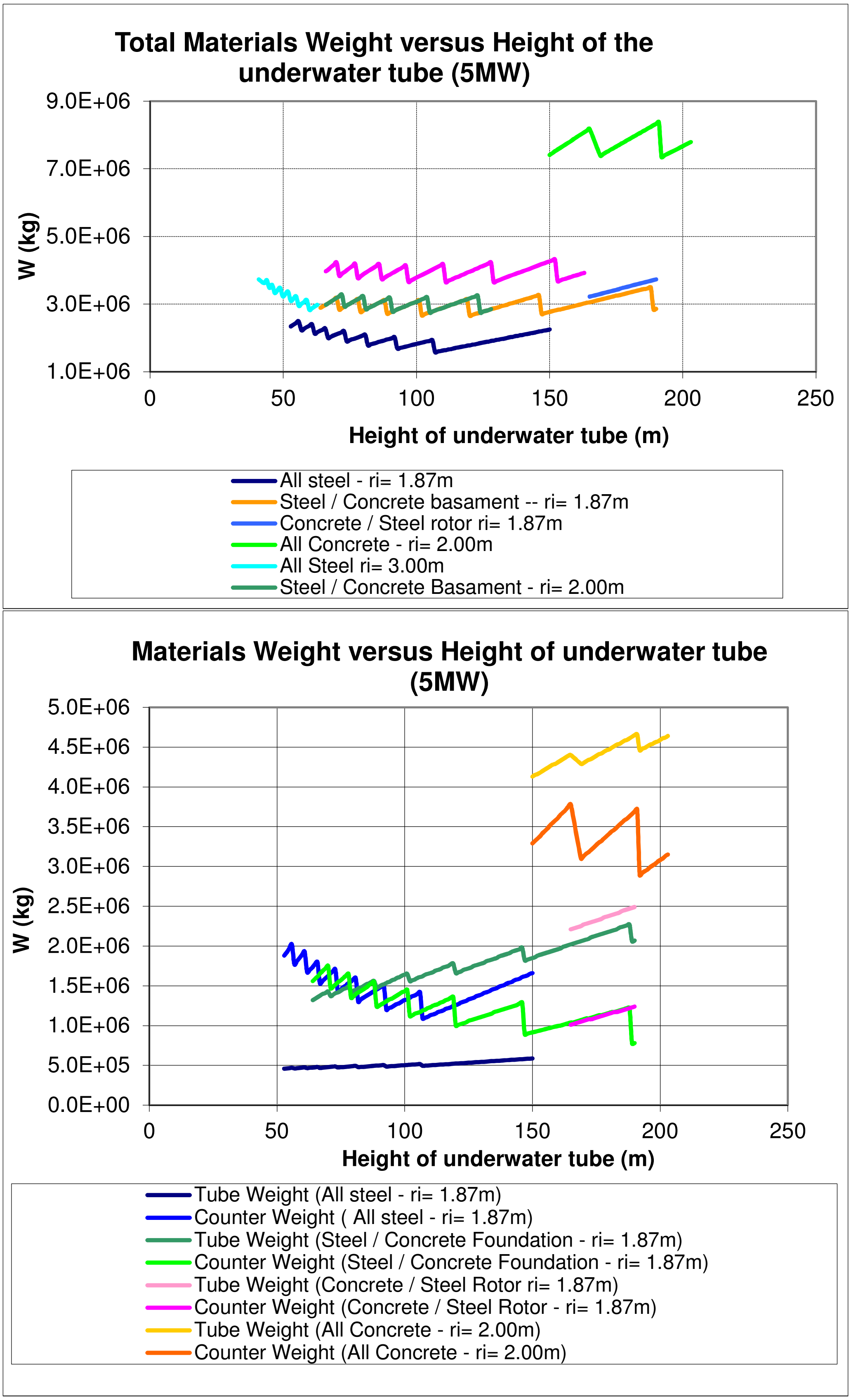

Figure 7.1.5   Total weight of system and weight of tubes with different material

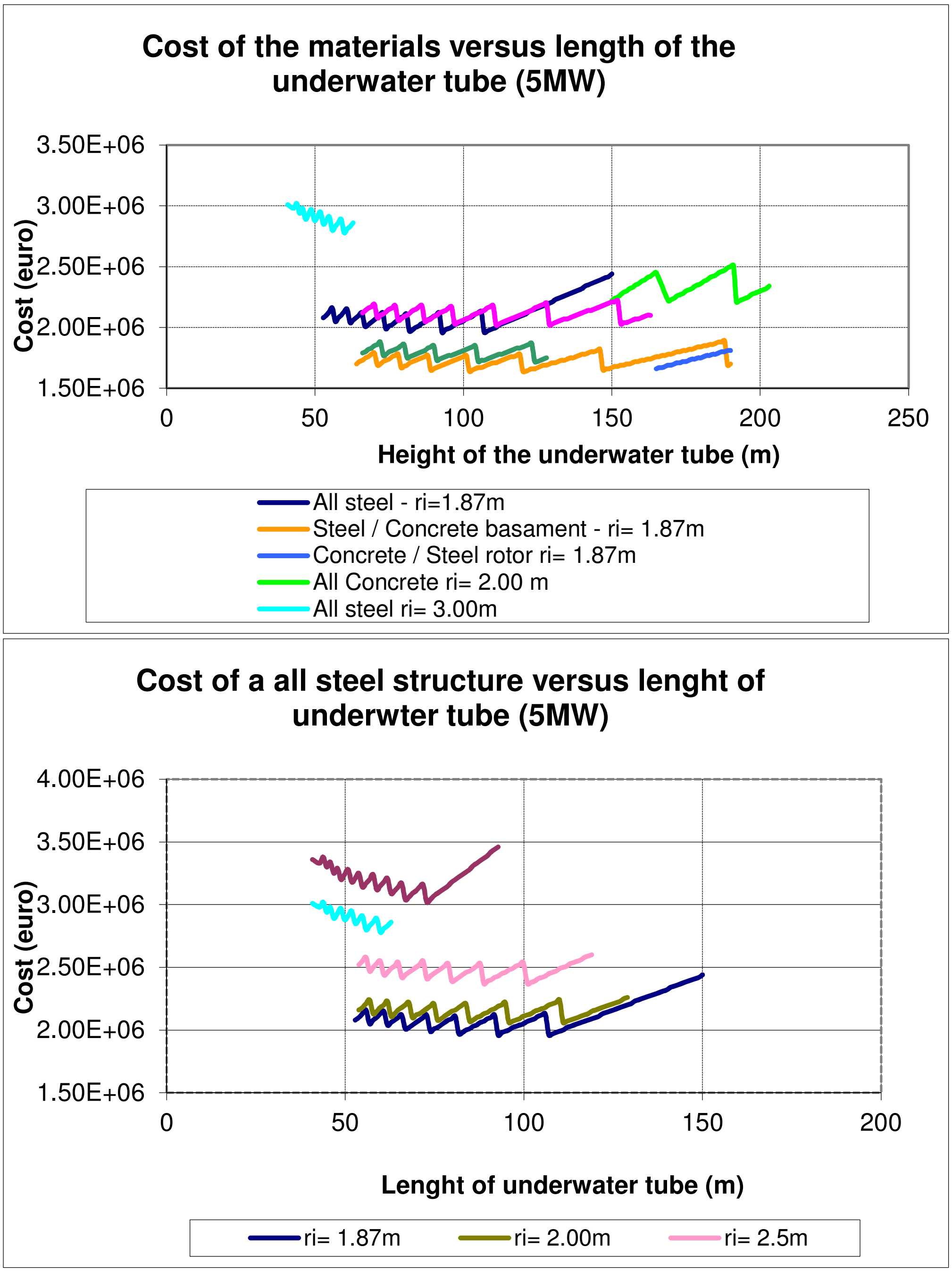

Figure 7.1.6 Best weight with length of tube

8. Conclusions

From the preliminary study on floating foundations for VAWT wind turbines, following conclusions can be made.

For the VAWT rotor itself it can be concluded that:

- a 2-bladed, self-supporting Darrieus rotor is preferable taking into consideration towing and erection.
- with respect to C_P calculations on a comparative 3-bladed rotor with NACA0018 profile a C_{Pmax} of about 0.38 was reached and an optimum height to diameter ratio is found in the range 1 to 1.5
- the rotor shall not be able to self-start, on the contrary self-starting capability must be specifically designed for the need of variable speed is prominent
- stall regulation should decrease power at higher wind (effective power control) but with over speed control
- thrust can be kept constant at constant rotational speed
- with respect to power per blade length P/L there is an optimum at a height to diameter ratio H/D of around 1.0
- there are possibilities to optimize the blade profile for higher C_P
- the safety system should include water brakes rather than air brakes
- floating of a ballast unit can provide a simple means of emergency brake.

On the floating foundation concepts the following conclusions can be made:

- floating VAWT and HAWT concepts were found and were described
- conventional land based VAWT concepts placed on fixed floating foundations were not found to be the most feasible
- the most feasible floating VAWT concept was found and proposed to be the three bladed Darrieus wind turbine on a tubular floating and rotating foundation, fixed at a bearing at the bottom of the floating foundation
- the proposed concept was described for a 1MW wind turbine and steel or a concrete rotating foundation in which the depth of the construction below sea level is about the same as the height above sea level
- the proposed concept seem appropriate for water depths from 60m for steel foundations and from 80m for concrete foundations
- a rough cost estimate of the proposed concept of a 1MW wind turbine was made which indicate that it may be 50% less costly than an offshore HAWT wind turbine. Foundation at the sea bed seem to be significantly less costly, and this indicate that the proposed concept potentially may be competitive to existing offshore technology
- the concrete rotating foundation seems more cost efficient than the steel foundation, especially for larger wind turbines and higher rated power

The revision of the concept has favored the 2-bladed version to be explored in the on-going studies. This incorporates the very symmetric rotor with 2 blades, and in particular this allows the towing of the installation with a little boat from port to site in one peace.

