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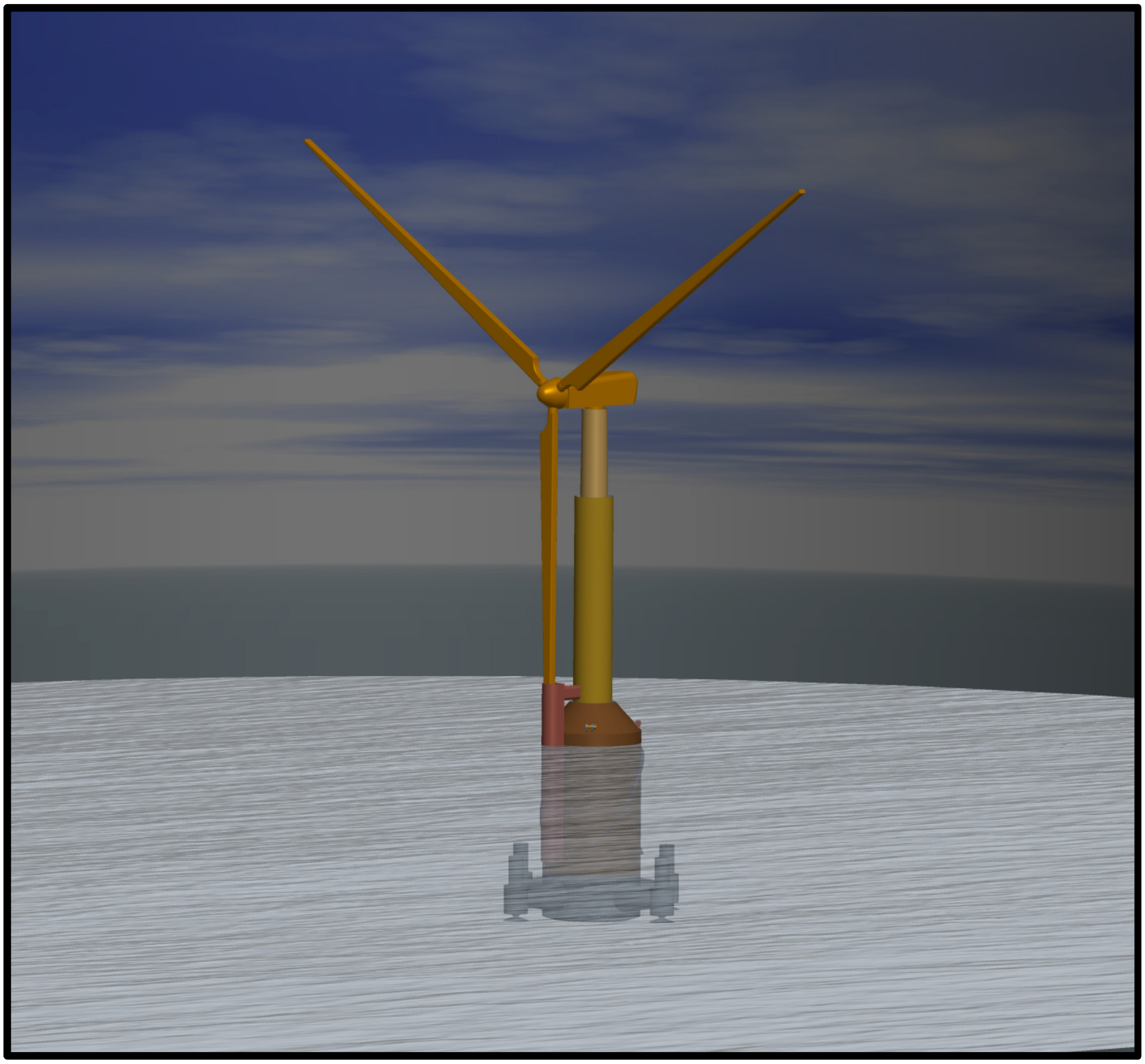

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2. Acknowledgement

My gratitude goes to project supervisor, Arunjyoti Sarkar for giving me opportunity to work on this project, guidance, discussion, references and valuable comments.

Ove T. Gudmestad for the idea of telescopic wind turbine development that has triggered this project.

To my family relatives for supporting and keeping faith in me.

3. Abstract

An offshore wind turbine today is a power generating unit driven by wind exposed blade system. Both are fixed at a certain height above the water level. Installation requires special built vessels, powerful cranes, special techniques, reliable weather conditions and crew working at high heights in marine environment.

Ones installed, a turbine needs maintenance and supervision. Working mechanism is subjected to loads rapidly changing in direction and value. They heavily wear mechanical parts that need to be attended or replaced on a regular basis. Parts are located tens of meters above water level and are difficult to access. When the time to scrap the whole structure will come installation process will have to be repeated again in reverse order for removal. All this drives overall lifecycle costs up and extends project pay-out time to virtually infinite.

This work is FEED like scope definition project. It presents and develops an idea of a mobile offshore wind turbine and key technology components behind this concept.

First element is telescopic tower that will allow installation with minimal marine operations and carry all necessary equipment onboard. The tower is built to be vertically floating with ability to adjust its draft and uses float-over type installation. Lifting mechanism will elevate the nacelle to working height when installation is completed and lower it down for removal.

Unified foundation pile with automatic electrical grid junction will eliminate today's manual operation.

Combined gravity based and legged foundation will ensure on bottom stability during operation.

On external command the whole structure can leave its foundation for then to be either relocated to another wind farm or to home base for upgrade or repair.

4. Introduction

World energy demand is increasing with growth of its population and world economy. High market cost of fossil energy sources, depletion of easily available oil and gas fields and increasing responsibility for environment and pollution mitigation has led to development of alternative and cleaner solutions.

Wind power investments have gained a big acceleration in the last decades including the offshore applications. High potential of the wind energy above the sea, less visual disturbance, turbulence and larger areas that allows implementing larger projects made the offshore wind zones highly attractive. Offshore placement reduces fatigue load on the turbine, lowers wind shear which allows shorter towers. The wind is much stronger off the coasts, and unlike wind over the continent, offshore breezes can be strong in the afternoon, matching the time when people are using the most electricity. Countries with extensive coastal line are highly interested in developing offshore wind parks. Nevertheless they are still more costly than the onshore applications. The major reasons behind it the high costs of electrical grid connections, foundations and the challenges in offshore installations such as weather, wind, and sea state dependency during offshore work and the limited number of purpose built vessels. The turbine itself represents just about one third to one half of costs in offshore projects today, the rest comes from infrastructure, maintenance, and oversight. [2]
Today governmental organizations support industrial development of wind power generation by subsidizing or cutting tax costs for green power generation. Industry is putting a lot of effort to reduce overall system cost and become competitive on the market.
Success of reducing the price of kilowatt per hour would trigger further popularization of electrically driven vehicles as this would eliminate the argument that electric cars are still charged with fossil energy. This would also save non-renewable resources and provide cleaner environment

Resent research around the world has revealed interesting concepts that are developed with a goal to decrease overall system cost to make wind generation profitable and outperform traditional combustion energy sources.
This study investigates design, manufacture and installation aspects of one of the recent concepts of fully integrated wind turbine installation. Key idea of the concept is to make wind tower telescopic thus reducing its size prior to installation. Conventional tower which is about 90 meters high makes it difficult to transport either onboard of the ship or in floating condition either vertically or horizontally. Making tower telescopic brings down the weight on top thus reducing overall VCG.
This work focuses on different practical aspects of the full life cycle of a wind turbine with telescopic tower. Several issues are considered that might have to be overcome throughout project realization. Solutions are proposed with discussion of preferable one in case there are several. Key design elements are investigated that will enable realization. Some proposed solutions are visions that have to be tested out to be confirmed practical. The main goal is to present a concept that would open another chapter in wind energy utilization on its way to become competitive nonpolluting and popular energy source.

5. Background

Offshore wind turbines development and installation have started few decades ago. Installation methods have been developed and implemented in parallel with the turbines maturity.
Wind power in an open air stream is proportional to the third power of the wind speed; the available power increases eightfold when the wind speed doubles. Generated electrical power is proportional to the square of the rotor diameter and to the cube of the wind speed at same mechanical efficiency. This is driving current industry trend to increase turbine power and blade sizes. There are two fundamental assumptions. First, it is assumed that the cost of foundations and other balance-of-plant items do not increase linearly with the turbine's power. Second, the cost of operating and maintaining a smaller number of bigger turbines is lower than operating and maintaining large number of smaller turbines. [3]
Capacities of the wind turbines are increasing as well as, the weights and heights of the machines consequently. This requires increasingly larger installation vessels in terms of carrying and lifting capacities and deck area. As the offshore industry is getting more developed, farm capacities, water depths and distances from the shore are also increasing.
This enlargement in the size of the machines adds other challenges to the offshore installations. The weight creates a demand for bigger lifting capacities; the increasing hub heights require taller booms for the onboard cranes. The increased volume of the turbine components occupies more space on the installation vessel which decreases the number of turbines that can be placed on the deck at a time.
The increase in the water depth brings a challenge to the installation industry as most of the vessels being currently used are not specially designed for wind turbine installations, and have limitations in terms of operational water depths.
The distance between the base port and the wind farm affects the sailing duration from the port to the site. This brings the need of larger available deck space on the vessel to be able to carry more sets of turbines at each voyage at higher service speeds. While larger cargo capacity reduces the number of trips, the higher service speed reduces the duration of the voyages between site and port significantly.

Offshore crane operations determine the time spent on each turbine installation and they are highly dependent on weather conditions. Commonly exercised carrying pre-assembled components have several advantages such as decreasing the number of offshore lifts and thus reducing the needed weather window.
Pre-assembly disadvantage is the need of calm sea during the transportation and it is another factor that increases the weather dependency of the travel that affects the project progression.
The wind and sea conditions always limit and narrow the time window for a safe installation. The time window is important and must be calculated accurately to avoid risky situations that can occur on the way and at the site.
The available shallow water (water depths < 20 meters) areas are limited hence the water depths of the potential future offshore wind sites are expected to be up to 50 meters (for non-floating turbines.)
There are different installation concepts were developed to reduce the duration of offshore works in order to fit it in narrow time windows.
A wind turbine (without the foundation and transition piece) consists of 6 main parts that are tower, nacelle, hub and three blades. Increasing the amount of pre-assembled pieces on the deck decreases the offshore installation time, but in fact leads to a less efficient way of using the available deck space of the vessel.

6. Methodology

This work is based on a concept introduced in patent application number P60902394NO00 where idea about telescopic wind turbine tower is presented. It investigates possibility to have a telescopic tower for a 5 MW reference offshore wind turbine. Most of weight, dimensions other parameters for hub nacelle, blades and tower are taken from NREL reference turbine model. Tower modification is proposed to enable this new design.

Ability to float is provided by concrete ballast at the bottom and empty tanks above it. Both are permanently attached to the turbine tower allowing not only installation but also removal of complete system in a matter of few hours. Submerged part and the tower represent one unit so transition piece is not required.

Fully assembled and integrated at shore site turbine has considerable advantage that all onboard systems are built in and tested prior to departure. Since nacelle is already installed all power cables can be laid inside the towers and only connection to the grid is to be made offshore. All risks of dropping or damaging parts during lifting, mechanical failures, parts misalignment, and wrong connections are eliminated. Offshore work is reduced to its minimum. Feeder vessel with different spare parts and large inventory is no longer required. Personnel risk exposure is reduced dramatically.

Pre-assembled partially or fully integrated system is launched into the sea to float freely in vertical position. Then it is towed out to installation point in vertical condition by several anchor handler tug boats (AH). Turbine has sufficient stability and stiffness. No special adaptation for market available tugs is required which means that any ship with sufficient bollard pull can be used.

Several anchor handlers or tug boats will enable the maneuver of the turbine. Tugs will be set in star constellation the same way as for example jack up rigs are relocated today. Anchor handler shall be selected due to high pollard pull value (up to 400 tons), and equipment installed on board like tugger winch and A-frame which are required in case guide wire will be used to install the turbine. Installation methods are discussed latter.

At installation point there is a pre-installed fully submerged mono-pile-shaped foundation which serves several functions:

- To provide exact location and azimuth angle for the turbine. Foundation may have a guide base with guide wires for exact positioning and easy installation
- To be an anchor for installed turbine preventing its lateral movement off position during operation due to wind or current forces.
- To have automatic electrical grid junction point so that turbine is online ones it is put in place.

Upon arrival to installation site wind turbine will be positioned over mono pile foundation and then air tanks will be flooded in controlled fashion. Internal subdivision will help to keep upright position during flooding which is required to be able to make connection with mono pile foundation. Turbine will stand on the seabed when fully installed thus making combination of gravity based, mono pile and tri pile like structure foundation provided by if integrated legs. Connection to mono pile is friction based and not permanent. Due to gap in between them an inclination of monopole of to up to 2 degrees can be allowed.

When position is secured a lifting operation of inner tower with attached to it nacelle and hub can start. Specially designed lifting mechanism arrangement is proposed. System is fairly simple and hydraulically operated. In addition to splitting the tower into two parts further modifications are proposed. Other lifting methods are discussed.

Overall system is more complex than traditional wind turbine but is cancels nearly all marine operations, waiting on weather costs, all parts except mono pile are integrated manufactured tested inspected and replaced at fast land base giving to it unmatched flexibility to the system. The whole can be seen as a wind turbine with integrated foundation and installation functions.

Damaged during storm wind turbine or one with major malfunction can be replaced completely by lowering upper tower, towing the whole system to home base and doing all necessary operations there instead of doing it offshore.

The whole nacelle including hub and blades can be more easily replaced giving opportunity to upgrade the power producing unit to more modern one. This option might be very attractive due to the fact that the turbines themselves are going through rapidly changing development to become more compact reliable and efficient.

Same applies to routine maintenance which will require critical part replacement. Several malfunction turbines can be assembled to one operational and shipped offshore. Without waiting on weather, available special vessel and so on.

The mobility may open completely new chapter in world energy supply. Mobile offshore wind turbine can be installed at temporary construction site like close to drilling rig or outside a place hardly accessible from the land. It can supply energy to locations far away from developed infrastructure or where creation of land based power lines is either not economically defendable or not possible due to climate or terrain conditions. There are regions depending on mobile energy sources. Some countries are developing mobile floating nuclear power plants today. Mobile offshore wind turbine can stop this development and become good alternative to that as an energy source.

7. Review current installation methods

There are different installation vessels or barges already being used by the offshore wind industry and their capabilities vary according to the year they were built, and the purpose they were designed for. Offshore turbine installations require lifting heavy parts and placing them with high accuracy at certain heights.

In order to safely install these heavy turbine components, installation vessels rise on their jack up legs to create a stable working platform. Offshore wind turbines are usually manufactured into several assembly blocks loaded to a barge or vessel and transported to installation site in one or several complete sets. There turbine is assembled in a sequence where complete system is build up from sea level. [118]

Several types of vessels are used for installation of offshore wind turbines. These are:

- Jack up vessel /Jack up barge
- Semi-submersible
- Vessel

For all type of vessels it is highly important to get proper forecasts of the local weather, wind and sea conditions in order to complete the installation work within the weather window, and transporting the turbines to the location safely.

7.1 Jack Up

Purpose built installation vessels are self-propelled units that are specially designed according to offshore wind industry's demands. This type of vessels have jack able legs to create a stable working platform at the offshore site in order to lift and install heavy parts with a high precision without being affected by the waves, wind and currents. They are equipped with high lifting capacities cranes. Service speeds are also slightly higher than the other installation units.

The sea conditions have effect on transportation and installation of the turbines. Sea conditions for each specific voyage can vary according to the vessel and cargo load. In general transportation of pre-assembled turbines or turbine parts requires calm sea conditions. Several more parameters like the variation in the water level, the, astronomical tide, surf currents seabed condition are important and must be analyzed before the installation as they affect the location and orientation of the vessel landings and jack up unit stability is highly dependent on it. [8]

Jack-Up barges are floating units that are capable of elevating themselves above the water on their jack up legs at the construction site. They are not self-propelled units and must be towed to the construction site. The service speed of the barges is dependent on the tug's power. They are designed for general construction and drilling purposes but still they are used in offshore wind industry commonly as well [3]. Some Jack up barges cannot actually carry any components and require additional feeder vessel.

The available shallow water (water depths < 20 meters) areas are limited and future development will move towards deeper waters above 50 meters. This limits the number of available installation vessels. New vessels will have to be constructed with leg length around 70 meters. [17]

One of the main operational limitations of current vessels is the maximum hook height and lift capacity of their cranes. Installation of 5MW turbines will require the capacity to lift a load of 75 to 300Te up to a hook height of 100m or more.

The length of the support legs sets a physical limitation on the maximum operating water depth. Legs have to penetrate the seabed to certain level to provide stable footing which may disturb local environment, damage already laid cable or pipeline, make next footing on the same are difficult due to left footprint. In some sea bed and weather conditions problems have been experienced withdrawing legs. According to the technical specification sheets for majority of vessels, the maximum significant wave height for legs landing is less than 1.5 meters.
For jacking operation it ranges between 1.5 - 3.7 meters and current 1-2 m/s. The period of the waves is important parameter to consider. Crane operations are limited to a maximum wind speed of between 10 – 15m/s. Limitation for alignment of components is approximately 12m/s. All parameters are targeted to be improved for vessels planned and under construction. Some specially designed vessels which are coming in near future will have H_S about 2.5m for continuous operation.

7.2 Semi-Submersible ship

Semi-submersible ship may be used for offshore wind turbine installation. This type of vessels has less weather sensitivity and can operate at large ambient condition window. Their cranes have larger capacity and due to higher placement above sea level and higher hook height.

There are different types of vessels exist. Some are built with jack able legs and operate the same way as a jack up vessel. Other are built for transport only and use flooding to release cargo from deck. Semi-submersible crane vessels may be used for offshore assembly only with feeder barge for transport.

The SWIV is a 3 Column Semi with a large recess. Calm sea is not required for the transportation and installation of offshore support structures and wind turbines. Installation work can be done year-round and this is best choice for water depths 12 meters and onwards. The 3 column solution has made it possible to develop a large recess, good transit speed and minimum motions. The significant vertical motions in the recess do not exceed 20 to 30 cm in H_s=2m

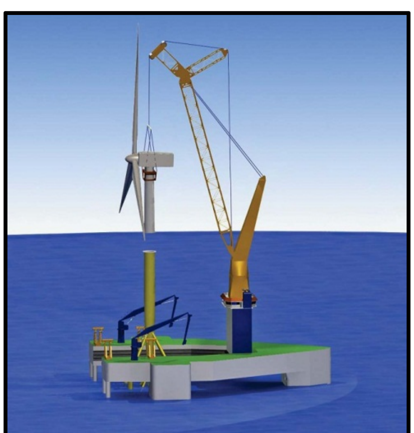

Illustration 2 SWIV, source: [23]

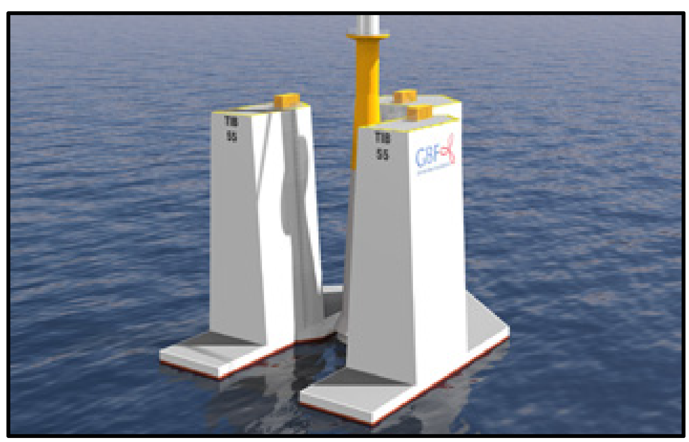

Illustration 1 GBF semi sub barge, source [24]

7.3 Vessel

Strive to reduce costs and speed up installation time has led to development of vessels that do not use jacking legs.

First example is Huisman Wind Turbine Shuttle that is a dynamically positioned, fast sailing (14 knots) SWATH - Small Water plane Area Twin Hull type construction vessel which can carry and install two fully assembled wind turbines. Satellite controlled dynamic positioning and motion compensation is used for stable position during installation. Vessel is capable of installing complete wind turbines jacket type and mono pile foundations, pile driving. [19]

Illustration 4 Huisman Wind Turbine Shuttle

Illustration 3 Windlifter by Ulstein

Second example is Windlifter by Ulstein. It is a dynamically positioned vessel suitable for single lift offshore wind turbine installations, and unlike jack-up units is not limited by water depth. The vessel transports 4 turbines at the same time. A modular, mechanical system is used to skid the turbines onto the foundation. The system is designed in such a way that all components are relatively close to deck level, improving accessibility and as thus reducing maintenance costs. Installation starts by approaching the stern to a pre-installed foundation. Then vessel reaches out locking mechanism with rails and locks it onto foundation. Fetching mechanism grabs closest fully integrated wind turbine and skids it out onto foundation. Turbine tower is fixed onto foundation and locking is released. [20]

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8. Foundations

There are many site specific parameters that determine the type of foundation and turbines for offshore wind farms. While seabed properties, sea depth, tides, currents, and wave heights determine the type of foundation, the wind profile and the other characteristics of the wind determine the type of wind turbine to select. The installation of a complete wind turbine structure is divided into two stages in general. Foundation installed first then transition piece where applicable then the turbine (tower + nacelle + rotor)

Brief description for major types used are given below

8.1 Tripod

Central column of this foundation is connected via braces with 3 pile guides. Attachment to the sea bottom achieved by first positioning the foundation with a crane, and then, driving piles through the guide sleeves. Verticality is ensured by a hydraulic device mounted on each guide that moves each corner in vertical plane. When piles are in place and verticality confirmed grouted connection is made between the pile and guide sleeves Tripods are used in waters up to 50 meters. They do not require much seabed preparation and scour protection. Drawback is complicated intersections between tubular members which increase manufacturing costs. Structure has large steel members which gives weight in a range of 650-950 tons. Wind tower tubular section is inserted onto the central column by tower installation team.

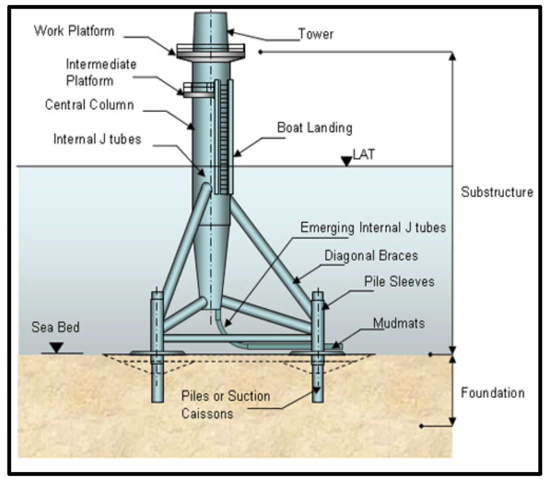


Illustration 5 Tripod structure (Third leg hidden) source: [26]

8.2 Jacket

Jacket is a truss structure that consists of several uprising legs connected with braces. This type of structures is widely used offshore due to their strength to weight ratio and that they act like a slender body in waves and wind rather bypassing them than withstanding. Whole structure is usually pre manufactured onshore and shipped onboard on a barge. The fixation to the bottom is the same as for tripod. Piles are driven through guiding sleeves at the corners and grouted to it after that verticality is ensured. Connection to wind tower provided by transition knot with flange that is mounted on top the jacket. Water depth to use jacket is around 50 meters. Dynamic amplification of the structure interacting with waves and the operating frequencies of the wind turbine set limitation on installation depth. The issue is targeted by variation in mass and stiffness to avoid resonance. Due to small footing area no or little sea bottom preparation required. Jacket has also many knot connection that makes fabrication complicated.

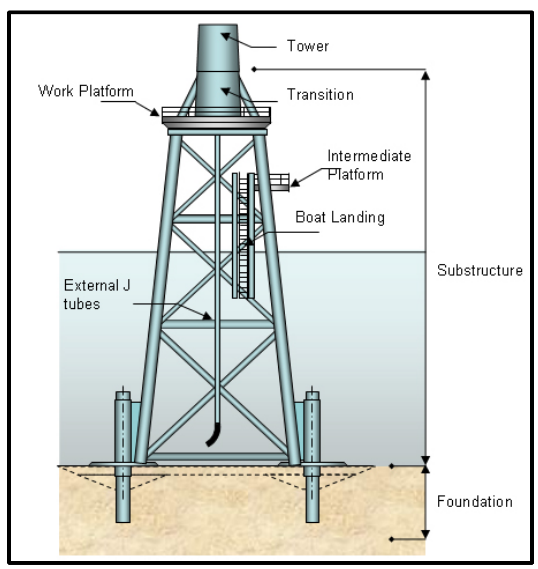


Illustration 6 Jacket structure source: [26]

8.3 Tri-pile

A tri-pile foundation consists of a central column and box type pylons that connects it to 3 vertical pins. Upper end of column has welded flange to connect to turbine tower. 3 Box pylons are key design element and are evenly distributed around the column. They are inclined an angle of 20° to horizontal plane and transferring the forces to vertical pins. Installation starts with driving 3 vertical piles into sea bottom few meters above sea bed at same template that vertical pins position is planned. Foundation is inserted with pins onto the piles, leveled and grouted. Weigh of tri pile alone is about 500 tons. Long foundation piles to about 90 meters are used. Structure is heavy but is completely above sea level.

8.4 Gravity based

This type of foundations uses heavy bottom or base structure that is many times bouncy force. In addition to heavy weight the base has also large seabed contact area. This way weight will prevent any vertical or lateral motion large support area increases friction forces and sustains overturning moments. Scour protection prevents erosion due to moving sediments. Structure requires certain clean and even seabed conditions that actually can support this heavy weight without collapse. Material used is mainly pre- or post- stressed steel reinforces concrete with sand fill. The concrete complies with compression strength class C45/55. Pre manufactured foundation is shifted onto a submersible vessel or barge. At installation site a thorough seabed preparation is required. An area of size order 4000 m^2 is first dredged to 5-10 meters depth. Than a filter layer is laid into the installation pit at an area of the footing then it is filled with crushed gravel and leveled to precision of less than 1 degree. Lifting is done by a heavy vessel capable of lifting up to 3300 tons. Foundation pit is then backfilled with sand or surrounding material. Sand infill in order of 60000 m^{3}is the started. Installation of turbine finalizes the project.

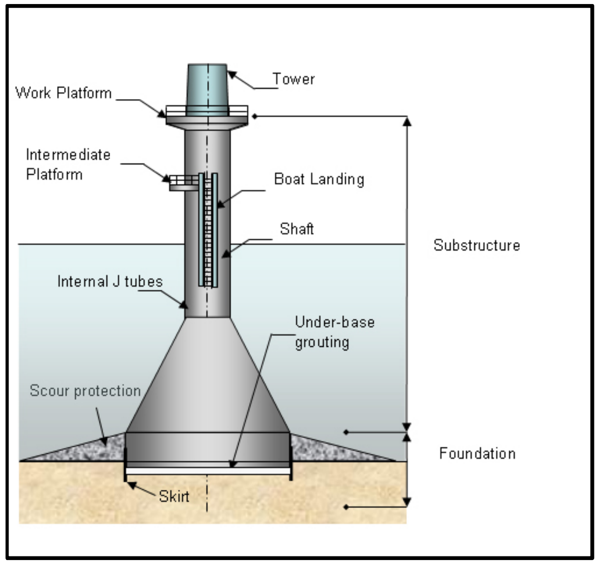


Illustration 7 Gravity based structure source: [26]

8.5 Mono-pile

The mono-pile is the most commonly used foundation for offshore wind turbines in shallow water depths, as they are flexible in design. This is simplest design foundation that consists of one foundation steel pile of about 6 meters diameter driven into sea bottom. This pipe is heavy walled up to 150 mm. thickness. Seabed penetration is done by either large impact or vibratory hammers, or the piles are grounded into the sockets drilled into rock. Compared to the gravity base foundation, the mono-pile has minimal and localized environmental impact. The required section properties will be governed by dynamic considerations than by strength and fatigue requirements. When the water depth increases, they have to be stiffer to avoid large natural periods and so end up with large, heavy and expensive structures. Therefore, this type of foundation has a water depth limit of about 30 m. [22] On top of foundation pile transition piece is installed It is the part that's carries the turbine tower and usually includes the boat landing, access platform and steel J- tube that protects the electrical cable going to other turbines and/or the transformer station. Tube is curved near the ground to allow the cable to go from its underground trench to the turbine. Transition piece conceals errors in foundation verticality.

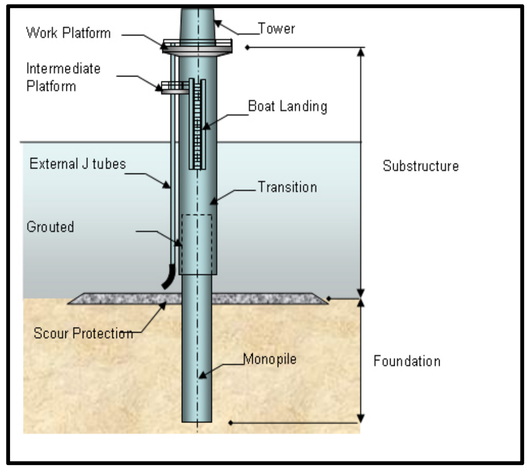


Illustration 8 Mono-pile structure source: [26]

9. Telescopic wind turbine

9.1 Model description

A 3D model of a telescopic wind turbine is built based on own design of new components and some dimensions from NREL 5 MW reference wind turbine. Illustrations in Appendix A visualize ideas proposed in this development. Each component of the system is described separately with features and focal points that might affect further development.

Today the average water depth of offshore project sites (in the North Sea, Baltic Sea and Irish Sea region) for both existing and the ones under construction is up to 40 meters and increasing.

Table summarizes relevant Gross Properties of NREL 5-MW Baseline wind turbine taken from [5] compared with the designed model of telescopic wind turbine.

Parameter	Reference turbine	Designed Telescopic turbine
Rating	5 MW	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades	Upwind, 3 Blades
Rotor, Hub Diameter	126 m, 3 m	128 m., 3m.
Hub Height	90 m	53m –floating, 85 m - installed
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s	3 m/s, 11.4 m/s, 25 m/s
Rotor Mass / Nacelle Mass	110,000 kg/240,000 kg	110,000 kg/240,000 kg
Tower Mass	347,460 tons	650 tons (dry)

9.2 Telescopic tower

Wind turbine tower is usually a cylinder section conically shaped in length. Uniform conical shape is used due to difference in foundation and nacelle mounting diameter but there are fully cylindrical towers available. Diameter linearly changes from about 6 meters on the bottom to 3.5-3.9 meters at the top depending on nacelle design. It is manufactured out of thick walled carbon steel metal plates of 28-36 mm. thickness. Plates 10-15 meters in length are bended and welded longitudinally. Sections are then either welded together or flange bolted. Tubular section wise assembly eases manufacturing and lifting. Usually no internal stiffeners are used.

