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EP 2479103 A
WO 2014/000802 A
WO 2017/157399 A
CN 107201991 A

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Other: **EPODOC, WPI**

(54) Title of the Invention: **Wind turbine and method for installing a wind turbine**
Abstract Title: **WIND TURBINE & METHOD FOR INSTALLING A WIND TURBINE**

(57) A wind turbine comprising a tower-float assembly which has a float 5 arranged to keep the tower 3 at least partially above the water's surface, a keel assembly which includes at least one keel 3 and at least one connector member 9, the connector member being moveably attached to the tower-float, the keel being moveable from a non-deployed position to a deployed position, and a drive system 11 which can move the keel from the non-deployed to the deployed position and which is releasably attached to the tower-float to be removed after the keel is deployed. The keel may include multiple keel modules that each have a drive unit. The drive system may have at least one drive unit per connector member. The drive unit may include electric or hydraulic motors. The drive mechanism may be a rack and pinion. Also included is a method of installing a wind turbine which includes the use of a submersible barge.

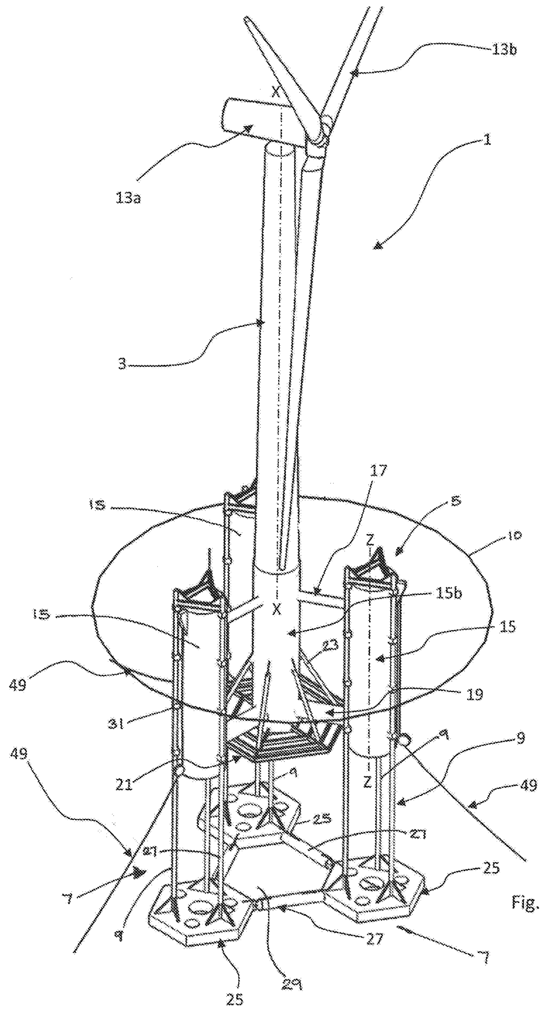

Fig. 5

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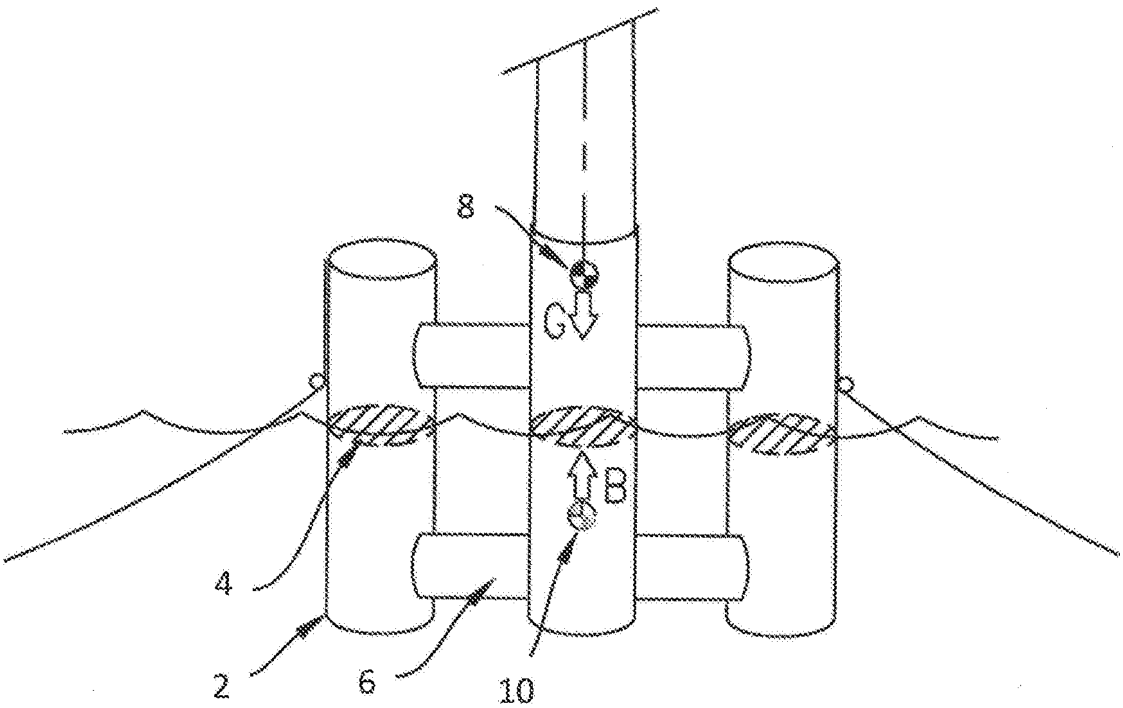

Fig. 1

(Prior Art)

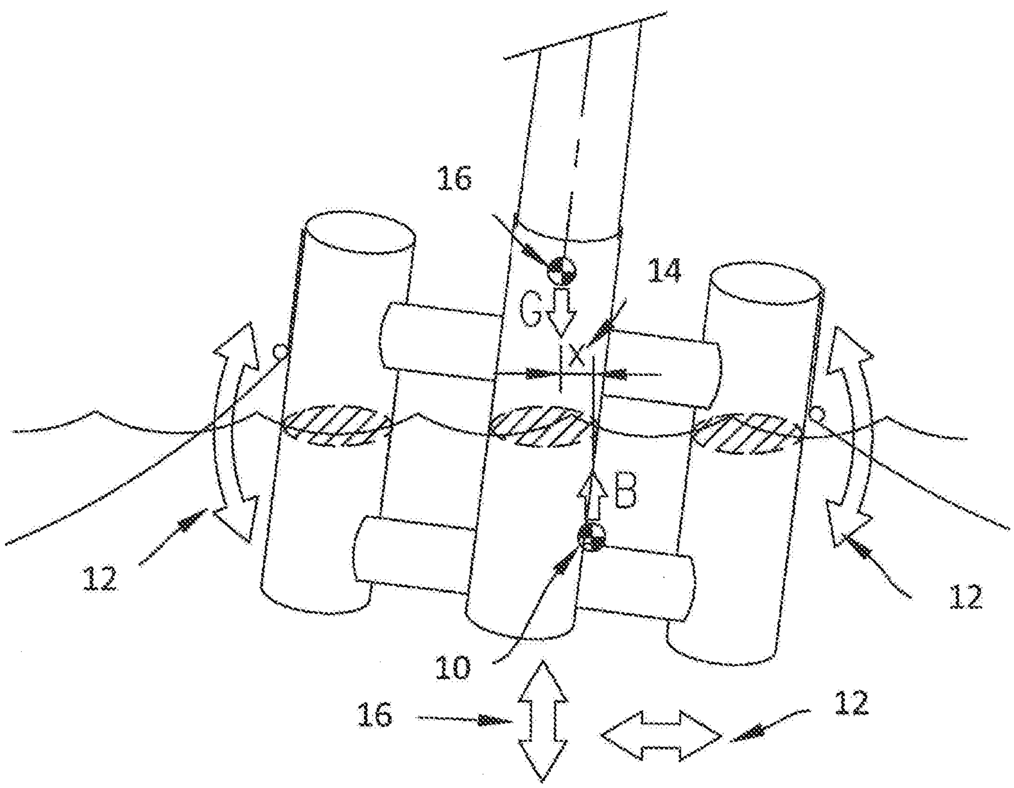

Fig. 2

(Prior Art)