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We have more than 240 staff members of which approximately 60 are PhD students. Research is conducted within nine research programmes organized into three main topics: Wind energy systems, Wind turbine technology and Basics for wind energy.

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Report

Floating spar buoy for the DeepWind concept

Deliverable D5.1

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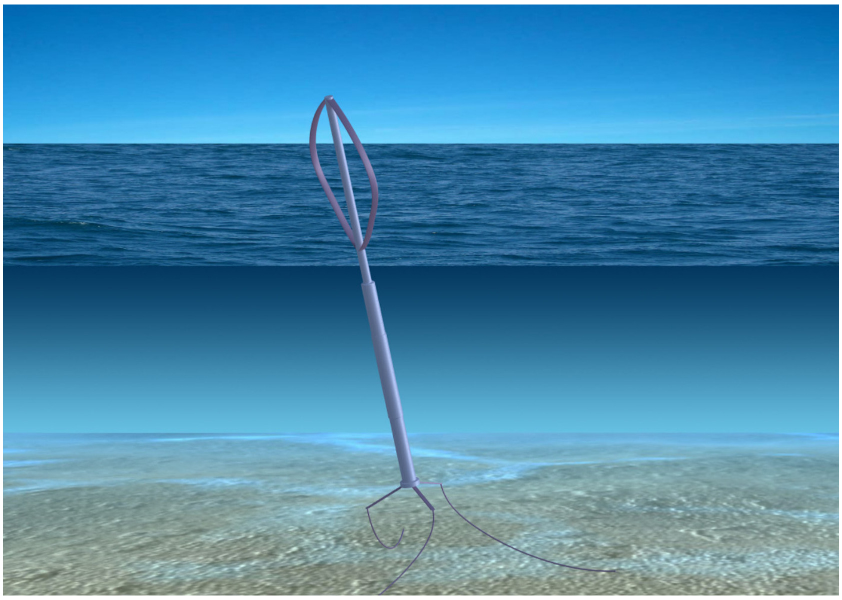

Norwegian Marine Technology Research Institute
Offshore Hydrodynamics
10th January 2014

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Report

Floating spar buoy for the DeepWind concept

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ABSTRACT

This document specifies the main dimension of a floating column with sufficient support capacity and stability that can serve as a base design for the DeepWind concept. The dimensioning is based on a simplified optimization approach. The design variables comprise the spar buoy geometry and ballasting. Dynamic responses due to wind and wave loads were not considered at this stage. Further, a simple sensitivity study on how the top weight, generator weight and main hull dimensions influence the conceptual design is included in the report.

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Table of Contents

1 INTRODUCTION

1.1 Background and objectives

This report has been worked out by MARINTEK, as part of the EU FP7 - ENERGY - 2010 - FET project DeepWind - Future Deep Sea Wind Turbine Technologies. The overall objective of this project is to explore the technologies needed for development of a new and simple floating offshore concept with a vertical axis rotor mounted on a rotating floating support structure. This document fulfils MARINTEK's contribution to deliverable D5.1 in WP5 - Mooring, floating and torque absorption systems. The objective of WP5 is to identify a feasible floating support structure and cost-optimized mooring system configuration for the floating support structure of a vertical-axis wind turbine.

The scope of the present work is primarily to specify main dimension of a floating column with sufficient support capacity and stability that can serve as a base design at the earlier stage of the development of the DeepWind concept. A secondary objective is to investigate how changes to the rotor and generator design may influence the design of the floating support structure. These results can be used for further sub-optimization of sub-components in order to get an optimal integrated system.

The main dimensions of the spar buoy is obtained from a simple optimization approach. Optimization in this context is the same as designing the system for minimum cost, while satisfying functional design requirements. The design variables comprise the spar buoy geometry and ballasting.

The approach used herein is somewhat simplified where only static stability and restrictions on natural periods have been considered. Dynamic responses due to wind and wave loads are not considered at this stage, but the effect of static wind load is included in the analysis. A more sophisticated approach for optimizing the spar buoy will be provided in deliverable D5.2 [1] and is also presented in [2] where the optimization tool WINDOPT [3, 4] is used to find a feasible spar type floating support structure and mooring system for the DeepWind concept. The current work is based on the first iteration rotor and generator designs.

1.1.1 The DeepWind concept

The interest for floating offshore wind turbines has increased the recent years. Limited access to shallow water areas in some key regions has driven the focus towards deeper water. While bottom-mounted offshore wind turbines are limited to water depths of approximately 30 $\sim$ 50 meters, floating concepts will allow installation in deeper water. This will allow deployment of offshore wind farms further offshore in areas with stronger and steadier wind, and with less visual impact. The potential is believed to be large, provided that cost can be brought down to a competitive level.

Most of the research and concept development have so far been based on traditional horizontal axis wind turbine (HAWT) technology. E.g. a full scale floating HAWT mounted on a spar buoy has been deployed off the south-west coast of Norway by Statoil in the Hywind project [5] in 2009. Principal Power deployed their first full scale pilot of their semisubmersible concept WindFLoat off the coast of Aguçadoura, Portugal [6] in 2011. Other examples of floating HAWT-concepts that are currently being developed are e.g. SWAY [7], BlueH [8], WindSea [9], the hybrid SPAR-Concept [10] and Fukishima MIRAI [11].

The DeepWind project is based on a spar type floater with an innovative offshore vertical axis wind turbine. The power is generated by a generator placed at the bottom of the structure which is held in position by the mooring system. Traditional vertical axis wind turbines (VAWT) requires large bearings due to the large reaction forces from the rotor axis. The DeepWind concept differs from other VAWT concepts since the entire structure is rotating. The rotating submerged substructure utilize the water as roller bearing to reduce the dynamic effect of bending moment on the turbine, eliminating the need for large mechanical bearings.

An illustration of the concept is given in Figure 1.1, and a general overview of the concept and its features are given in ref. [12] which also includes a discussion on the choice of concept.

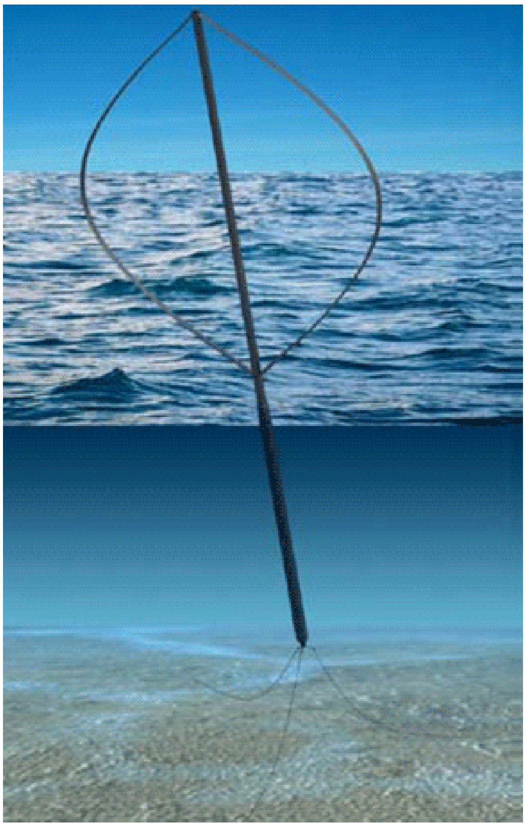


Figure 1.1: Artistic illustration of the DeepWind concept.

The remaining part of the present report can be outlined as follows:

- Chapter 2 gives a brief qualitative discussion of various floating platform concepts.
- Chapter 3 outlines the governing equations that relates the design constraints to structural mass and geometrical parameters.

- Chapter 4 presents the optimization of floating spar buoys for the DeepWind concept.
- Chapter 5 provides a sensitivity analysis of the base case design.

2 SUPPORT STRUCTURES FOR FLOATING WIND TURBINES

2.1 General properties of floaters

A floating structure can be regarded as a rigid body moving with 6 degrees of freedom (DOF), three in translation and three in rotation. All types of floating structures utilise excess buoyancy to support the deck payload and provide tensions to mooring (and riser) system. Therefore, they are to some extent weight sensitive. It is important to make a distinction between whether the support structure is *freely floating*, *compliant* or *restrained*. All floating structures have compliance in one or more directions, whereas some of them are restrained by structural connections to the seabed. In the latter case one or more degrees of freedom (DOFs) becomes “stiff”, allowing only as much motion as the structure can yield.

The offshore oil and gas industry has long tradition for developing floating structures for explorations in harsh environment. Examples concepts are shown in Figure 2.1.