Tubular sections have to be both straight linearly and circular in section in order to mate. Lying on a side and welding alongside creates shape deviations. Before final assembly sections are to be checked.

Offshore wind turbine towers used today are constructed by two base concepts. First is to construct it with very high stiffness so that its natural frequency stays away from the range of the excitation frequencies. Second and more widely used is to make a tower flexible with damping ratio in a range

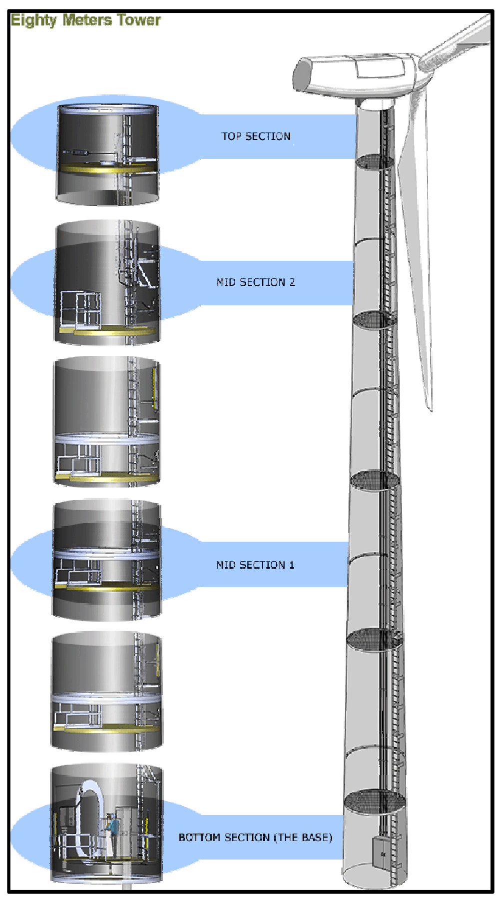


Illustration 9 A 80 meters conventional tower [17]

of 1-2% so that whole structure is way below resonance spectrum. Proposed concept will have a combination of these two principals. Bottom part is a large diameter section made robust to support lifting mechanism while upper tower remains flexible. Diameter change section of tower shall be made with decreasing wall thickness to avoid step change in stiffness value

There is an overlap of about 8 meters between upper and lower towers where lifting mechanism is installed. It provides both centralization of inner tower inside the outer and has 2 points of contact vertically to create lateral support of inner tower when lifted. Illustration 15 gives general overview of proposed design. Nacelle modeled to dimensions as on illustration 14.

9.2.1 Upper Tower

Upper tower dimensions are shown on illustration 16. This tower is conical shape and very similar to towers produced today. Except for bottom section which is cylindrical and forward gear wheel with lifting pistons is attached to it. This section has longitudinal cut outs in trajectory of forward and aft gears. These windows allow gears being fixed to inner wall of upper tower to reach the rack profile on inner side of the lower tower. Whole lifting mechanism is attached to this cylindrical section except for rear gear wheels. At the top of the cylindrical section there is a positive stop plate welded on outer edge with rubber gasket on upper edge to prevent sea water ingress when tower is completely lifted up. At the bottom this tower is open but has also positive stop plate at lower edge which acts as a support prior to and during sea voyage. Opening in the bottom allows access for inspection, drains liquids that may condense inside and prevents pressure built up. Upper tower is constructed taller than the lower one. It has smaller diameter to by-pass the racks profile. Clearance between towers is shown on illustration 26. This design is considered as basic.

9.2.2 Alternative upper tower design

To reduce lifting weight and wind exposed area of the tower it is also proposed to design it as a jacket type structure. Today's tower is a solid steel tube type. This is done for section wise lifting and installation offshore. Using preventive maintenance philosophy the whole structure can be brought to harbor for land based inspection and repair after some period of operation. This period can be determined by FMECA analysis, based on average time before failure or both. This means that having a passage through tower height is not that critical anymore and upper tower shape can be changed. This will reduce the load onto the locking mechanism that keeps this tower elevated.

There are two immediate designs available. First is to have a pipe with ladder in the center of the towers cross section. Pipe with diameter around 2 meters will allow access along the length and provide protection for power cable inside. Radial stiffeners around it will ensure bending resistance capacity. This concept is shown on illustration 33

Second design is to have a jacket structure made of small diameter tubulars. Ladder can still be fitted in between but climbing along it will be in open air. Same applies to power cable. This structure will give less wind resistance. See on illustration 34

Thorough economic and structural evaluation has to be performed to qualify best design. Both alternatives can give less diameter and lighter tower but unlike basic one will require several different size spares and more welding and inspection thus more expensive manufacturing.

9.2.3 Lower tower

This tower has cylindrical section and full diameter overall. At the bottom there is a funnel for easy mating with foundation pile. Outside there is welded-on permanent ballast tank at the bottom and air filled tanks above it. Design and volume of tanks can be adjusted in order to achieve desired draft during tow, amount of flooding and GM value. Proposed design has uniform outer diameter for all tanks with smooth reduction to tower diameter at the top.

Lower tower has to have internal longitudinal HP profile stiffeners at least close to lifting racks at inner side to prevent deflections and deterioration of gear meshing. Since cross section of this tower part is 2 stacked cylinders (tower itself and surrounding tanks) the lower tower can have reduced wall thickness.

Bottom part on one side supports weight of the upper tower with nacelle and hub. On the other side it is watertight and interfaces with top of foundation pile. It serves as positive stop to upper tower when it is lowering down and may withstand drops from very low height if lifting mechanism will fail in the very beginning of the elevation. Difference in the lengths of the towers ensures that the nacelle is above lower tower at all times.

Coupling to the grid connection can be placed on the bottom of the tower so that junction is done ones turbine is in place. Illustrations 17 show principal dimensions.

9.2.4 Blade protection during tow

One of the main obstacles to telescopic tower development is the fact that at initial position, when both towers are folded together, a single blade is about the same length, as the tower itself. This means that if the system is put into water and has several meters draft some portion of turbine blade will come into water. The blade will be subjected to sea actions like waves. Normally each blade of a 5MW wind turbine weight about 18 tons. It is mostly made of fiber glass with layers of other composite materials. The structure is rigid and can support its own weight. Set into water it is a great danger that the blade will be damaged or even broken as free end part of it is more flexible and less rigid. Moreover it is not designed to operate in other medium than air. Therefore blades have to be protected against sea water action.

Patent application [1] suggests either twisting the shaft of the hub or the whole nacelle so that rotor rotation axis will become vertical. Twisting the shaft means breaking it into 2 sections with one able to rotate about the other by 90º. This will require extra set of radial bearings to support both parts of the shaft. A rotational mechanism able to move the weight of the hub and three blades, totally about 110 tons would have to be fitted inside or right outside the nacelle. Tilting the whole nacelle according to a turbine manufacturer would drain oil filled parts that are difficult to refill in the field. It will also require a mechanism able to rotate and lock in position in a safe manner about 340 tons. Another reason is need to design the base connections of heavy machineries to resist gravity and transit acceleration vertically as well as horizontally due to turning.

Both methods would complicate nacelle structure and make it even heavier.

This concept proposes another approach to the problem. There are many designs of a wind turbine on the marked including those with very unconventional tower, rotor and hub shapes with different shapes of blades, and their numbers, even with static ones. The most conventional is three blades evenly and radially spaced on a circle. Majority of offshore wind turbines have this configuration as well as considered in this project one.

When deciding position of the hub prior to sea launch, it is not possible to find a pitch angle so that blades will not be submerged. The best solution would be to submerge fully only one. This means that it is enough to protect this blade only as the two others are in that case are high above MSL. Illustration 15 shows the principal idea of this protection. At assembly stage when nacelle is mounted onto the tower a single blade is mounted inside tunnel like structure called blade protector. It is both longer and bigger than the blade itself for following reasons:

- Blade protector is oversized to give large volume and space margin to allow blade mounting without damage even due to its deflection by own weight, accelerations and vibrations. At upper edge of protector a rubber bumper will prevent damage during insertion. It shall be noted that at some designs blade itself is not symmetric about vertical nacelle plane but blade protector is. This means that blade inside its protector will not be placed symmetrically about vertical plane. It shall give extra buoyancy to compensate for hub weight. During sea voyage telescopic wind turbine would not float upright due to heeling moment created by hub and blades weight. Center of gravity will move towards blades so the heeling angle. This moment can be compensated by constructing blade protective shield as an air tank that will give buoyancy right under eccentric mass and thus compensate for it. Submerged volume of protector shall be calculated for particular blade design to cancel heeling moment.
- It gives space to enter inside telescopic tower directly without entering air tanks. Blade protector is open at the top and closed at the bottom therefore even that its edge is several meters above waterline still waves and sprays will enter inside and water will gather at the bottom. For this reason blade protector is made 1.8 meters longer than lower edge of the blade inside. A lensing pump and bottom plug can be fitted inside to drain overboard excessive water. This pump will also be required for mobile turbine concept. As it can be seen from illustrations during installation blade protector will also have to be flooded to keep sinking vertically. To remove the turbine, bottom plug has to be closed and compartments dried for water. Blade protector is constructed as an air tank with internal stiffeners. During tow hub brakes in nacelle have to be engaged to protect it from uncontrolled rotation which can damage the blade inside protector.
- It acts as wave maker during sea tow the same way as a ships bulb. This reduces resistance to movement in forward direction during sea tow.

9.2.5 Access to tower

Today there are 2 ways to access a working wind turbine. Either there is a platform elevated above sea level and accessible from a vessel. Technician enters the tower by opening a door or a hatch from this platform and then going all the way up using stairs. Inside tower there is arranged several horizontal platforms making elevation similar to going between floors in a building. (See illustration 9). This is done for safety reasons in case someone would fall down. The same platforms are used during offshore assembly, as tower sections are bolted together manually. When one upper tower section is set upon the lower technicians are going up this stairs to make up bolts in flanged connection between sections.

Second method is to become airborne with helicopter and either land on helideck at nacelle top or lower down technicians on a rope. This method is very risky as helicopter operates close to rotating blades and in case of wind cast can crash into them. It is unsafe for descending personnel for the same reason. This method can be used only at calm weather conditions and only when turbine is fully assembled.

Proposed concept of telescopic tower cannot have internal stair case platforms as they would stand in the way of elevating upper tower. The whole system is assembled prior to departure so access from top can be used preferably when whole system is installed or fixed at the bottom. While floating freely the system anticipated having long return period and good weather conditions would allow landing.

The way from sea level is preferred for going down to lifting mechanism as wind farm work boat can be used in most weather conditions. For the accesses from sea it is proposed to have a door or hatch opening at the front end of blade protector. Work boar approaches with stern to tower as shown on illustration 24. A small platform with grating floor and rails is arranged outside entrance door. Technician enters the door and climb the ladder inside blade protector until a connection bridge which supports upper end of protector and also large enough to give space to pass through. See illustration 25. Stairs can be arranged inside upper tower and there should be corresponding cut outs in upper and lower towers for the technician. Blade protector is used because lower tower have large empty tanks around it and the way through them would be more complicated. Entrance inside towers may be required to make ready lifting mechanism, for connection of hydraulic lines or making other adjustments to the system. Climbing inside blade protector and towers is to be arranged as spiral stair going alongside cylindrical walls. Walkway is to be arranged with rails and attachment point for safety wire if vertical climbing will be used. Illustrations 24, 25 show possible progression from sea level down to lifting mechanism. Door opening at wall side of blade protector will come to sea level when tower is flooded and installed. If it is required to go inside tower before turbine is flooded a second platform can be arranged or vertical stair lead to main access door. Doors and stairs are not shown.

9.3 Air tanks

A vertical tow telescopic wind turbine shall no longer be treated as over sea structure only but partially a subsea. In case of vertical tow submerged part will be fully exposed to waves and pressure and shall be constructed the same way as ship's hull with shell plating supported by internal stiffeners. Vertical HP profile steel bars are proposed to be welded on inner side of outer wall

Air tanks are used to add buoyancy to the turbine to enable floating and vertical tow. They are integrated into the tower to add strength to lower tower and protect from grounding and damages during tow. Air tanks will be submerged throughout turbine lifecycle. During installation they will also be flooded. Concept of mobile offshore wind turbine conditions that air tanks makes same structural unit with the tower to enable multiple flooding and draining. This is same concept and mode of operation like a submarine air tanks has. Same type of pneumatic air drain system may be considered installed here to enable quick buoyancy restoration.

9.3.1 Internal subdivision

Telescopic tower has most of what is called a transition piece integrated. It is common practice to divide submerged volumes of the tower into several isolated tanks for following reasons.

- Internal subdivision allows to have controlled flooding which will prevent large heel and trim angles. Each tank will have own remotely controlled adjustable bottom valve.
- It will mitigate free liquid surface effect which dramatically decreases GM value and decreases stability during flooding operation.
- Internal subdivision will strengthen the air tank structure and make it stiffer.
- Internal subdivision can be done in any suitable way but shall be made so that in case of damage or collision with tow boat whole structure remains buoyant and float upright. One proposed solution internal subdivision is shown on illustration 18.
  Internal subdivision will allow to decrease shell plate thickness without reduction is structure stiffness and will allow to sustain hydrostatic pressure. At normal draft of approx. 25 meters hydrostatic pressure alone at lowest part will be: $P.h = \rho * g * h$; $P.h = 25{,}14\ bar$

9.4 Permanent ballast tank

At the very bottom of telescopic wind turbine there shall be placed a heavy and solid weight that can balance the weight of nacelle on top of the tower. Several methods are used today to achieve that.

- Solid metal balls (metal ore grains). This is spherical, cylindrical or other shape metal containing pieces that are filled into ballast chamber. The advantage is that quantity of the balls can be measured accurately and they can be moved or removed if necessary. Widely used for filling offshore with a crane from a barge. Disadvantage is that they are able to shift during roll on waves if the room is not filled completely and create heeling moment. Ball like form factor gives air gaps between balls.
- Lead pellets are heavier than steel and can be used the same way as steel balls except for they cannot be poured but have to be laid by hand. This is suitable for several tons ballast but will be uneconomic for large quantities. Very good to use where space for ballast is limited.
- Concrete occupies all the space it will get and when solidified makes strong structure. It is very good ballast material as it is largely available and fairly cheap. With density of 2,5 ton per cubic meter it is the best choice for most applications. Concrete can be used in marine environment due to low chemical reaction with sea water and thus corrosion. The only disadvantage that once fixed it cannot be dismounted but it is not required in our case.

It is recommended to use concrete and pour it into reinforced steel tank. That will give it a shape, prevent chip off and sea water absorption. The amount of concrete is to be calculated depending on overall system design. Calculation shows that minimum amount is to be approx. 3100 tons which would correspond to approx. 1240 cubic meters of concrete.

In case the telescopic wind turbine will be designed as permanent structure attached to a foundation via concrete grouted connection, permanent ballast tank can be made removable. This can be designed as separate ballast tanks with a buoy attached that could be fired off the tower with a small explosive charges or with an installation vessel.

Permanently fixed ballast tank serves the idea of elimination of costly marine operations. Any detachable part will make turbine dependent on specially build vessels. Making some parts detachable would probably make them reusable for other installations but then at the point of removal they would have to be attached back or the whole tower has to be designed for offshore disassembly.

Bottom shape of the ballast tank is proposed to be inclined so that during installation onto the foundation pile ROV or diver would have opportunity to estimate correct landing and ensure coaxially of foundation pile with the tower by simply looking from the side.

9.5 Foundation pile

To ensure exact position and easy electrical grid junction use of foundation pile recommended. Pile portion above seabed shown on illustrations 20 and 35. It has conical head to ensure coupling to lower tower even at larger installation angle. At rough sea pile and tower may not meet at 180 angle but ones engaged proper landing can be ensured. As the tower moves down along the pile it is guided downward by it. Maximum installation angles are shown on illustration 21. Exact azimuth angle is ensured by two orientation grooves outside the pile see illustrations 36. This orientation technique is the same as the one used in oil industry for orienting down-hole tools.

Wind turbines are usually arranged in farms where each produces electricity to transformer station that is connected to the shore distribution net. To power the turbine which is not yet operational a separate utility line from transformer station can be used. Power to this line will be provided either by other operating turbines via transformer platform or from the shore base. Electric utility cable is laid together with power cable inside J-tube (not shown on illustrations) of the foundation. Both cables are connected to foundation pile at its installation phase only one time but not powered until turbine is in place.

During flood down, ones the lower tower reaches the top of the pile automatic plug type connection is engaged thus eliminating grid connection operation. This connection is made at last and thus mechanically protected both on the pile and tower. On top of the pile connection is socket type and not subjected to hammering forces. On lower tower it is a plug at the end of the interface tunnel. 3 phase AC current is used for offshore wind turbine so there are three poles. Utility connection with industrial voltage is planned for auxiliary systems like HPU. Ones poles are engaged they can be electrically isolated by replacing sea water in between them with dielectric liquid, foam or gas. BX-type seal ring outside electrical connection will ensure connection's watertight integrity which shall be field tested before full amperage switch on. Poles on both sides are open to the sea but short circuiting will not occur because until connection is engaged, isolated and tested poles are not powered with electricity. Test voltage will be sent first and if resistance is in place then connection is made.

Automatic junction to electrical grid system opens possibility for installation of all required systems onboard. Telescopic tower turbine is installed in sequence. First flooded onto foundation pile then elevated to working height. To flood air tanks bottom plugs shall be opened. This can be done at radio signal command. Power source for plugs as well as other equipment prior to electrical grid connection is batteries. Lifting mechanism cannot be powered with batteries as they would occupy most of the space to be powerful enough.

When the turbine is landed on the pile and signal connection is made all machinery onboard is powered from the grid. With electricity present the hydraulic pump that drives all pistons can be installed onboard. All logical circuits, lights and bottom plugs are powered. The same for lensing pumps that will empty all air tanks when turbine is ready to be uninstalled and relocated. This way no physical connection between turbine and tug vessel is required. Only wireless signal communication is needed.

Without electricity and hydraulic power unit installed onboard a utility line will have to be laid between tug vessel and the turbine. If this solution is chosen then there have to be designed a special plug connection outside turbine that is accessible from the vessel. Hydraulic hoses and electric lines have to be laid in between lower and upper towers. This will require special cable gates and cut outs in upper tower as during elevation one moves relative to another with limited clearance in between. During lifting operation tug vessel that will provide power will have to position itself at fairly close proximity of the turbine as hydraulic line can put limitation to length. This is potential danger of collision between these two, unless vessel is locked onto the tower so that distance between them is secured. Elevation time is estimated to several hours and this creates dependency on weather conditions and in case of worsening a quick disconnect plug has to be designed so that vessel can interrupt lifting operation and seek shelter. When weather is acceptable again utility line has to be fished and reconnected. If hydraulic hoses will be used so special valve has to be installed to prevent oil spill and pressure drop in hydraulic system at emergency disconnection. With everything built in lifting can continue even at strong waves and winds.

Automatic electrical junction is another key step forward on the way to mobile offshore wind turbine development.

10. Sea voyage

10.1 Tow method

There are different concepts, except for conventional on board of a vessel transportation, that is developed on the market today. Several parameters decide the most suitable. At different stages of the project combination of methods can be used like it has happened with Hywind. Below are the options.

1) Fully vertical tow.

The benefit of vertical method is that it is possible to balance the weight of nacelle and make tower floating by itself. As the lower part is submerged it can naturally be mated with a foundation. A drawback is that foundation is fully submerged and system is a deep draft floater which creates launching and grounding risks. Installation is possible at water depth over 25 meters. Tower height above sea level is in the order of 50 meters. Transportation with nacelle and blades increases height to 100 meters. Most of the bridges will not clear this. A foundation that is above sea level can likely not be used as floating tower uses permanent ballast to float upright. The amount of ballast used is several thousand tons. Offshore lifting of that weight, if possible, will require stable ground platform and eliminates the point of making the tower buoyant. It will also create high load onto foundation.

Illustration 10 The Hywind 1 floating turbine is towed to its test site off Karmøy, Norway. Photograph: Statoil

2) Horizontal tow at surface

Towed horizontally a turbine will have a draft comparable to conventional ships. This allows the tower float freely on sea surface. Depending on weight either buoyancy elements or extra ballast are added. Tower is subjected to sea action and being (if fully assembled) hundreds of meters long will see sag and bending forces along its length. Tower has to be designed for that and made stiffer in case of long journey. Unlike towing installation can be performed only at deep waters as turbine operates in vertical position. To turn the tower from horizontal to vertical position is a complicated operation that involves several vessels to fill ballast from one side to make it heavier at the same time

Illustration 11 Hywind tow floating windmill at sea in deep water (Photo: Kim Laland/StatoilHydro)

controlling buoyancy reserve so the tower does not sink. This method shall be used only for very long and heavy towers that cannot be transported onboard and assembled offshore. Most famous example is Hywind project. It has cost NOK340 million for building and NOK60m for operating it for two years.

Installation process was probably one the most complicated and expensive part of the project. Horizontal tow does not give solution on how to transport the nacelle with blades. Only separate transportation can be accepted as neither nacelle nor blades are designed for direct contact with water at all.

There have been cases that turbine towers have been damaged or lost their geometry during sea voyage as they were not made stiff enough for waves

3) **Horizontal subsurface tow.**

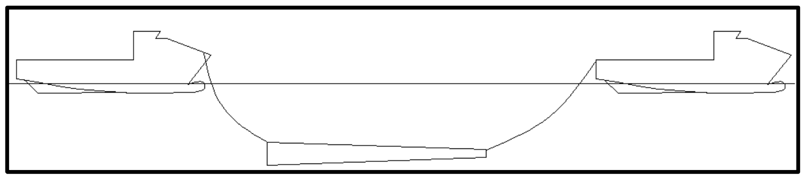


Illustration 12 Underwater tow schematics

Subsurface towing saves the tower for wave action but requires 2 vessels and a crane to lift the tower out of the water upon arrival to installation site. Brought to surface tower has to be turned vertical and separate transportation of other turbine parts remains.

4) **Partial or full barge transportation**

Illustration 13 WindFlip model, source: http://www.windflip.com

This method is improvement of horizontal tow. Turbine is transported horizontally or at a small inclination angle and installed fully assembled. One of the best examples would be a WindFlip project. A fully assembled turbine is installed on a barge at an angle about 5-10 to horizontal plane and barge is towed out to installation side. There the barge is flooded to vertical angle so that lower end of the tower reaches the bottom and installs. Several issues arise with the concept. First is whether turbine manufacturer allows lying nacelle to about 90 degrees off operating position as mechanical gear box pars are oil filled which may leak out. It is not clear how tower is fixed at the bottom and other.

10.2 Environmental conditions

The purpose of installing a wind farm is utilizing the wind energy as much as possible, so that the proposed project sites are likely to have high wind speeds. This is very good for electricity generation and profitability of the project, but the same environmental conditions put limitations on the crane operations and making current installation methods very weather dependent and drives project costs up. Today, installation of the towers and the nacelles can be carried on up to 10 m/s of wind speeds while the same kind of limitation for lifting the blades is 7m/s [9].

For floating telescopic wind turbine concept there are two major conditions. It is either floating or attached to the bottom. Since no offshore lifting operation is planned the old limitations are cancelled.

During sea tow the limiting factor will be not the turbine itself but safety level of the towing wire and winch and their ability to tolerate mass accelerations at strong waves. Second limiting factor is the tug itself. As the tower has a freeboard of 56 meters a vessel can have it down to 500 mm. This just indicates the difference in buoyancy reserve between a vessel and the tower.

Third limitation is operation safety level as no one would take unnecessary risk for any cause.

Weather limitations settled by an insurance company found on if.com can be used as follows

- The significant wave height to be less than 2.5 meters.
- The maximum wind speed to be 12 m/s.
- The weather forecast must be followed at least 24 hours forward during the route

During flooding and draft increase to reach the sea bed or foundation pile calculation shows increase in stability or at least in GM value. Limiting factor again are other vessels. As flooding operation is to be supervised by a ROV then typical values for operating conditions for that can be taken.

• Wind speed	14-17 m/s				
• Wave height	Significant	4.0 m.	Maximum	5.0 m	
• Current speed	1.0 m/s				

10.3 Sea launch

Complete wind turbine tower is to be assembled at shore base construction site either completely or to blocks that can be moved. Final assembly will depend on ability to launch the whole system into the water. Launch is very critical operation even for ships and there are many failures in the history. Usually a ship is launched from a slip where it is installed on small trolleys and pulled down to water level very slowly until it floats freely. Ships are commonly launched with aft part first as it usually more buoyant and to avoid damages to rudder and propel but sometimes side launch is also used.

Same can be applied for telescopic wind turbine. Launch methods that can be considered:

1) Only towers assembly is launched into the sea at quay side and then air tanks flooded. Nacelle, hub and blades installed with onshore crane. Air tanks are then lensed and whole structure towed out. This method will probably work if the depth of the harbor is sufficient and starts from about 30 meters. This is value due to fact that floating turbine has a draft over 20 meters and passage out has to be clear. Few harbors can match this criteria but one can be specially build in case of mass production. Special route out from ground to deeper waters to be established. Forward tug shall use sonar to verify the route.
2) Another option is to assemble everything on land and then use crane to lift and then lower everything into water. This will require a crane with lifting capacity over 600 tons which only heavy ship yards have. It will still require same water depth at quay side.
3) More available method would be to use floating dock. Parts of turbine could be assembled on the harbor inside floating dry dock. When the system is ready and tested then the dock is towed out to depth about 100 meters or more and turbine is launched from there. Even if dropped out in the water concrete at the bottom will make it float upright and there is no thread for low free board as tower is very tall compared to a ship. Dry docks have large deck area and could take several turbines at the time and launch them simultaneously. Instead of floating dock a crane barge can be used to carry the turbine into deeper waters and lower to the sea.

Other options may be developed and found more reasonable.

10.4 Sea tow

Vertical sea tow represents two major challenges. First is very heavy payload in form of wind turbine that is mounted on top of the tower with high VCG. This gives very large overturning mass moment and the whole system tends to float rather upside down as lower part is much lighter. Concrete at the very bottom balances the system around air tanks.

Second challenge is overall system draft which is much higher than any commercial ship has. Estimated draft for the model proposed is 22-30 meters. This means that during sea voyage the whole route shall be carefully planned so that distance from bottom of the tower to seabed is always larger than length of submerged part, taking into account wave roll and heave movement.

Concrete ballast tank at the bottom will minimize damage in case of grounding preventing damage to air tanks above. In case of grounding concrete will not leak out and pollute the environment.

Design of submersed volume and volumes that are going to be flooded during installation shall have the same horizontal cross section. The open air tank protecting the blade shall also be flooded the same manner as main air tanks. This is to avoid heeling of turbine during installation.

To perform successful flooding closed air tanks shall be fitted with ventilation pipes open or a gate valve on top. This is to avoid sea water to come into air tanks during sea voyage when the wind will make the turbine to roll and pitch on waves.

Illustration 22 shows one possible tow arrangement of the turbine under sea voyage. Top view crossed at towing pin of the turbine shows tug boat star constellation. It is proposed to have main heading at the direction of the turbine hub. There are several reasons for that.

1) Heeling moment created by eccentric weight of hub and blades cancels by blade protector. Dynamic forces of sea tow will help to lean the turbine to the side opposite this weight.
2) In case of strong wind forward tug boat can in deep waters choose to go against wind and waves. Turbine blades will then be pointed against wind as well and will not create turning or heeling moment to the tower. The moment created by blades can reach high values as they already are effective at wind speed above 4 m/s. Turbine brakes inside nacelle shall be securely engaged during whole voyage and installation.
3) Captain of the main tug will have best overview and control.

Towing pin shall be fixed at the exterior edge of the turbine so that it would be possible to reach from the stern of the tug vessel and attach tow wire manually. Therefore it is shown fixed close to outer edge of the air tank few meters above waterline so it is within range of a tug crane or able seaman can make the connection. Whole is done in harbor or protected waters so is represents small risk to personnel. When installation is done free end of the towing wire can be dropped into the water with a buoy attached to it. Next time turbine will be towed this end can be fished onboard from the water and attached to the winch.

The front tug creates movement in main direction. Most suited vessel is a modern anchor handler as they are equipped with a towing winch up to 400 tons bollard pull, special cranes for mooring operations, guiding equipment on deck like shark jaw, rollers and towing pins. DP and navigation systems will enable positioning. Offshore crane is able to launch ROV either from the side of the vessel or through the moon pool. Two towing wires each with 100% towing capacity will create safety redundancy and give possibility to control heading angle of the turbine by controlling the length of each wire separately. This way turbine can be positioned against wind if its direction is at an angle to the heading course. Quick release or wire cutting device shall be fitted to towing winch to avoid collision or overturning the tug.

Two or more side tugs will control lateral movements sway, yaw and turns.

10.5 Stability at vertical tow

A wind turbine is initially not designed to float in the water. It has some buoyancy due to hollow tower structure but its own weight is much larger than water displacement. Moreover dropped into the water turbine would immediately turn upside down and sink with nacelle at the bottom as it is the heaviest part. Design has to be changed so that the whole structure will get enough buoyancy and weight of the nacelle is overbalanced at the bottom so that it is heavier than the top as we would like turbine to float with nacelle upward. Putting the same weight at the bottom as weight of nacelle and rotor would not be sufficient as they have to be certain height above waterline. Considering moment about waterline bottom part has to be much heavier to keep balance. Floating turbine has to have a stability reserve to sustain heeling moments due to tow forces, waves, wind. Convectional ships are constructed so that when it heels a small angle across beam additional volume comes into water thus increasing righting arm and ship rolls back. Ships longitudinal stability is usually superior to transverse due to high length to breadth ratio. Wind turbine is symmetric except for side where rotor hub is. This chapter considers floating tower and its sea keeping properties.

Stability model corresponds to illustrated 3D model with the same dimensions. Both models had to be adjusted against each other in iterative calculation and design process until reasonable result was achieved. Model considers only submerged watertight body as contributive to buoyancy. This will include concrete-, air tanks and lower tower. As lower tower is open at the top at heeling angle about 90 degrees water will come inside and stability considered to be lost. Damaged stability cases have not been calculated at this time as no crew will be present onboard during tow. Upper tower with nacelle and hub has sail class.

Weight calculation and center of gravity location is critical for a floating body. Weights are applied as point acting at their respective centers of gravity which are found from 3D model Telescopic tower has a great advantage of bringing VCG to a lower height compared to conventional tower. Concrete brings VCG further down. It is found from calculations (see Appendix C) that VCG of the permanent ballast compartment is not that important as the amount of it. There shall be at least 3000 tons of concrete to have minimum positive GM values.

Weight of the tower has nearly doubled compared to reference turbine due to extra mechanisms and tanks and is calculated to be 650 tons.

Wind turbine has a shape of cylinder far from conventional ship shape. There is at least one floating vessel designed as a cylinder shape is Sevan drilling rig. Ratio of diameter to height is more favorable for it than for telescopic tower. On the other hand telescopic tower can be considered as a slender structure regarding the wind action.