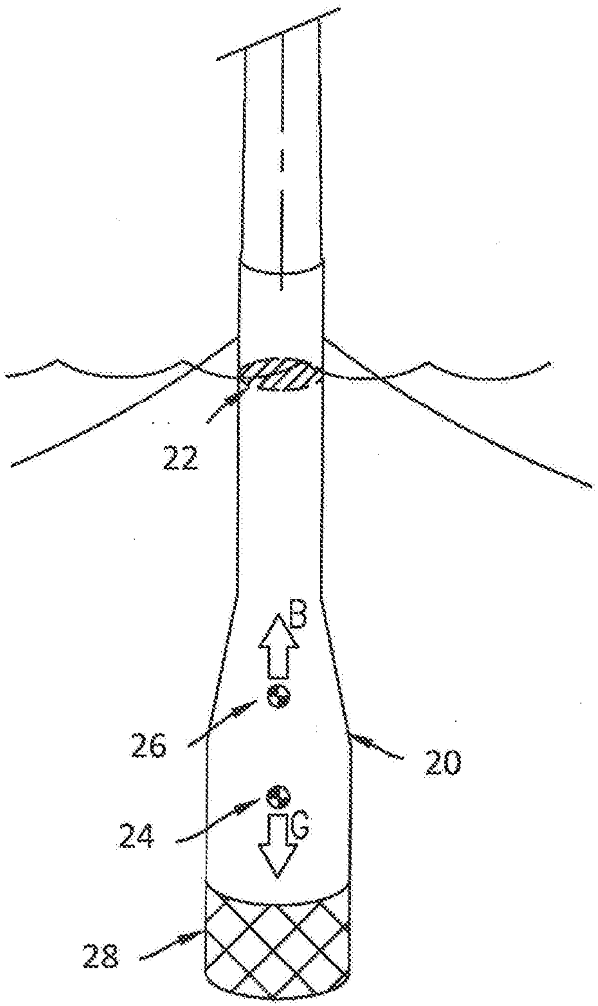

Fig. 3

(Prior Art)

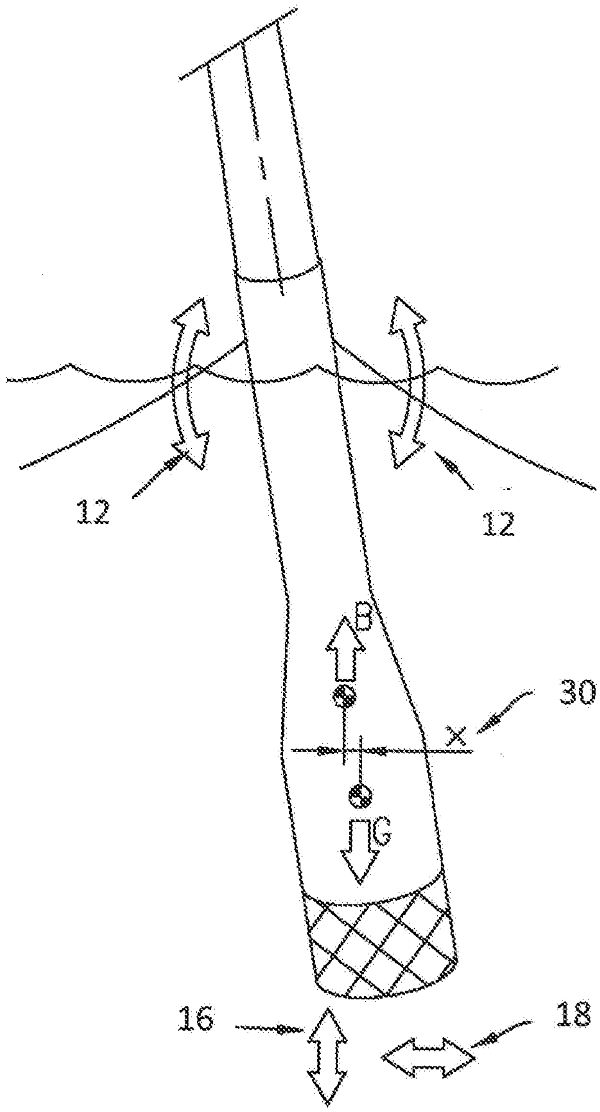

Fig. 4

(Prior Art)

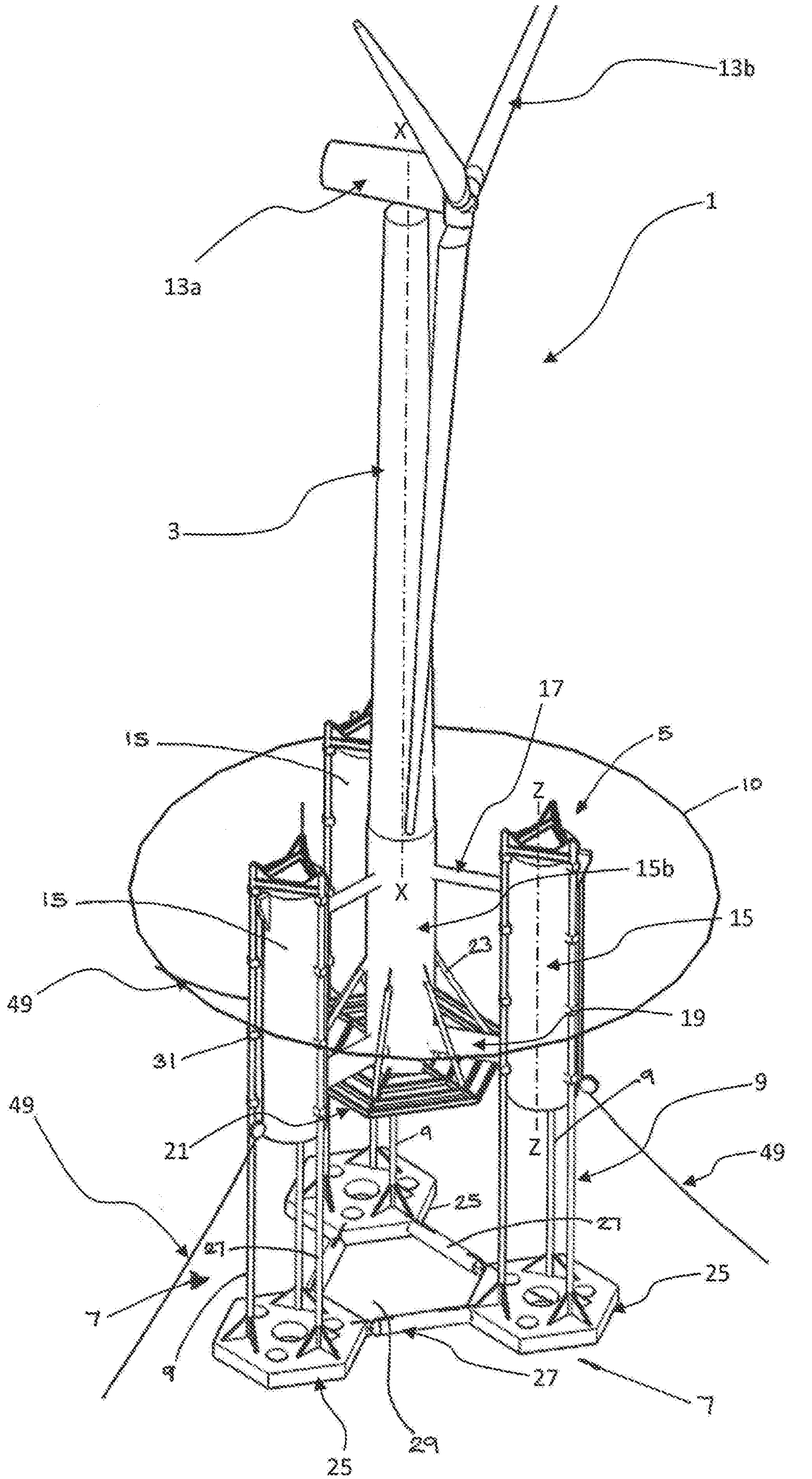
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Fig. 5