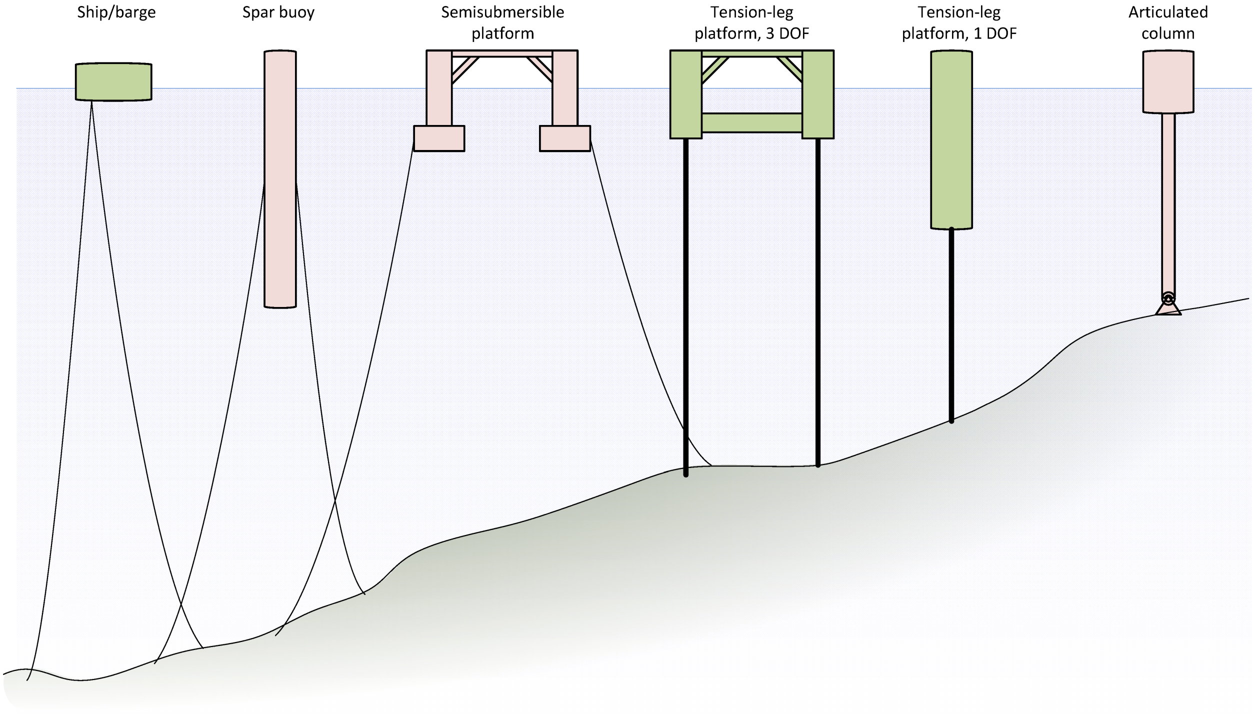
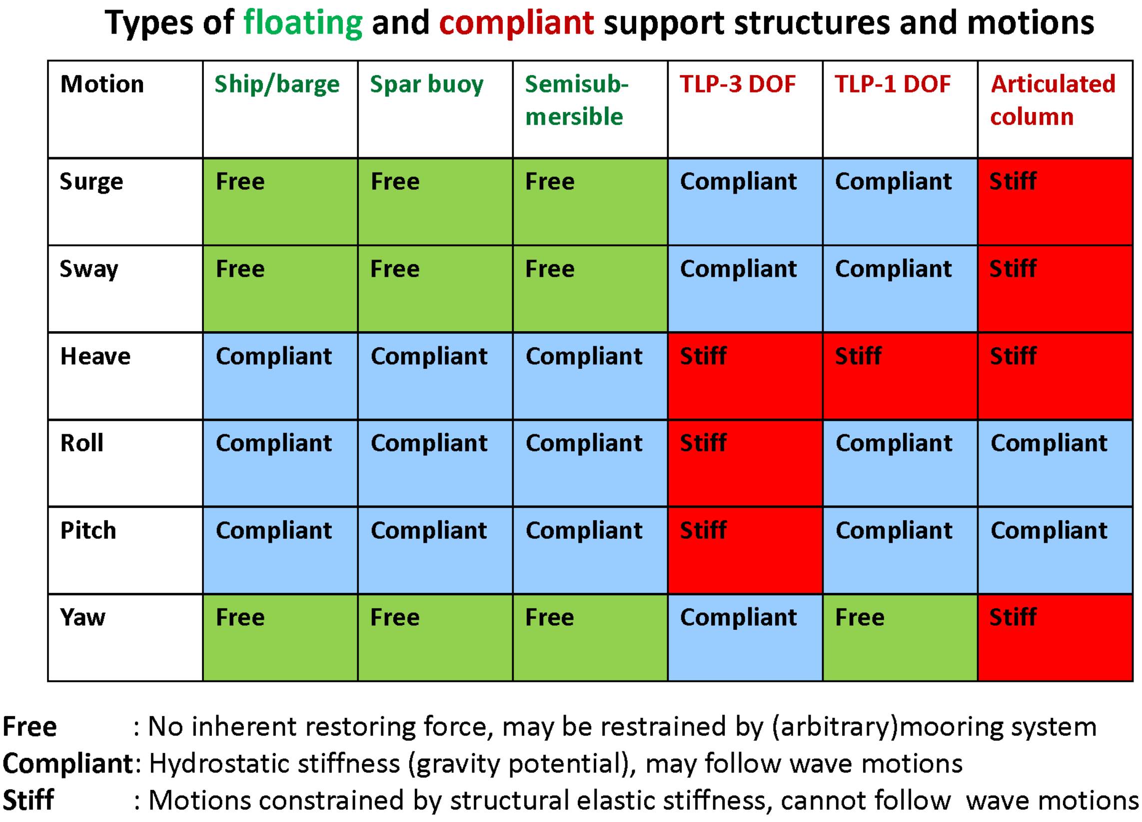


Figure 2.1: Illustration of conventional support structures for offshore installations.

Table 2.1 categorize the conventional support structures according to free, compliant and stiff modes of motion. Examples of floating structures are semisubmersibles, spar buoys and ship type structures. Types of restrained structures include tension leg platforms (1-DOF and 3-DOF TLPs) and articulated columns.

A common characteristic of the floater types (except for articulated columns) are that they are compliant

Table 2.1: Types of floating and compliant structures.



Types of floating and compliant support structures and motions

Motion	Ship/barge	Spar buoy	Semisub-mersible	TLP-3 DOF	TLP-1 DOF	Articulated column
Surge	Free	Free	Free	Compliant	Compliant	Stiff
Sway	Free	Free	Free	Compliant	Compliant	Stiff
Heave	Compliant	Compliant	Compliant	Stiff	Stiff	Stiff
Roll	Compliant	Compliant	Compliant	Stiff	Compliant	Compliant
Pitch	Compliant	Compliant	Compliant	Stiff	Compliant	Compliant
Yaw	Free	Free	Free	Compliant	Free	Stiff

Free : No inherent restoring force, may be restrained by (arbitrary)mooring system
Compliant: Hydrostatic stiffness (gravity potential), may follow wave motions
Stiff : Motions constrained by structural elastic stiffness, cannot follow wave motions

(or free) in the horizontal plane, i.e. surge, sway and yaw periods are generally long. The main differences among the floaters are related to their motions in the vertical plane, i.e. heave, roll and pitch.

The ocean waves usually contain significant wave energy for wave periods in the range 5–20 s. The natural periods for a floating structure of the 6 different degrees of freedom are therefore of importance with regards to design philosophy. For a floating structure the mooring system should normally be soft to limit the dynamic wave induced loading. However, the horizontal stiffness must be sufficient to keep the horizontal excursion within limits governed by seabed connections such as power cables, and clearance to other structures. The wave loading for a structure restrained in one or more DOFs is transferred to the structural anchoring components.

Important design considerations for floating and compliant platforms are:

- For restrained DOFs the following apply:
    - restrained DOFs require restraining forces as large as the wave forces. Typically, they are of the same order of magnitude as the structure displacement × water acceleration

  - the natural period of restrained DOFs must be much shorter than the energetic wave periods (i.e. below about 4 s) to avoid resonance effects

- The compliant DOFs must either have:
  - resonance periods longer than the energetic wave periods, typically above 20 s.
  - small wave excitation or large damping for DOFs with natural periods in the energetic waves periods range (5-20 s), such as heave, pitch and roll motion of a ship/barge shaped structure.
- The free DOFs do not require restraining forces, except a stiffness sufficient to keep position offset within acceptable limits.

Typical natural periods of different floaters used for oil and gas exploration are presented in Table 2.2.

Table 2.2: Typical natural periods for floaters [13] used for oil and gas exploration. Numbers are given in seconds.

Mode	FPSO	SEMI	SPAR	TLP
Surge	>100	>100	>100	>100
Sway	>100	>100	>100	>100
Heave	5-12	20-50	19-35	<5
Roll	5-30	30-60	50-90	<5
Pitch	5-12	30-60	50-90	<5
Yaw	>100	>100	>100	>100

2.2 Characteristics of different floaters

In this section, some typical floating systems and their key features are outlined.

Monohulls

Ship and barge-type structures. Some key attributes are:

- Typically large water plane area and shallow draught.
- Pitch stiffness is provided by the large water plane area.
- Provides a large work area, with large deck load and storage capacity.
- Transportable, has inherent structural strength and is relatively cheap to construct.
- Suitable for shallow water due to the shallow draught.

An unwanted side effect of its large displaced volume near the free surface is the excessive wave loads and motion responses. The mooring system must therefore be designed to withstand these motions. For oil and gas exploration, alternative mooring systems have been developed to allow the vessel to weathervane in order to reduce environmental loads and wave induced motions. Spread mooring can be applied in extremely mild and directional environments.

Semisubmersibles

Semi-submersibles are common concepts used in the exploration and production of oil and gas. These platforms comprise of a set of vertical, surface piercing columns connected to submerged horizontal pontoons. Horizontal and cross-diagonal bracing provide structural strength of the platform.

Some key attributes are:

- The motion response for a semi-submersible can be minimized by carefully selecting combination of column diameter and number of columns, distance between columns, draught and shape of the underwater structure that give natural periods away from the period range where the wave spectrum has most energy.
- The restoring coefficients in heave, roll and pitch are determined by the number of columns, column diameter and distance between the columns. The pitch stiffness can be increased by either increasing the water plane area or increasing the distance between the columns.
- Active ballast shifting system can be designed to counteract the moment of the mean rotor thrust force.
- Suitable for shallow water due to the relative shallow draught.
- Cancellation or magnification effects will occur at integer ratios between wave length and column distance. Another cancellation effect is the force compensation caused by the opposite wave pressure on top and bottom of pontoons.
- Transportable.