10.5.1 Stability criteria

Initial load condition shown in Appendix C is tested against general stability criteria for passenger and cargo ships up to 100 meters, found in IMO resolution A.167. Not all of them are applicable some are exaggerated for this floating body due to cross section symmetry but are included for comparison purposes. Brief description of criteria:

1) Area under righting arm curve is to be over 0.055.
2) Area under RA curve at inclination heel angle up to 30 deg. is to be over 0.015
3) Area under RA curve from 0 up to 40 deg. angle or to closest defined flood point is to be over 0.09
4) Area under RA curve from 30 up to 40 deg. angle or to closest defined flood point is to be over 0.03
5) Righting arm at 30 deg. heel angle is to be over 0.2
6) Absolute angle at maximum righting arm is to be over 25 deg.
7) GM value at equilibrium is to be over 0.15
8) Area form 0 deg. Heel to max RA value heeling to port or starboard at 15 deg. heel angle is to be over 0.055
9) Area form 0 deg. Heel to max RA value heeling to port or starboard at 30 deg. heel angle is to be over 0.055

For the proposed tower design all these parameters are fulfilled with good margin.

10.5.2 Air tank Flooding

Air tank has total displacement of 3272 tons. During turbine installation it is proposed to flood this tank to achieve deeper draft and either auto install the tower at the foundation pile or reach the bottom. Tank flooding progression is shown in the table where filling of the tank from 0% up to 61% increases the draft from 24 to 59 meters. This gives delta of 35 meters. Flooding volume shall be limited to 60% as after that weight surpasses buoyancy limits and tower sinks uncontrolled. Foundation or seabed shall be reached before that. Sinking progression is controlled by regulation of bottom valves opening area. When installation is complete tanks are after filled with seawater.

Air tank can have horizontal subdivision in addiction to radial. Volume above 60% of the tank shall be separated by a watertight bulkhead to give buoyancy reserve. This reserve will prevent tower from complete loss in case it will be damaged during sea tow.

As flooding progresses shown values for VCG, draft, GM increases. Increasing in GM gives more stable tower. No free water plane surface correction during flooding is considered as internal subdivision will diminish this factor. Free surface has direct influence on GM values. During flooding the tower still has positive stability and satisfactory righting arm values.

Cross curves of stability shows hydrostatic values for righting arm at different heel angles, ranged for different drafts and displacement values. These curves are useful at estimation response action to different heeling moments like tow wire, wind, waves.

Stability calculations indicate that satisfactory margin and sea keeping values can be achieved by balancing the weight of nacelle with permanent ballast at the bottom. Tower can be installed at the water depth close to 50 meters but then upper tower has to be made longer to give required air gap. Deeper waters can be used for installation but then whole model has to be scaled up accordingly.

11. Turbine installation

Upon arrival to installation spot it is proposed to flood air tanks to reach either sea bottom or foundation pile. The draft will increase by 5-10 meters. This implies that height of foundation pile above seabed and draft of turbine has to correspond within a narrow limit.

According to NREL a 5 MW reference turbine can be designed with 15 meters air gap. Proposed tower can be lifted to about 43 meters height over the base. Initially turbine blades are longer compared to folded tower and lower edge is below sea level by 13-15 meters. During installation tower will be flooded by additional 5-15 meters. Summarized 43 meters elevation -13 m. to surface level – 15 meters flooding gives 15 meters air gap. Illustration 23 gives comparison of these two major states.

11.1 Landing on foundation pile

Foundation pile is fully submerged and thus not visible from the surface. To ensure correct position ROV vessel shall be used for supervision of the process provision of telemetry data.

There are several ways to arrange mating between foundation pile and lower tower.

11.1.1 Guide base.

This method comes from oil industry subsea development. In oil industry after completion of the large bore well drilling a temporary guide base with guide wires is installed on top of wellhead that is above the sea bottom. This creates reference guides for all equipment installed after that. Same principal applies here. Proposed procedure is first to drive inn pile to certain height above the ground with installation vessel. Then attach a specially designed guide base that will be locked on to foundation pile. 3-4 Guide wires run to the surface and will be attached to pulleys on floating turbine. Free ends are then fished onboard of the tug vessel and attached to tugger winch. Number of wires shall correspond to number towing boats. When all wires are attached and tugs are placed in star constellation around the turbine above foundation pile flooding of air tanks can start. This way each wire is at one end attached to guide base and other at the tugger winch. In between it slides around pulley attached to the turbine tower. By moving away tugs will keep wire tensioned thus keeping the tower directly above foundation. This method gives more control over installation as wire tension can be adjusted to keep the tower in right installation trajectory, it also gives good control over heel and trim angle of the wire. Disadvantage is that it is a marine operation that requires several tugs and coordination vessel. Fishing of buoy with attached wire will set restrictions to weather conditions. Whole operation will have to be controlled by ROV to ensure successful landing and locking into foundation. Weather restriction will not be as strict as for today's assembly at sea operation and can be undertaken at waves of 6 meters although 2m significant wave height if divers are in the water. Higher waves can be accepted with use of ROV only.

11.1.2 Gravity base

Heavy ballast at the bottom part of the wind turbine is required to balance the weight moment created by hub and nacelle. This bottom weight gives opportunity to use gravity principal foundation. Air tanks provide floatation to the system but in order to install the turbine tanks are flooded which adds more weight to the bottom part. Open air tanks will be filled up until the turbine reaches the bottom then bottom valves can be closed and rest of the tanks after filled with overboard water pumped with help of tug vessel. This will overbalance the system and turbine will stand on the ground. To make turbine position stable more friction has to be added. Turbine will also have to withstand large overturning moment created by wind acting on the blades and upper tower. This can be achieved by setting down leg like structures which can be released to drop down and fixed at position by ROV in rocky or solid ground. Foundation legs can be equipped with suction cans anchors where sea bottom allows for that. This method gives simplest installation but there is always risk for turbine instability during disadvantageous combination of waves wind and currents.

11.1.3 Combined foundation

The most robust solution would be to combine a foundation pile with heavy bottomed turbine. This combination only is shown on illustrations. Installation on to the pile can be performed without use of guide base. To ensure final correct position and azimuth angle foundation itself has to be placed and oriented at installation phase and this will ensure correct turbine orientation when installed.

Bullseye, elevation check tool used for installation of subsea equipment in oil industry or similar instruments are to be used while driving down foundation pile to ensure position and verticality. Failing to achieve vertical angle will create lateral forces and increase friction loss during upper tower elevation and uneven wear of turbine bearings. Correct orientation shall be confirmed by ROV camera.

Foundation pile will have guide slots on outer surface automatically orienting corresponding grooves on lower tower. While tower sinks due to flooding of air tanks ROV can help to coordinate tug vessels which shall use their thrusters and DP systems to keep in tension tow wires and ensure correct position according to GPS coordinates and ROV telemetry data.

Top of foundation pile proposed made conical so it is going to be possible to install the turbine even with some inclination angle. Conical surface will easy guidance ones one side is engaged then pile will straighten up landing trajectory.

There are several ways to arrange mating between lower tower and foundation pile. The oil industry commonly uses principle that box connection faces up and pin down. Piles are usually hammered or driven down therefore there should be solid surface interfacing sledge hammer preferably pin. Any connection on impact zone will likely be damaged or destroyed. Box connection has only outer walls and provides limited impact area. For this reason pin foundation pile is chosen.

Turbine tower is also shown with 4 extension legs welded on to concrete tank. These legs can be mounted if extra stability against overturning of tower is required. As mobile wind turbine is designed for water depth more than 20-30 meters, where the border of mono pile foundation usually lies. Therefor it has to be reinforced with tri pod like structure. The difference with tripods legs is that they are lower than central pile. Proposed design turbine has to have tower as lowest structure as it is to be connected with mono pile foundation and to avoid damage to legs during sea voyage. Legs are for this reason placed higher than lower edge of the tower during sea voyage. This can be seen as combination of three foundations used today: mono pile, gravity base, and multi-pile.

Legs design can be like presented on illustration 19 or similar to piled foundation structure. The one that is shown has vertically extending legs that are fixed by locking pin or locking mechanism in folded and unfolded positions. When turbine is fully installed ROV retrieve the pin and extensions of the legs can move down as shown on illustration 29. A hydraulic piston attached to each leg will help to adjust vertical position is case the foundation pile is not fully vertical because it has some gap to the turbine tower and is hold in place by friction only.

The end of the leg can be equipped with suction can for soft seabed. For solid or rocky seabed it will be extend onto the ground and locked in this position. Legs are increasing on bottom stability of the tower and can be used as permanent ballast containers as well, thus reducing the volume of concrete tank and lowering center of gravity. Number of legs shown is 4 but this is subject of individual design conditions.

11.1.4 Corrosion protection

Coating

Marine environment requires corrosion protection to metallic structural elements. Unlike floating structures conventional OWT cannot be brought to the harbor for secondary treatment and have to be designed with protection for whole lifecycle of about 20 years. Corrosion protection decreases the rate of material vanish with time which normally is 0.05-0.07 mm/year in atmospheric zone, 0.12-0.27 mm/year in splash zone, 0.03-0.09 mm/year in submerged zone and 0.015 mm/year in buried zone. [21] Protection can reduce these values up to 0.01 mm/year.

Coating is most widely used in atmospheric and splash zone. It prevents direct contact between material and oxidizing elements. Coating itself has to be designed for application, tested and inspected prior and after application.

Cathode protection

This method is used in submerged and buried zones. Protection is reached by impressing external voltage or using sacrificial anode made of aluminum or zinc. Surrounding sea water acts as electrolyte. To ensure sufficient protection the structure has be polarized to values of 0.25 mV for zinc and -1.1 mV for Copper electrode. Cathode protection system shall be compatible with coating.

For telescopic tower the draft value will vary during towing and after installation. This will extend the splash zone with several meters of tower height. Conventional tower after installation and assembly is exposed to atmosphere only externally. Telescopic tower has to be protected at inner and outer sides as during towing upper end of lower tower is open. After installation the tower will not be sealed completely watertight but it may be closed spay tight.

Inside tower there is lifting mechanism made of different materials which shall be considered during coating selection. Materials with different electrolytic properties shall be welded to a transition piece. Generally combination of coating of the whole turbine and zinc offer anodes placed over extended splash zone and submerged zone is recommended.

11.1.5 VIV mitigation

Proposed concept can be seen as deep draft floater system in a way similar to a SPAR platform. The shape of spar platforms is usually a long hollow large diameter cylinder. It is normally moored by means of conventional spread chains. Mobile OWT is designed removable and thus only attached to sea bottom via foundation pile but not fully fixed to it. Permanent connection like concrete or weld used in conventional systems fully restricts inter parts movements. Detachable connection always means some clearances in locking mechanisms and therefore allowances to shift. The consequence is that VIV (vortex induced vibration) due to underwater currents can occur. Model proposes the same solution that is used today for a SPAR platform - helical strakes attached to the hull air tanks. If model study will show that VIV is not an actual problem than strakes are to be skipped.

12. Lifting mechanism

12.1 Design considerations

Lifting mechanism is the key component to enable telescopic tower technology. It will finalize turbine installation bring and keep upper tower in elevated position. Lifting can be done externally with help of a crane vessel by lifting upper tower directly or through use of pulley and wires system.

This project concentrates on developing built-in lifting device. There are several reasons for that. First is in a frame of mobile wind tower concept whole system has to be independent of any special built equipment and rely only on few broadly available support vessels. An incorporated lifting mechanism will allow multiple lifting and lowering operations. Mechanism shall be placed at the interior of the tower because it primarily is empty with a large available volume and mechanism shall not change the outside symmetry of the tower. No unnecessary bending or twisting moment shall be created which can cause vibration or fatigue load. Internal machinery will not depend on weather conditions and be subjected to wind, waves, sprays and damages due to that.

Like any other mechanism it shall have a power source. This can be a hydraulic pump or electricity provided by external vessel or produced onboard. Installing a diesel engine inside wind turbine would mean high maintenance costs and development of safety, ventilation, fuel, fire detection, cooling and other systems. Since installation requires towing by tug vessels which usually have auxiliary engines onboard power from them can be used. Lifting mechanisms are widely used by jack up platforms to elevate themselves above sea level. Usually they use electric engines with reduction gear for smooth and continuous lifting. Their system develops high torque and lift ample amount of weight. Disadvantage of electric drive is that there shall be a gear box present. High ratio gears develop a lot of heat and have to be oil/water cooled. Gear shall work in oil bath and be frequently inspected and maintained. In the enclosed, remote and limited space conditions of wind turbine tower a gear box is a challenge. Electric motor with direct drive would be the best choice. High torque and low revolution motors with speed range of 0.3-1.2 m/min. like a jack up rig has will require a VSD. This is very costly, large size and heavy electrical equipment that can only be run from onboard of a support vessel.

Hydraulic systems produce highest power to volume ratio. Components are very easy available and technology is well developed. Hydraulic systems require only clean oil supplied by pump which can be either installed on support vessel or onboard. System is operated by valve blocks controlled by logic elements and can be fully automated. Relative speed of components is slow and virtually no dynamic forces are involved.

There are jack up rigs that utilize hydraulics to lift platform. One example is Siri production platform as described in [6] uses hydraulic mechanism as described in [7]. Rigs legs are tubular cylinders with perforated in certain pattern holes. 2 of 4 large pistons fixed to deck strokes out to attach itself to upper holes of the leg on corresponding pitch of the piston height, then fixation to lower holes released and piston strokes in to make relative to leg lifting movement. Two cylinders are holding platform in place while two other stroking out.

Using hydraulic piston makes forward movement discontinuous and slow. Inertia of the system has to be overcome at each stoke. At the other hand slow movement do not require cooling and can be discontinued at any moment.

Jack up platform has deck as reference fixture point for its legs. When legs are lowered they get into second reference point which is seabed. Platform is moving one reference point from another, thus deck away from seabed. Therefore lifting mechanism can be attached to platform deck. For telescopic tower reference points are fixed at certain distance which is length of cylindrical section of upper tower. Principal of increasing distance will partially work here. This distance is a stroke of main piston. After that cycle has to be reloaded and therefore lifting mechanism will have to travel upwards along with the upper tower. This sets restriction on the size and weight of lifting mechanism because it has to bear its own weight as well.

12.2 Lifting mechanism description

Proposed design consists of following main parts: Forward and aft pinion gears running on same rack. Forward and afterward frames with attached locking mechanisms. Three or more equal sets are distributed evenly on outer circumference. Forward gear and its frame are fixed to upper tower and their movement is synchronized by it. Lower gears are connected to same frame to synchronize their vertical movement and to restrict radial shift inside the tower. Forward gear is connected to lifting piston. Aft gear is connected to gear spacer and lifting piston rod. See illustration 28.

It shall be noted that illustrations provided gives only principal picture of the working mechanism. For simplicity and easy of visualization most of the minor components are omitted. For example no protective covers, drip trays, guards, locks, wires, hoses plugs, pumps, stairs and so on are shown.

12.2.1 Lifting piston

Total amount of weight to be lifted is sum of weight of nacelle 240 tons, rotor 110 tons and upper tower. NREL gives figure of 340 tons for total tower weight. 233 tons is calculated from 3D model.

Weight of gears from model is 6 by 1 ton each is 6 tons. Rest of lifting mechanism is 3x20 tons=60 tons. Total weight of lifting mechanism is 66 tons.

Nacelle	Lifting mechanism	Upper tower	Total weight to be lifted
340	66	233	639

Total weight to be lifted is rounded up to be 650 tons.

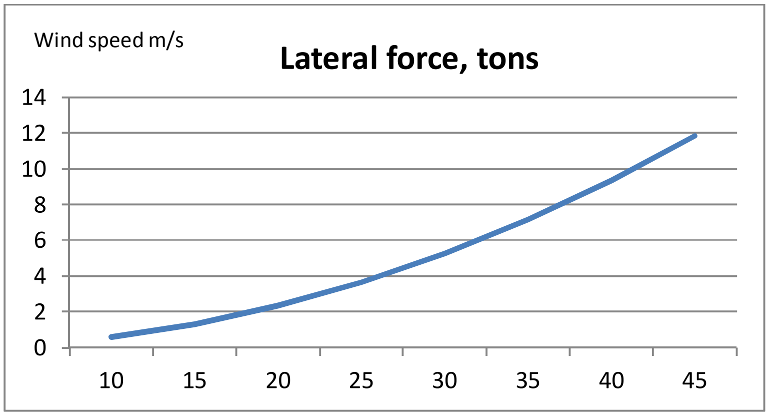
Proposed design of lifting mechanism has 3 large main stroke pistons. Each piston working in parallel shall be capable of taking 650/3=217 tons. It is recommended to use at least 300 tons jacket piston.

Hydraulic system shall be oversized to take overloads that may occur during operation. Some overload can come due to friction caused by side wind load. Eccentric hub and nacelle side wind area is calculated to be A_w=78 m^2including edge of the blades. Nacelle height above MSL expected to be 85 meters with arm around yaw center t_a=7.44 m. Lateral wind force on this area [8]:

$$F.l = \frac{1}{2} * \rho * C.d * A.w * U.m^2$$

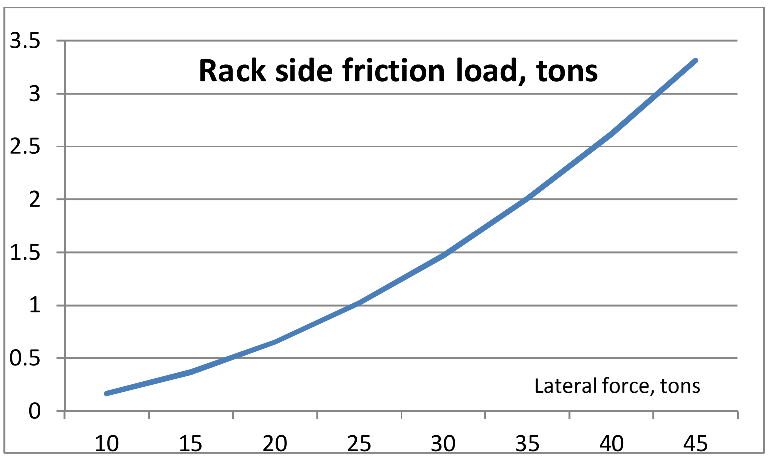
U_m is one hour mean wind speed which is taken as a range of reasonable values for installation of turbine as 10-45 m/s

C_d is drag coefficient is taken as 1.2 value, ρ is air density 1.225 kg/m^3



This creates a side friction force on rack $F.f = \mu * F.l$

Friction coefficient is set to $\mu = 0.28$ as rack is lubricated with solid grease.



A commercially available double acting high capacity piston can be used. Pump driving the piston has a hydraulic valve block to switch oil pressure between ports on the bottom and top of the piston. Double acting piston offers both pushing and pulling actions with pressure. Pulling and pushing capacities differ because when pushing the oil fills the entire bottom of the ram cylinder. When pulling, due to rod thickness only small gap between the cylinder wall and piston itself is filled resulting in force reduction. This means force drop ratio about 5 to 1. To lift telescopic tower a 300 tons cylinder is proposed. Here is data found on supplier web site [9] for a suitable one:

Parameter	Imperial units	Metric
Capacity Tons Pushing	-	300
Capacity Tons Pulling	-	147
Stroke	13 in	330 mm.

Low Height	24.28 in	615 mm.
Maximum Height	37.28 in	947 mm.
Oil volume	782 in3	13 liter
Outside Diameter	10.75 in	273 mm.
Bore	8.75 in	222 mm.
Piston Diameter	6.25 in	159 mm.
Weight	660 lbs.	300 kg.

This is the piston with longest stroke available from this supplier of 13" which is about 330 mm. at a time. There are limitation on rod length as longer rod may give buckling and failure. Seals and packers are also limiting the stroke length. Main piston is placed upside down so that its main pushing direction is directed upwards and mechanism is mainly fixed to upper tower.

12.2.2 Gear Locking

Lifting mechanism consist of 2 gears spaced with 5 meters distance. This is to create 2 longitudinal support points for upper tower and centralize it. Gears are sliding along rack profile which is fixed to lower tower. Each gear has a locking mechanism. Forward gear has locking mechanism in front and aft gear has it behind because this way locking mechanisms shall be placed as far as practical from each other to create most fixation moment when upper tower is lifted completely. They are also placed at outer edges because there is a piston with connecting rod in between gears.

Gears are fixed to respective frames which have sidetrack levers to keep the pinion gears on the rack. Side wind acting on nacelle will try to twist upper tower around vertical axis. Levers will prevent this and keep mechanism on track.

Gears are fixed to their frames via a radial ball bearing with solid grease lubrication. Since mechanism is enclosed inside tower it will run clean.

Locking mechanism consist of a lock that has the same inverted profile as a rack with 3 or more teeth for best engagement. Lock is operated by locking piston fixed to a frame running together with forward gear. Lock is hinged to piston shaft and piston shall have a 3 degree of freedom so that teeth will be engaged even if the stroke is not complete by few millimeters. There shall be installed end switch to confirm that lock is either engaged or released. This can for example be achieved by proximity switch or optical sensor. Locking is provided for each pinion.

Lifted weight is calculated to be 650 tons. This is force acting vertically down. Gear locking mechanism has to be dimensioned according to this. Gear has a 25^0 pressure angle. At the tip of a rack tooth it is 50^0. Locking mechanism has 3 teeth to engage. But calculated very conservative we consider that weight is acting on one tooth only. Therefor force acting against cylinder piston trying to retract is: $F.r = \frac{W}{3} * \cos 25 * \sin 25 = 83.11\ tons$. Piston can be selected from the same supplier. A 100 tons spring return piston with following parameters can be found suitable:

Parameter	Imperial units	Metric
Capacity Tons Pushing	-	100 tons
Stroke	6.63 in	168 mm
Low Height	14.06 in	357 mm.
Maximum Height	20.69 in	526 mm.
Oil volume	137 in3	2.25 l
Outside Diameter	7 in	178 mm
Bore	5.13 in	130 mm
Piston Diameter	4.13 in	105 mm
Weight	130 lbs.	59 kg

For security reasons locking mechanism is to be designed to lock the system in place even if hydraulic power has been lost. This can be resolved with spring loaded actuators or pistons like the one proposed above. Design of the piston has to be changed. Usually a piston has normal condition retracted and when hydraulic line pressurizes it strokes out. Here it has to be opposite. Normal condition is stroked so that gear lock is engaged and then cylinder overcomes the spring force and retracts to release gear lock. Probably changing places of in and out port would solve this. Another, more commonly used solution is a non-return valve on upstream side that will hold the pressure even when the oil supply has failed.

When tower is fully elevated and operational its position on top is ensured by all gear locks so it can withstand at least twice its weight vertically. It has to be noted that when totally lifted upper tower cannot be hold in place by engaging hydraulically operated locks for long term. A mechanical, specially designed lock has to be engaged.

There also shall be developed emergency plan in case of different critical parts and mechanism failure. There are 2 gear locks in 3 mechanisms, totally 6 so even if the forward or aft gear set will be set out of operation, still system have to respond the way that will minimize damage to itself and environment.

On illustrations provided gear lock is hanging on actuating piston only. It shall be noted that rod shall take minimum lateral load. Any bending of piston rod will lead to leakages and reduction in pushing capacity. Lock itself is running along mechanical guides that are not shown on illustrations. They would complicate visual understanding of the lifting mechanism but have to be incorporated on final design.

12.2.3 Hydraulic pump sizing

Due to difference in operation of two piston types described above it is proposed to use 2 separate pumps for main stroke and locking functions with possibility to route oil flow from one to another. This will create redundancy and increase safety.

There are 3 main pistons each with 13 liters oil capacity, totally 39 liters of oil for one stroke. As estimated above one stroke is to take about 30 seconds which gives 2 strokes a minute. It will require oil flow of 78 liters a minute. Equipment has to be oversized to include some losses in the system and have appropriate reliability level. Therefore it is proposed to increase pump capacity by 30%. This will give a pump of 102 liters/minute capacity. Load pressure is calculated based on diameter piston 159 mm. and load of 300 tons. This gives 151 bars internal pressure.

Pump parameters assumed and calculated using method found in [16]:

Motor speed (min-1) M.s	Flow rate (L/min) F.r	Load pressure (bar) L.p	Motor efficiency (%) M.e	Pump displacement (cc/rev) P.d
1450	102	151	85	100

Power input:

$$P.in = \frac{M.s * P.d * L.p}{6 * M.e} = 59.705\ kW$$

Shaft Torque:

$$S.t = \frac{P.d * L.p}{20 * \pi} = 3141\ N * m$$

Power output:

$$P.out = \frac{M.s * P.d * L.p}{600} = 50.75\ kW$$

A commercially available pump with similar parameters would require a 440 V power line and occupy about 3 square meters deck space

Same pump for 6 locking pistons can be used. Oil volume for each piston is 2.25 liters. During normal operation only 3 pistons engaged simultaneously but at upper position all locks have to be engaged. Pump has to then be sized for all 6 pistons simultaneously. Total volume is 13.5 liters. 30% increase gives 17.6 liters. For the same pump parameters

Motor speed (min-1) M.s	Flow rate (L/min) F.r	Load pressure (bar) L.p	Motor efficiency (%) M.e	Pump displacement (cc/rev) P.d
1450	17.6	115.5	85	12

Power input:

$$P.in = \frac{M.s * P.d * L.p}{6 * M.e} = 3.94\ kW$$

Shaft Torque :

$$S.t = \frac{P.d * L.p}{20 * \pi} = 217\ N * m$$

Power output:

$$P.out = \frac{M.s * P.d * L.p}{600} = 3.349\ kW$$

12.2.4 Gear frame

Gear frame is structural unit that provides support for the gear bearing and shaft. It is made of square section extruded metal profile. Corners are chamfered or rounded to prevent stress build up. Whole frame is welded together and all welds are to be controlled by combination of 2 or more NDT techniques like dye penetration, radiographic inspection, ultra sonic inspection. Frame also supports locking pistons and spacer. Frame is to be designed for long fatigue resistance performance as wind will create changing in direction and force load onto upper tower which will be directly transferred into the frame. Frames for aft gear are welded together to single structure for synchronization. Frame is to be installed ones upper tower is set inside lower tower at initial lifting position. A test run onshore is the whole lifting mechanism is recommended with 30-50% overload to verify manufacturing. After test construction elements are to be inspected.

The most critical part of the frame is spacer which is a 2760 mm. long hollow round steel bar exposed to buckling load by the lifted weight. It is checked against axial load of 250 tons which is more than expected 1/3 of total weight to be lifted. Following parameters have been set: Outer diameter is 200 mm. inner diameters: 100 mm. Steel 355 MPa yield strength. Mounting type: clamped – hinged. Calculation shows that this section is strong enough. For additional security section wall thickness can either be increased or reinforced by radial ribs. Appendix D shows all calculation parameters and results performed with MITCalc spreadsheet software [30].

Second quick calculation is performed on longest span bending in the middle of rectangular frame. Same weight load is applied at the beam center which is supported at ends. Longest span from the model is 520 mm. Section of 220 mm square with wall thickness of 50 mm. is required to sustain the load Material calculated has 213 MPa permissible bending stress. Welding of parts with wall thickness of 50 mm. imposes extra challenge to quality control, especially for welds designated for fatigue loads. Better material quality and reinforced shape will reduce wall thickness in both cases. No dynamic factors are included.

12.2.5 Rack and pinion

Rack and pinions are the key elements of lifting mechanism that will enable lifting of the tower. Design is based on assumption that the lifting speed is very low and does not require special cooling system. Grease lubrication is to be used to enable smooth run. Rack profile is 49 meters which is very long.

Most common stock length is 6' and 12 '(1,83 and 3,66 meters) it will require machining of 36 individual rack profile pieces per turbine. This means that no precision machining is to be used. Rack has a simple close to triangle profile. Pieces are joined together on the lower tower. Rack profile is designed as low as possible so that strong reduction of tower diameter is avoided. At the same time to increase capacity width is increased. It is therefore proposed to fix it to the tower with combination of bottom and side wall fasteners

Rack teeth can also be machined individually and welded on to upper tower one by one using a template. Illustration 27 shows that during meshing of rack and pinion teeth are not fully overlapped. The root of the rack is free of contact which gives opportunity to perform welding. Difference in material properties may require indirect welding using intermediate piece.

Gears are designed as a spur profile with pressure angle of 25 degrees. Helical gears are not considered for this application. They have higher capacity but create lateral load which is not desirable for telescopic tower application. They still can be used if design would be based on 2 or 4 racks to cancel lateral forces action. Pressure angle is the angle between pressure (contact) line and the common tangent to the pitch circles. This angle gives most loads bearing capacity. It is common to design a gear with as many teeth as possible to have several of them in contact simultaneously which gives smooth run. In our case design is based on 8 teeth due to high load, low speed and tolerance to bumpy ride. Jack up rigs lifting mechanism operates with the same number of 7-8 teeth.

Gears and gear racks should have backlash designed into their mounting dimension. [11] Backlash is the amount of which the tooth space of a gear exceeds the tooth thickness of the mating gear at the pitch circle. It can be determined in the plane of rotation. If mating gears have zero backlashes, gears and mountings need to be dimensionally perfect. To retain zero backlash with varying operation conditions, all parts need exactly the same thermal expansion characteristic. [12]. If there is not enough backlashes, there will be a lack of smoothness in action, and there will be premature wear. Designed gears have a backlash below standard values as it is not desired to have clearances due to high bending moment created by elevating tower. This can create beating effect between rack and gear and impact loads due to reversing across backlash which can be significant [13]. High wear will not occur due to only few hours operation time.

Rack and pinion pair is designed to carry the most loads on the cost on smoothness and angular velocity. Gears are designed to carry 250 ton load each which is also oversized by 17% each compared to lifting weight. All 3 forward and 3 aft ward gears are synchronized and total load distributes evenly between them.

Material selected is high alloy steel with high chromium contents so that no extensive corrosion protection is required. Pinion is designed to be less than one meter in diameter so face width is increased correspondingly for the load. Internal cut out of 300 mm. should give enough space for shaft and a roller bearing. Topping tool is used on rack profile and it is wider than pinion to ensure 100% contact surface at all mode of operation. Sidetrack lever on the frame of pinion will prevent side movements.

Meshing in between gears is only few hundred millimeters in height so in worst case teeth can slip or loose contact area so that crushing, plastic flow or other local failures will occur.

Term Crushing means a local surface fatigue failure in a heavily loaded hardened surface gear. Nitrided, carburized or induction hardened surfaces are especially subjected to it due great difference in hardness between surface and core material.

Plastic flow is a surface deformation caused by combination of high contact stresses with sliding and rolling action of a meshing gear teethes. It is a cause for cold working of the tooth surfaces. It can affect soft as well as those gears that are heavily loaded. [100].

Calculation performed with trial version of Kiss soft Z013 spur gear calculation software (http://kisssoft.ch/). Result summary for gear shown on illustration 27 present below [14].