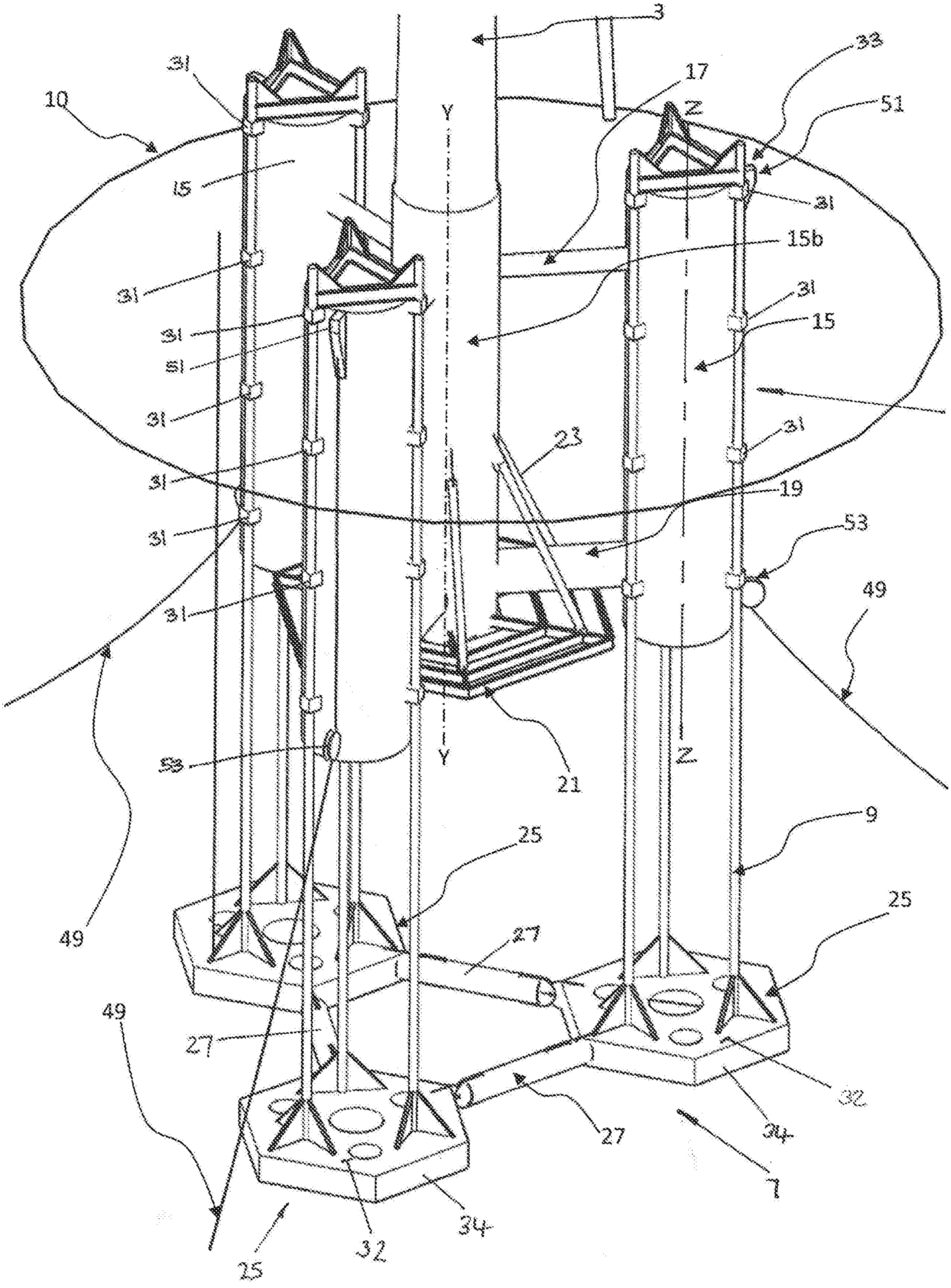
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Fig. 6

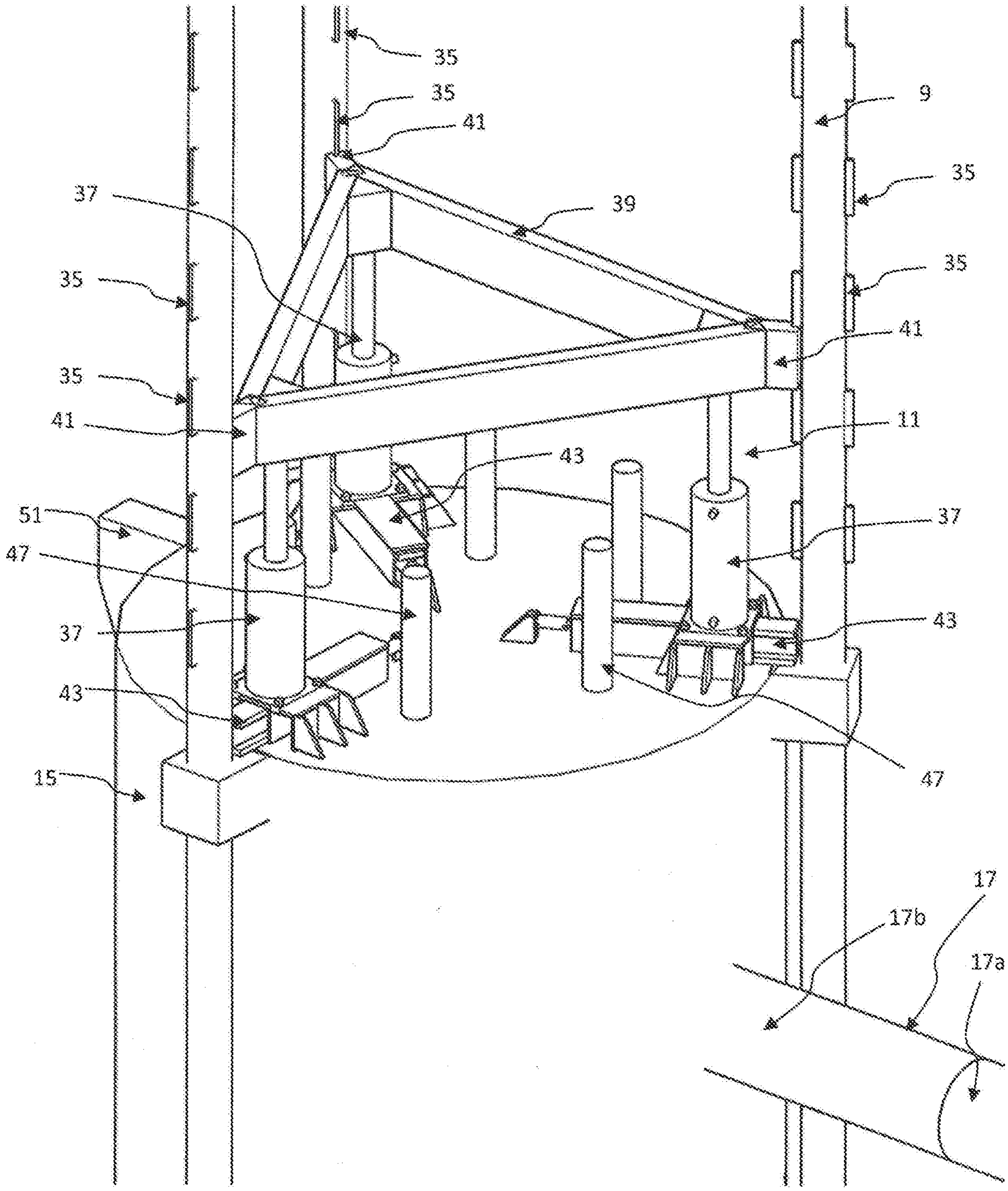
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Fig. 7a