The semi-submersible has a better response characteristic than a barge-type structure, it does not need to weathervane in extreme environment such that spread mooring can be applied for station keeping. The relatively shallow draft makes the semi-submersible a more suitable concept for shallow water than the deep draft spar buoy. The unit cost, however, is expected to be higher than for a spar or barge-type structure, because of the increased structural complexity including the small-diameter bracing elements for structural integrity. Stability is crucial for semi-submersibles, and it can be dramatically reduced if the hull is damaged and water enters empty compartments in the hull.

Tension leg platforms

Tension leg platforms (TLP's) were originally developed to eliminate vertical motions for oil and gas exploration. Some key attributes are:

- Platforms moored to the sea bed by vertical tethers which are maintained at high tension by the excess buoyancy of the platform.
- High stiffness in heave, roll and pitch. The high stiffness virtually eliminates these modes of motion and also shorten the natural periods below the energetic wave periods.
- Highly compliant in surge, sway and yaw with natural periods well above dominant wave periods.
- A simpler form of the classical TLP is the single column 1-DOF TLP where only the heave motion is restrained from moving. These types of structures will in addition to surge, sway and yaw also experience roll and pitch motion.
- Suppression of vertical motion is advantageous in operation when vertical motions are critical, e.g. due to critical sea bed connections. It allows for dry wellheads with short-stroke motion compensators (oil and gas installations).

The tethers are an integral part of the structural design, and constitutes the critical support element for vertical forces. TLPs require foundations capable of withstanding large upward forces. The pretension must also be large enough to prevent the tethers from becoming slack in large waves (deep wave trough). The high stresses in the tethers require careful design and maintenance, and the installation is complex and costly.

Spar buoys

The spar buoy is a deep draft, slender structure with a relatively small water plane area. Some key attributes are:

- Gravity-stable, the roll and pitch stiffness are governed by the distance between the mass centre and the buoyancy centre.
- The low centre of gravity provides large righting moment ensuring that the floater stays upright with low roll and pitch motion.
- The deep draught limits vertical wave forces such that the vertical motion of the spar buoy is small.
- For floating offshore wind turbines the upper part of the spar buoy is narrowed such that a small cross-sectional diameter is obtained in the wave zone, which limits the horizontal wave loads on the structure and contributes to a vertical resonance period well above the dominating wave periods (small water plane area).
- Difficult to transport in upright position in shallow water. The transportation must then be done by towing the cylindrical buoy in horizontal position (or slightly inclined), either floating or on a barge type structure. For many locations, this will require on-site assembling of turbine.

The spar buoy has shown to be a promising solution for floating offshore wind turbines due to its favorable motion behaviour and the relatively simple and cheap structure to build.

2.3 Floating offshore wind turbines

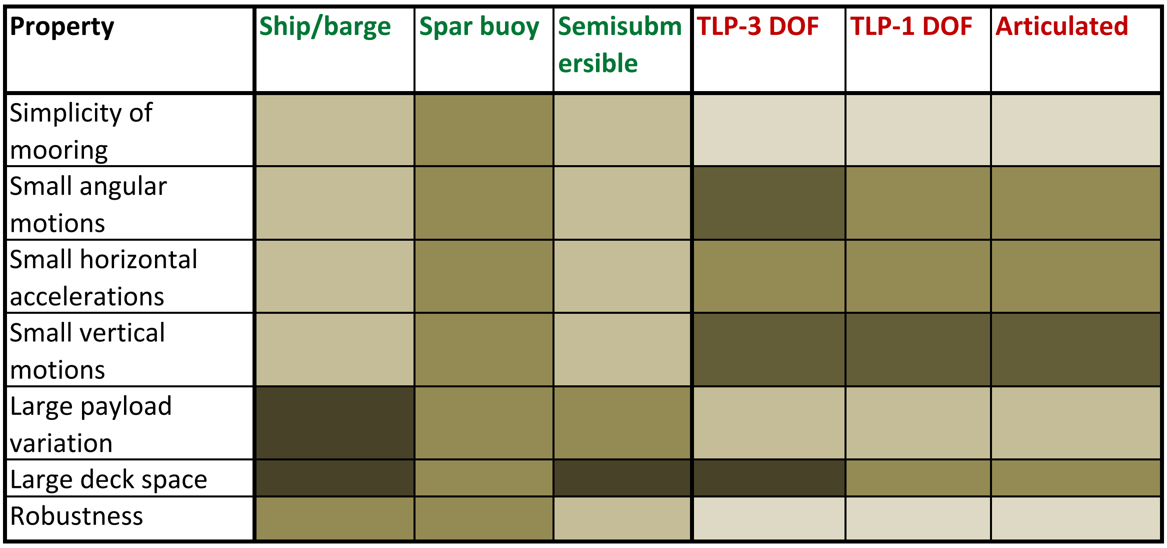
Various conventional floater concepts have been explored as support structures for floating offshore wind turbines. Examples are Hywind [5], SWAY [7], BlueH [8], and WindFloat [6]. Hywind is the first full scale floating HAWT, and it was deployed off the south-west coast of Norway in 2009 by Statoil. The Hywind concept is based on a floating soft moored spar buoy. Another full scale pilot is the WindFloat concept deployed by Principle Power off the coast of Aguçadoura, Portugal, in 2011. WindFloat has the turbine mounted on a spread moored semi-submersible. The WindFloat concept has an active ballasting system that compensates for mean wind loads and reduces the static tilt angle. The SWAY concept is based on a spar-type buoy, but anchored to the seabed with a single tendon (TLP-1 DOF). The BlueH floating wind turbine is also based on the TLP concept. The BlueH platform has several vertical tendons tethering the floater to the seabed which restrain the motion in 3 degrees of freedom (TLP-3 DOF).

For applications of conventional floating platforms as wind turbine support structures, it is important to identify the properties relevant to functional requirements. These are typically:

- Accelerations at the generator/machinery components (should be small)
- Range and speed of angular motions (should be 'reasonable')
- Vertical load variation (are small)
- Vertical motions (allow for wide tolerance)
- Offset on horizontal positions (allow for wide tolerance)

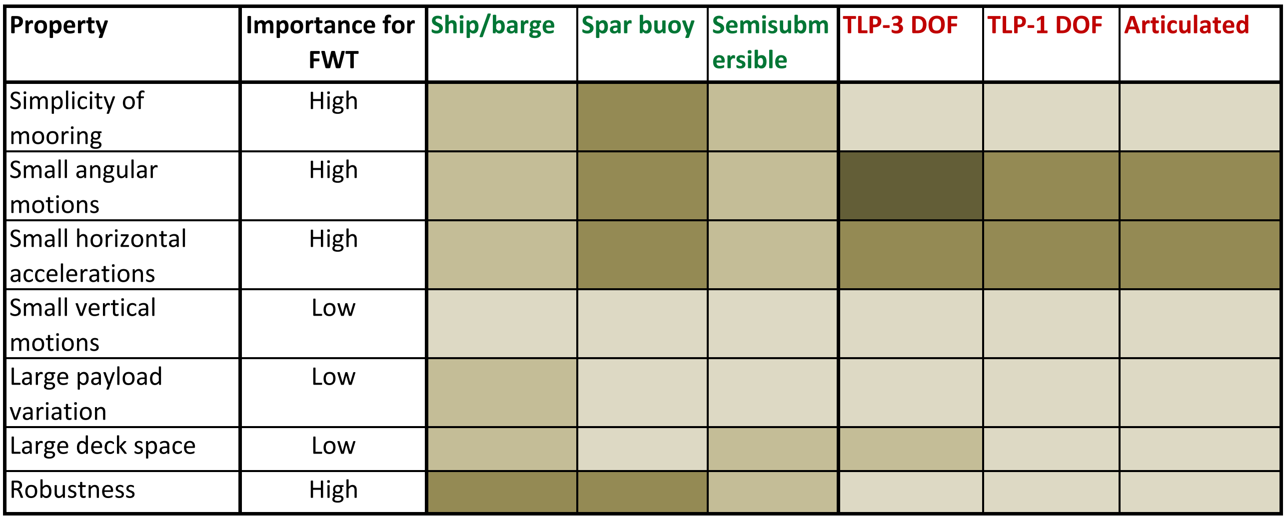
A qualitative rating of some key properties for different platform concepts are shown in Table 2.3. A darker color in the table indicates a higher performance factor. These performance factors are given a qualitative weighted rating in Table 2.4 based on the importance for floating wind turbines, i.e. properties of high importance for floating wind turbines are given a higher weight factor than properties of low importance. For instance, ship type structures are given a high performance rating for large deck space; however, large deck space is of low importance for floating wind turbine and hence the property is given a low weighted performance rating.

Table 2.3: Qualitative rating of some key properties for floaters applied in offshore oil and gas installations (not including cost). Darker color indicates higher performance.



Property	Ship/barge	Spar buoy	Semisubmersible	TLP-3 DOF	TLP-1 DOF	Articulated
Simplicity of mooring	▒	▓	▒	░	░	░
Small angular motions	▒	▓	▒	█	▓	▓
Small horizontal accelerations	▒	▓	▒	▓	▓	▓
Small vertical motions	▒	▓	▒	█	█	█
Large payload variation	██	▓	▓	▒	▒	▒
Large deck space	██	▓	██	██	▓	▓
Robustness	▓	▓	▒	░	░	░

Table 2.4: Qualitative rating for floating wind turbine (FWT) application. The table is produced by giving relevant weights to the properties presented in Table 2.3. Darker color indicates higher performance.



Property	Importance for FWT	Ship/barge	Spar buoy	Semisubmersible	TLP-3 DOF	TLP-1 DOF	Articulated
Simplicity of mooring	High	▒	▓	▒	░	░	░
Small angular motions	High	▒	▓	▒	█	▓	▓
Small horizontal accelerations	High	▒	▓	▒	▓	▓	▓
Small vertical motions	Low	░	░	░	░	░	░
Large payload variation	Low	▒	░	░	░	░	░
Large deck space	Low	▒	░	▒	▒	░	░
Robustness	High	▓	▓	▒	░	░	░

3 ANALYSIS

In the remaining part of the report we will focus on the spar buoy as the floating support structure for the floating VAWT DeepWind concept.