Common parameters, metric units:

Torque (Nm) [T]	73500000.0
Application factor [K_A]	1.25
Required service life [H]	200.00
Running center distance (mm) [a]	595.800
Rack height (mm) [Hz]	300.000
Normal module (mm) [mn]	85
Pressure angle at normal section (°) [αn]	25
Nominal circum. force at pitch circle (N)[Ft]	216176470.6
Radial force (N)[Fr]	100804743.7
Normal force (N)[Fnorm]	238524344.2
Tangent. Load (N/mm) (N/mm)[w]	514705.88
Mean coefficient of friction [mum]	0.178
Lubrication type	Blasolube 330-01 Mineral-oil base
Kinem. viscosity base oil at 40 °C (mm^2/s) [µ40]	375.00
Kinem. viscosity base oil at 100 °C (mm^2/s) [µ100]	27.00
Specific density at 15 °C (kg/dm^3) [roOil]	0.930
Grease temperature (°C) [TS]	70.000
Ambient temperature (°C) [TU]	20.000

Parameter	Pinion	Rack
Number of teeth [z] 8	8	infinite
Face width (mm) [b] Accuracy grade [Q-ISO1328] 6 6	420.00	480.00
Material	Pinion: 34 CrNiMo 6 (3), Through hardened steel, nitride ISO 6336-5 Figure 13a/14a (MQ)	18CrNiMo7-6, Case-carburized steel, case-hardened ISO 6336-5 Figure 9/10 (MQ), core strength >=25HRC Surface hardness HV 650,HRC 61
Fatigue strength. tooth root stress (N/mm²) [σ_{Flim}]	370.00	430.00
Tensile strength (N/mm²) [R_m]	1200.00	1200.00
Yield point (N/mm²) [R_p]	1000.00	850.00
Young's modulus (N/mm²) [E]	206000	206000
Poisson's ratio [v]	0.300	0.300
Average roughness, Ra, tooth flank (µm) [RAH]	3.00	0.60
Mean roughness height, R_z, flank (µm) [RZH]	20.000	4.800
Mean roughness height, R_z, root (µm) [RZF]	20.000	20.000
Profile shift coefficient [x]	0.5000	0.0000
Tooth thickness (Arc) (module)[s_n*]	2.0371	1.5708
Operating pitch diameter (mm) [dw]	680.000	255.909
Tooth form factor [Y_F]	1.67	1.77
Stress correction factor [Y_S]	2.29	1.92
Bending lever arm (mm) [hF]	131.25	137.51
Working angle (°)[αen]	42.39	25.00
Tooth thickness at root (mm)[sFn]	180.78	198.98
Tip relief [Ca] (µm)	5.20	2.00
Tooth root radius (mm)[r_{oF}]	20.96	39.91
Contact ratio factor [Y_{eps}]	1.00	
Deep tooth factor [Y_{DT}]	1.000	
Gear rim factor [Y_B]	1.360	1.979
Gear rim thickness (mm) [sr]	144.950	126.600
Nominal shear stress at tooth root (N/mm²)[σ_{F0}]	31502.25	35724.83
Tooth root stress (N/mm²) [σ_F]	41451.84	47008.07
Support factor [Y_{dre}l]	1.061	0.977
Surface factor [Y_{Rrel}T]	0.996	0.986
Size coefficient (Tooth root) [Y_X]	0.951	0.931
Stress correction factor [Yst]	2.00	2.00
Limit strength tooth root (N/mm²) [σFG]	1070.86	1440.54
Permissible tooth root stress (N/mm²) [$\sigma_{FP}=\sigma_{FG}/SF_{min}$]	764.90	1028.96
Required safety [SF_{min}]	1.40	1.40
Single tooth contact factor [Z_B,Z_D]	1.33	1.00
Flank pressure (N/mm²) [σ_H]	18366.47	13773.09
Limit strength pitting (N/mm²) [σ_{HG}]	1300.00	2400.00

Proposed rack and pinion design shows that it is possible to design lifting mechanism with only 3 pinions but to achieve satisfactory root and flank safety more expensive materials are to be used. Meshing profiles becomes very tight so that topping tool is to be used to have enough strength at the tip.

Gear is at its very strength limit while increased safety factors or heavier lifting weight may make this design very unpractical. The pinion contact surface is heavily loaded and there is great danger of scuffing (local contact surface welding) scoring (scratches on sliding direction) and other surface failures described above.

It is strongly recommended to go for double or even triple pinion design for each rack to distribute the load on several pinions. Two or three pinions on the same frame on upper and lower end of lifting mechanism working with load distributed among them will give reduction in envelope size and better redundancy and safety. This means that each rack will have up to 6 instead of 2 gears shown, up to 18 in total. Rack is not limiting factor for this application and can be used at provided dimensions but if its width will give complications in attachment to tower wall, can be split in two. If this will be the case then racks can be moved away by 5-10^{0} at circumference and pinions correspondingly. This way pinions axes will not be coincident seen from the top of the tower. This will give increased centralization and lifting mechanism stability inside the tower. This is the scope of future designs development when tower parameters are carefully calculated for specific purpose.

12.2.6 Operational sequence

Illustration 31 shows how lifting mechanism operates. Upper and lower towers are not shown for clarity. There are totally 5 sequences that complete full cycle of one main piston stroke.

Number	Main piston	Forward lock piston	Aft. Lock piston
Sequence 1	Retracted	Retracted	Stroked
Sequence 2	Stroked	Retracted	Stroked
Sequence 3	Stroked	Stroked	Stroked
Sequence 4	Stroked	Stroked	Stroked
Sequence 5	Retracted	Retracted	Retracted

If counted that a stroke would take 30 seconds to complete and 30 seconds to lock/release lifting mechanism in place included delays in between. The whole cycle consist of following operations: Stroke out cylinder (30s), lock forward stop (30s), retract aft stop (30s), retract main cylinder (30s), lock aft stop (30s), retract forward stop (30s). All these 5 steps will take 2.5 minutes and displacement 0.33 m. Travel distance is about 43 meters. Lifting time is then about 5.5 hours. This is rather ideal estimate but a turbine ready to operate in a matter of few hours than days is very different from time spent today.

12.2.7 Hydraulic diagram

Lifting system is operated by Control unit that communicates via VHF signal with support tug vessel and is coordinated by it. Communication is wireless with confirm signal routines to verify operation completion and error reporting system by designated codes. High definition video cameras will provide lifting operation surveillance as no personnel shall be inside tower during it. Video transmitted wireless as well. Elevation marks are to be painted inside tower so operator is always informed about travelled distance. Should video signal fail system can be backed up with proximity switches along racks to provide check point marks along route. A sensor system including load cells, vibration, pressure, and temperature measuring devices are to be installed at critical parts to prevent overheating and overloading. Operator shall identify hazards and failure modes long before failure occur. Sensor signals will help to diagnose abnormal operation. Emergency stop shall be coded into logical circuits in case of lost connection or delayed reply from remote operator. System shall automatically go into locked position and wait for confirmed operator information.

Illustration 30 shows principal hydraulic diagram for lifting system. Two similar block valves are used for aft and fwd. lock pistons. These block valves are spring returned so when there is no other signal then gear locking pistons are in locked position. Logic circuits prevents that locking is on at the same time as main pistons stroke. System is supplied with oil by a hydraulic pump. Two pumps shall be considered as there are different pressure values in main and locking systems. Two pumps will also give safety redundancy. Hydraulic system is provided with overrun, pressure relieving, filter and other safety systems that are not shown on diagram. All pistons are to have mounted on proximity switches or end sensors to physically confirm piston rod position. Time delay in between strokes sequence is controlled by timer.

Main stroke pistons are to be supplied with self-adjusting valve system. Detailed description is given in [15]. The adjusting valve is required to compensate any skewing of the load caused by micro-leakage past seals. A skew position will occur if the rams aren't fully extended/ retracted during normal operation. To correct this, the built-in self-adjusting valve will automatically remove any skew position. System pressure will not increase more than load requirement, disregarding pressure drop even though the self-adjusting valves are open when the rams are fully extended/retracted. The precision of the parallel motion is due to the fact that an equal quantity of oil is always kept between rams. Any skew position that may occur can be caused by elasticity in the hydraulic lines and to a certain extent, oil compression. Skewing may occur due to uneven load in between 3 main pistons. Tower to be lifted has mostly symmetric weight distribution but nacelle is not. It has a rotor hub with blades on one side. This will misbalance loading on main lifting rams which is going to be corrected by adjusting valves.

12.2.8 Safety measures

By design telescopic wind turbine has mechanisms enclosed into watertight lower tower. Nevertheless safety measures shall be taken to prevent oil leaks and spills to environment. Drip tray to be arranged around hydraulic components and fitted with level alarm with communication to operator. This will indicate both the loss of pressure in the system which suggests major failure and hydraulic oil spill. Level alarm will also indicate breach in watertight integrity of the tower. From time to time operator will have to enter the tower so all stairs, passages are to be designed with guard rails, and passage height shall be about 2 meters and at least 600 mm. wide. Dedicated local firefighting system can be installed inside tower in case overheating in working parts will develop smoke or flames. Portable fire extinguisher and air mask are to be visible if operator stays over longer period with working machinery.

To prevent electrical shock hazard all parts and metallic surfaces to be grounded. Tower is to be ventilated to prevent gases to build up or provided with pressure relive valve if the tower will be sealed during operation so that negative pressure will not prohibit entrance door opening. Telescopic wind turbine tower is no longer empty and has to be maintained and inspected on regular basis.

12.2.9 Other lifting methods

Instead of conventional lifting mechanisms based on hydraulics or electric motors unconventional methods can be used to lift the tower.

1) One of the proposals is to use a rocket jet engine same principal that is used to launch missiles. Those engines develop very high thrust in short period of time able to lift heavy loads. Especially this can be useful if it will be decided to use elevating mechanism only one time for permanently installed turbine. In this case lifting mechanism will be an investment that is used only one time which is difficult to defend from economic stand point. Jet engine can be used only ones but it will require different tower design approach first of all to lead away gases produced during combustion. When fired, jet will bring up the upper tower to working height and automatic locking mechanism will fix it there. Instead of fuel a water jet can be used but they likely are not powerful enough.
2) Another method is to use external lifting with large crane boom vessel. After installing tower on foundation it can be lifted externally by fetching the tower from outside with fork lift-like mechanism and pull the tower up and lock in lifted position. Instead of crane a system of pulleys and wires can be used. High bollard pull vessels would connect their winches with wires from telescopic tower and move away from it thus elevating upper tower in relation to lower. Their movement has to be synchronized carefully. At the top the tower is locked in place and wire is released by deploying an explosive charge at a weak point close to tower. Wire is then winded onto the winches and this way turbine is installed.
3) The fact that telescopic tower can be flooded over a foundation pile, installed onto it and locked in place creates a stable point at sea. Any external vessel that might be used for elevation after that does not require raising itself on the jacking legs to get steady ground. It is already provided by wind turbine tower so vessel has only to lock itself to it and use as foundation for itself. This means that a vessel with vertical lifting tower can be used. Mode of operation is to lock the vessel into grounded tower then lock lifting crane mechanism to upper tower and lift and lock it. Lower tower acting like an anchor point will allow performing this operation without jacking the vessel above the sea level.

13. Conclusion and future development

This work's objective is development of an idea of a multi megawatt mobile offshore wind turbine that may become a next step in offshore wind power generation. Different aspects of potential benefits, drawbacks limitations and possibilities are discussed. General design presented as it is seen at first approach. Several key elements for success are indicated and proposals to their design are made.

The idea is built on patent application [1] of telescopic tower that enables a sea tow in vertical position. A special cover will protect wind blade during sea tow as well as provide access to the tower. A subsea mono pile foundation design is proposed with automatic electrical grid junction.

Design dimensions and constrains of a telescopic tower are shown with indicated way to make design floating with satisfactory sea keeping abilities. Stability during tow is discussed with variation on different parameters.

Whole project main focus is to minimize or eliminate completely all marine operations during installation. This would give freedom from weather conditions, special built vessels and their availability. Eliminating those vessels means that some of their capabilities are to be built into the turbine tower like lifting mechanism. Elevation method for telescopic tower is proposed with design calculation of key mechanism elements – rack, pinion, frame and pump.

There is a tradeoff between cost of extra hardware that has to be incorporated into wind turbine structure and probably used only few times and multiple use special vessels. This discussion is no longer that important when water depth is close or over 50 meters. Mobile wind turbine can be adapted to depth like this more easily than an installation vessel would be. One time hardware investment will be paid off fairly quickly if several turbine installations and removals will take place throughout its life cycle. In this case it is skipping not only one but several marine operations with all costs they imply. Mass production will eventually also minimize the overall hardware cost.

A roadmap for further detail development of turbine components is indicated here. Several more systems have to be detail engineered and this will show whether whole concept is realistic. One of examples of such systems is long term mechanical locking of upper tower at final phase of elevation procedure.

A permanent mechanical lock has to be designed regardless of what lifting technique finally will be used. Any lifting mechanism is good for a short term empowerment. As turbine operating time window is quite large, use of lifting mechanism for fixation is unpractical. Vibration and fatigue loads can lead to malfunction of the mechanism. A permanent lock can be activated by upper gear wheel when approaching the top. Secure engagement is then activated when upper stop plate is on its apex.

A further modification to lifting mechanism in form of introduction several pinions per rack and changes to operational modes shall be considered.

Upper tower weight can be reduced by introducing not a solid tubular section but a jacket like structure. This will also reduce wind loads onto the tower and locking mechanisms due to reduction in lateral uninterrupted wind area.

By design there are not only one but two towers and their mutual behavior shall be investigated against variable and fatigue loading. Reliability of locking mechanism against operational time shall also be investigated. Towers will have different stiffness values and will behave like 2 degree vibration system. Vibration analysis has to be performed when envelope and constrains are finalized.

A scaled model of lifting mechanism and its controls have to be built to verify and improve the design. Towing of scaled model of the full turbine at indoor pool will show marine environment behavior wind and wave response.

Finally concept of combination mono pile foundation with legs supported gravity based installation has to be mathematically verified. Practical solution to replace sea water in automatic junction chamber has to be detail developed.

A mobile offshore wind turbine concept will hopefully attract attention of the industry and found worth practical realization.

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15. Terms and Acronyms

Air gap	Is the distance between lower tip of turbine blade to mean sea level
DP	Dynamic positioning
FEED	Front end engineering design
FMECA	Failure mode, effects, and criticality analysis
GM	Distance between Center of gravity and metacenter.
GPS	Global Positioning System
HP profile	Hot-rolled flat bulb steel
HPU	Hydraulic power unit
IMO	International Maritime Organization
MSL	Mean Sea Level
NDT	Nondestructive testing
NREL	National Renewable Energy Laboratory
PLU	Programmable Logic Unit
ROV	Remotely operated vehicle
SONAR	Sound Navigation And Ranging
SWH	Significant wave height
VCG, TCG, LCG	Vertical, -Transverse, - Longitudinal Center of Gravity.
VIV	Vortex induced vibration)
VHF	Very High Frequency
VSD	Variable speed drive

16. Appendix A. Illustrations

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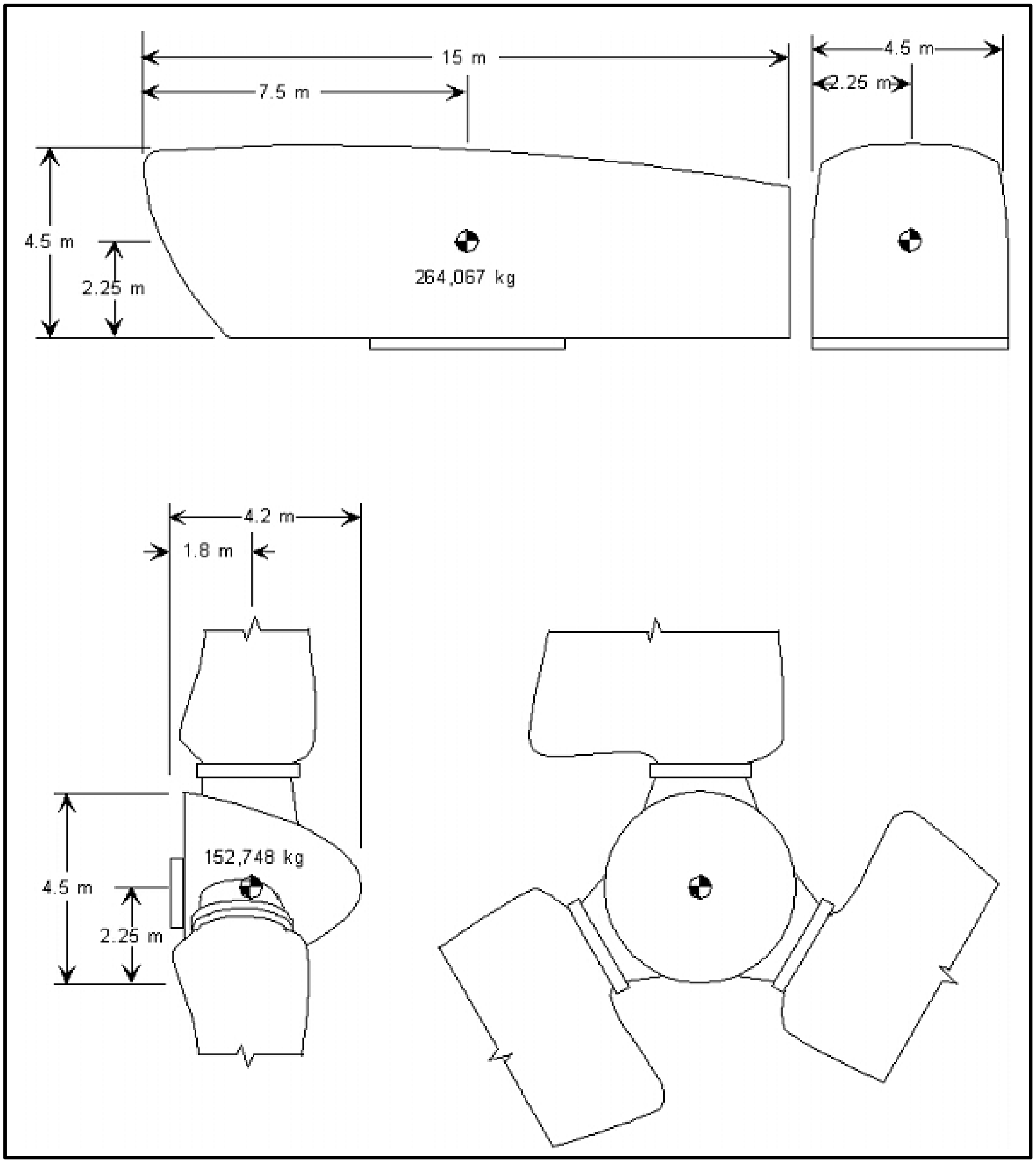


Illustration 14 Courtesy NREL; 5-MW Turbine Center of Gravity Data, source [4]