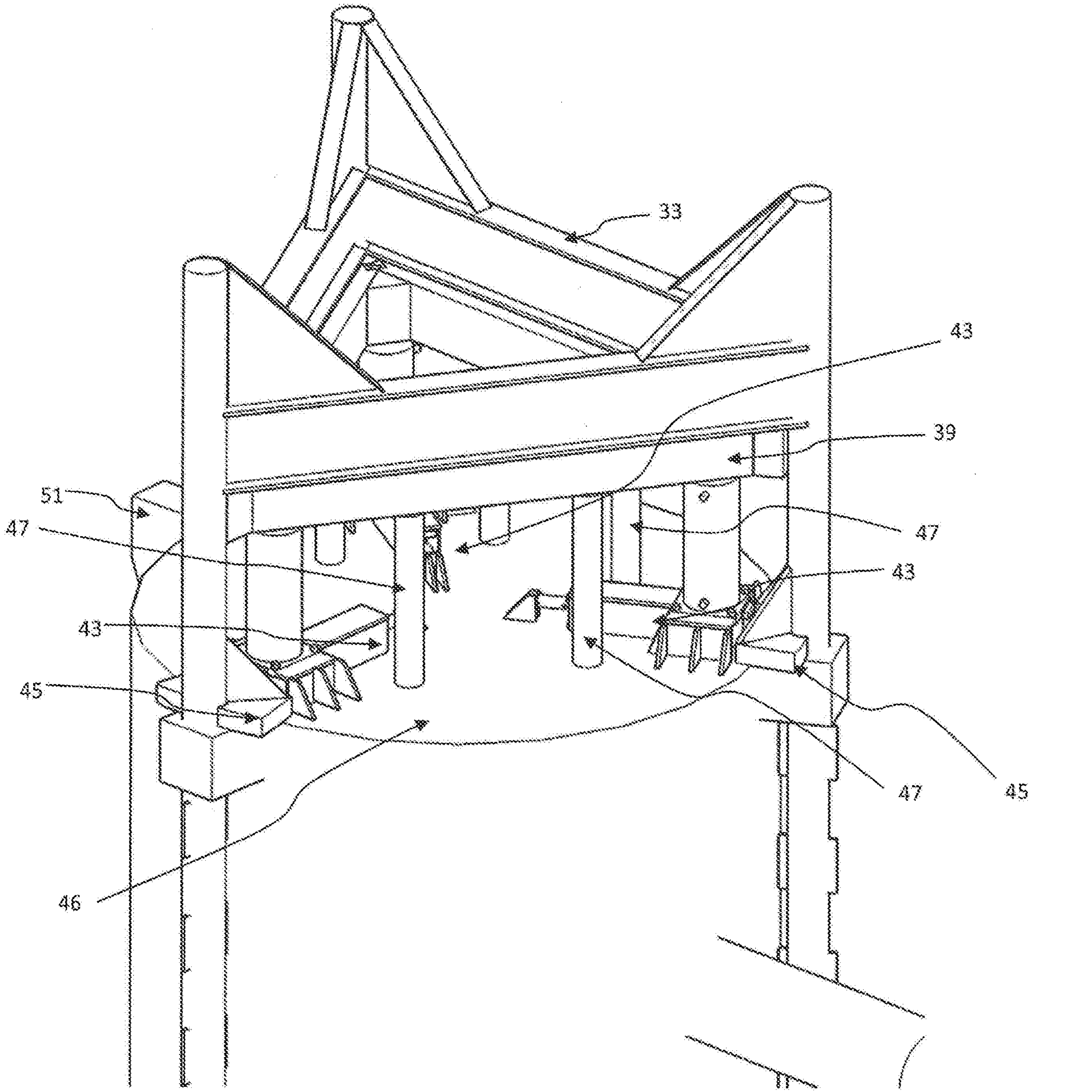

Fig.7b

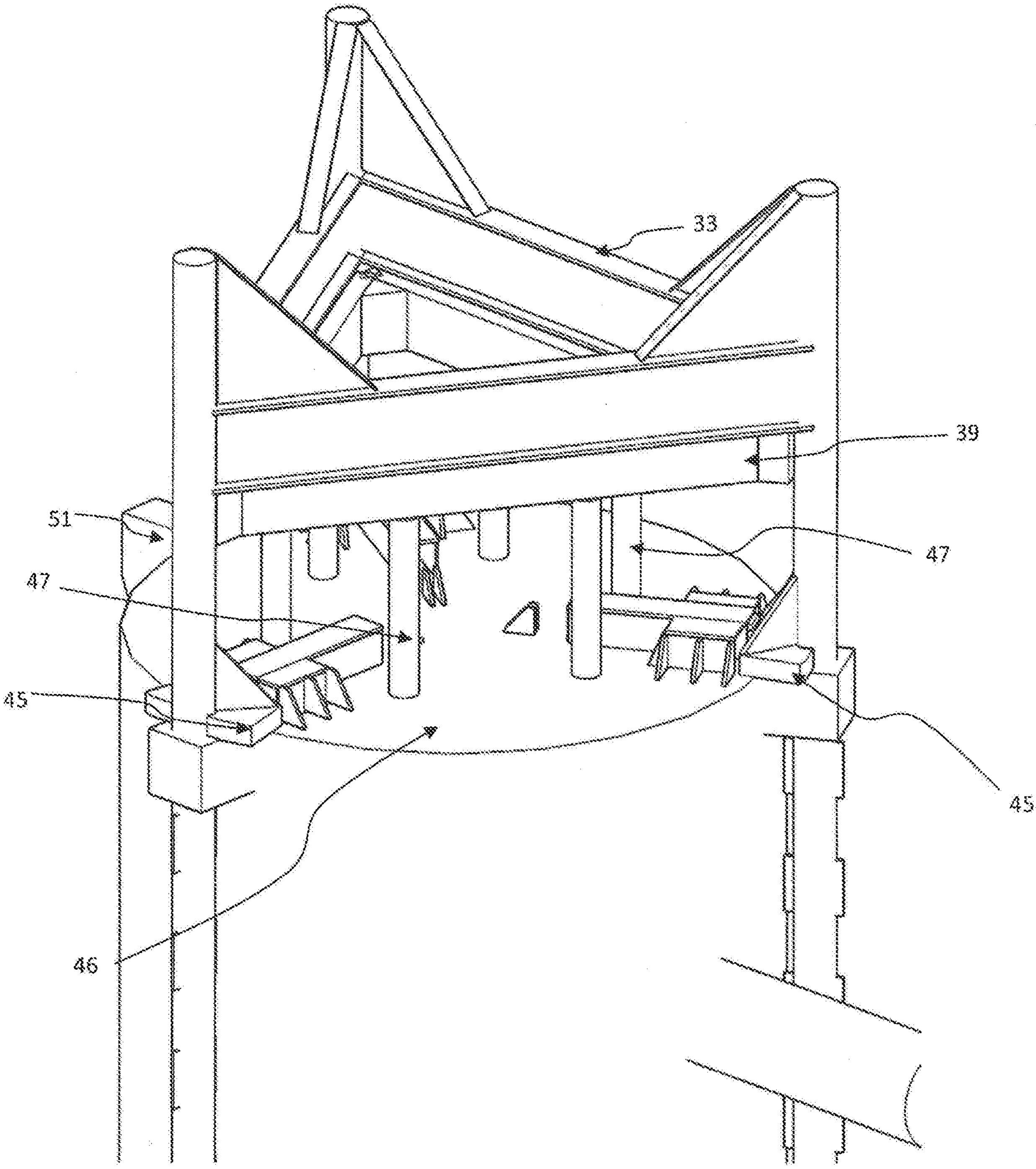

Fig. 7c

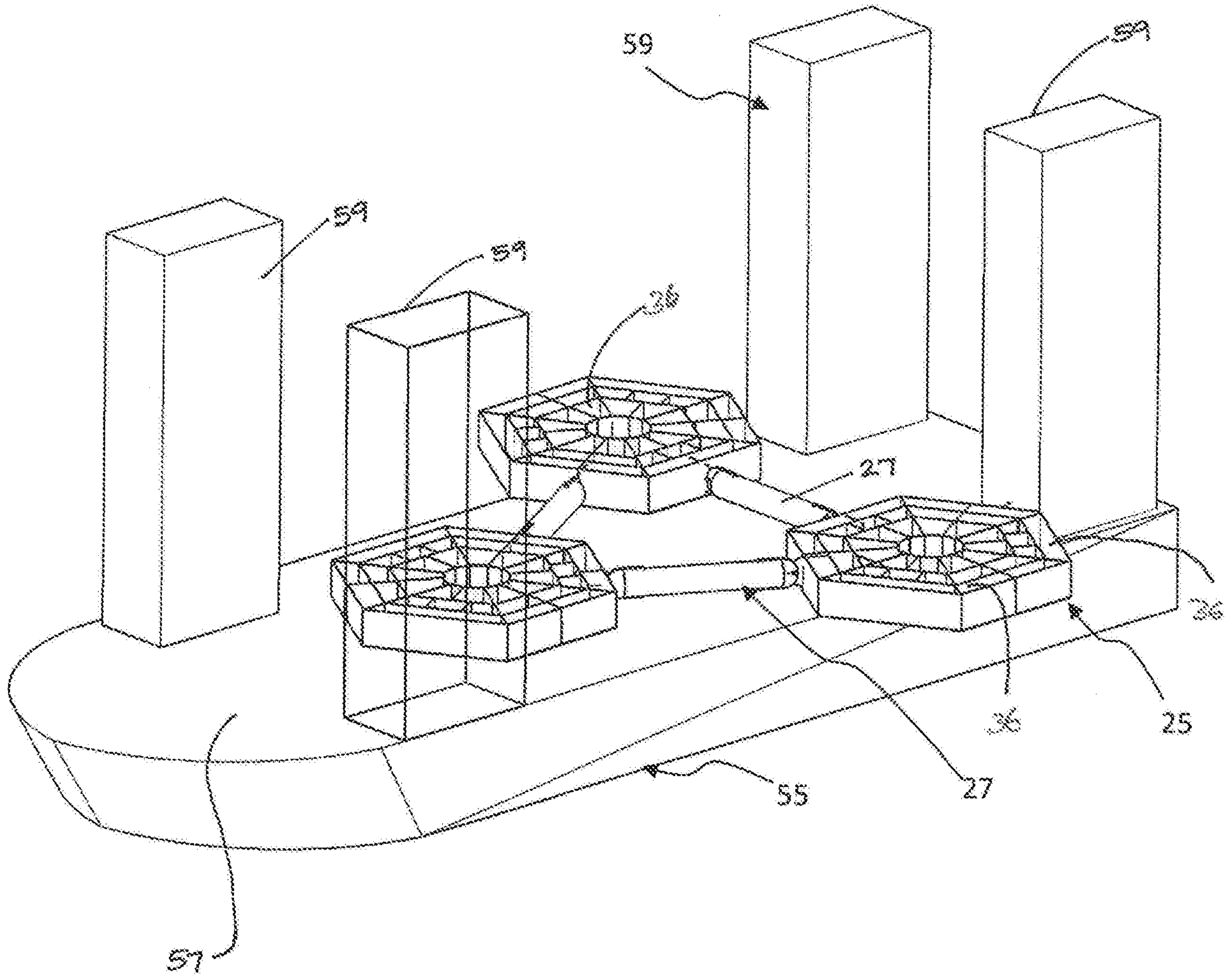