The sizing of a floater in the present work is based on simplified approach. The design requirements are limited to a floater with sufficient buoyancy to carry a given payload with design constraints on the maximum tilt angle due to static wind load and constraints on the floaters natural periods in heave and pitch. These optimization constraints are given in Chapter 4 where the cost function is specified to represent the total cost of the material used for the floating structure. It is therefore necessary to establish a relationship between the structural mass and geometrical parameters and the design constraints. These relationships are outlined in the following sections.

3.1 Spar buoy parameterization

The spar buoy is modelled as a symmetric structure built up from a set of cylindrical cross sections (See Figure 3.1). The upper and lower sections have constant diameter with a uniform mass distribution along the length. A section formed as a tapered cylinder connects the upper section with the main section. A footing section is connected to the lower end of the main section, where the generator is located. Fixed ballast is stored in the bottom of the main section, to keep center of gravity low. No bulkhead deck inside the spar hull is considered at this stage. The mooring line fairleads are located at the bottom of the structure.

The wall thickness of the spar steel hull is related to the hull diameter by

$$\tau_w = \tau_{w,0}\left(\frac{D}{D_0}\right)^{pd},$$

where the subscript 0 denotes the initial (reference value) and pd is a diameter dependency exponent. The exponent is set to zero for the upper section ($pd_1 = 0$), i.e. constant wall thickness. For the main hull pd_2 is set equivalent to 0.5, such that the wall thickness varies with the square root of the diameter.

The ’payload’ is assumed to be fixed, and specified by the following parameters, separately for tower, rotor blades and generator:

1. Mass
2. Centre of Gravity
3. Mass moment of inertia

The anchoring system is assumed to be fixed and is specified by

1. Vertical force
2. Stiffness coefficient in surge

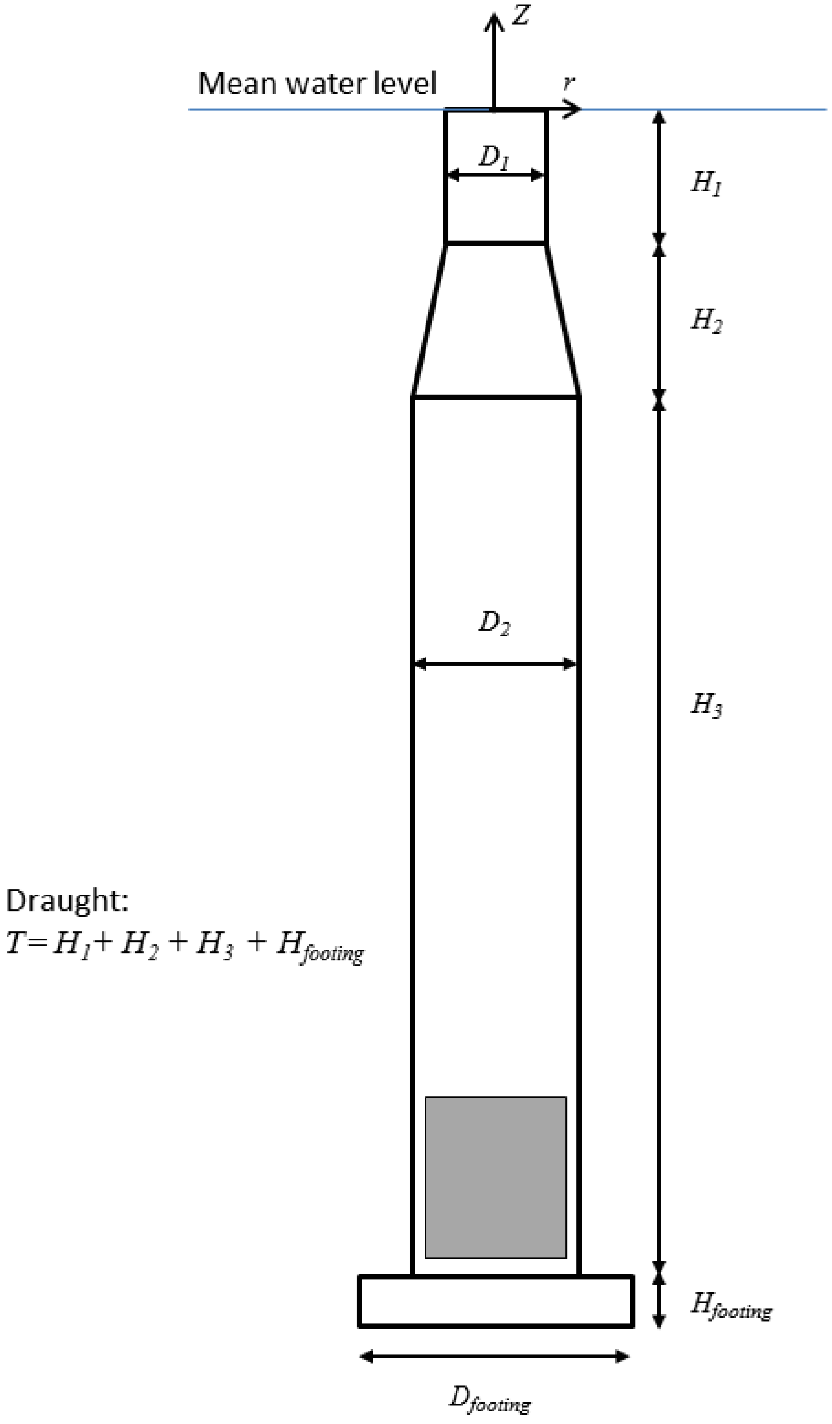


Figure 3.1: A simple illustration of the main dimensions describing the spar buoy.

3.2 Natural periods

The natural periods for the floating structure is obtained from the eigenvalues of the un-damped dynamical system described by the following matrix equation:

$$(\mathbf{M}+\mathbf{A})\,\ddot{\mathbf{X}}+\mathbf{K}\,\mathbf{X}=0, \tag{3.1}$$

where **M** is the system mass matrix, **A** is the added mass matrix due to the motion of entrained water, and **K** is the stiffness matrix containing contributions from hydrostatic stiffness and linearized mooring stiffness. The vectors $\ddot{\mathbf{X}}$ and **X** denote the floater's acceleration and relative position, respectively.

Due to the axisymmetric body of the spar buoy, the dynamical system can be reduced into three degrees of freedom considering surge, heave and pitch only. The system matrices take the following forms:

$$\mathbf{M}=\begin{bmatrix} m & 0 & mz_G \\ 0 & m & 0 \\ mz_G & 0 & I_{55} \end{bmatrix},\quad \mathbf{A}=\begin{bmatrix} a_{11} & 0 & a_{15} \\ 0 & a_{33} & 0 \\ a_{51} & 0 & a_{55} \end{bmatrix},\quad \mathbf{K}=\begin{bmatrix} k_{11} & 0 & k_{15} \\ 0 & k_{33} & 0 \\ k_{51} & 0 & k_{55} \end{bmatrix},$$

where m is the mass, $I_{55}=I_{55}^0+mz_G^2$ is the moment of inertia, z_G is the vertical coordinate of centre of gravity. The added mass coefficient depend only on the external shape of the buoy and can be approximated by two-dimensional ”strip theory”. The stiffness matrix consists of linearized contribution from the mooring system and contribution from hydrostatic stiffness. Note that for this simple geometry the heave motion becomes uncoupled to the two other DOFs, and that $a_{15}=a_{51}$ and $k_{15}=k_{51}$.

Assuming a harmonic solution on the form $\mathbf{X}=\mathbf{X}_0e^{-i\omega_n t}$, and substituting into Eq. (3.1), gives a polynomial equation to be solved for the un-damped natural frequencies:

$$\det\left|\mathbf{K}-\omega_n^2\left(\mathbf{M}+\mathbf{A}\right)\right|=0.$$

This gives us the following expressions for the un-damped natural periods in surge, heave and pitch:

$$T_{n1}=2\sqrt{\frac{2a}{-b-\sqrt{b^2-4ac}}},\quad T_{n3}=2\sqrt{\frac{m+a_{33}}{k_{33}}},\quad T_{n5}=2\sqrt{\frac{2a}{-b+\sqrt{b^2-4ac}}},$$

where we have used the relation $T_n=2\pi/\omega_n$, and

$$\begin{aligned} a &= (m+a_{11})(I_{55}+a_{55})-(mz_G+a_{15})^2 \\ b &= -k_{11}(I_{55}+a_{55})-k_{55}(m+a_{11})+2k_{15}(mz_G+a_{15}) \\ c &= k_{11}k_{55}-k_{15}^2 \end{aligned}$$

3.3 Stiffness coefficients

The restoring force in surge is provided by the mooring system, i.e.

$$k_{11}=k_x,$$

where k_x is the linearized, resultant horizontal restoring stiffness from all the mooring lines.

For a soft-moored system, the restoring force in heave is dominated by hydrostatic effects. The vertical hydrostatic restoring stiffness k_{33} is given by

$$k_{33} = \rho g A_w,$$

where ρ is the density of water, g is the gravitational acceleration, and A_w is the water plane area, i.e. a larger spar diameter at the water plane will give a larger restoring force to heave excursions.