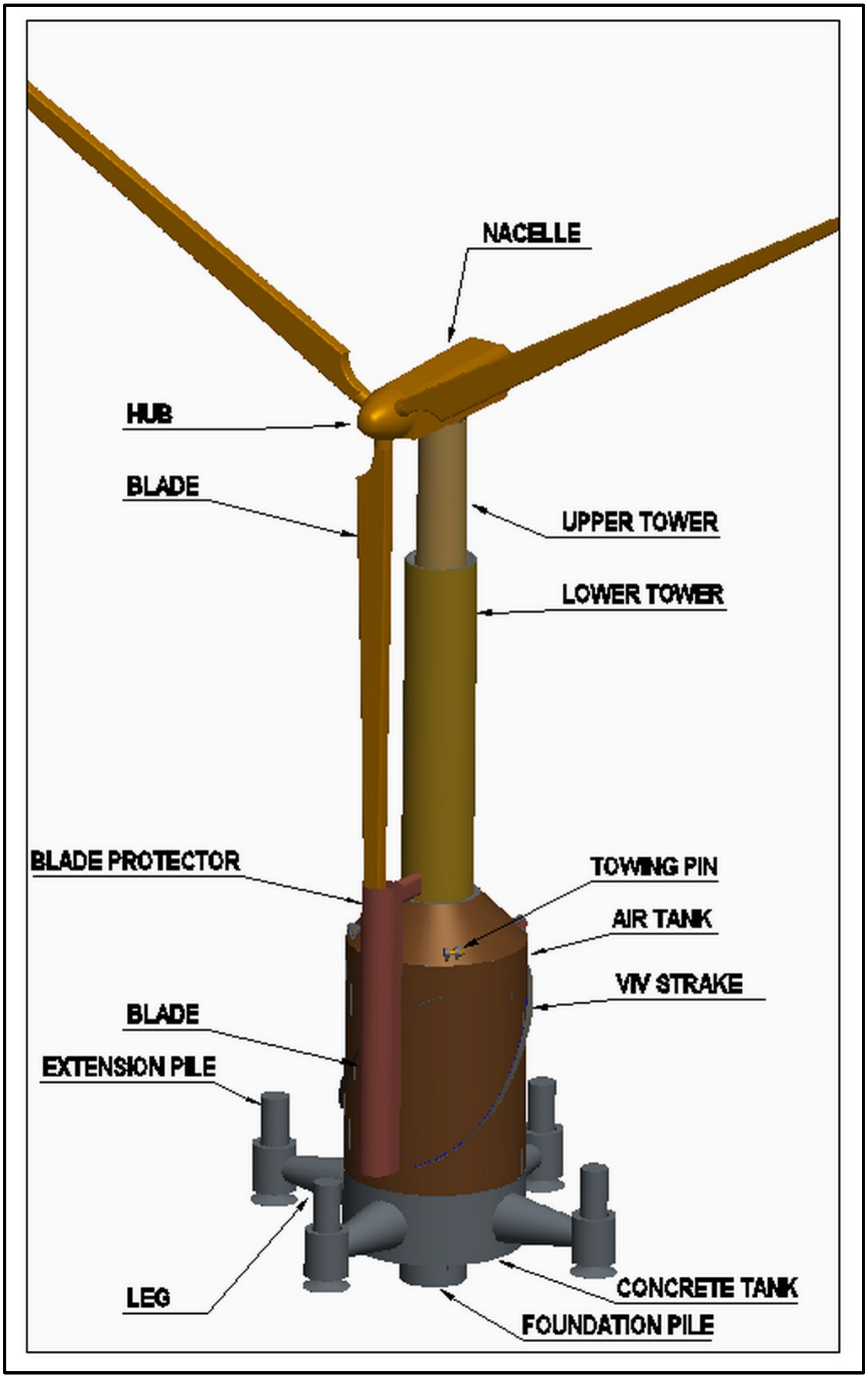


Illustration 15 General over view

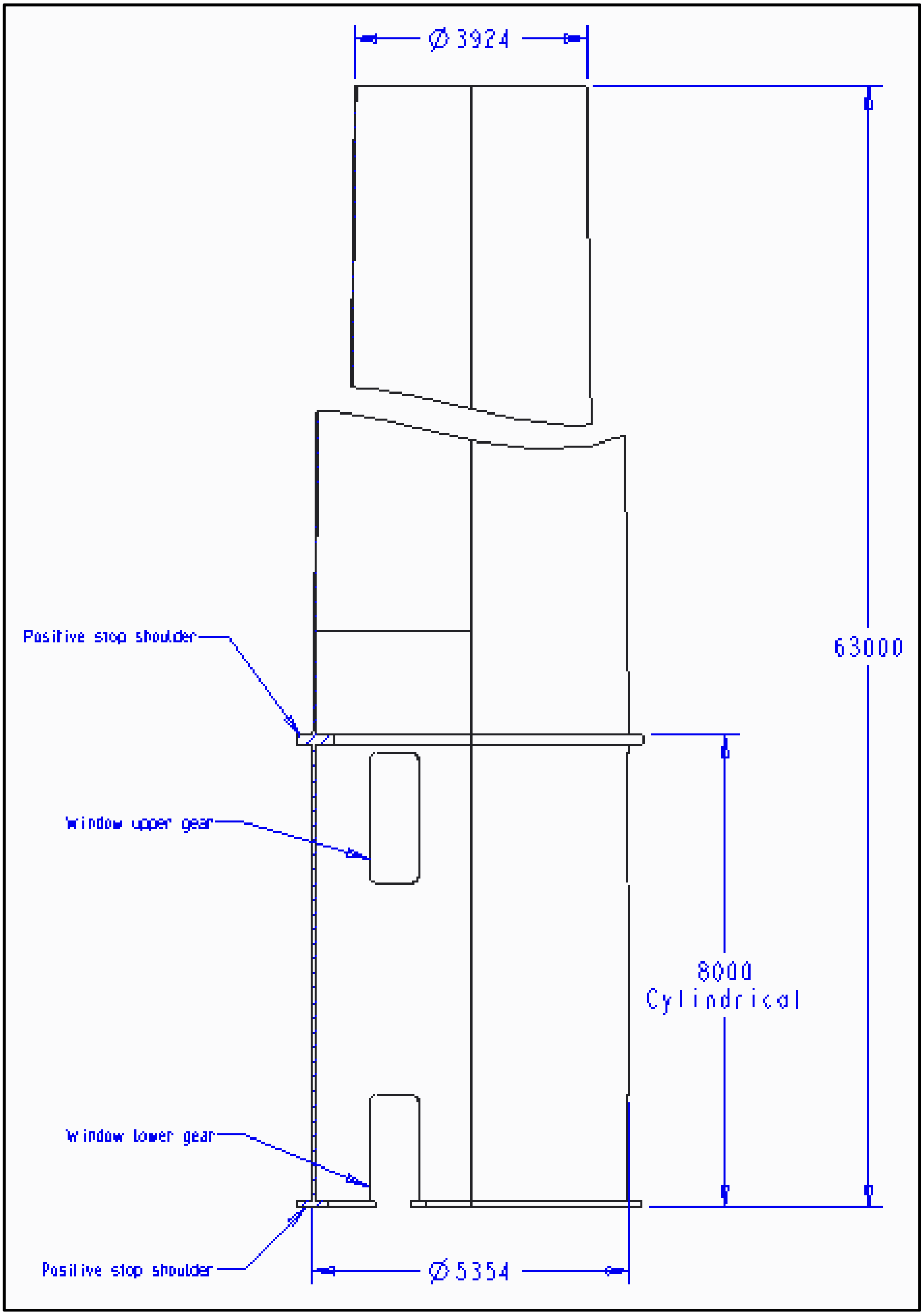


Illustration 16 Upper tower principal dimensions

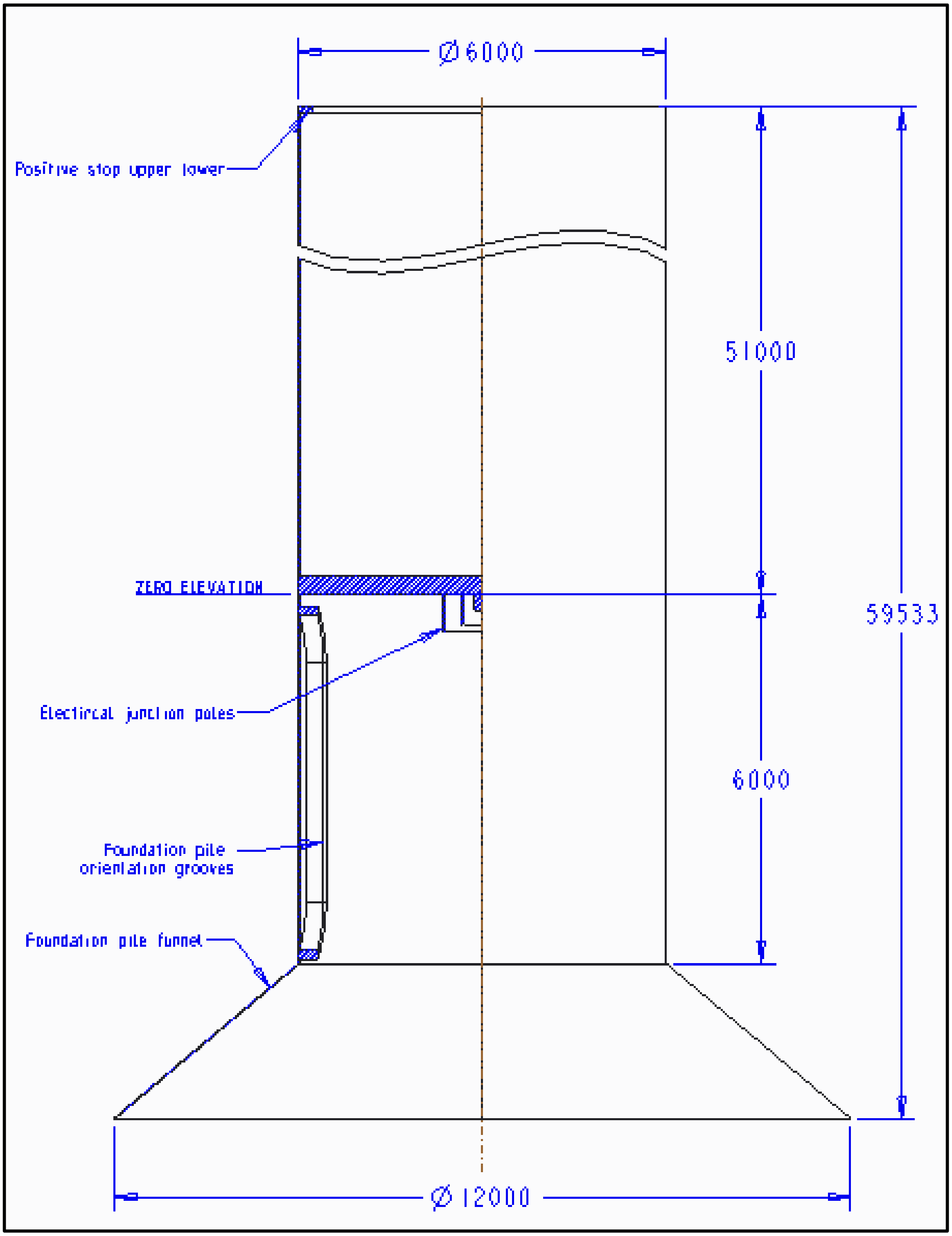


Illustration 17 Lower tower principal dimensions

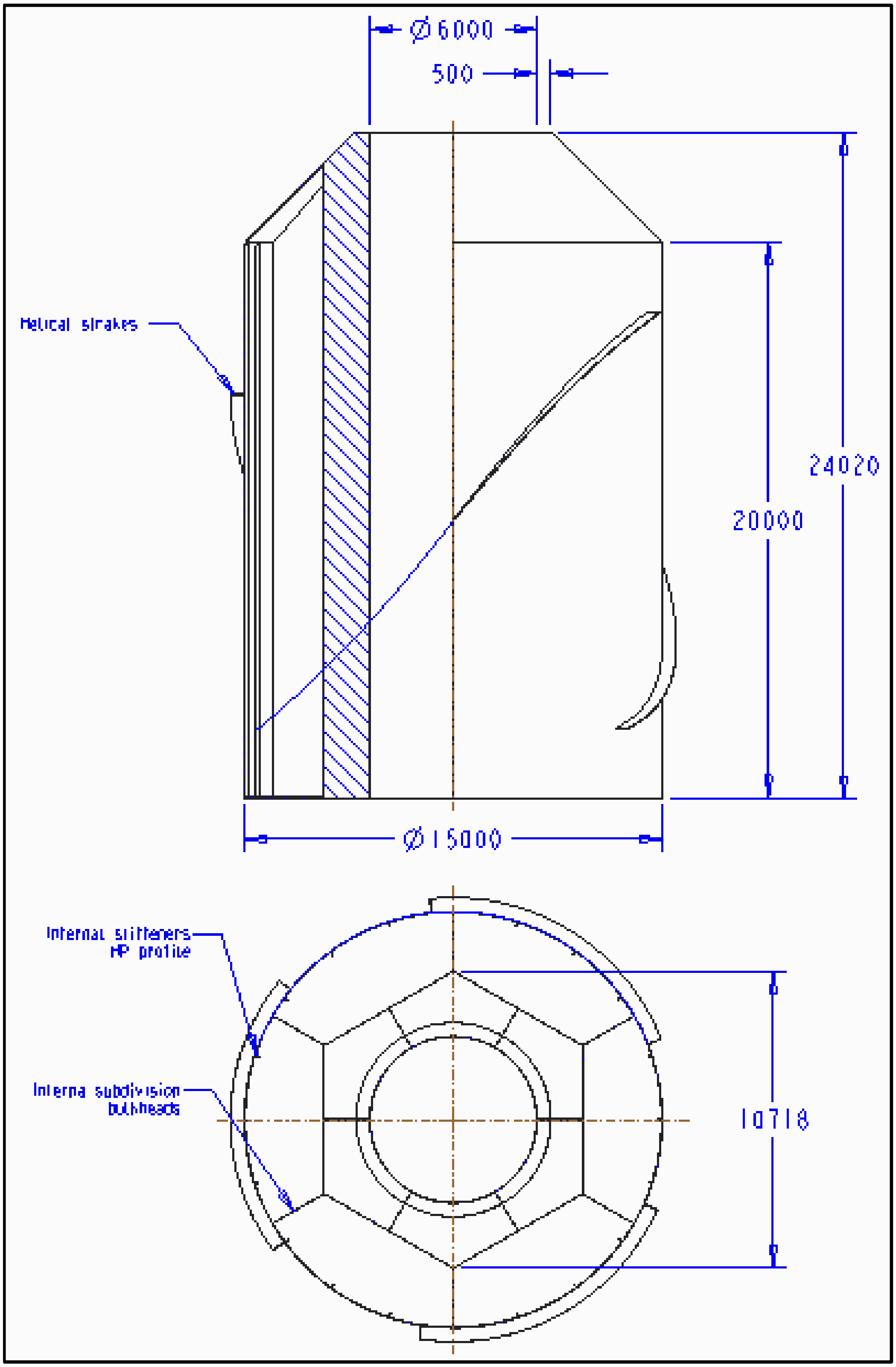


Illustration 18 Air tanks principal dimensions

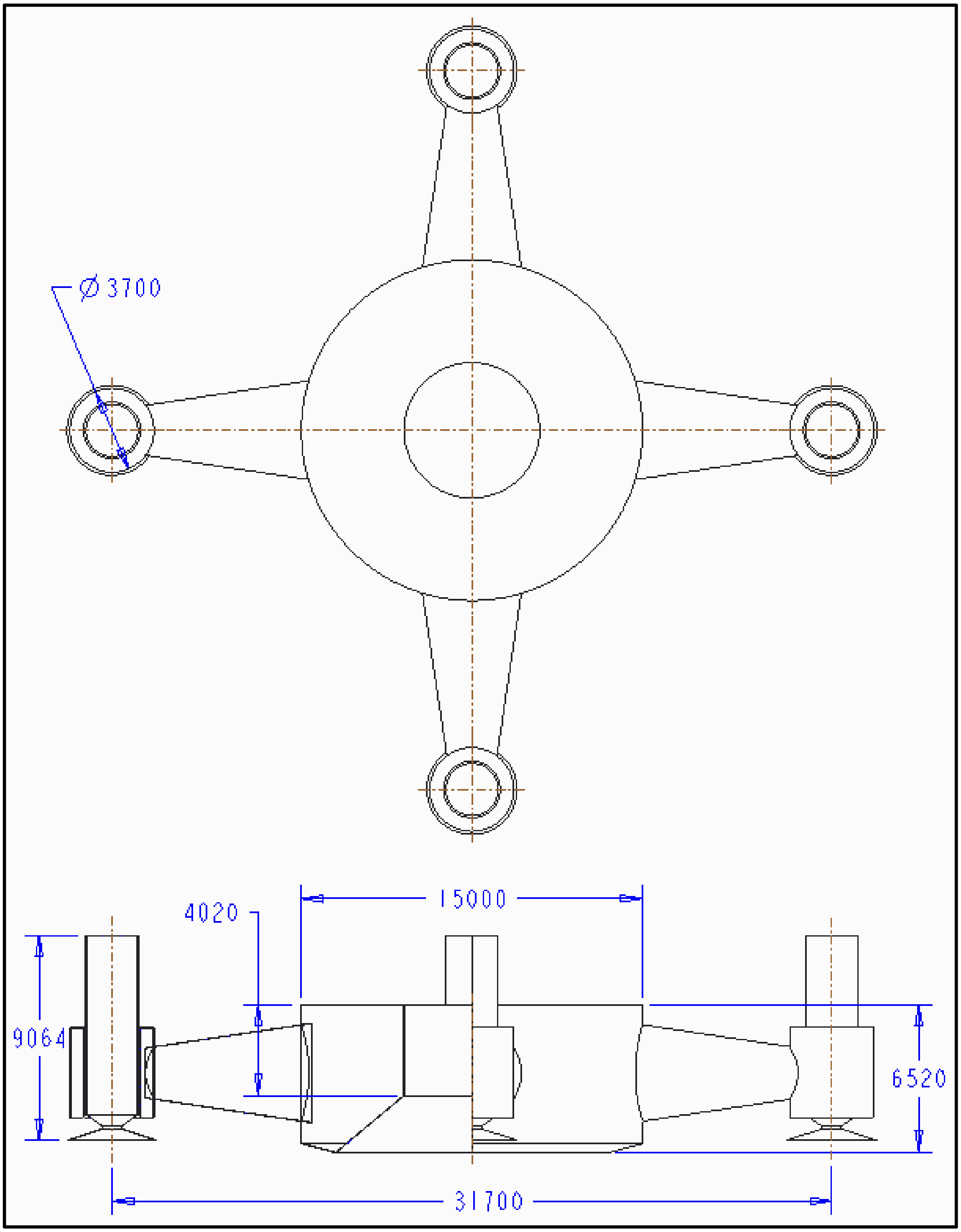


Illustration 19 Concrete tank principal dimensions

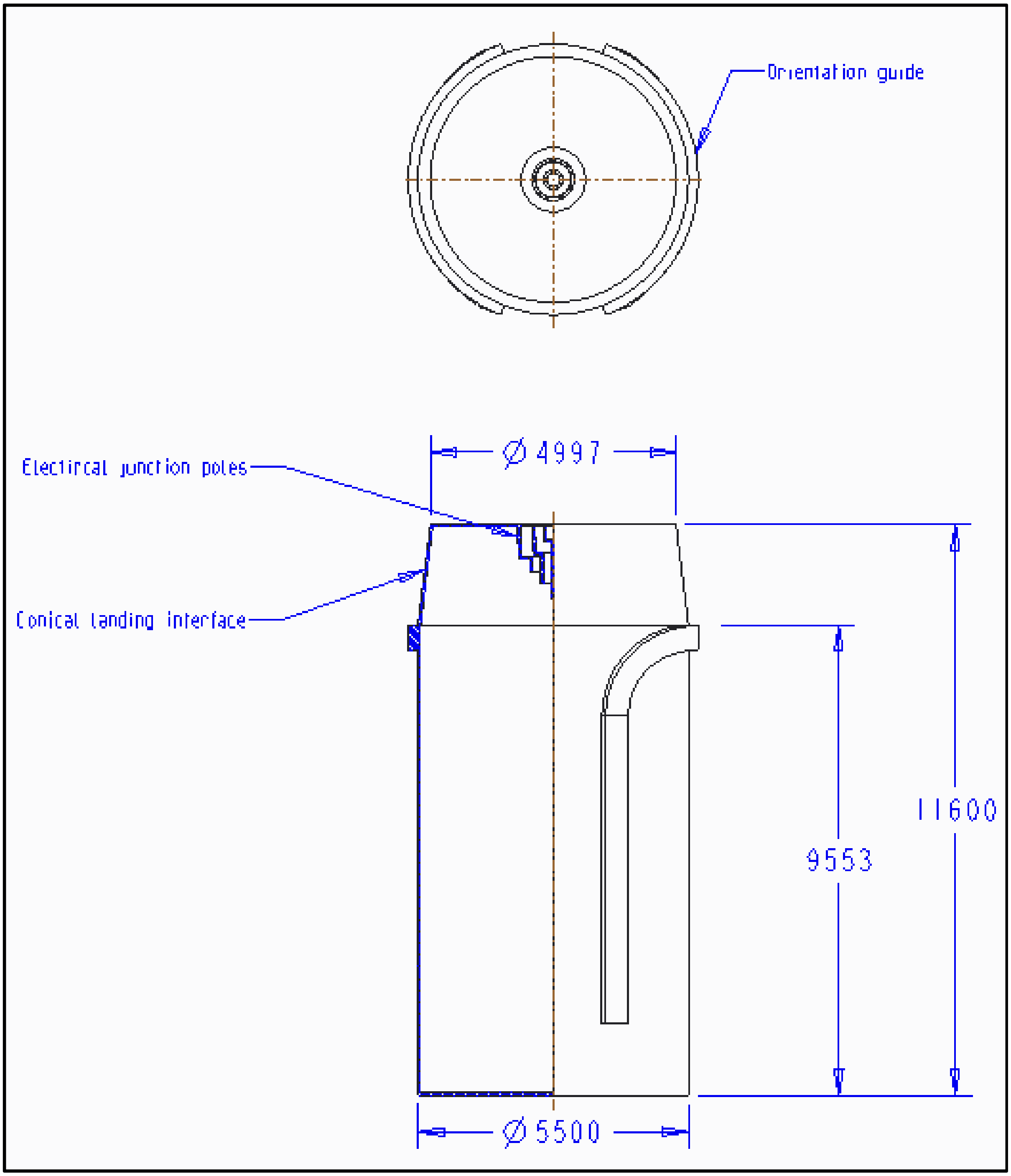


Illustration 20 Foundation pile principal dimensions

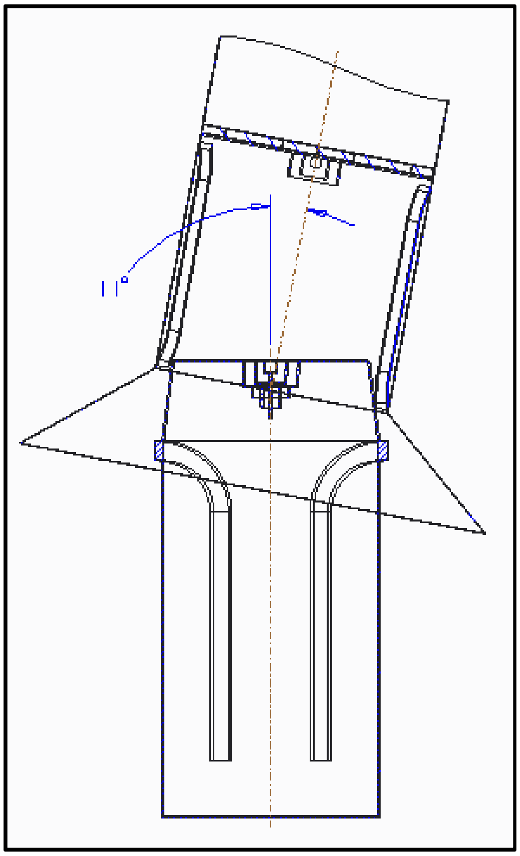


Illustration 21 Maximum installation angle

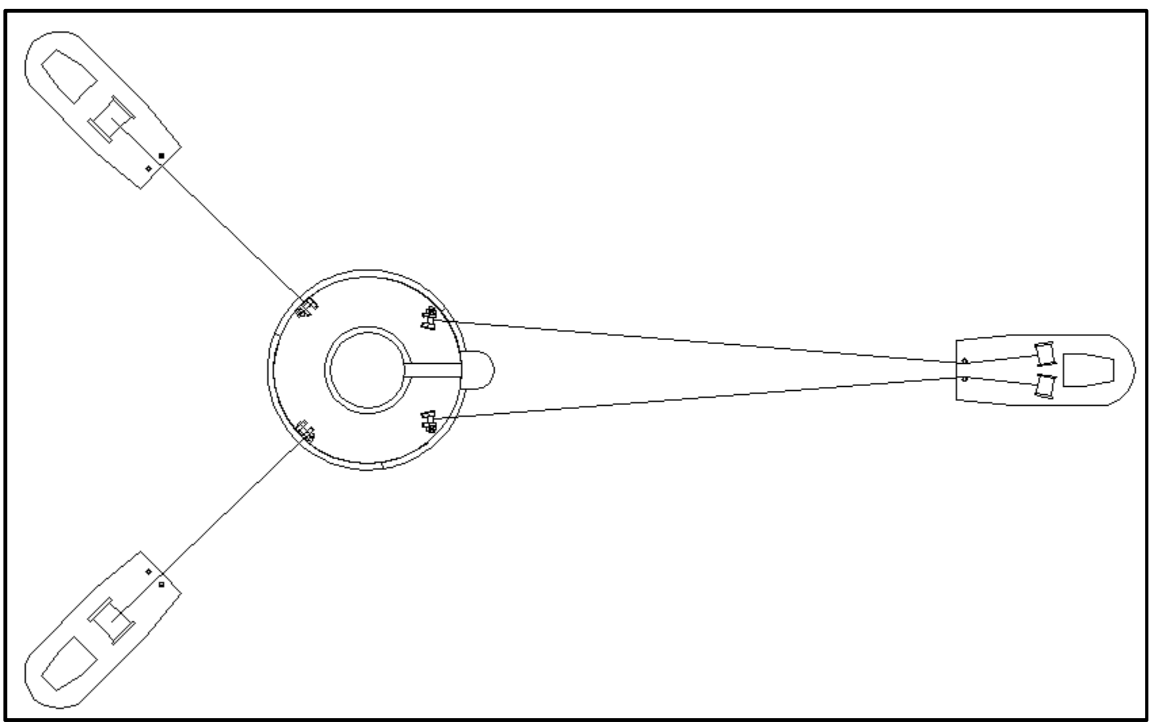


Illustration 22 Sea towing arrangement. Top view at mooring level

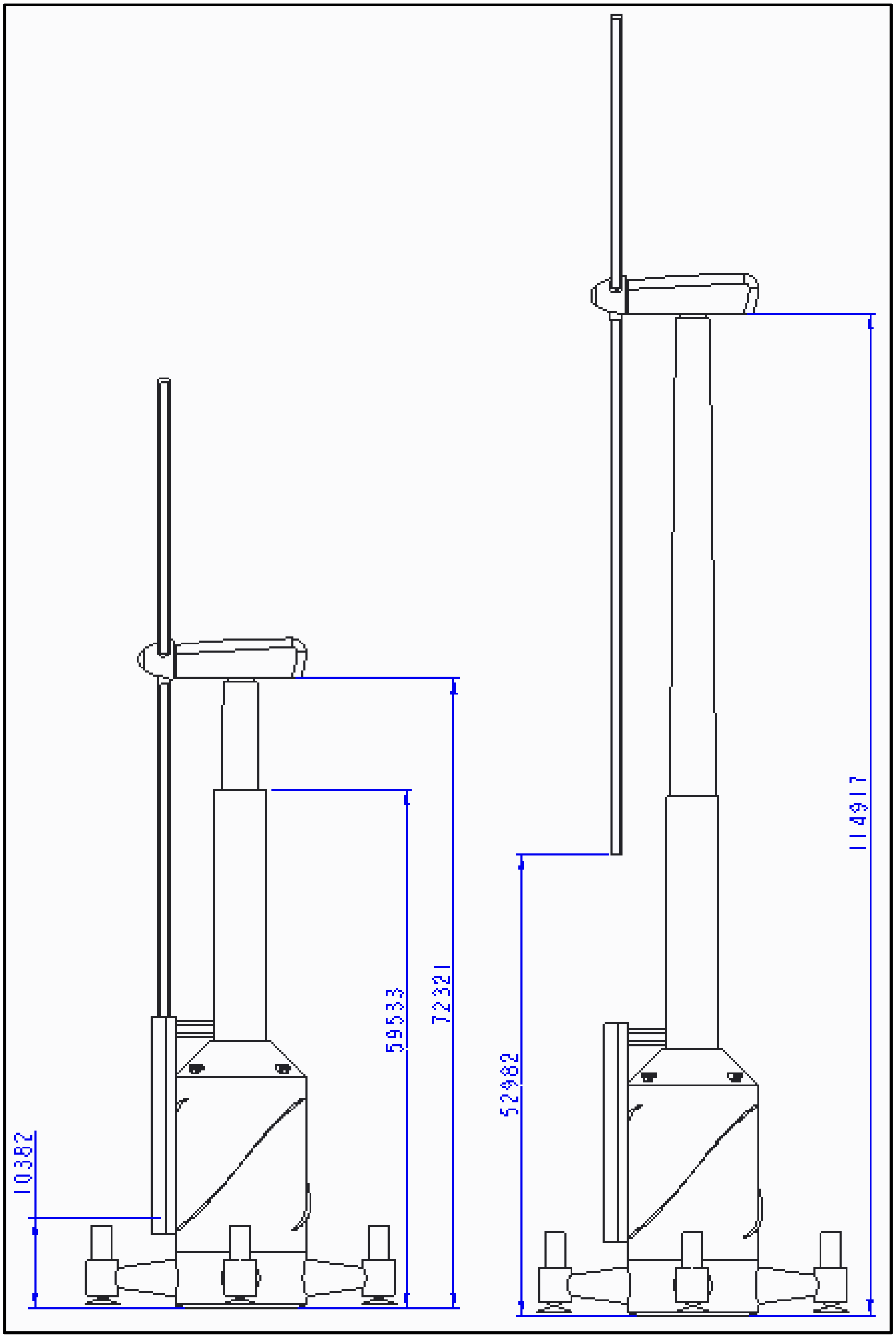


Illustration 23 Tower elevation parameters

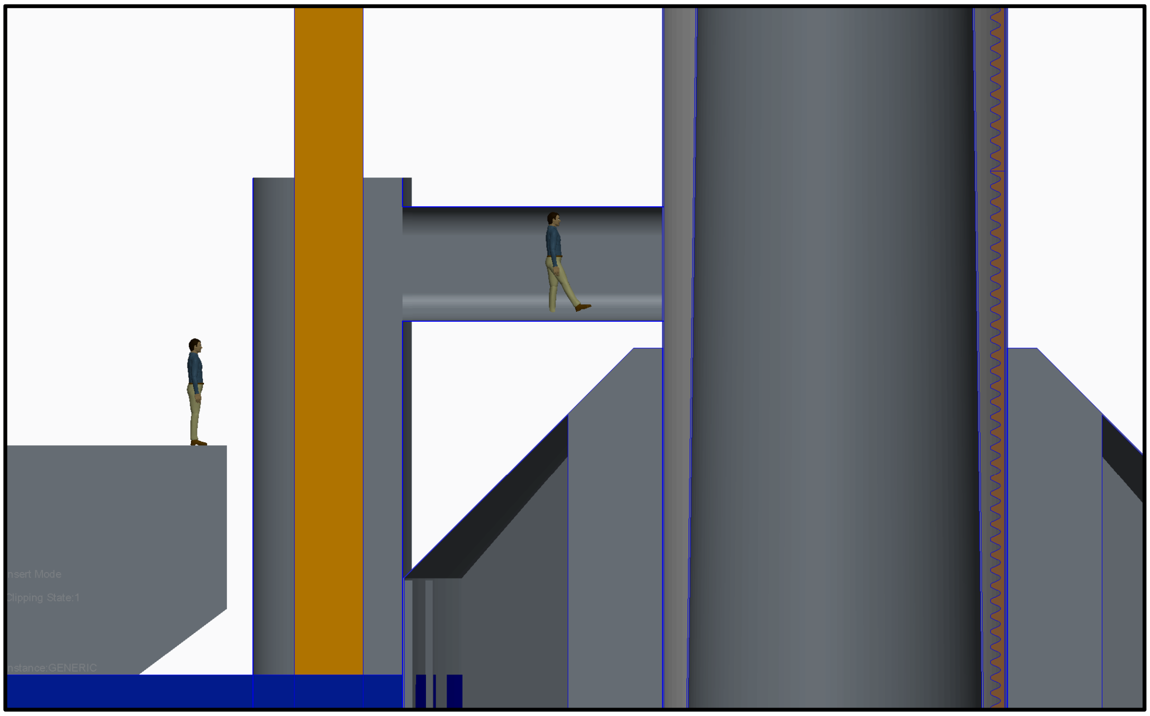


Illustration 24 Access to tower 1

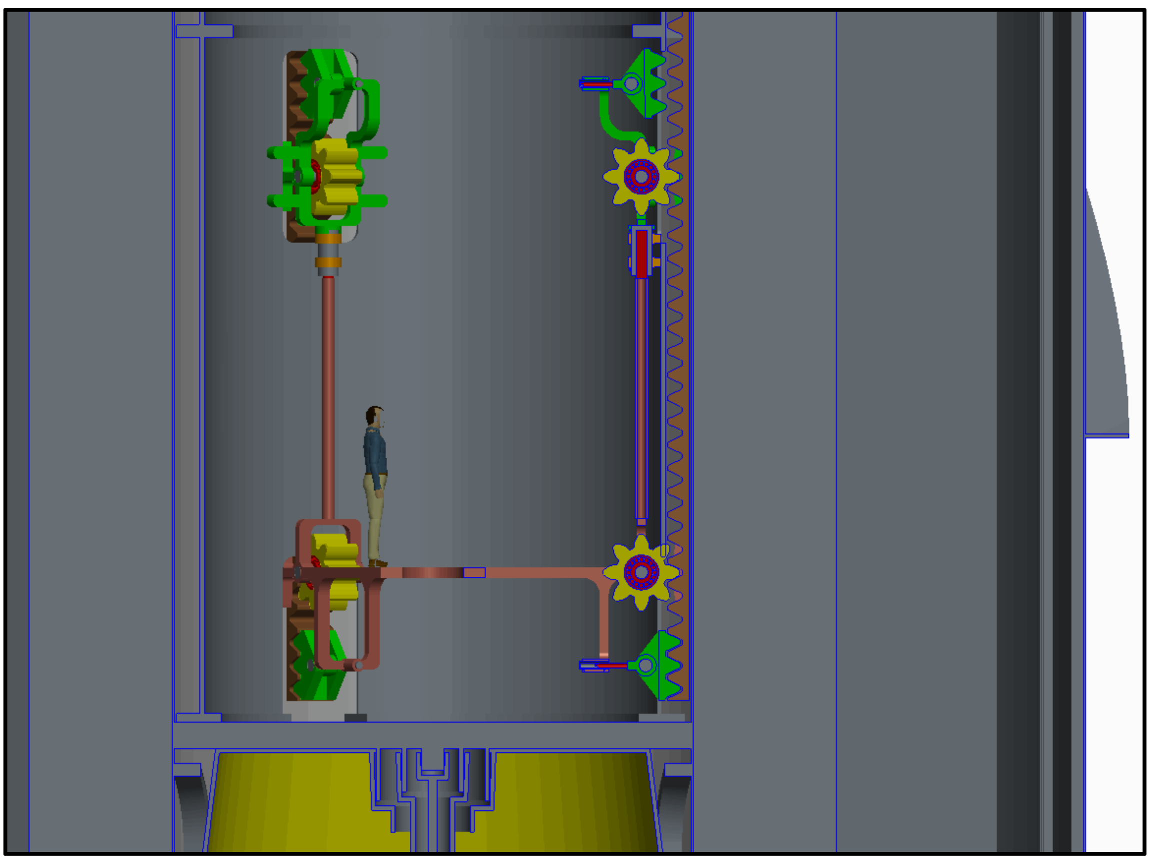


Illustration 25 Access to tower 2

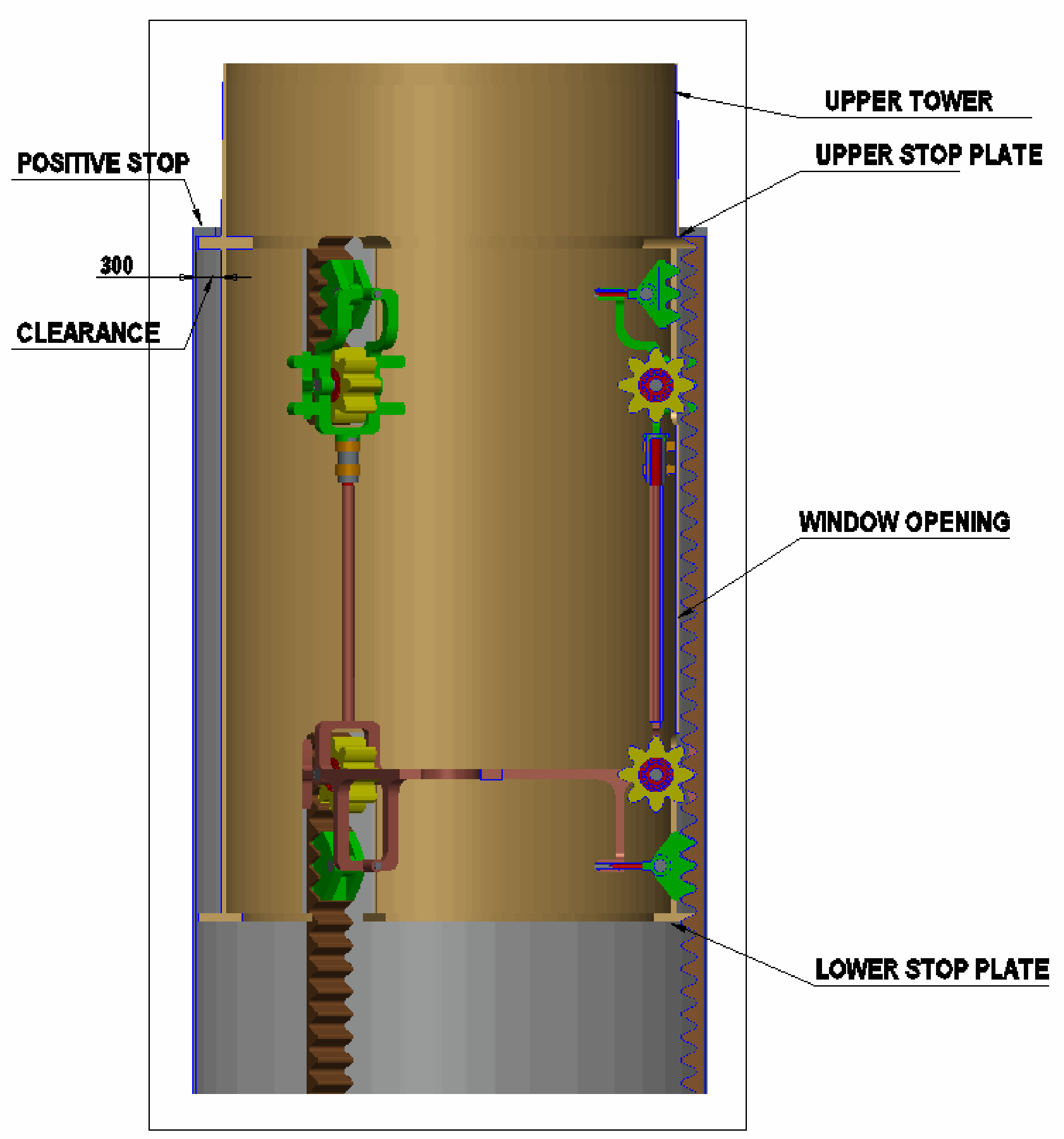


Illustration 26 Elevation at top position

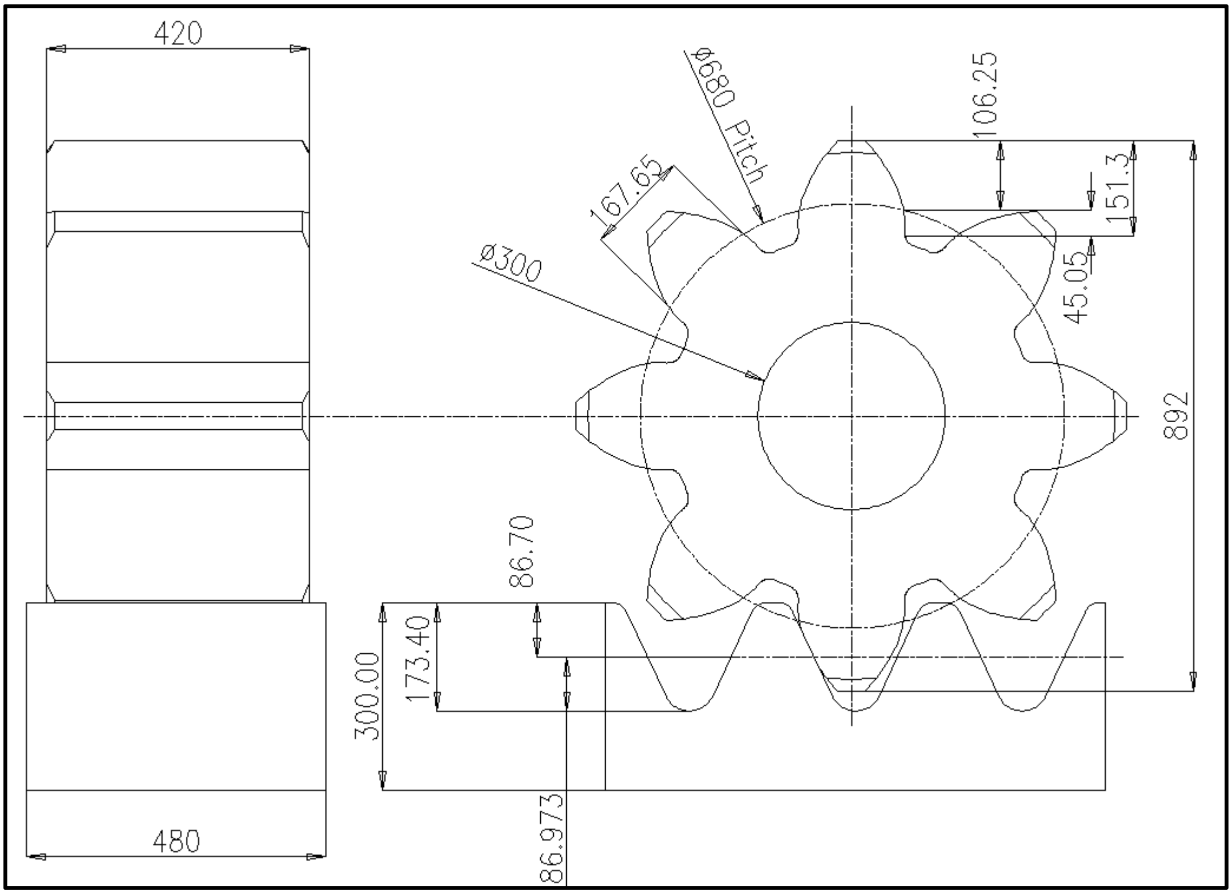


Illustration 27 Rack and pinion main dimensions

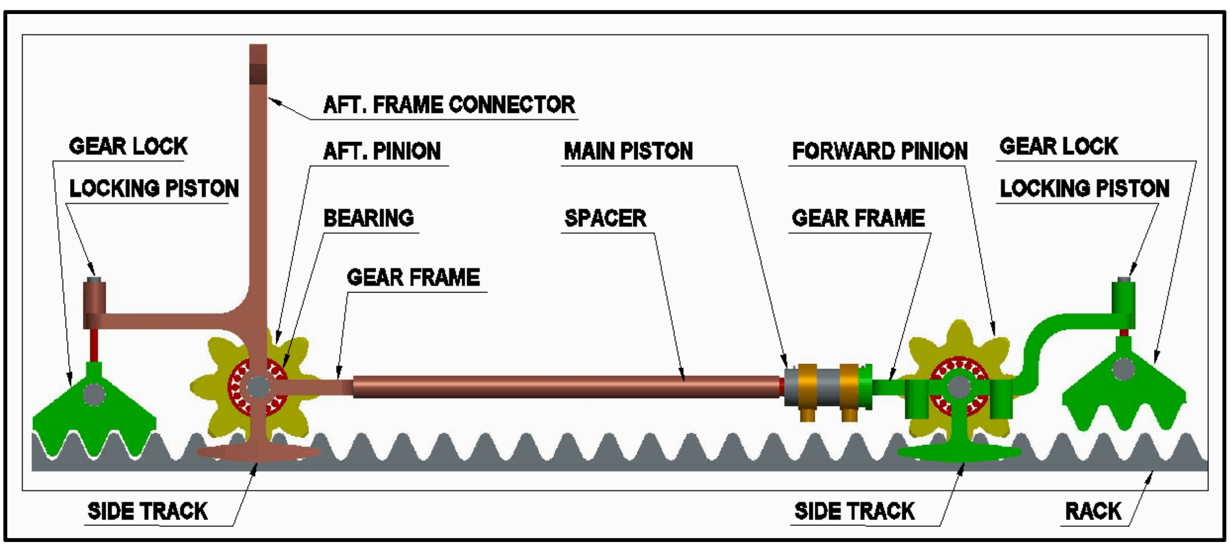


Illustration 28 Lifting mechanism overview

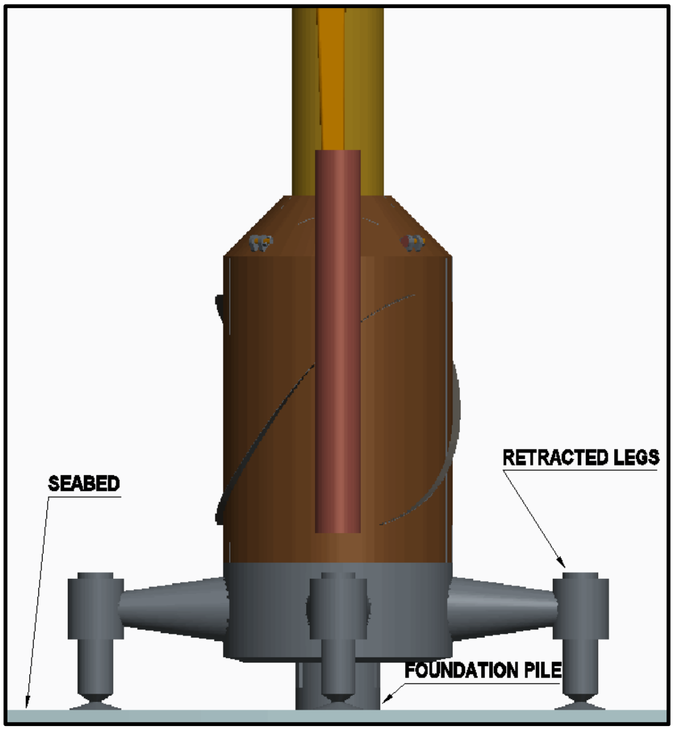


Illustration 29 Retracted legs

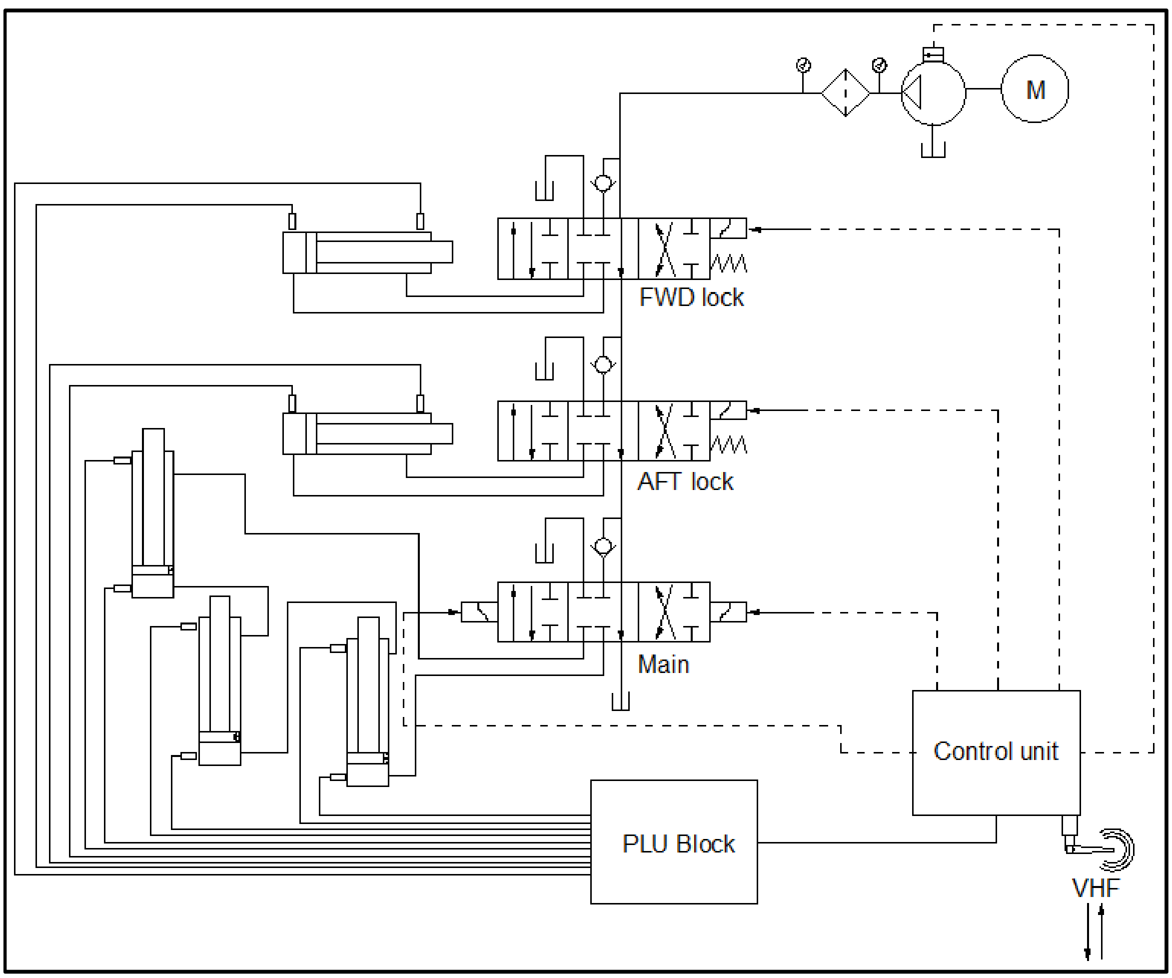


Illustration 30 Hydraulic diagram

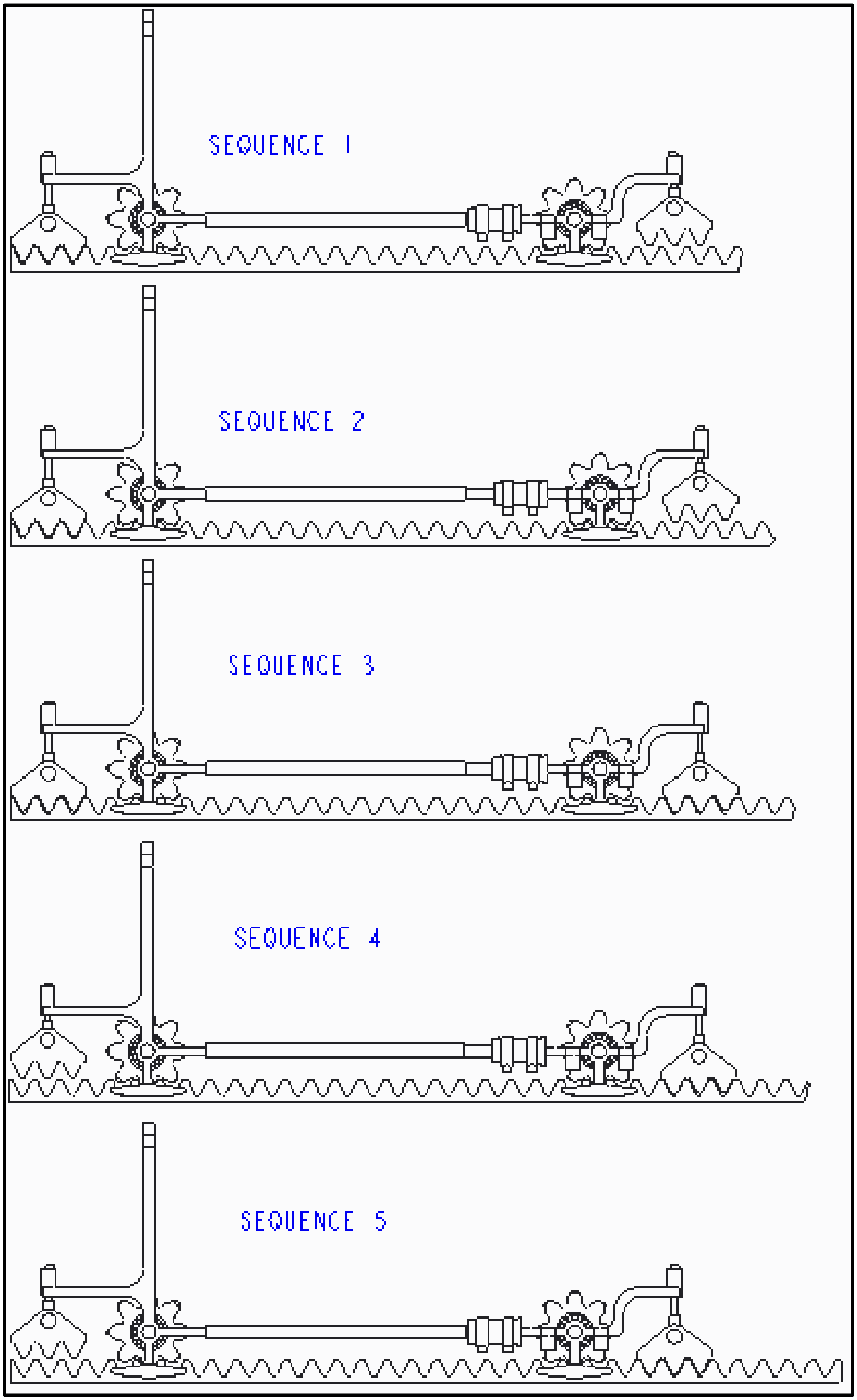


Illustration 31 Lifting mechanism sequence

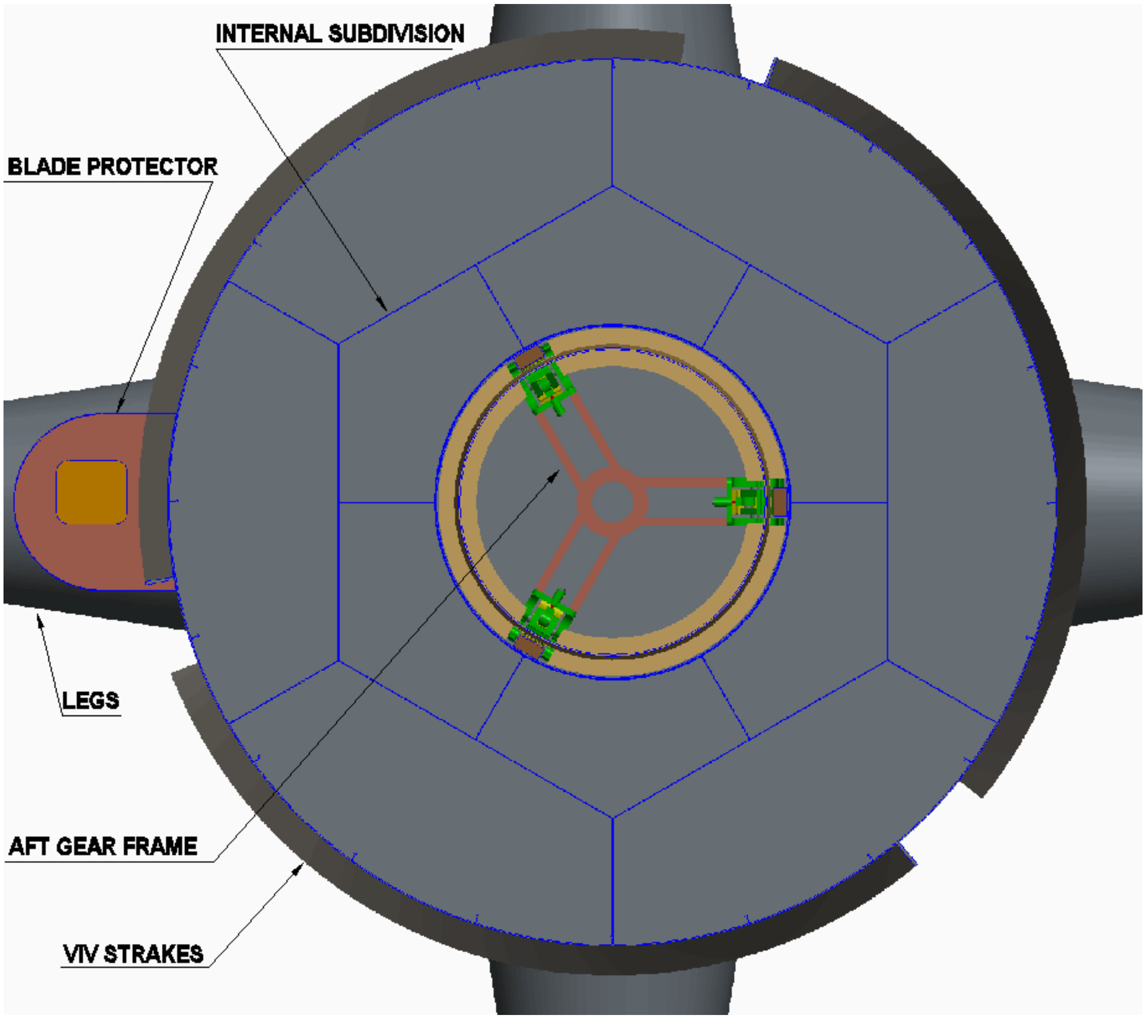


Illustration 32 Horizontal cross section at aft gear frame

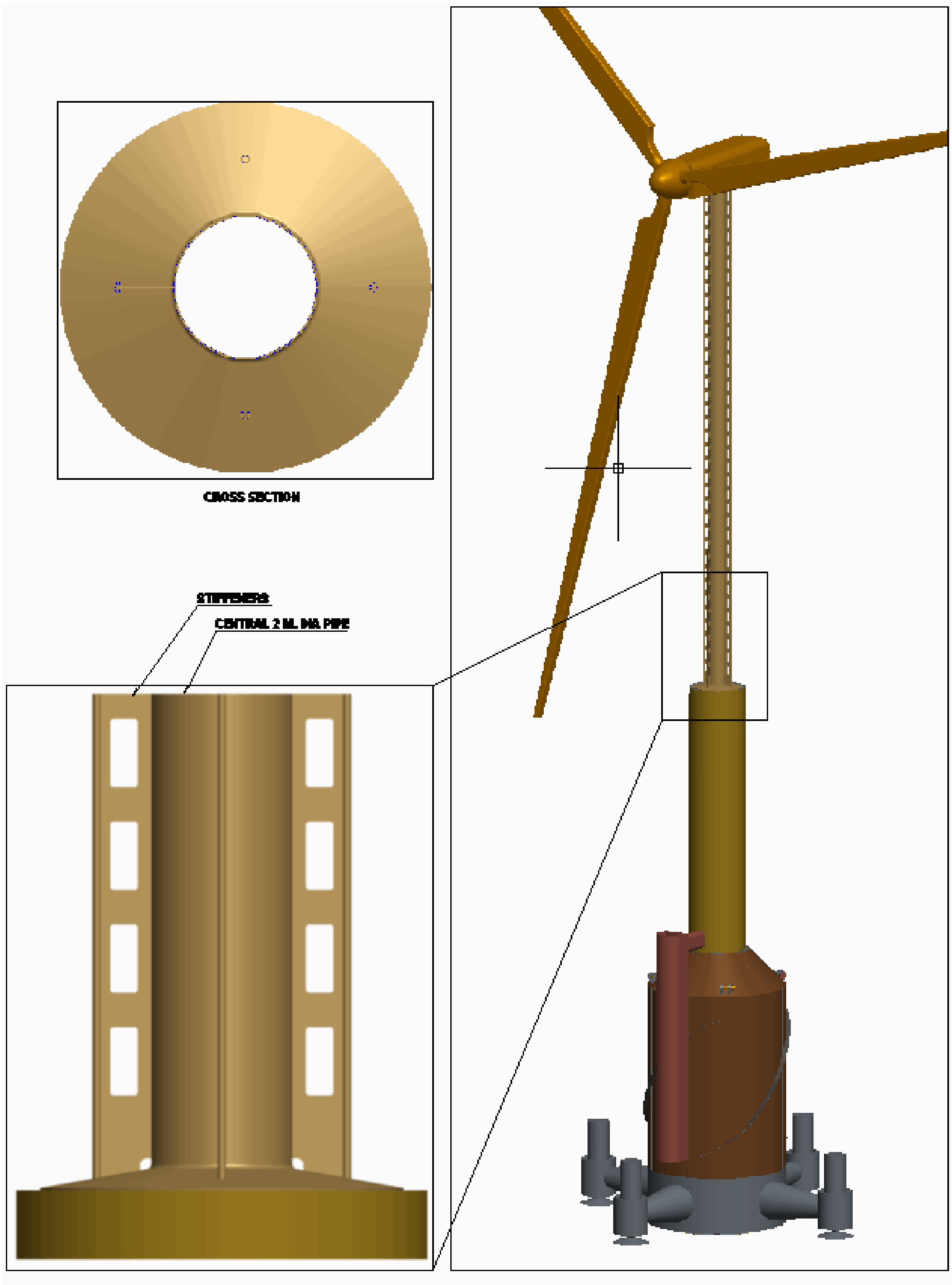


Illustration 33 Upper tower alt. 1

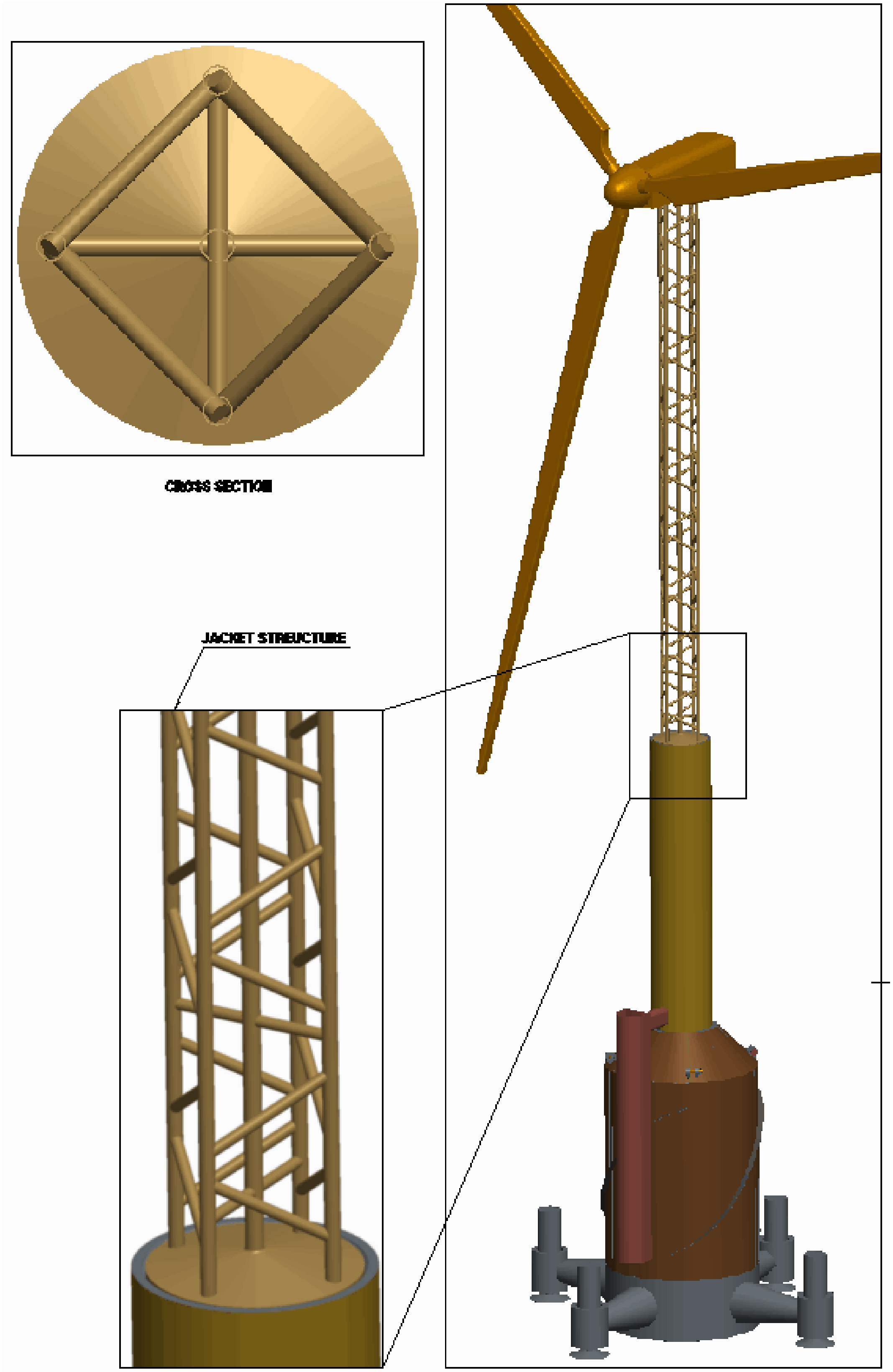


Illustration 34 Upper tower alt. 2

Illustration 35 foundation pile

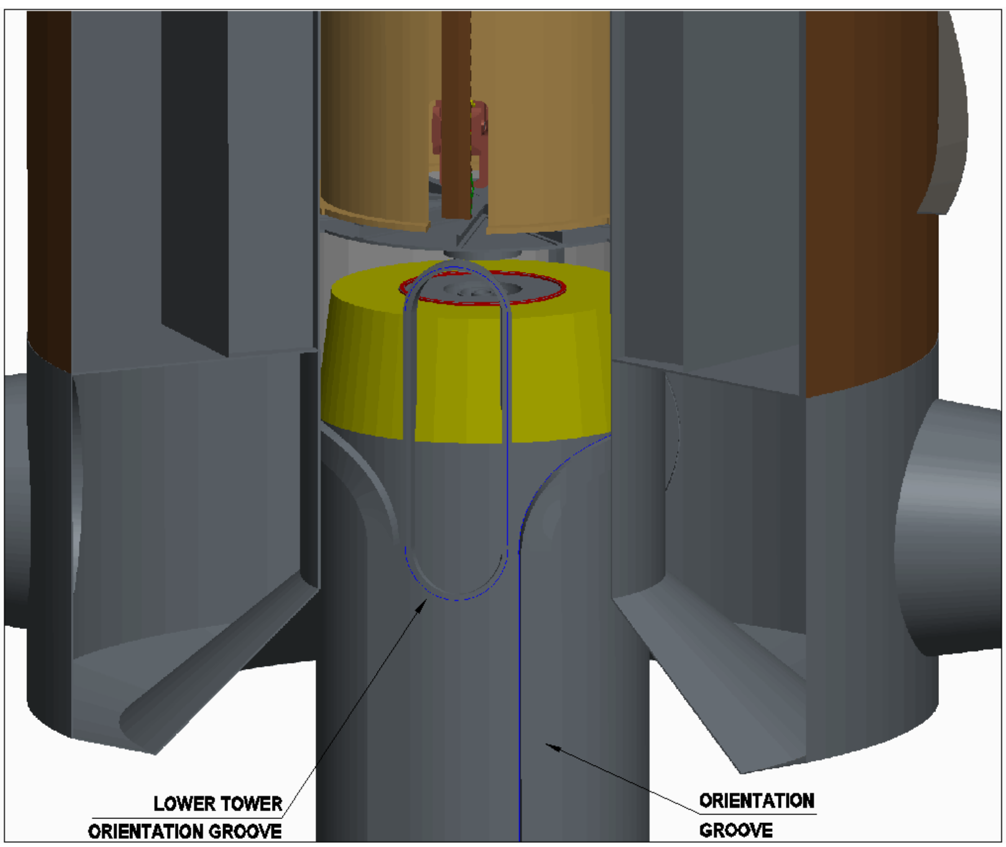


Illustration 36 Mating tower with pile

17. Appendix B. Notes on gear calculation method

This chapter is written in accordance to [28].

Application Factor

Spur gear is calculated according to DIN 3960 Method B. Calculation methods for geometry calculation is quite similar in most standards.

Measures and backlash are calculated according to DIN 3967, fabrication tolerances according to DIN 3961 (tooling parameters are not shown)

Strength calculation with re-calculation of usual defects is carried out according to DIN 3990. This norm includes the most comprehensive and detailed calculation method at present. The safety against scoring according to the integral-temperature method is employed.

The application factor considers uncertainties in load and impacts. It is always larger than 1. A hint for the factor can be found in the following table and more comprehensive information is available in DIN 3990, DIN 3991 or ISO 6336. Working condition

Working condition of the driving	Working condition of the driven			
	Uniform	Moderate Impact	Medium Impact	Heavy Impact
Uniform	1.0	1.258	1.5	1.75
Moderate Impact	1.1	1.35	1.6	1.85
Medium Impact	1.25	1.5	1.75	2
Heavy Impact	1.5	1.75	2	2.25

For calculations Ka is set to 1,25 as recommended by DNV [14]

Strength Calculation Method