Fig. 8

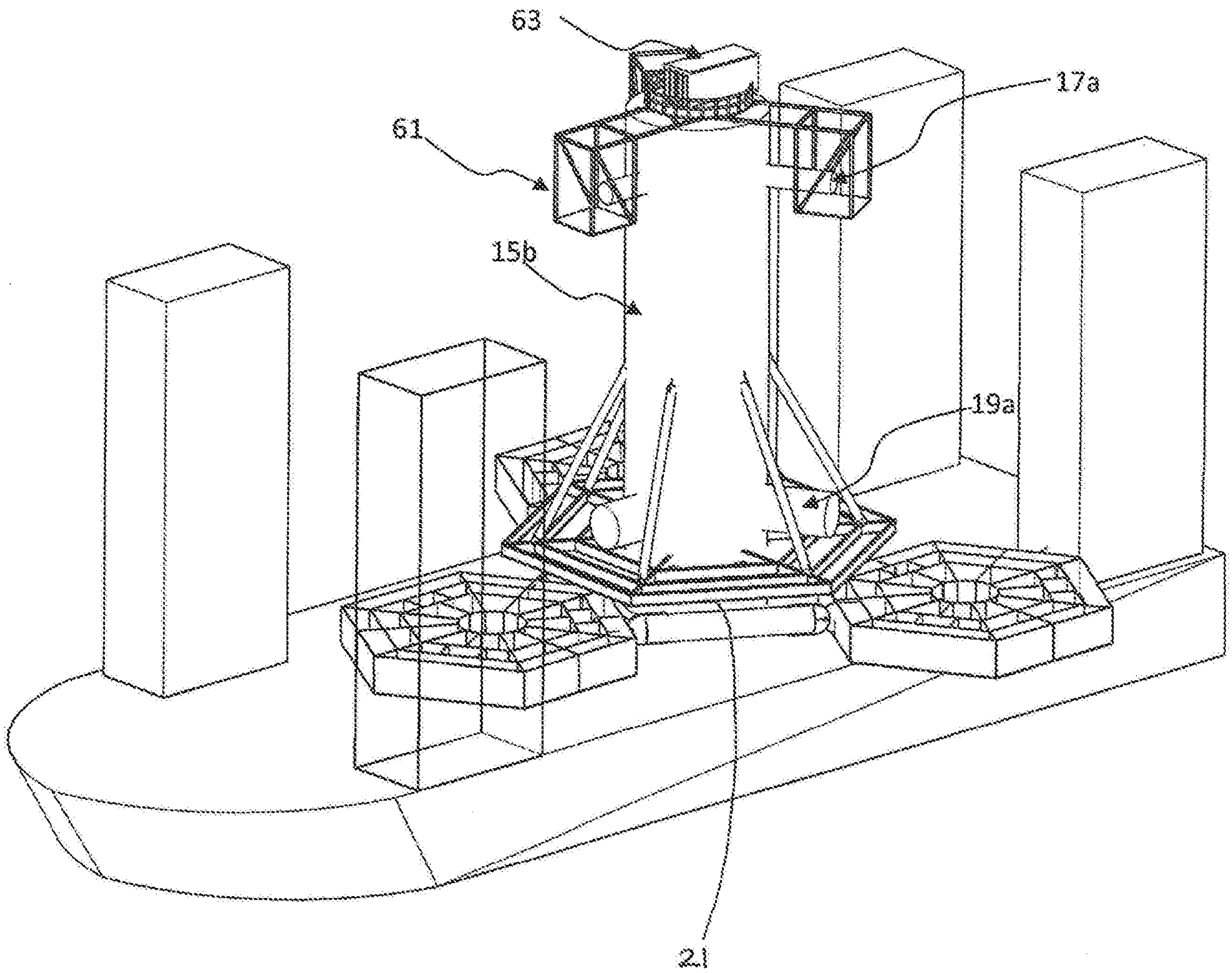

Fig. 9

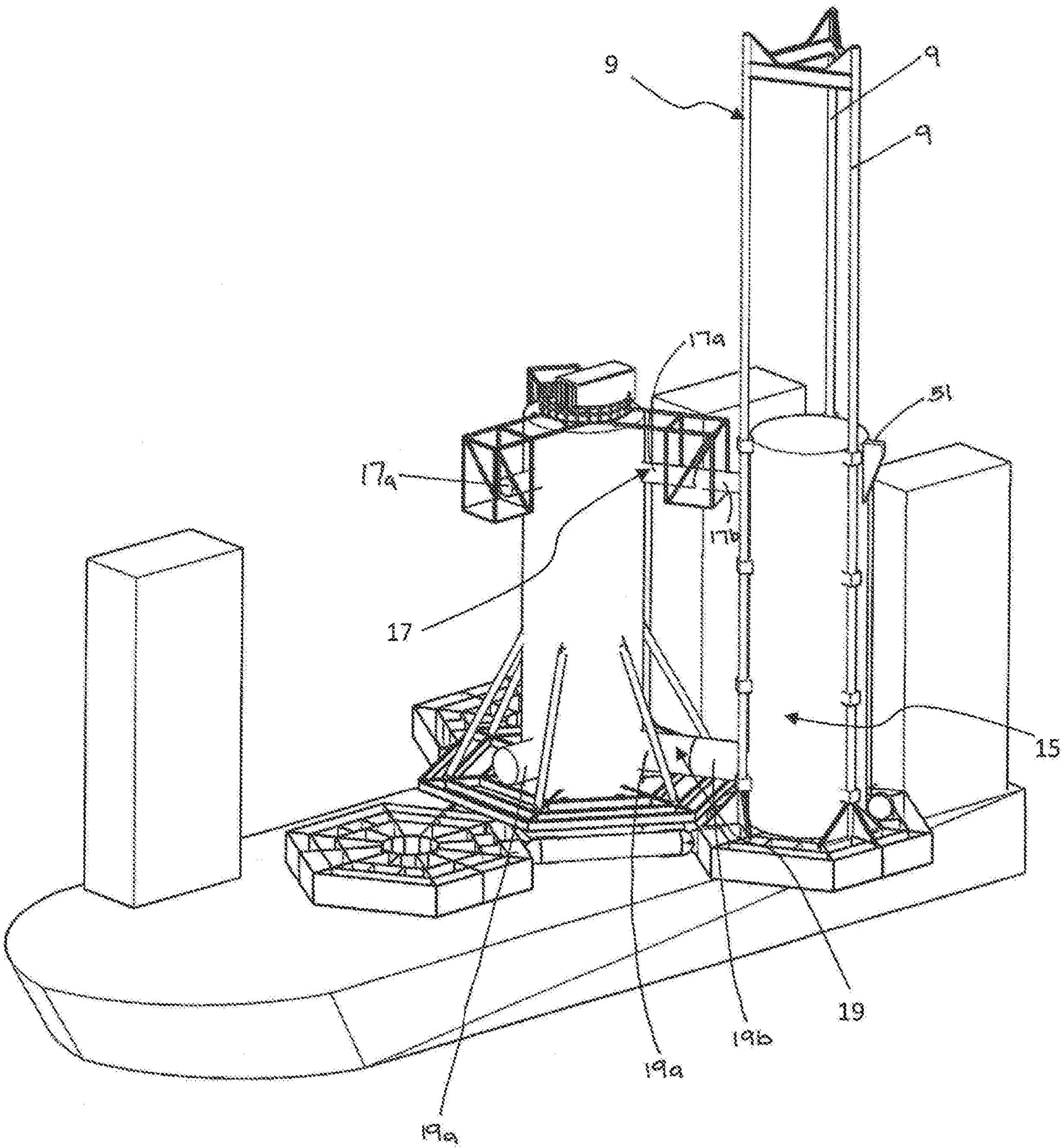