When the radius of the buoy is small and the mooring lines are attached far below the centre of rotation, the linear restoring stiffness k_{55} against rotation about the y-axis (pitch) may be expressed by

$$k_{55} = \rho\, g\, V\, z_B - m\, g\, z_G + \rho g\, I_w + k_x z_F^2 + F_z\, z_F,$$

where the first three terms are due to gravitational and hydrostatic effects, and the latter two are due to the mooring system. Here, V is the displaced volume, m is the total mass, I_w is the second moment of inertia (also called the second moment of area) of the water plane area, F_z is the vertical force from the mooring lines (and power cable), z_B is the vertical centre of buoyancy, z_G is the vertical centre of gravity, and z_F is the vertical position of the fairleads (i.e. where the mooring line departs from the buoy).

The coupled surge-pitch stiffness is given as

$$k_{15} = k_{51} = k_x z_F.$$

3.4 Added mass coefficients

For a simple, cylindrical structure, a strip theory approach based on 2D added mass coefficients will give a fairly good approximation of the added mass for the spar buoy.

The surge added mass is approximated by

$$a_{11} \simeq \sum_{N_{sec}} C_{a,x} \rho \pi (D_i/4)^2 H_i,$$

where N_{sec} is the number of cylindrical sections in Figure 3.1, the coefficient $C_{a,x}$ is set to 0.97, and H_i and D_i are the height and diameter of the ith section, respectively. The diameter of the tapered section is an equivalent diameter of a cylinder with the equivalent volume.

Heave added mass is estimated by

$$a_{33} \simeq \frac{2}{3} \rho \pi (D_{footing}/4)^3 + \frac{2}{3} \rho \pi \sum_{N_{sec}-1} \left[(D_{i+1}/4)^3 - (D_i/4)^3 \right].$$

Pitch added mass is approximated by

$$a_{55} \simeq \sum_{N_{sec}} C_{a,x} \rho \pi (D_i/4)^2 H_i \left[\frac{1}{12} (z_{t,i} - z_{b,i})^2 + \frac{1}{4} (z_{t,i} + z_{b,i})^2 \right]^2,$$

where $z_{t,i}$ and $z_{b,i}$ are the top and bottom position of section i, respectively. The coupled surge-pitch added mass is given by

$$a_{15} = a_{51} \simeq \frac{1}{2} \sum_{N_{sec}} C_{a,x} \rho \pi (D_i/4)^2 (z_{t,i}^2 - z_{b,i}^2).$$

3.5 Vertical equilibrium

The floating structure is in vertical equilibrium when the total weight of the structure, including rotor tower, blades, generator, steel hull, ballast, power cable and anchor lines, is equivalent to the displaced volume of water, i.e.

$$mg - F_{\text{z,anch}} = \rho_{\text{water}} g \nabla,$$

where m is structural mass, ∇ is the submerged volume of the structure and $F_{\text{z,anch}}$ is the total vertical loads from the mooring lines and power cable.

3.6 Static offset

Horizontal offset and platform heeling due to static loads can be calculated by solving

$$\begin{bmatrix} k_{11} & k_{15} \\ k_{51} & k_{55} \end{bmatrix} \begin{bmatrix} x_{stat} \\ \varphi_{stat} \end{bmatrix} = \begin{bmatrix} F_{stat} \\ M_{stat} \end{bmatrix}.$$

4 SPAR BUOY OPTIMIZATION

In this chapter, a simple optimization approach is used to obtain the main dimensions of a floating spar buoy for the DeepWind concept. The floater is designed to minimize material cost, while satisfying functional design requirements. Three configurations of the spar buoy are considered, all based on optimization of the same base case using different design constraints.

The optimization procedure used in the present work utilizes the standard optimization package provided by the Solver tool in Microsoft EXCEL. The solver program needs a model that specifies:

- The measure or function to optimize, the objective function
- The resources to be used, using control (or design) variables
- The restrictions to be satisfied, called constraints

The solver function will find values for the design variables that satisfy the constraints while optimizing the objective functions.

4.1 The cost minimization problem

4.1.1 Objective function

The function to be minimized specifies the cost of the floating substructure and has two contributions:

$$F = F_{\text{steel}} + F_{\text{ballast}},$$

where F_{steel} and F_{ballast} denotes cost for steel and fixed ballast, respectively, and are defined as

$$F_{\text{steel}} = m_{\text{steel}} \cdot q_{\text{steel}}$$
$$F_{\text{ballast}} = m_{\text{ballast}} \cdot q_{\text{ballast}}$$

for unit price q and mass m.

4.1.2 Design variables

Three design variables are specified for the spar buoy:

- Water plane diameter D_1
- Main spar hull diameter D_2
- Spar buoy draught T

This allows for sufficient manipulation of buoyancy and weight. Water plane stiffness is governed by the water plane diameter. The fixed ballast is governed by the displaced volume. The vertical position of buoyancy and mass centre are mainly governed by the length and diameter of the main hull section.

4.1.3 Constraints

The following constraints are applied:

Upper and lower bounds on the natural periods in heave and pitch:

$$T_{\text{n3,l}} \leq T_{\text{n3}} \leq T_{\text{n3,u}}$$
$$T_{\text{n5,l}} \leq T_{\text{n5}} \leq T_{\text{n5,u}}$$

Upper bound on static inclination angle:

$$\phi \leq \phi_{\text{max}}$$

Upper bound on spar buoy draught:

$$T \leq T_{\text{max}}$$

The design limits for the three different configurations are summarized in Table 4.1. The natural periods and the static inclination angles are calculated as described in Chapter 3.

Table 4.1: Design constraint values.

Parameter	unit	Case 1	Case 2	Case 3
$T_{\text{n3,l}}$	[s]	25.0	25.0	25.0
$T_{\text{n3,u}}$	[s]	35.0	35.0	35.0
$T_{\text{n5,l}}$	[s]	25.0	25.0	25.0
$T_{\text{n5,u}}$	[s]	35.0	35.0	25.0
ϕ_{max}	[deg]	15.0	10.0	10.0
T_{max}	[m]	110.0	110.0	150.0

4.2 Material selection

The spar hull is made of steel with density 7850 kg/m^3. The ballast material is un-compact, water saturated Olivine with density 2600 kg/m^3.

The cost of material is:

$$q_{\text{steel}} = 3750 \text{ Euro/t},$$

$$q_{\text{ballast}} = 50 \text{ Euro/t}.$$

4.3 Wind force

The maximum static horizontal wind force is given in Table 4.2.

Table 4.2: Maximum horizontal wind force.

Description	Parameter	unit	Value
Max horizontal force	F_{wind}	[kN]	700
Point of attack (above SWL)	H_{wind}	[m]	79.78

4.4 Payload

The payload is assumed to be fixed and comprise of rotor tower, rotor blades, generator, mooring lines and power cable. The input data used in the calculation is summarized in Table 4.3.

Table 4.3: Payload for spar buoy optimization.

Description	Parameter	unit	Value
Tower			
Mass	m_{tower}	[t]	450.6
Height	H_{tower}	[m]	145
Diameter	D_{tower}	[m]	6.3
Wall thickness	$t_{\text{w,tower}}$	[m]	0.02
Blades			
Mass (1 blade)	m_{blade}	[t]	132
VCOG	z_{blade}	[m]	79.78
Moments of inertia	I_{55}^{0}	[t·m^2]	7.73E+05
Generator			
Height	H_{gen}	[m]	1.4
Diameter	D_{gen}	[m]	10.5
Mass	m_{gen}	[t]	90
Moments of inertia	I_{55}^{0}	[t·m^2]	634.9
Mooring line forces (including power cable)			
Vertical force	$F_{\text{z,anch}}$	[kN]	-2000
Stiffness surge	$K_{\text{11,anch}}$	[kN/m]	150

4.5 Results

The optimization of the base case has been run for the three different sets of design constraints given in Table 4.1. The results are summarized in Table 4.4 and 4.5. Base case in the table gives the initial values that was used as starting conditions for the optimization. The optimized cases all satisfy the given design constraints.

For all cases, the natural period obtained for the heave mode was 25 s, i.e. converged to its lower bound. In pitch, the natural period obtained was in the range 29.0 - 31.2 seconds for all cases, safely within the upper and lower bounds. The static inclination angle appears to be a limiting constraint as the results converged to the upper bound for all cases. A stricter condition on the inclination angle yields a more costly spar buoy.

A reduction in cost indicates less use of steel and ballast for the spar hull in order to satisfy the design requirements. For the configurations considered here the cost varies with about 10%. Note that the optimization method tries to find a better solution in the vicinity of the initial conditions, and due to the complex shape of the constraint functions and inaccuracies of the numerical algorithm the search may converge to a local optima inferior to the best solution.

Table 4.4: Static and dynamic properties of the spar buoy design.

Description	Parameter	unit	Base Case	Case 1	Case 2	Case 3
Static pitch angle due to wind load						
Static heel angle	ϕ_{static}	[deg]	13.6	15.0	10.0	10.0
Natural periods						
Surge	T_{n1}	[s]	75.2	76.7	72.4	74.5
Heave	T_{n3}	[s]	27.9	25.0	25.0	25.0
Pitch	T_{n5}	[s]	31.3	31.2	29.9	29.0

Table 4.5: Main dimensions of spar buoys from optimization. Base case provides the starting conditions for the optimization. Rows with design variables are highlighted with light cyan.