Strength verification is done on the basis of current standards. Resistance to root break, pitting, and scoring is calculated. Minimum resistance the transmittable power or achievable service life is also calculated.

Geometry calculations provide all relevant dimensions and test dimensions based on applicable standards and under full consideration of relevant tolerances.

A series parameter ranges for the module, wheelbase, width and number of teeth; has been considered throughout optimization work. Final design validates solutions based on a variety of criteria such as profile offset, tooth thickness tolerances etc.

ISO 6336, 1996 edition, parts 1, 2, 3, 4, 5'Calculation of load capacity of spur and helical gears'.

All calculations are generally based on Method B, the tooth form factor can be calculated according to Method B or C

The calculation method determines the local temperature at the tooth flank and tooth root and from this value the number of load cycles and permissible loads. The temperature has been manually entered as 70 deg. C

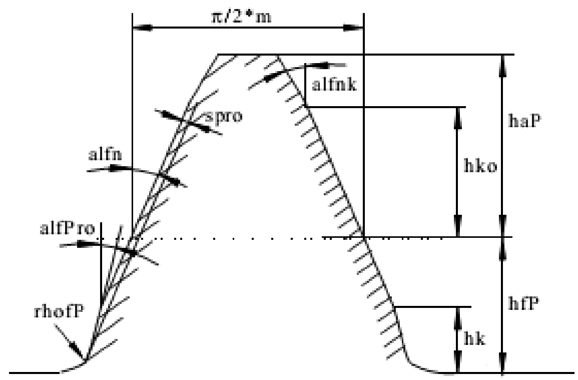
Static strength calculation

In the static strength calculation, the occurring bending stresses are compared with the yield point and the breaking strength of the material. There is no standard for this calculation; the method derives from DIN3990. All factors (application factor, face load coefficient, transverse coefficient) are 1.0. The load on the tooth root is calculated with tooth form factor, helix angle factor and contact ratio factor according to method C (without stress correction factor).

$$\sigma_{F0} = \frac{F_t}{b_{eff} \cdot m_n} \cdot Y_F \cdot Y_\varepsilon \cdot Y_\beta$$

$$\sigma_F = K_A \cdot K_V \cdot K_{F\alpha} \cdot K_{F\beta} \cdot \sigma_{F0}$$

$$\sigma_{F0} = \frac{F_t}{b_{eff} \cdot m_n} \cdot Y_F \cdot Y_S \cdot Y_\varepsilon \cdot Y_\beta$$



It also calculates the local tooth root stress multiplied by the stress correction factor Y_S. This stress is approximately the same as the normal stress calculated in an FEM model.
All factors are presented in results table.

The profile calculated is achieved by taking a reference profile form a database which corresponds to DIN 867 or DIN 54800. The profile parameters are the modified to achieve root and flank safety above 1 as well as smooth meshing. Recommended tolerance and backlash could not be achieved.

The data are referred to as tool proportion (the addendum of the tool eg1.25 ∗ module results in the dedendum of the gear.

Some reference parameters shown on illustration above:

- Dedendum of gear (in module) (h_{fP}: normal 1,25)
- Root radius (in module) (ρ_{fP}: normal 0,20)
- Addendum of gear (in module) (h_{aP}: normal 1,00)
- Protuberance height (in module) (h_{kP}; no data: no protuberance)
- Protuberance angle (αnP; no data: no protuberance)
- Buckling root flank height (in module) (h_{k0}; no data: no buckling root flank)
- Protuberance angle (α_{nP}; no data: no buckling root flank)

The reference data in mm can be obtained by multiplication with the normal module.