Fig. 10

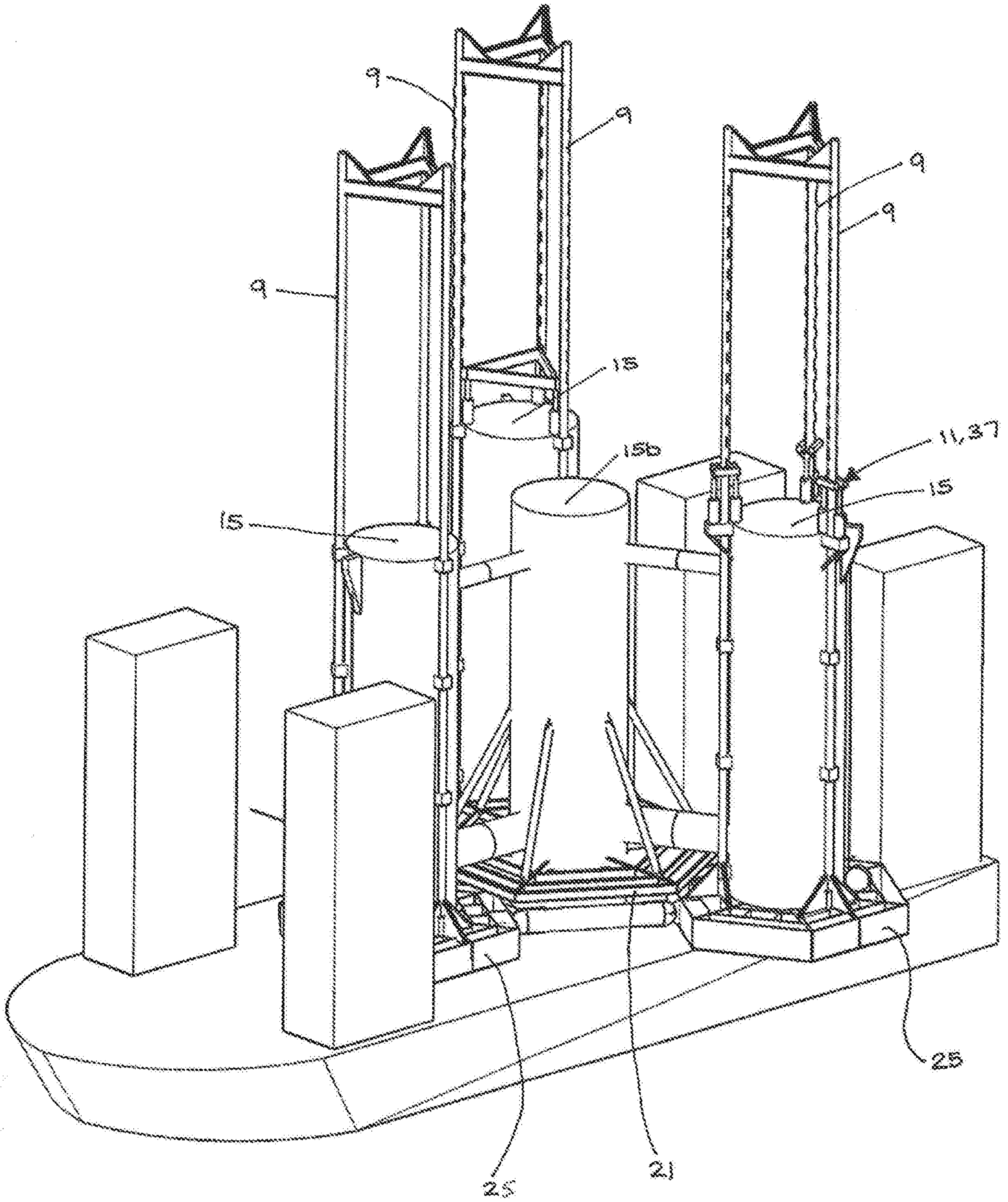

Fig. 11

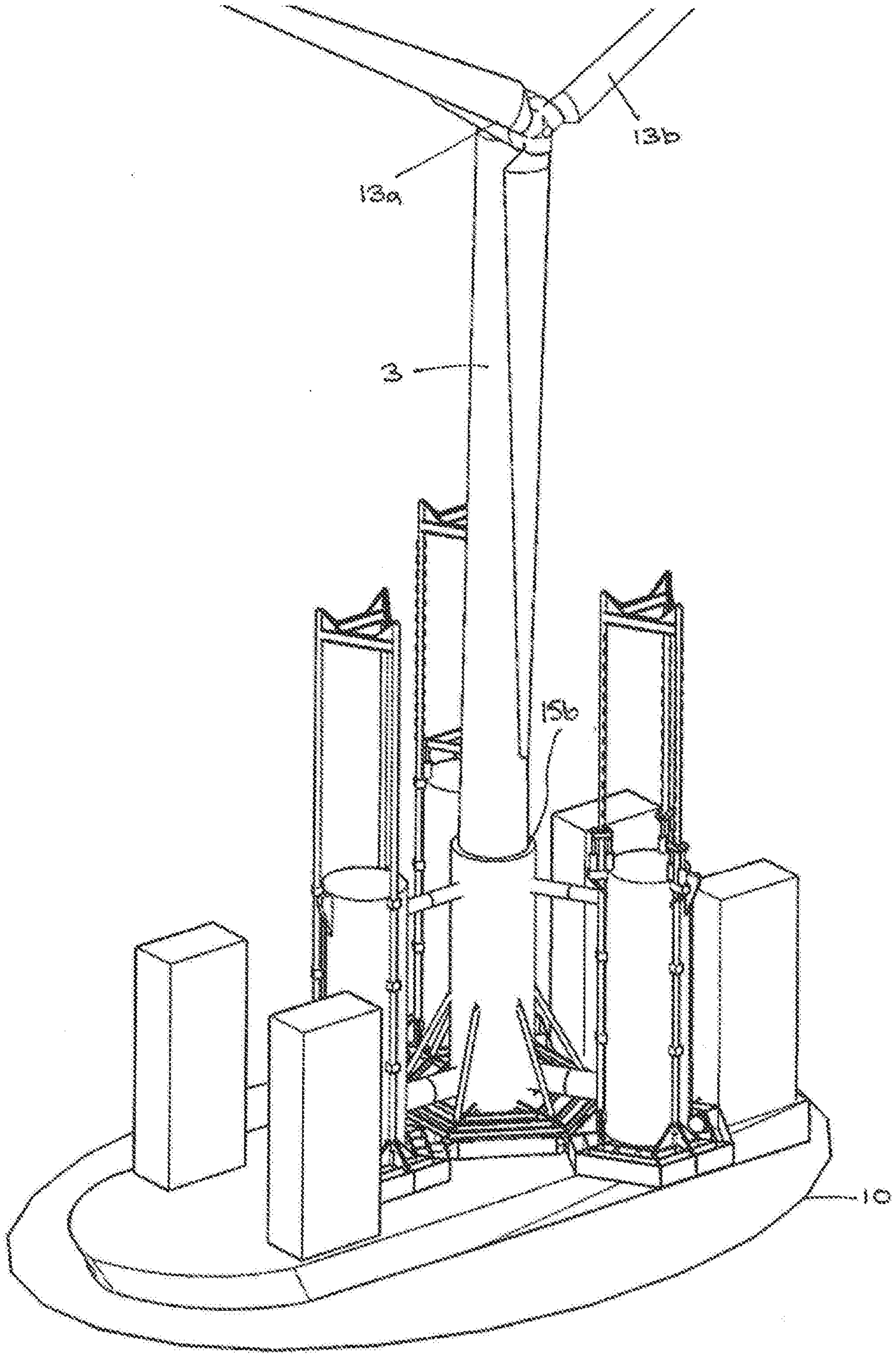

Fig. 12