Description	Parameter	unit	Base Case	Case 1	Case 2	Case 3
Spar hull						
Wall thickness (upper)	τ_1	[mm]	50	50	50	50
Wall thickness (main)	τ_2	[mm]	50	49	50	46
Height upper cyl	H_1	[m]	5.00	5.00	5.00	5.00
Height tapered cyl	H_2	[m]	10.00	10.00	10.00	5.00
Height main cyl	H_3	[m]	91.55	93.55	93.55	124.55
Height footing	H_{footing}	[m]	1.45	1.45	1.45	1.45
Draught	T	[m]	108.0	110.0	110.0	141.0
Upper diameter	D_1	[m]	6.30	6.83	7.29	6.9
Main diameter	D_2	[m]	8.30	7.92	8.52	7.0
Footing diameter	D_{footing}	[m]	10.60	10.60	10.60	10.60
Position fairlead	Z_{fairlead}	[m]	-108.0	-110.0	-110.0	-141.0
Sum hull + payload						
Mass (total)	m	[t]	5595.98	5273.29	6110.26	5421.58
Fixed ballast	m_{ballast}	[t]	3672.65	3390.90	4114.83	3448.53
Inertia about COG	I_{55}	[t·m^2]	2.09E+07	2.10E+7	2.17E+7	2.67E+7
Centre of gravity	Z_G	[m]	-61.11	-63.17	-67.54	-85.54
Volume	V	[m^3]	5658.39	5343.57	6160.13	5488.25
Centre of buoyancy	Z_B	[m]	-56.48	-56.76	-56.64	-71.53
Water plane area	A_w	[m^2]	31.17	36.60	41.75	34.52
Displacement	Δ	[t]	5799.85	5477.16	6314.13	5625.46
Cost						
Total cost spar		[kEuro]	4379	4211	4671	4554

5 SENSITIVITY ANALYSIS WITH BASE CASE DESIGN

In this chapter, a simple sensitivity analysis is carried out by varying some key parameters in order to investigate the influence on the static and dynamic properties of the spar buoy. The parameter variations are carried out on a base design, varying one variable while keeping the other ones fixed.

The following parameters are varied:

- Centre of gravity of the blades
- Mass of blades
- Mass of tower section above still water sea level
- Mass of generator
- Water plane diameter
- Main hull diameter
- Draught of spar hull

The static and dynamic properties of the spar buoy considered are:

- Static heel angle due to static wind load
- Natural periods in heave and pitch mode of motion

The properties are calculated based on the formulations given in Section 3.

Note that the displaced volume of the floater remains the same when varying the weight of the payload components. For all of these cases, the amount of ballast is adjusted accordingly in order to balance the buoyancy force with the weight of the floater. This will also influence the centre of mass.

5.1 Input base design

The base case given in Table 4.5 is used as initial configuration in the sensitivity analysis.

5.2 Results

Results from the parameter variations are shown in Figures 5.1 - 5.7. The vertical dashed line indicates the base case values.

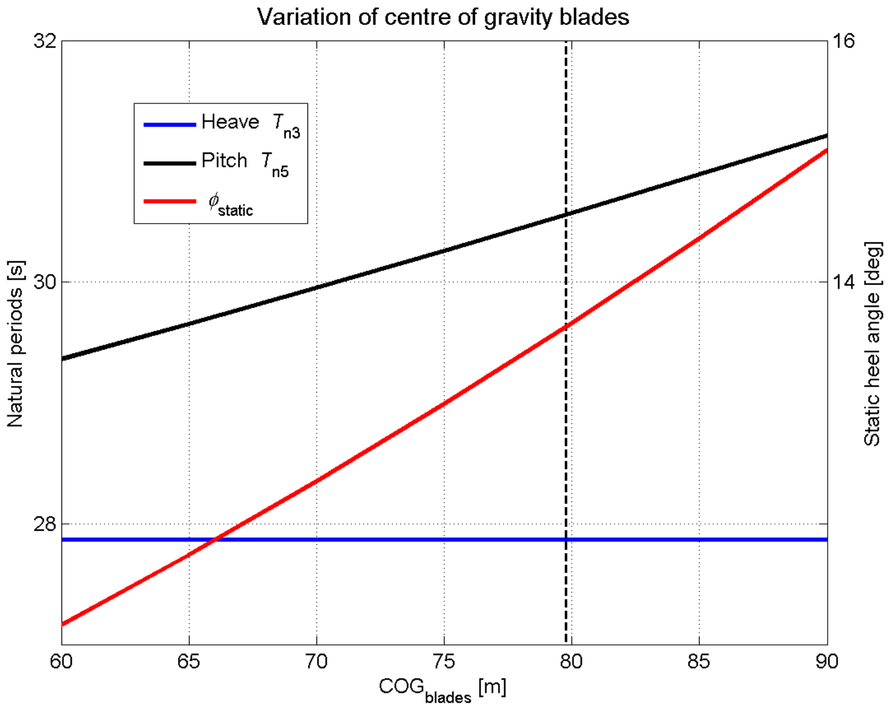


Figure 5.1: Variation of blades centre of gravity. Vertical dashed line indicates base case.

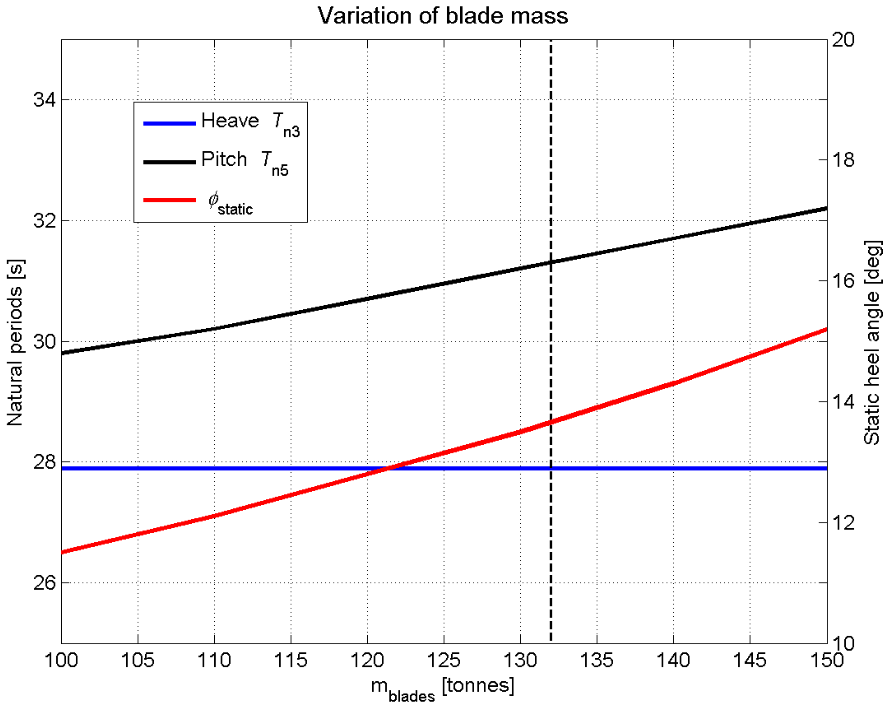


Figure 5.2: Variation of blade mass. Vertical dashed line indicates base case.

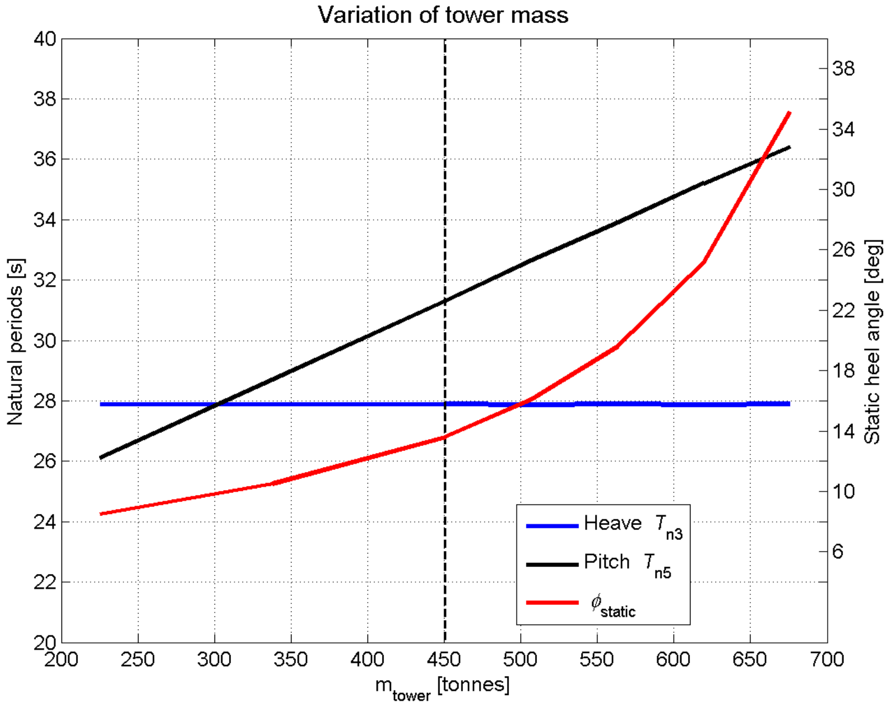


Figure 5.3: Variation of tower mass. Vertical dashed line indicates base case.

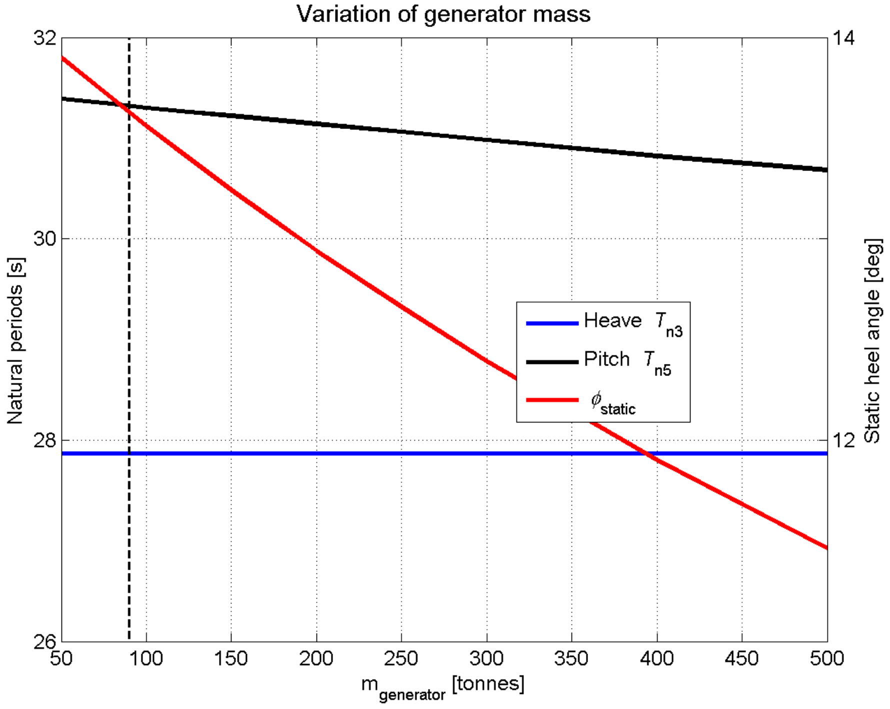


Figure 5.4: Variation of generator mass. Vertical dashed line indicates base case.