For geometry calculation tolerance systems are available in accordance with ISO 1328, DIN 3967; DIN 58405 for tooth thickness tolerance, ISO 286, DIN ISO 2768, DIN 7168, DIN 58405 for center distance; quality systems in accordance with ISO 1328, DIN 3961-3963, AGMA 2000, AGMA 2015 and DIN 23961-23963.

Table values for applied force decompose into components as shown below.

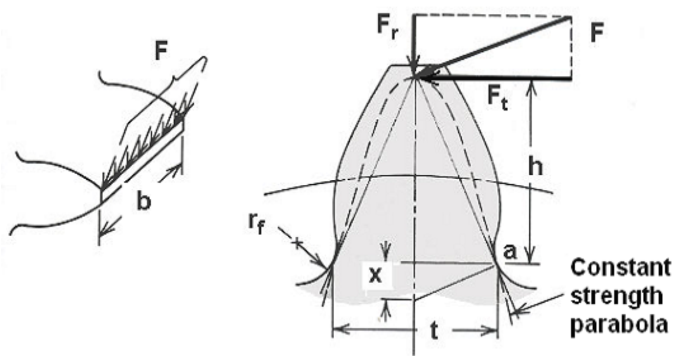


Illustration 38 Gear tooth as cantilever beam [29]

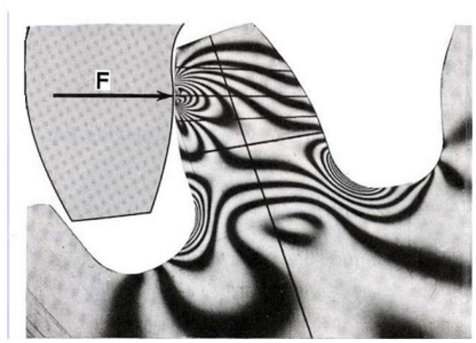


Illustration 37 Tooth load distribution [29]

The tooth form factor Y_F takes into account how the tooth form affects the nominal tooth root stress σ_{F0}. The stress correction factor Y_S takes into account the effect of the notch on the tooth root. These two factors Y_F and Y_S are calculated in accordance with the formulae in ISO 6336 or DIN 3990.or using graphical method below.

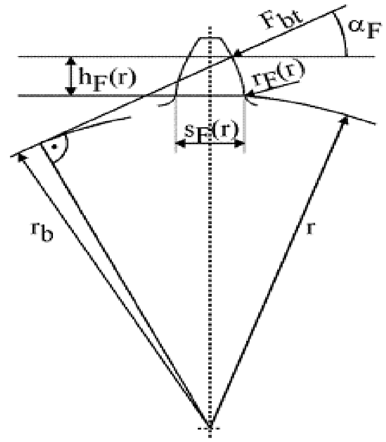
$$Y_F(r) = \frac{6h_F(r)\cos\alpha_F}{[s_F(r)]^2\cos\alpha_n}$$

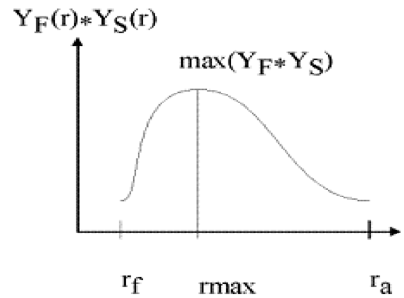
$$q_s = 0,5 s_F(r)/r_F(r)$$

$$a = 1,2 + 0,13[s_F(r)/h_F(r)]$$

$$b = 1,21 + 2,3/[s_F(r)/h_F(r)]$$

$$Y_S(r) = a \cdot q_s^{(1/b)}$$





Where h_F -Bending lever arm (mm), sF(r) -Tooth thickness at radius (mm), α_F - Pressure angle, $r_{F(r)}$ - Tooth root radius (mm)

Materials

The indicated materials are taken from the common material database. Materials are selected based on strength and chemical composition. Only metallic and corrosion resistant materials were considered.

Lubrication

The type of lubrication has low influence on the results of the calculation. The characteristics of the lubricant (especially the viscosity) have a major influence on the scoring and little influence on the margin of safety on the flank. The lubricant type is selected from database. Base for selection is high viscosity and good lubrication under high contact stress.

Service life

Based upon the minimum safety value for the tooth root and flank strength, the service life (in hours) for pinion gear is calculated. The service life is calculated in accordance with ISO 6336-6:2006 using the Palmgren-Miner Rule. Service life is set to low value of 200 hours. This does not affect strength but fatigue life resistance. No load spectrum was defined.

Center distance

Centre distance calculated from the given sum of the addendum modification factors according to DIN 3992. Proposed tolerance class is js 7. Same class is proposed for individual manufacturing.

Tooling parameters

Manufacturing tooling parameters has not been considered same applies to rolling pin and ball protuberance parameters and tip radius. Topping tool is used only on rack. Manufacturing tolerance parameters and reference profile has not been calculated. Sufficient chamfers are added to avoid contact interferences.

18. Appendix C. Stability calculations

This section validates design and floating abilities of the 3D model for telescopic wind turbine. Only one load case is considered. This is departure condition from harbor to installation site. During voyage no weight is either added or consumed so the same condition applies until flooding begins.

18.1 Load case 1 Departure from harbor no wind no waves

Illustration below shows actual stability model for the case. Air, concrete tanks and lower tower are displacer class compartments and upper tower with blades is sail class. Actual water draft is shown. Margin line deck immersion is drawn at upper edge of lower tower. Flooding occurs at 89 degrees heel and maximum righting arm is at 40 deg. heel.

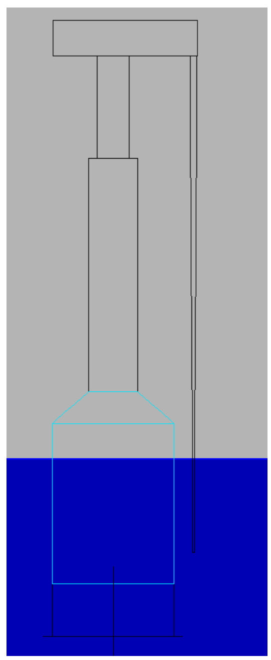


Illustration 39 Stability model at harbor departure

Floating Status

Draft MS	22.144 m	KMT	11.707 m
Trim	zero	Wave/Wind	No
Heel	zero	VCG	10.944 m
GM(Solid)	0.763 m	TPcm	1.81

Fixed Weight Status

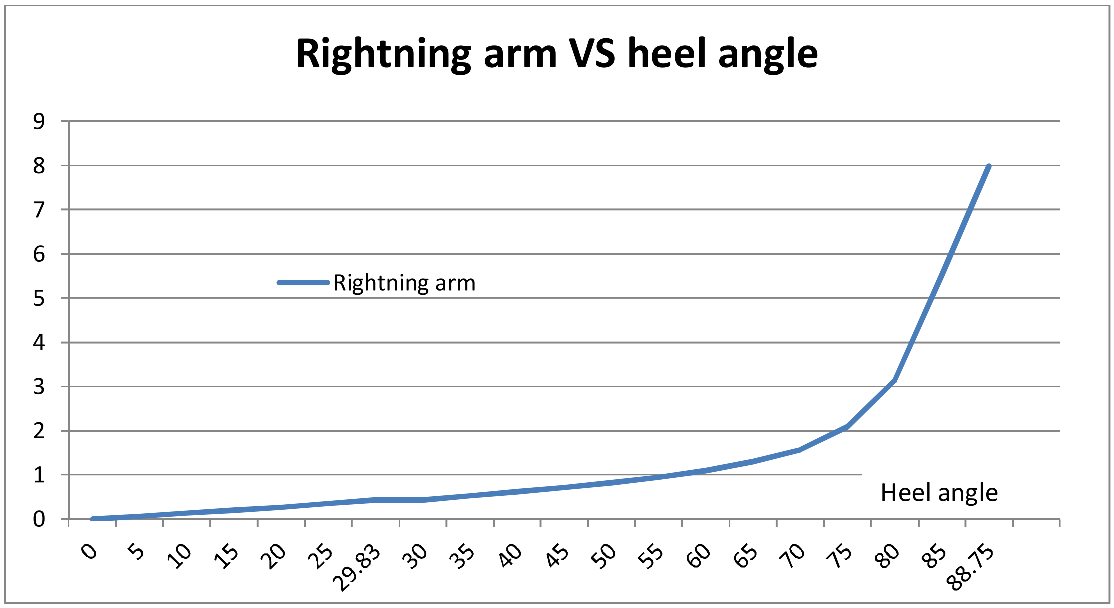
Item	Weight (MT)	LCG (m)	TCG (m)	VCG (m)
Telescopice tower	650.00	0.000	0.000	25.000u
Permanent ballast	3,121.00	0.000	0.000	3.168u
Nacelle	240.00	0.000	0.000	74.000u
Total Weight:	4,011.00	0.000	0.000	10.944u

Displacer Status

Item	Status	Spgr	Displ (MT)	LCB (m)	TCB (m)	VCB (m)	Eff /Perm
Telescopic tower	Intact	1.025	4,011.00	0.000	0.000	11.072	1.000

Righting Arms vs Heel Angle

Heel Angle (deg)	Origin Depth (m)	Righting Arm (m)	Heel Angle (deg)	Origin Depth (m)	Righting Arm (m)
0.00	22.144	0.000	45.00s	15.746	0.718
5.00s	22.059	0.067	50.00s	14.410	0.828
10.00s	21.808	0.134	55.00s	13.001	0.955
15.00s	21.389	0.203	60.00s	11.544	1.106
20.00s	20.809	0.275	65.00s	10.065	1.301
25.00s	20.069	0.352	70.00s	8.583	1.579
29.83s	19.210	0.431	75.00s	7.107	2.094
30.00s	19.177	0.434	80.00s	5.553	3.132
35.00s	18.146	0.524	85.00s	3.661	5.542
40.00s	16.997	0.619	88.75s	2.129	7.985
			90.00s	1.627	0.003



Limit report

IMO RESOLUTION A.167

Limit	Min/Max	Actual	Margin	Pass
(1) Area from 0.00 deg to 30.00	>0.0550 m-R	0.109	0.054	Yes
(2) Area at 30.00 deg	>0.0150 m-R	0.109	0.094	Yes
(3) Area from 0.00 deg to 40.00 or Flood	>0.0900 m-R	0.201	0.111	Yes
(4) Area from 30.00 deg to 40.00 or Flood	>0.0300 m-R	0.092	0.062	Yes
(5) Righting Arm at 30.00 deg	>0.200 m	0.435	0.235	Yes
(6) Absolute Angle at MaxRA	>25.00 deg	87.50	62.50	Yes
(7) GM at Equilibrium	>0.150 m	0.763	0.613	Yes
(8) Area from 0.00 deg to MaxRA at 15.00	>0.0550 m-R	0.109	0.054	Yes
(9) Area from 0.00 deg to MaxRA at 30.00	>0.0550 m-R	0.109	0.054	Yes

18.2 Turbine installation flooding of air tank

Next step upon arrival is to flood air tanks to reach seabed or foundation pile. Following calculations shows how draft, VCG and GM values are changed at progressive flooding of air tanks. Permeability of air tank is set to 99% Tank is flooded in present fraction of its total available volume. Further changes in righting arm are shown

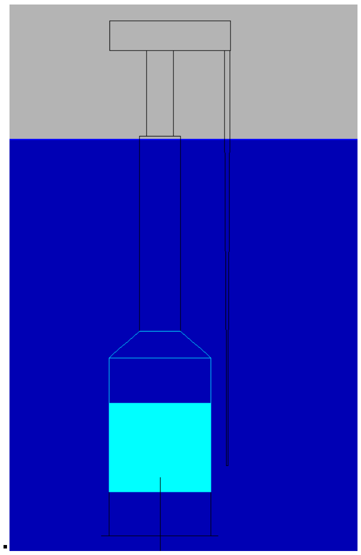


Illustration 40 Stability model at maximum air tank flooding

Floating Status

Tank load	10%	20%	30%	40%	50%	60%	61%
Draft MS	23.951	25.756	27.805	35.402	46.685	57.969	59.099
VCG	10.691	10.626	10.711	10.920	11.230	11.625	11.669
GM(Solid)	1.872	2.798	3.281	3.912	5.120	6.694	6.869

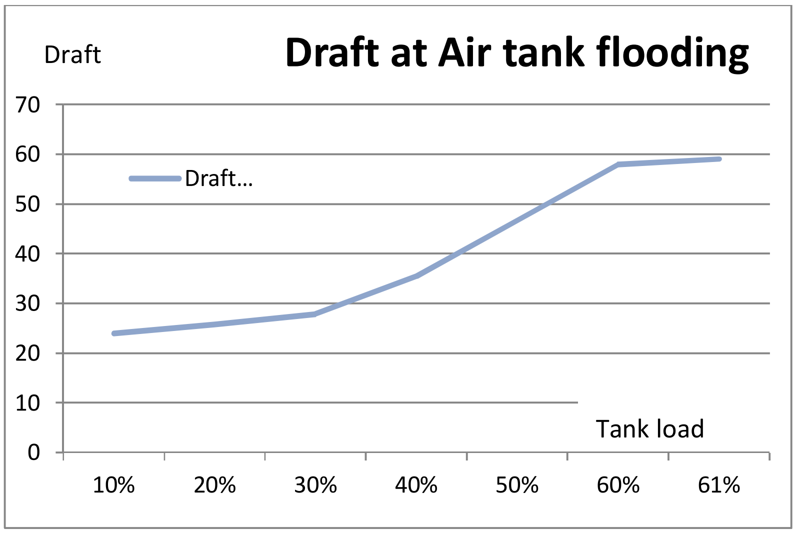
Tank Status

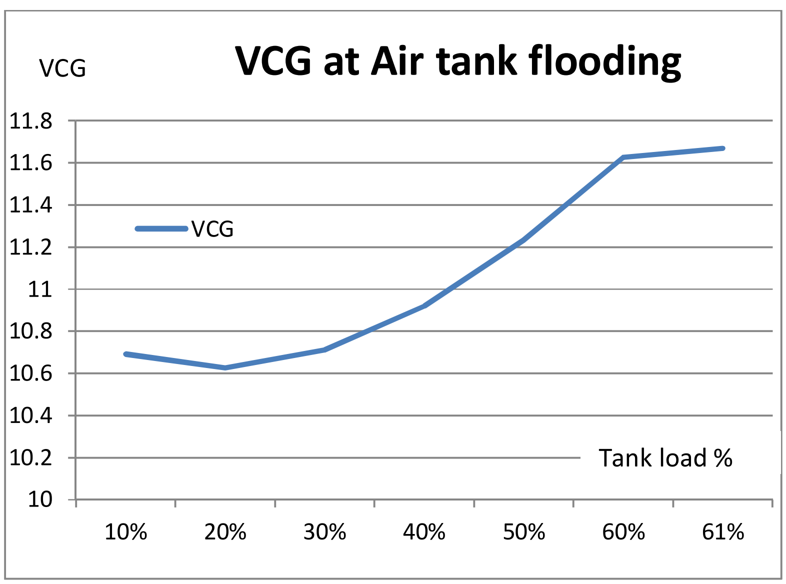
SALT WATER (SpGr 1.025)

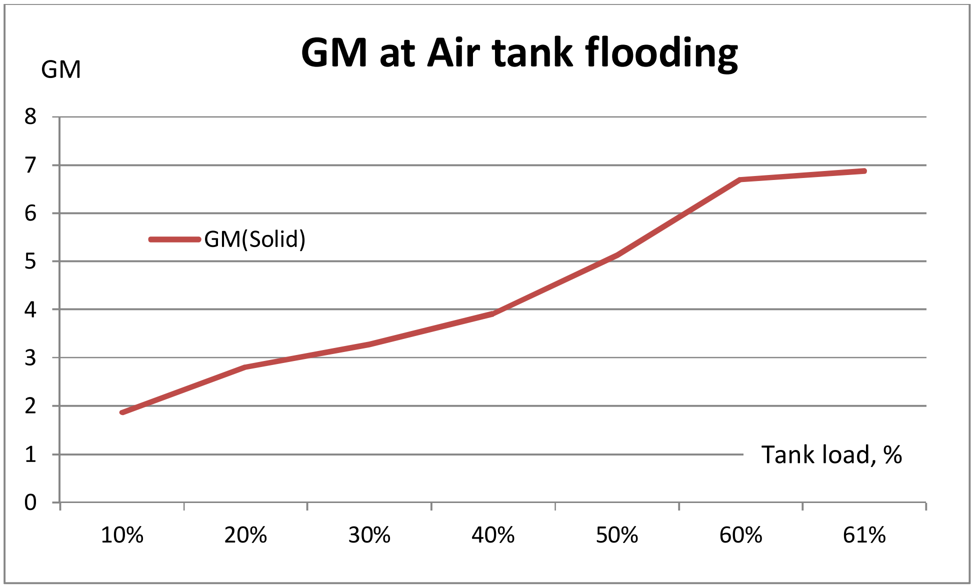
Tank Name	Load (%)	Weight (MT)	LCG (m)	TCG (m)	VCG (m)	Perm
AIRTANK.C	10.00%	327.21	0.000	0.000	7.586	0.990
AIRTANK.C	20.00%	654.42	0.000	0.000	8.672	0.990
AIRTANK.C	30.00%	981.64	0.000	0.000	9.758	0.990
AIRTANK.C	40.00%	1,308.85	0.000	0.000	10.844	0.990
AIRTANK.C	50.00%	1,636.06	0.000	0.000	11.931	0.990
AIRTANK.C	60.00%	1,963.27	0.000	0.000	13.017	0.990
AIRTANK.C	61.00%	1,996.00	0.000	0.000	13.125	0.990

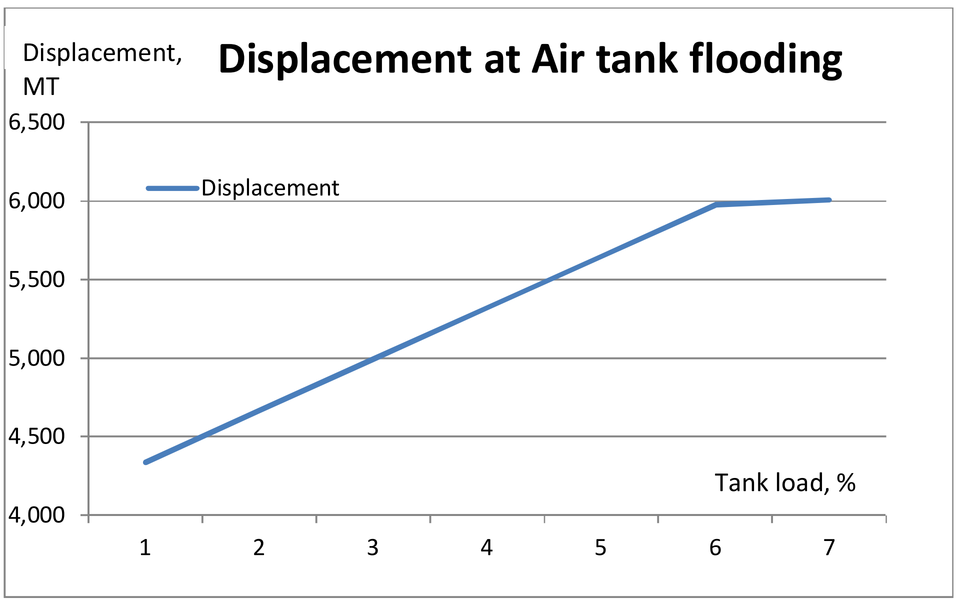
Displacer Status

Item	Status	Spgr	Displ (MT)	LCB (m)	TCB (m)	VCB (m)	Eff /Perm
TOWER	Intact	1.025	4,338.23	0.000	0.000	11.975	1.000
TOWER	Intact	1.025	4,665.19	0.000	0.000	12.878	1.000
TOWER	Intact	1.025	4,992.81	0.000	0.000	13.785	1.000
TOWER	Intact	1.025	5,320.11	0.000	0.000	14.820	1.000
TOWER	Intact	1.025	5,647.12	0.000	0.000	16.338	1.000
TOWER	Intact	1.025	5,974.14	0.000	0.000	18.308	1.000
TOWER	Intact	1.025	6,006.89	0.000	0.000	18.527	1.000



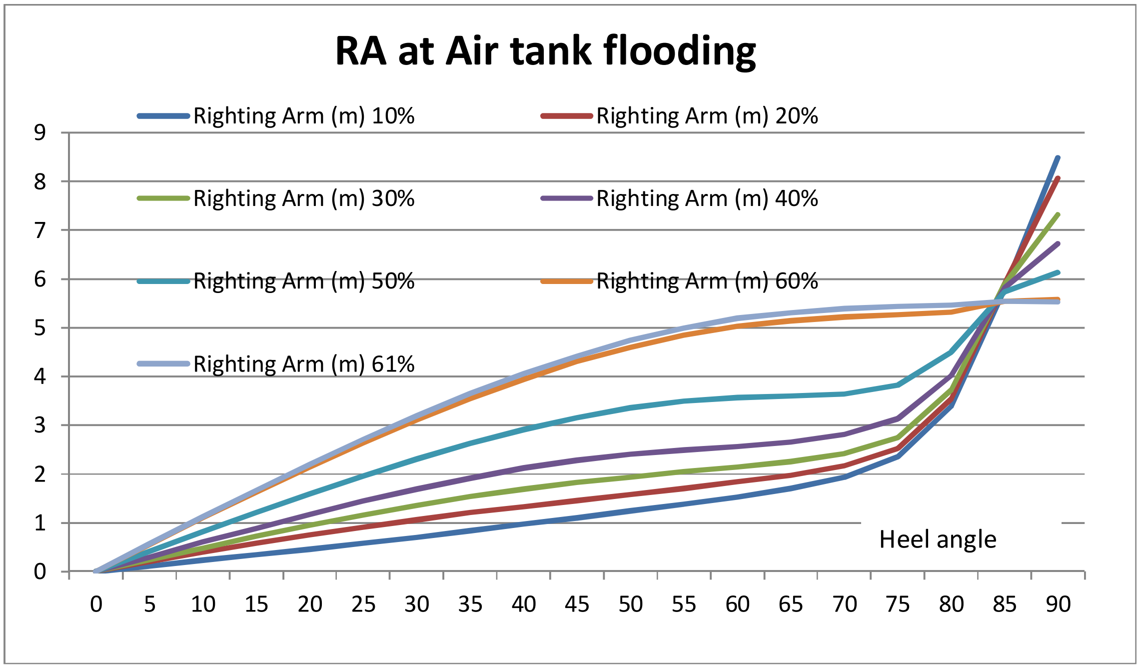



GM at Air tank flooding
GM
8
7
6
5
4
3
2
1
0
GM(Solid)
Tank load, %
10%
20%
30%
40%
50%
60%
61%


Displacement at Air tank flooding
Displacement, MT
6,500
6,000
5,500
5,000
4,500
4,000
Displacement
Tank load, %
1
2
3
4
5
6
7

18.2.1 Righting arm VS heel angle at air tank flooding

Heel Angle (deg)	Righting Arm (m) 10%	Righting Arm (m) 20%	Righting Arm (m) 30%	Righting Arm (m) 40%	Righting Arm (m) 50%	Righting Arm (m) 60%	Righting Arm (m) 61%
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5.00	0.114	0.198	0.243	0.300	0.408	0.547	0.563
10.00	0.227	0.393	0.484	0.598	0.812	1.090	1.120
15.00	0.338	0.579	0.721	0.888	1.208	1.623	1.668
20.00	0.451	0.754	0.948	1.170	1.592	2.140	2.199
25.00	0.573	0.917	1.163	1.437	1.960	2.637	2.710
30.00	0.702	1.065	1.361	1.687	2.307	3.109	3.195
35.00	0.833	1.201	1.539	1.915	2.627	3.547	3.647
40.00	0.967	1.333	1.693	2.115	2.915	3.948	4.057
45.00	1.101	1.459	1.823	2.280	3.162	4.300	4.420
50.00	1.238	1.583	1.937	2.398	3.358	4.602	4.735
55.00	1.377	1.704	2.040	2.486	3.489	4.846	4.993
60.00	1.523	1.833	2.140	2.561	3.562	5.028	5.187
65.00	1.695	1.977	2.250	2.654	3.606	5.139	5.308
70.00	1.930	2.170	2.417	2.806	3.632	5.211	5.386
75.00	2.357	2.525	2.755	3.133	3.828	5.264	5.441
80.00	3.391	3.542	3.723	4.023	4.503	5.315	5.469
85.00	5.798	5.894	5.900	5.818	5.735	5.541	5.535
90.00	8.480	8.072	7.312	6.721	6.125	5.576	5.522



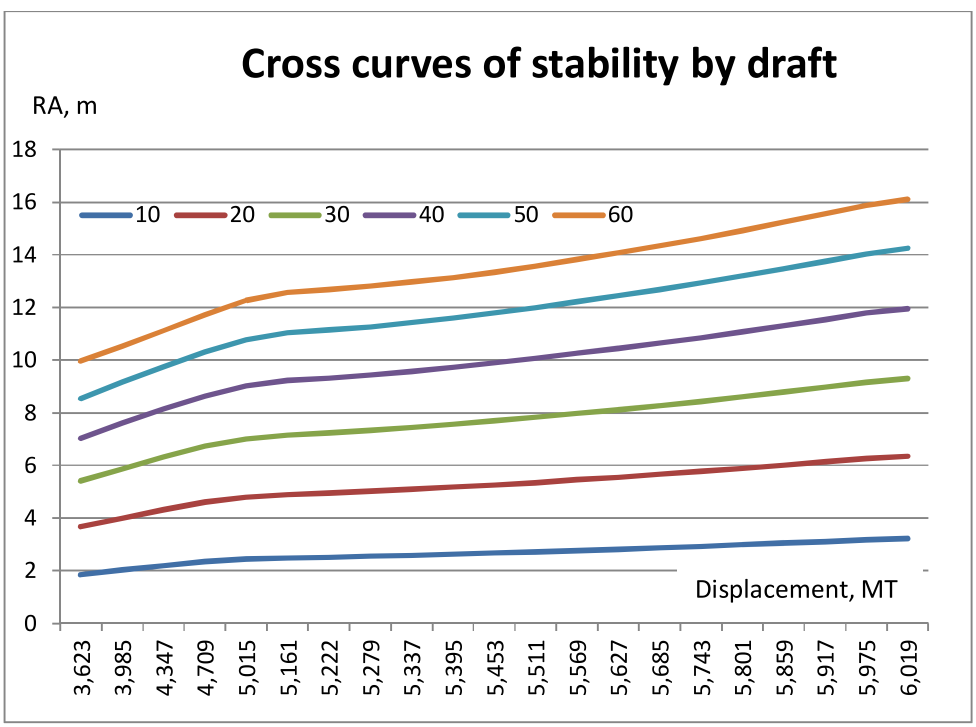
18.2.2 Hydrostatic curves

Cross Curves By Drafts

Righting Arms(heel) for VCG = 0.00
Trim zero at heel = 0 (RA Trim = 0)

Di pl (MT)	10.000	20.000	30.000	40.000	50.000	60.000
3622.661	1.860	3.677	5.410	7.039	8.556	9.961
3984.927	2.023	3.995	5.873	7.613	9.169	10.543
4347.194	2.187	4.318	6.326	8.152	9.757	11.123
4709.459	2.348	4.612	6.731	8.649	10.316	11.717
5014.656	2.436	4.803	7.023	9.034	10.790	12.267
5160.731	2.482	4.891	7.161	9.228	11.038	12.561
5221.530	2.514	4.951	7.239	9.319	11.150	12.694
5279.491	2.549	5.021	7.341	9.438	11.267	12.826
5337.453	2.587	5.096	7.451	9.580	11.421	12.970
5395.414	2.628	5.177	7.570	9.733	11.602	13.135
5453.375	2.672	5.264	7.696	9.896	11.796	13.345
5511.337	2.719	5.356	7.831	10.069	12.003	13.577
5569.299	2.769	5.454	7.973	10.252	12.221	13.824
5627.261	2.820	5.556	8.123	10.444	12.450	14.082
5685.222	2.875	5.663	8.280	10.645	12.691	14.354
5743.184	2.932	5.775	8.443	10.856	12.941	14.637
5801.146	2.991	5.892	8.614	11.075	13.200	14.932
5859.107	3.052	6.013	8.791	11.301	13.472	15.238
5917.069	3.116	6.138	8.974	11.538	13.754	15.554
5975.030	3.182	6.268	9.162	11.781	14.040	15.873
6018.502	3.231	6.364	9.303	11.960	14.253	16.113

Water Specific Gravity = 1.025.

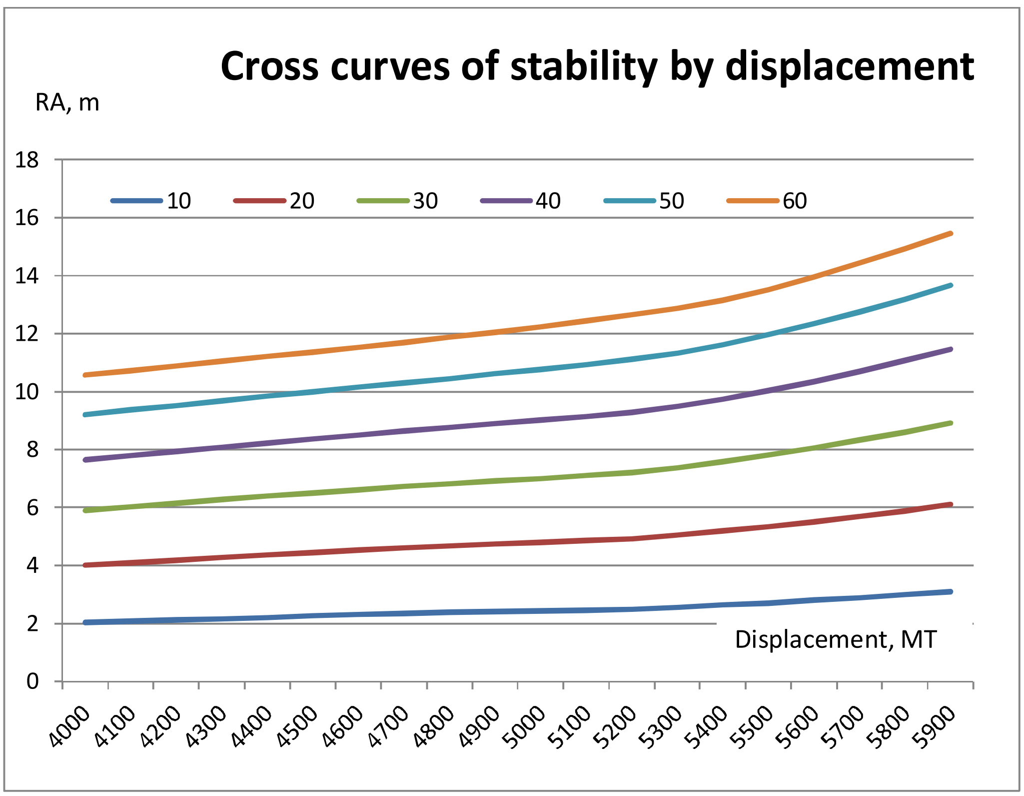


Cross Curves By Displacement

Righting Arms(heel) for VCG = 0.00
Trim zero at heel = 0 (RA Trim = 0)

Displ (MT)	10.000s	20.000s	30.000s	40.000s	50.000s	60.000s
4000.000	2.030	4.009	5.893	7.637	9.194	10.567
4100.000	2.075	4.097	6.021	7.789	9.359	10.727
4200.000	2.120	4.186	6.147	7.938	9.521	10.887
4300.000	2.166	4.276	6.270	8.084	9.682	11.047
4400.000	2.211	4.364	6.389	8.228	9.840	11.208
4500.000	2.257	4.449	6.504	8.367	9.997	11.369
4600.000	2.303	4.530	6.615	8.504	10.151	11.532
4700.000	2.345	4.606	6.721	8.637	10.302	11.701
4800.000	2.380	4.674	6.822	8.765	10.453	11.874
4900.000	2.409	4.737	6.918	8.890	10.608	12.053
5000.000	2.433	4.795	7.010	9.016	10.766	12.239
5100.000	2.461	4.851	7.101	9.145	10.932	12.436
5200.000	2.501	4.927	7.207	9.286	11.109	12.647
5300.000	2.562	5.047	7.379	9.487	11.315	12.875
5400.000	2.632	5.184	7.579	9.745	11.617	13.150
5500.000	2.710	5.338	7.804	10.034	11.961	13.531
5600.000	2.796	5.507	8.052	10.352	12.341	13.959
5700.000	2.889	5.691	8.321	10.698	12.753	14.428
5800.000	2.990	5.889	8.610	11.073	13.195	14.927
5900.000	3.097	6.101	8.919	11.469	13.670	15.459

Water Specific Gravity = 1.025.