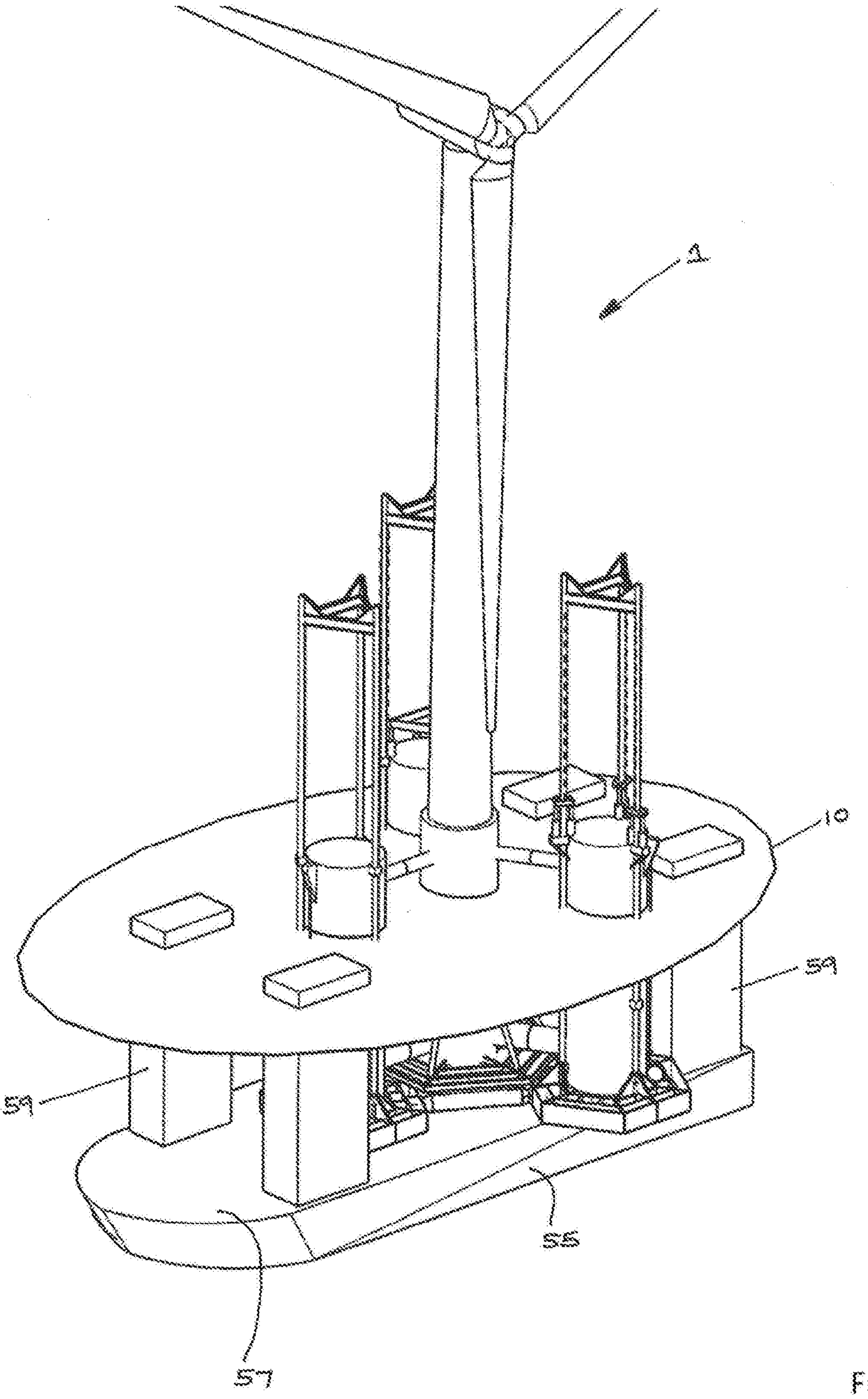

Fig. 13

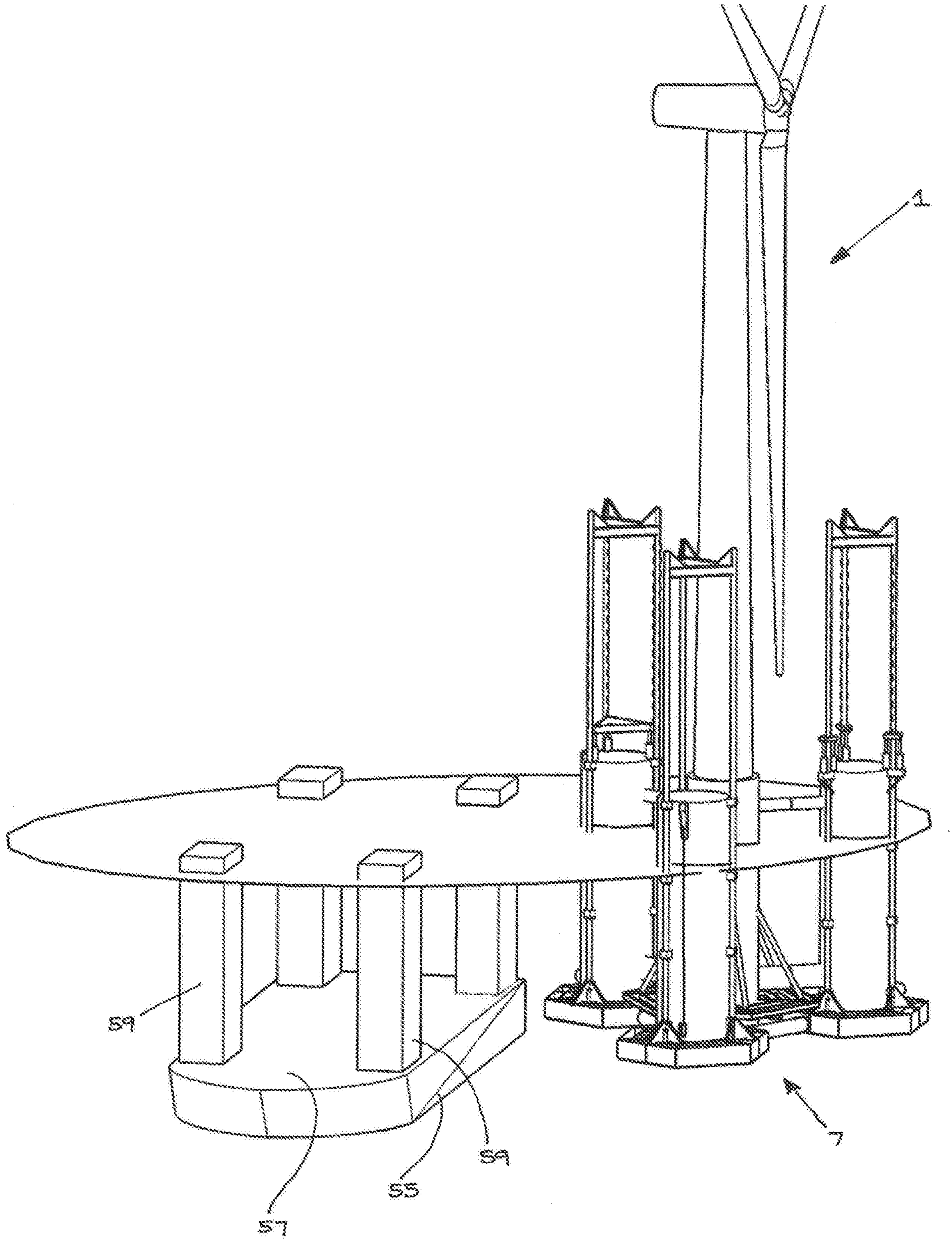

Fig. 14

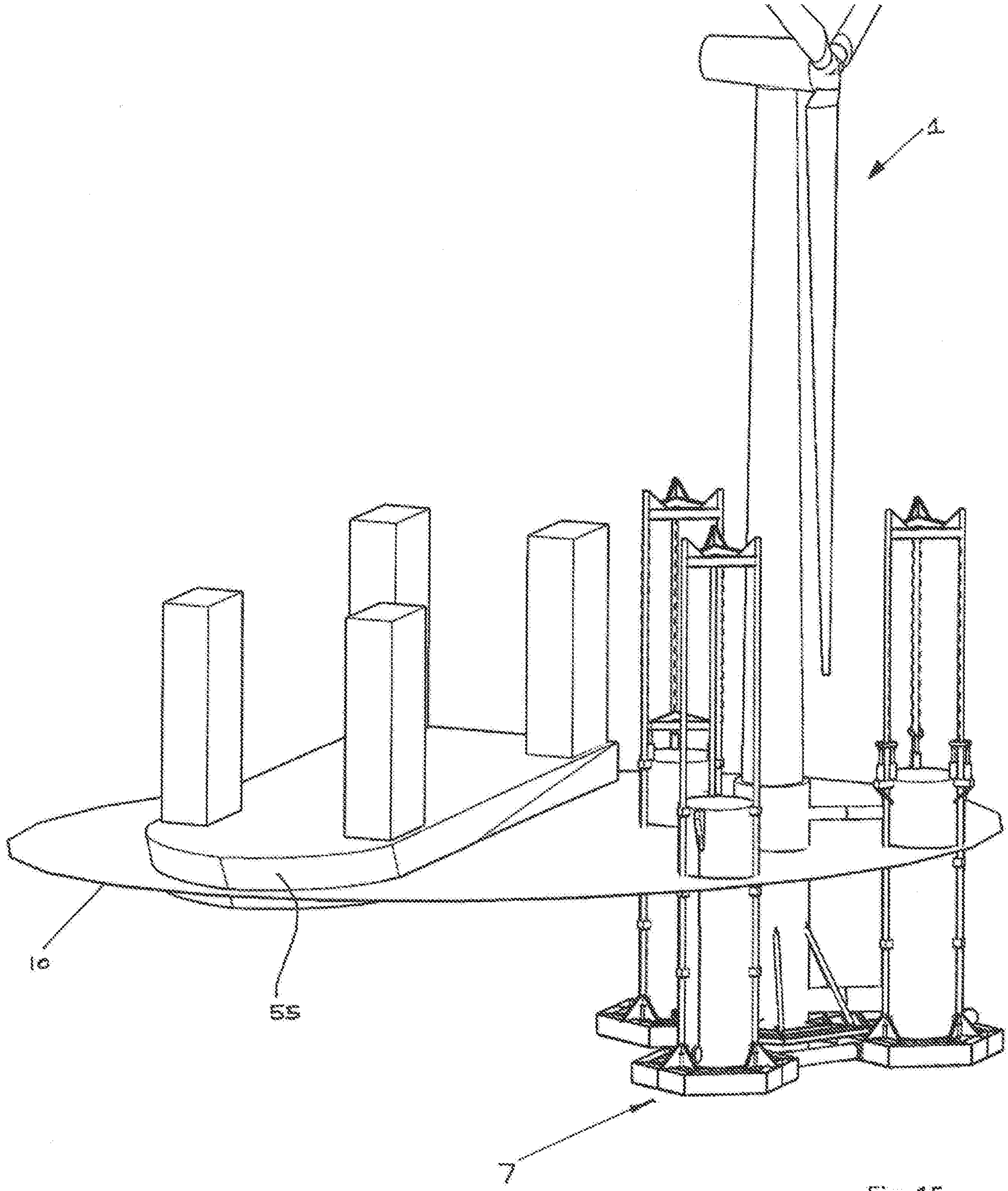