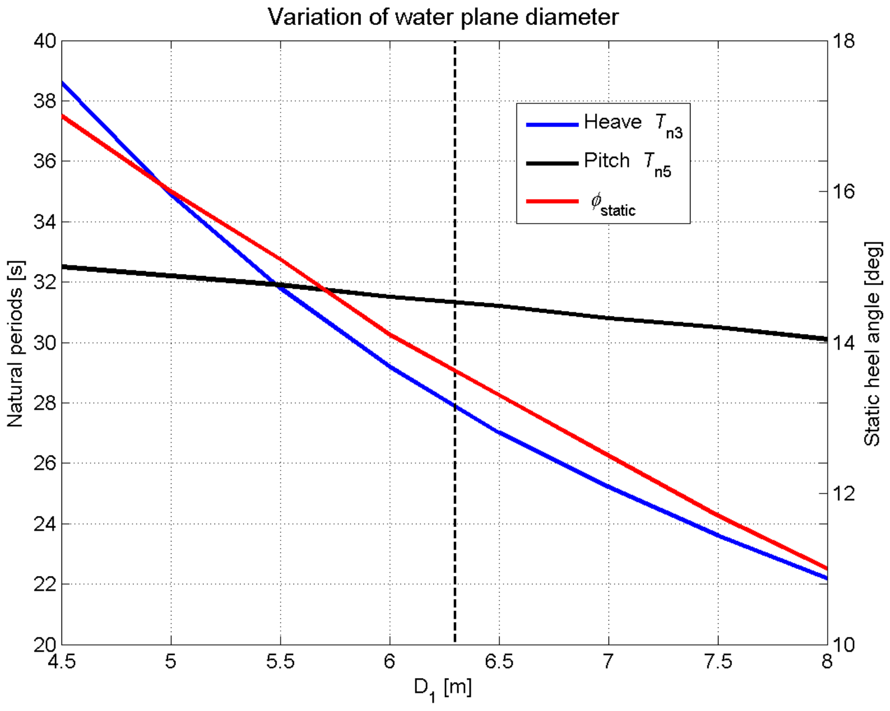


Figure 5.5: Variation of water plane diameter. Vertical dashed line indicates base case.

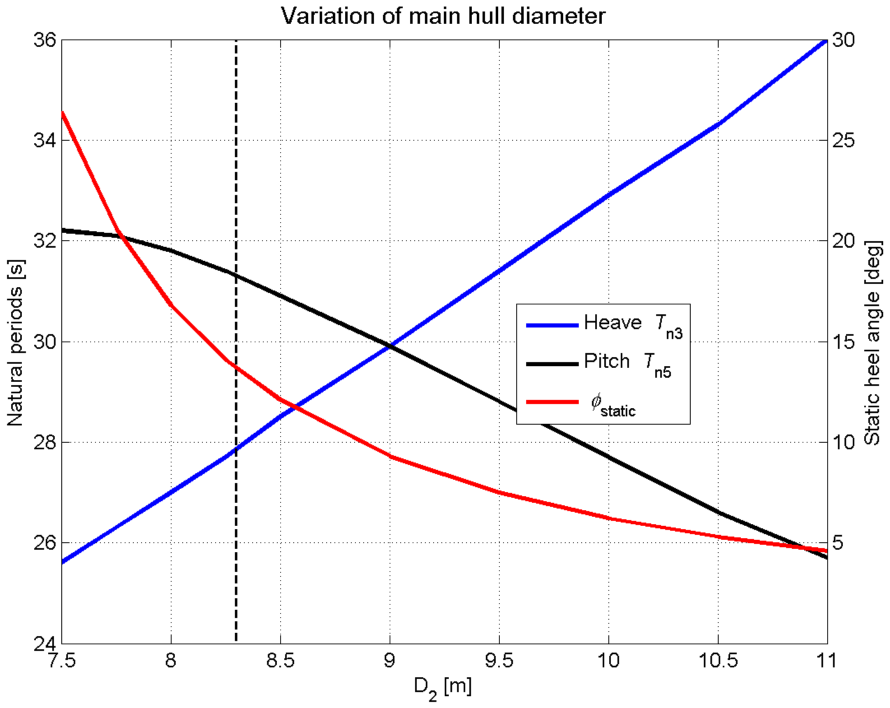


Figure 5.6: Variation of main hull diameter. Vertical dashed line indicates base case.

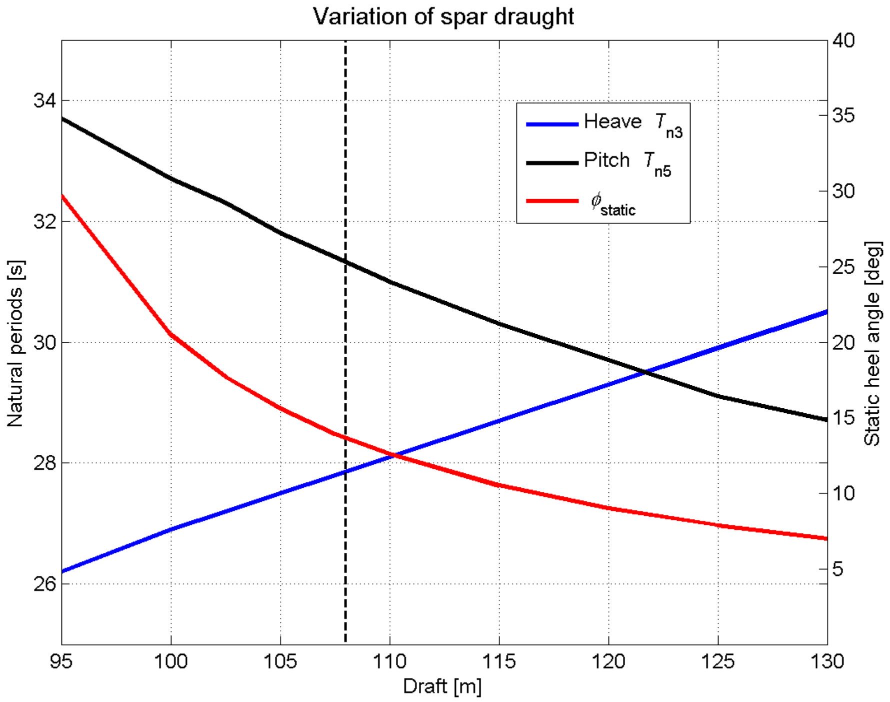


Figure 5.7: Variation of spar draught. Vertical dashed line indicates base case.

5.3 Comments on the results

In practice, the stability of a free floating spar buoy relies primarily on gravity stability: the vertical distance between the mass centre and the buoyancy centre. Rotational stiffness is then obtained by having a non-homogenous mass distribution, i.e. a light voluminous upper part and a heavy lower part. Further, if we consider rotation about the centre of gravity ($Z_\mathrm{G} = 0$) and assume that the coupling between surge and pitch is weak; the pitch natural period can be approximated with the expression for the uncoupled resonance period:

$$T_{5\mathrm{n}} = 2\pi\sqrt{\frac{I_{55} + a_{55}}{k_{55}}}.$$

To avoid resonance motions of the spar buoy, the natural periods should be tuned to be larger than the wave periods with significant energy. Increasing the pitch natural periods can be done by either increasing the mass moment of inertia (and added mass moment of inertia) or decreasing the stiffness. Decreasing the stiffness may have adverse effect on the restoring ”stability” of the system, e.g. it may result in excessive heeling of the platform.

Lowering the centre of gravity would increase stability, and this can be achieved by (re)moving mass from the upper sections and add mass to the lower sections, below Z_G. The mass moment of inertia can be increased by moving bulk of mass to the outer ends of the spar buoy, further away from Z_G.

From the parametric variations, we may observe that

- Lowering the centre of mass for the blades decreases the static heel angle, increases the pitch stiffness, and reduces the pitch natural period.
- Decreasing the blade mass or tower mass decreases the static heel angle, increases the pitch stiffness, and reduces the pitch natural period.
- Increasing the generator mass decreases the static heel angle, increases the pitch stiffness, and reduces the pitch natural period.
- Increasing the water plane diameter decreases the static heel angle, increases the pitch stiffness, and decreases the natural periods in heave and pitch.
- Increasing the main hull diameter decreases the static heel angle, increases the pitch stiffness, increases the heave natural period, and decreases the pitch natural period.
- Increasing the spar draught decreases the static heel angle, increases the pitch stiffness, increases the heave natural period, and decreases the pitch natural period.

In particular, the results show that decreasing (or lowering) mass above Z_{G} and/or increasing mass below Z_{G} increases the static pitch stability, but tends to decrease the pitch natural period. For the given parameter ranges, it appears that changes in moment of inertia does not compensate for the increased pitch stiffness which cause the pitch natural periods to decrease.

Note that the natural period in heave is only affected by changes in total mass (mass and added mass) or water plane area.

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