18.2.3 Variation permanent ballast weight

In the next experiment amount of permanent ballast is varied to see how displacement and GM values varies. All other parameters left unchanged, initial weigh and displacement is the same for all conditions as follows.

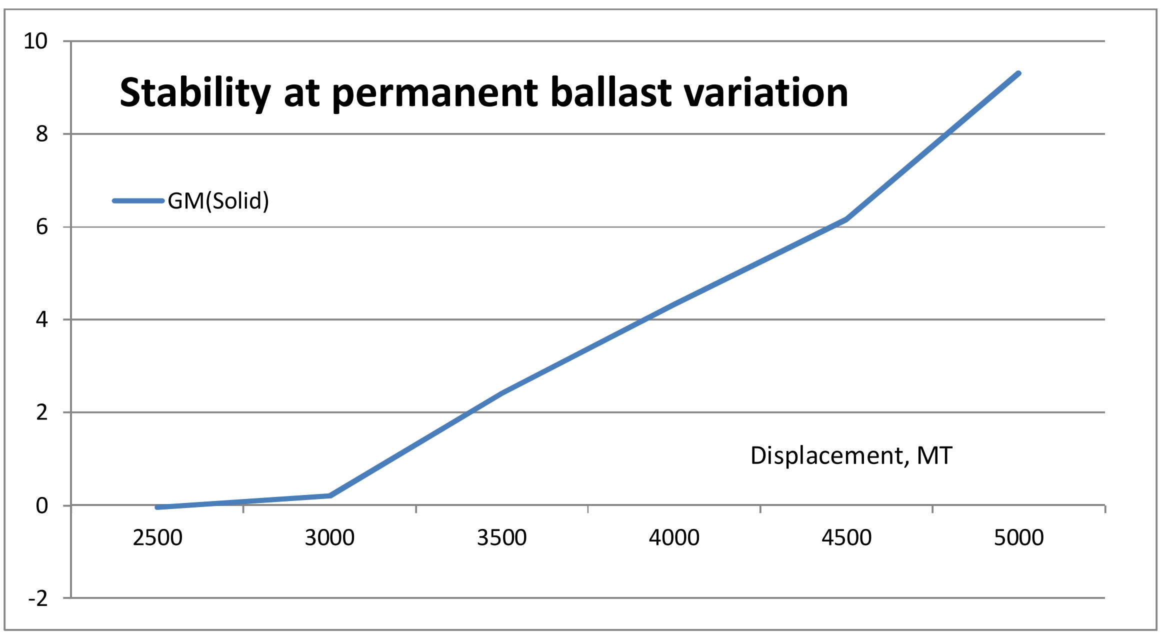
Loading Summary

Item	Weight (MT)	LCG (m)	TCG (m)	VCG (m)
Tower and nacelle	3,390	0.000	0.000	12.369
Displacement	3,390	0.000	0.000	12.369

Then permanent ballast (concrete) added with increment of 500 tons from 2500 to 5000 tons. This range is taken because below lower value stability is not sufficient and above upper level lower tower will come completely into water and all stability will be lost.

Fixed Weight Variation Status

Permanent ballast	Total Weight:	VCG(m)	Draft MS	Trim	Heel	GM(Solid)
2500	3,390	12.369	26.770 m	fwd 74.63 deg	zero	-0.045 m
3000	3,890	11.186	21.477 m	fwd 0.16 deg.	stbd 0.33 deg	0.206 m
3500	4,390	10.273	24.234 m	0.02 deg	zero	2.424
4000	4,890	9.546	27.046 m	0.00 deg	zero	4.322
4500	5,390	8.955	37.814 m	0.00 deg	zero	6.160 m
5000	5,890	8.463	55.066 m	0.00 deg	zero	9.310



From the graph it can be seen that permanent ballast shall be at least 3100 tons to give optimum GM value and upright turbine floating. This is also minimum ballast to satisfy stability criteria for given stability model. The more ballast the more is GM value but draft increases as well which reduces air gap when tower is elevated.

18.2.4 Variation permanent ballast VCG

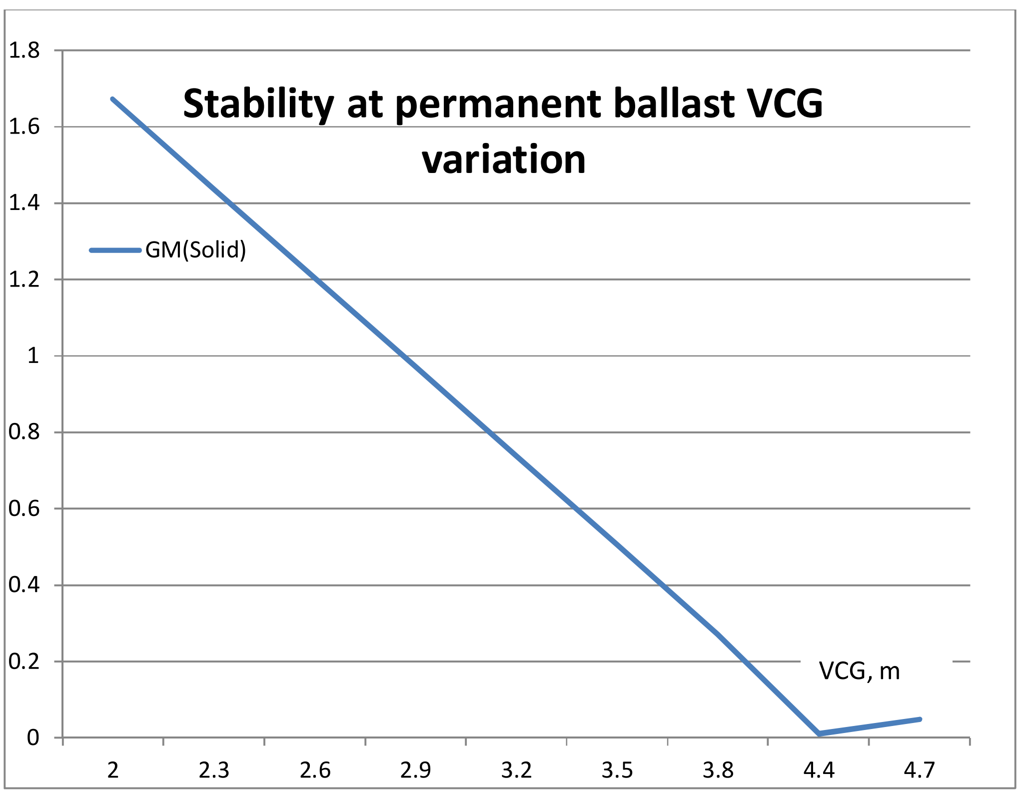
In this experiment the same permanent ballast is used as in initial condition called departure from harbor. All parameters are static except for permanent ballast VCG.

Fixed Weight Status

Item	Weight (MT)	LCG (m)	TCG (m)	VCG (m)
Permanent Ballast	3,121.00	0.000	0.000	-
Nacelle	240.00	0.000	0.000	74.000u
Telescopic tower	650.00	0.000	0.000	25.000u
Total Weight:	4,011.00	0.000	0.000	-

Permanent Ballast VCG Variation Status

Permanent ballast VCG	Draft MS	VCG(m)	Trim	Heel	GM(Solid)
2.0	22.144	10.035 m	zero	zero	1.672
2.3	22.144	10.269	zero	zero	1.438
2.6	22.144	10.502 m	zero	zero	1.205
2.9	22.144	10.736 m	zero	zero	0.972
3.2	22.144	10.969	zero	zero	0.738
3.5	22.144	11.203	zero	zero	0.505
3.8	22.144	11.436	zero	zero	0.271
4.4	23.524 m	11.903 m	fwd 41.86 deg.	port 7.25 deg	0.011
4.7	25.387 m	12.136 m	fwd 58.72 deg	port 9.68 deg	0.048



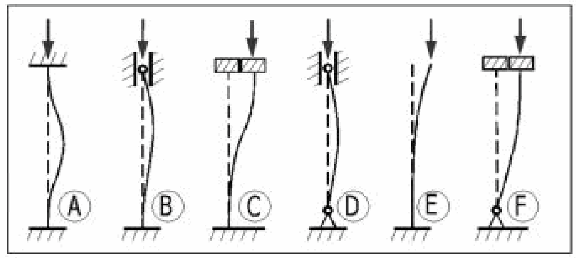
Calculation shows that increase in VCG for permanent ballast reduces stability. Reduction goes almost linear and trend for it is not that strong. It takes several meters of VCG increase until stability is reduces to intolerable values. The effect of course depends on amount permanent ballast and if ballast is reduced then stability reduction will be stronger.
This shows also that diameter of permanent ballast tank does not have to be larger than air tank to bring VCG down. As long as the amount of ballast is sufficient it does not have that great influence.

19. Appendix D – Frame calculation

19.1 Buckling due to weight load spacer calculation [30]

1.0 Strut (column) mounting

1.1	Calculation units	SI Units (N, mm, kW...)
1.2	Type of strut mounting	B. Clamped - Hinged
1.3	Effective length coeficient	
1.4	Theoretical value	0.70
1.5	Engeneering value	0.80
1.6	Value used for calculation	0.80

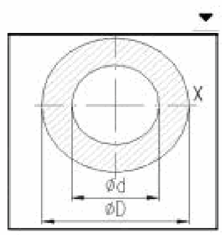


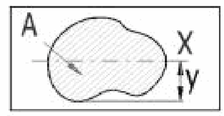
2.0 Static values of the profile and material values

2.1 Strut (column) profile

2.2	Profile type		09...Tube (Calculated)	
2.3	Profile dimensions		Empty table	
2.4	User's parameters of the profile		No	
2.5	Area	A	2.3562E+04	[mm^2]
2.6	Quadr. moment of inertia	Ix	7.3631E+07	[mm^4]
2.7	Max. distance of fibre	y	100.000	[mm]
2.8	Radius of gyration	r	55.902	[mm]

D	200.00	[mm]
d	100.00	[mm]



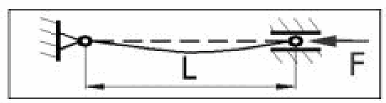


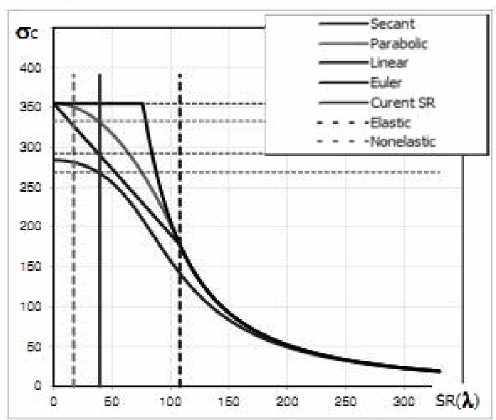
2.9 Column material

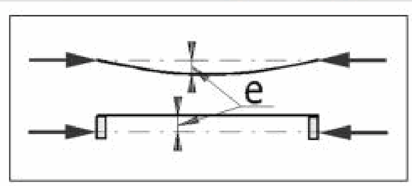
2.10	List of materials		Structural steel EC 3, EN 10025; Fe 510 / Sy=355 MPa		Recomendet values
2.11	Modulus of elasticity in tension	E	210000	[MPa]	
2.12	Yield strength	σy	355	[MPa]	
2.13	Limiting slenderness ratio (intermediate/long)	SRc (λc)	108		108
2.14	Limiting slenderness ratio (short/intermediate)	SRcs (λcs)	17		17

3.0 Calculation and check of buckling

3.1	Actual strut length	L	2760.00	[mm]
3.2	Axial load (force)	F	2500000.00	[N]
3.3	Effective length	Leff	2208.00	[mm]
3.4	Slenderness ratio	SR(λ)	39.50	
3.5	**Design of profile dimensions (Secant)**			
3.6	Safety coefficient	SF	5.00	
3.7	Excentricity ratio	μ	0.25	
3.8	**Euler (elastic buckling)**			
3.9	Critical stress	σc	355.00	[MPa]
3.10	Critical force	Fcr	8364490	[N]
3.11	Safety coefficient	SF	**3.35**	
3.12	**Linear formula, Tetmajer**			
3.13	Critical stress	σc	290.10	[MPa]
3.14	Critical force	Fcr	6835206	[N]
3.15	Safety coefficient	SF	**2.73**	
3.16	**Parabolic formula, Johnson**			
3.17	Critical stress	σc	331.28	[MPa]
3.18	Critical force	Fcr	7805716	[N]
3.19	Safety coefficient	SF	**3.12**	
3.20	**Secant formula**			
3.21	Eccentricity	e	7.81	[mm]
3.22	Max. fibre distance	y	100	[mm]
3.23	Eccentricity ratio	μ	0.25	
3.24	Stress in column	σ	135.4759912	[MPa]
3.25	Critical stress	σc	267.2925218	[MPa]
3.26	Critical force	Fcr	6297931.671	[N]
3.27	Safety coefficient	SF	**2.52**	
3.28	**Pure pressure**			
3.29	Compressive stress	σ	106.10	[MPa]
3.30	Critical force	Fcr	8364490	[N]
3.31	Safety coefficient	SF	**3.35**	







3.32 Calculation of the max. force

3.33	Safety coefficient	SF	5.00	
3.34	Max.F (Euler)	Fmax	1672898	[N]
3.35	Max.F (Parabolic)	Fmax	1561143	[N]
3.36	Max.F (Secant)	Fmax	1259586	[N]

19.2 Bending due to weight load box girder [30]

i **Calculation without errors.**

ii **Project information**

? **Input section**

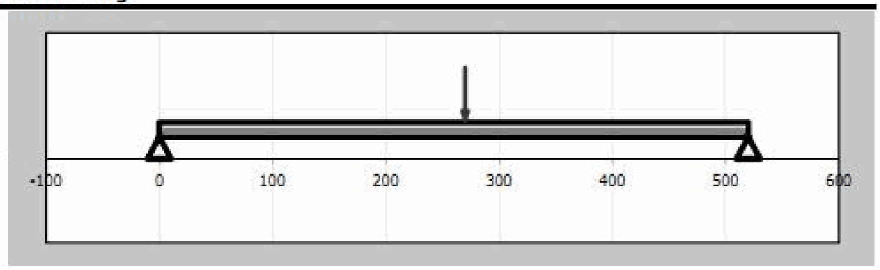
1.0 Beam type, dimensions and loading

1.1 Calculation units
SI Units (N, mm, kW...)

1.2 Left beam end
B...Support

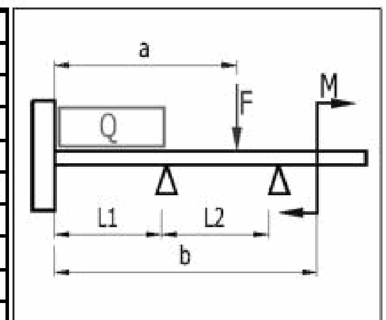
1.3 Number of supports between
0

1.4 Right beam end
B...Support



1.5	Beam field no:		L1					
1.6	Length of beam field	L	520.0	5080.000	2540.0	64516.0	645.2	645.2	[mm]
1.7	Continuous loading	Q	0.000	0.175	0.000	0.031	0.000	0.000	[N/mm]
1.8	Field begining co-ordinates			520.0	5600.0	8140.0	72656.0	73301.2	[mm]

1.9	**Beam loading**	**a [mm]**	**F [N]**	**b [mm]**	**M [Nm]**
	Force F1 / Moment M1	270.0	2500000.0	0.0	0.0
	Force F2 / Moment M2	0.0	0.0	0.0	0.0
	Force F3 / Moment M3	0.0	0.0	0.0	0.0
	Force F4 / Moment M4	0.0	0.0	0.0	0.0
	Force F5 / Moment M5	0.0	0.0	0.0	0.0
	Force F6 / Moment M6	0.0	0.0	0.0	0.0
	Force F7 / Moment M7	0.0	0.0	0.0	0.0
	Force F8 / Moment M8	0.0	0.0	0.0	0.0
	Force F9 / Moment M9	0.0	0.0	0.0	0.0
	Force F10 / Moment M10	0.0	0.0	0.0	0.0
	Force F11 / Moment M11	0.0	0.0	0.0	0.0
	Force F12 / Moment M12	0.0	0.0	0.0	0.0



1.10 Dead weight load Yes

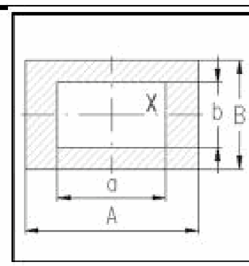
1.11 Other input field for force:

2.0 Static values of the profile and material values of the beam

2.1 **Beam profile**

2.2 Profile type 04...Rectangle B (Calculated)

2.3 Profile dimensions Empty table



A	220.00	[mm]
a	120.00	[mm]
B	220.00	[mm]
b	120.00	[mm]

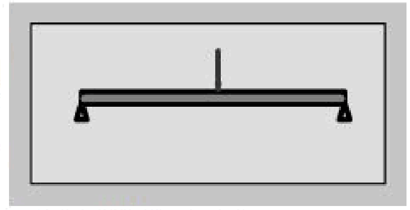
2.4	User properties of the profile		No	
2.5	Number of beams abreast		1	
2.6	Area	A	34000	[mm^2]
2.7	Quadratic moment to the axis	Ix	177933333.3	[mm^4]
2.8	Cross-ection bending modulu:	Sx	1617575.758	[mm^3]

2.9 **Beam material**

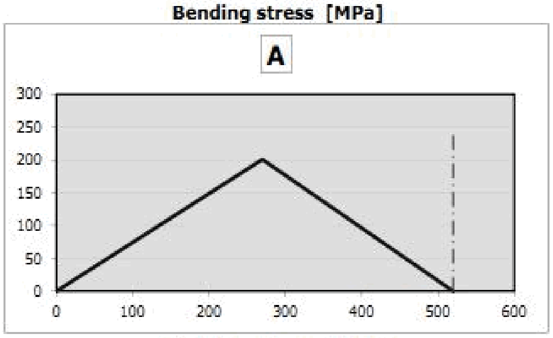
2.10	List of materials		Structural steel EC 3, EN 10025; Fe 510 (210000)	
2.11	Density	γ	7850.0	[kg/m^3]
2.12	Modulus of elasticity in tension	E	210000	[MPa]
2.13	Permissible bending stress	σ_b	213	[MPa]

Results section

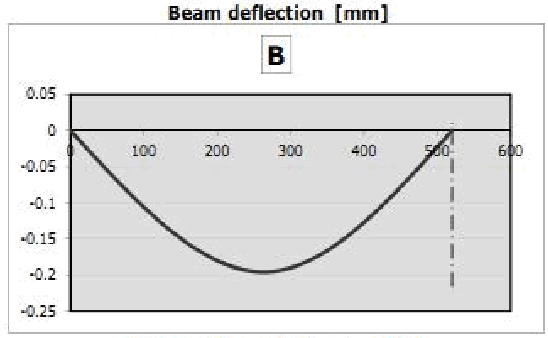
3.0	Calculation results							
3.1	Support number from left		R1	R2				
3.2	Reaction in supports		1202617.02	1298770.86				[N]
3.3	Bending moment Min. / Max.	Mo	0.00	324590.08	[Nm]			
3.4	Beam deflection Min. / Max.	y	-0.196	0.000	[mm]			
3.5	Bending stress Min. / Max.	σ_b	0	200.7	[MPa]			
3.6	Weight of the beam	m		138.8	[kg]			
3.7	Max. length of the free end (buckling).	Lmax		0.0	[mm]			
3.8	Relative beam deflection Max.	y'		0.038	[%]			



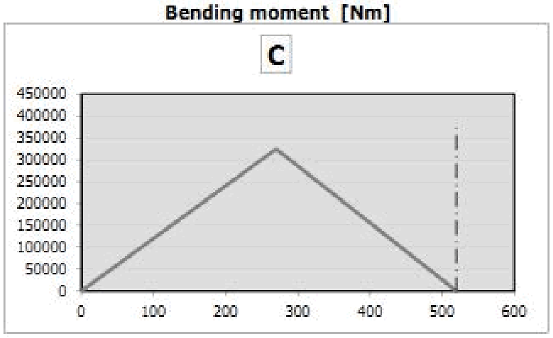
Bending stress [MPa]



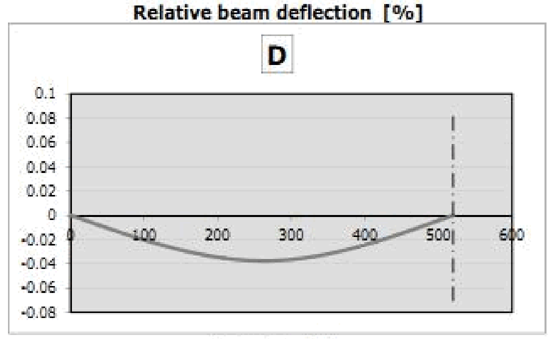
Beam deflection [mm]

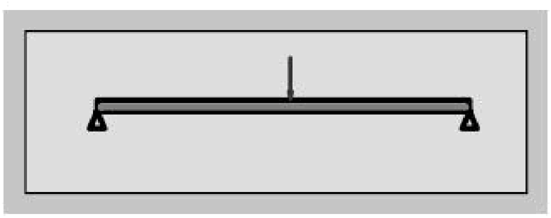


Bending moment [Nm]

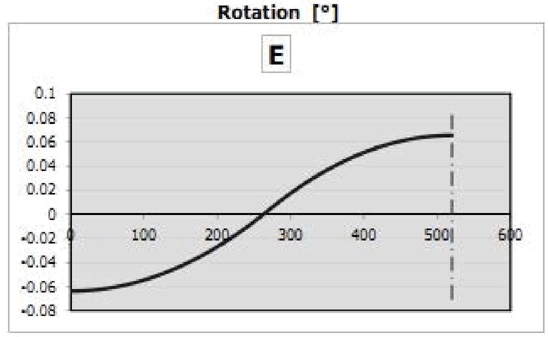


Relative beam deflection [%]





Rotation [°]



3.9

3.10 Move the force no: 1 X= 270 [mm]

20 Appendix E. Idea registering.

Following document written with great help from Mr. Arunjyoti Sarkar and Ove T.Gudmestad has been presented at Jæren tingrett for idea registration.

Presented at Jæren tingrett
on 12 June 2012
Sonja Niel
Notary Public
Sonja Nielsen
saksbehandler

NOTARIUS PUBLICUS I JÆREN

Mobile Offshore Wind Turbine Unit

Invertor:
Pavel Korovkin, Madlamarkveien 6, 4041 Hafrsfjord

Introduction:
A new concept is presented for the design, manufacture and installation aspects of a fully integrated offshore wind turbine installation.

The key idea of the concept is based on the use of making the wind tower telescopic thus reducing its size prior to installation. A conventional tower which is about 90 meters high is difficult to transport either onboard of the ship or in floating condition either vertically or horizontally. Making the tower telescopic brings down the weight on the top thus reducing the overall VCG.

This new concept focuses on different practical aspects of the full life cycle of a wind turbine with a telescopic tower. Several issues are considered that might have to be overcome throughout project realization. Solutions are proposed with discussion of the preferable one in case there are several. Key design elements are investigated that will enable realization. Some proposed solutions are visions that have to be tested out to be confirmed practical. The main goal is to present a concept that would open another chapter in wind energy utilization on its way to become a competitive nonpolluting and popular energy source.

State of the art:
There are different installation vessels or barges already being used by the offshore wind industry and their capabilities vary according to the year they were built, and the purpose they were designed for. Offshore turbine installations involve lifting heavy pieces and placing them with high accuracy at certain heights.
In order to safely install these heavy turbine components, some suggested installation vessels rise on their jack up legs to create a stable working platform.
Offshore wind turbines are usually manufactured into several blocks loaded to a barge or vessel and transported to installation site in one or several complete sets. There the turbine is assembled in a sequence where the complete system is built up from the sea level.

Several types of vessels are used for installation of offshore wind turbines. Purpose built installation vessels are self-propelled units that are specially designed according to the offshore wind industry's demands. These self-propelled installation vessels typically have jack up legs and cranes with high lifting capacities. Their service speeds are also slightly higher than the other installation units. These vessels are called "Wind Turbine Installation Vessels" (WTIV).

Jack-Up barges are floating units that are capable of elevating themselves above the water on their jack up legs at the construction site. They are not self-propelled units and must be towed to the construction site. The service speed is dependent on the tug's power. They are designed for general construction and drilling purposes but still they are used in offshore wind industry commonly as well. "Jack-Up Barges" are referred to as JUBs.

This type of vessels must have jack able legs to create a stable working platform at the offshore site in order to lift heavy parts and install them with a high precision without being affected by the waves, wind and currents.

The sea conditions have effect on transportation and installation of the turbines. According to the technical specification sheets for the majority of WTIVs or JUBs, the maximum significant wave height for the jacking up operation ranges between 1.5 - 3.7 meters and with a current 1-2 m/s. The period of the waves is important parameter to consider in order avoiding resonant motions.

The sea conditions for each specific voyage can vary according to the vessel and cargo load. In general transportation of pre-assembled turbines or turbine parts requires calm sea conditions. Several more parameters like the variation in the water level, the, astronomical tide, surf currents seabed condition are important and must be analyzed before the installation, as they affect the location and orientation of the vessel landings and the jack up unit's stability is highly dependent on it.

Our invention:
This basic architecture is based on a concept introduced in patent appl. number P60902394NO00 Windmill and method of installation, intervention or decommissioning by O. T. Gudmestad, J. Grønli, H. A. Gudmestad

The tower is telescopic and consists of upper and lower towers (Illustration 15). The outside lower tower is permanently attached first from the bottom with a permanent ballast tank and an empty tank above it. The nacelle with blades is fixed on top of upper tower. One of the blades is set vertically down inside a blade protector (Illustration 15). The blade protector is open on the top and sealed at the bottom. When fully assembled and integrated, the wind turbine is set into the water where it floats vertically. The purpose of the blade protector is to shield the vertical down blade from waves and sea actions so that it is not coming into contact with water. Two other blades are high in the air and will not get in contact with the water. The blade protector has an opening at the side with a door so that it can be entered from a boat (Illustration 24). The blade protector is built larger than the blade itself so that the latter will not come into physical contact with walls. The upper opening is fitted with rubber bumper. The blade is released by the upward movement of the upper tower when it is elevated by the lifting mechanism. (Illustration 35, 35)

Towers stack up assembly is shown on the illustration in Illustration 26. Upper tower is elevated with help of the lifting mechanism. Lifting mechanism main parts are illustrated below. Forward and aft pinion gears are running on the same rack. Forward and afterward frames with attached locking mechanisms are included. Three equal sets are distributed on the outer circumference. Forward gear and its frame are fixed to the upper tower and their movement is synchronized by it. Lower gears are connected to same frame to synchronize their movements and to restrict radial movement inside the tower. Forward gear is connected to a lifting piston. Aft gear is connected to a gear spacer and rod of lifting piston.

The foundation system is developed to withstand all loads during the operating phase. It mainly consists of receptacles which will be able to accept preinstalled pile(s) (Illustration 28) at the site. The structure will be placed over a main foundation pile by controlled ballasting of the air tank. (Illustration 31) Provisions for four other extension piles are also added to meet up any stability requirements. All the piles together will enable the structure to transfer any superimposed load to the seabed.

The mechanism works in a sequence, illustrated in Fig 6.

Number	Main piston	Forward lock piston	Aft. Lock piston
Sequence 1	Retracted	Retracted	Stroked
Sequence 2	Stroked	Retracted	Stroked
Sequence 3	Stroked	Stroked	Stroked
Sequence 4	Stroked	Stroked	Stroked
Sequence 5	Retracted	Retracted	Retracted

Advantages with our invention:
This mobility may open completely new chapter in world energy supply. The mobile offshore wind turbine can be installed at a temporary construction site like close to a drilling rig or outside a place hardly accessible from the land. The mobile wind turbine can supply energy to locations far away from developed infrastructure or where creation of land based power lines is either not economically defendable or not possible due to climate or terrain conditions. There are regions depending on mobile energy sources. Some countries are developing mobile nuclear power plants today. The mobile offshore wind turbine can stop this development and become a good alternative to that as a source of energy.

Potential patent claims:
1. Mobile offshore wind turbine unit *characterized by* incorporating a permanent ballast tank and an empty ballast tank which will allow a fully integrated offshore wind turbine structure to be afloat and be towed to the site for being a temporary / permanent installation.
2. Mobile offshore wind turbine unit *characterized by* a 2 stage telescopic tower which will keep the center of gravity of the whole system at a suitable height so that it may have sufficient stability during the transit phase.
3. Mobile offshore wind turbine unit *characterized by* the addition of a structural component called “blade protector” which will house one blade inside it during the transit phase so that the blade doesn’t encounter any hydrodynamic loads.
4. Mobile offshore wind turbine unit *characterized by* a passage way through the blade protector which will provide accessibility of the tower’s inside by the working personnel.
5. Mobile offshore wind turbine unit *characterized by* the application of a modified version of an existing hydraulic lifting mechanism to lift the inner tower from the outer tower.
6. Mobile offshore wind turbine unit *characterized by* a foundation system composed of one central supporting pile and four outer extension piles to withstand all superimposed loads during the operating phase.