Fig. 15

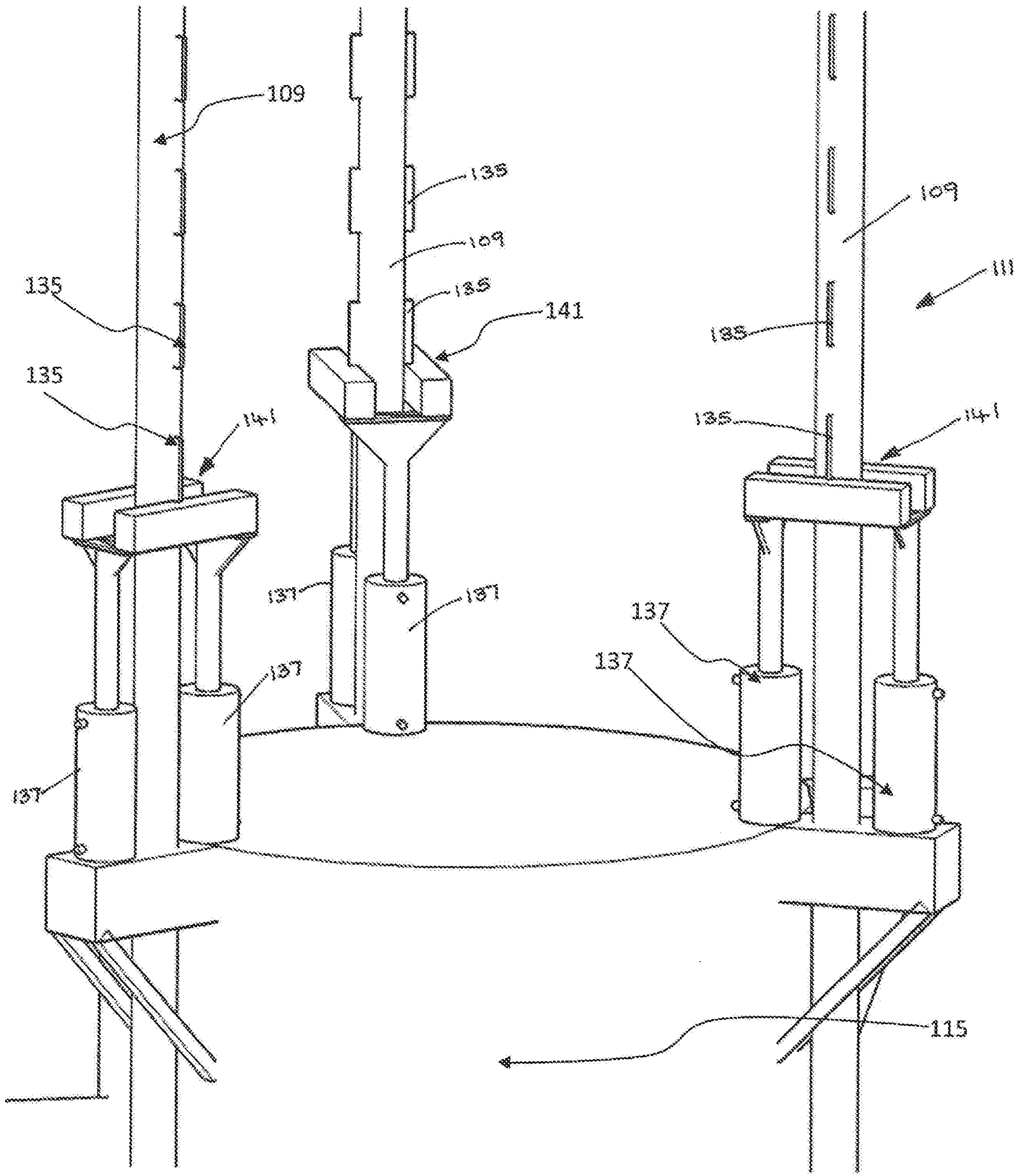
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Fig. 16

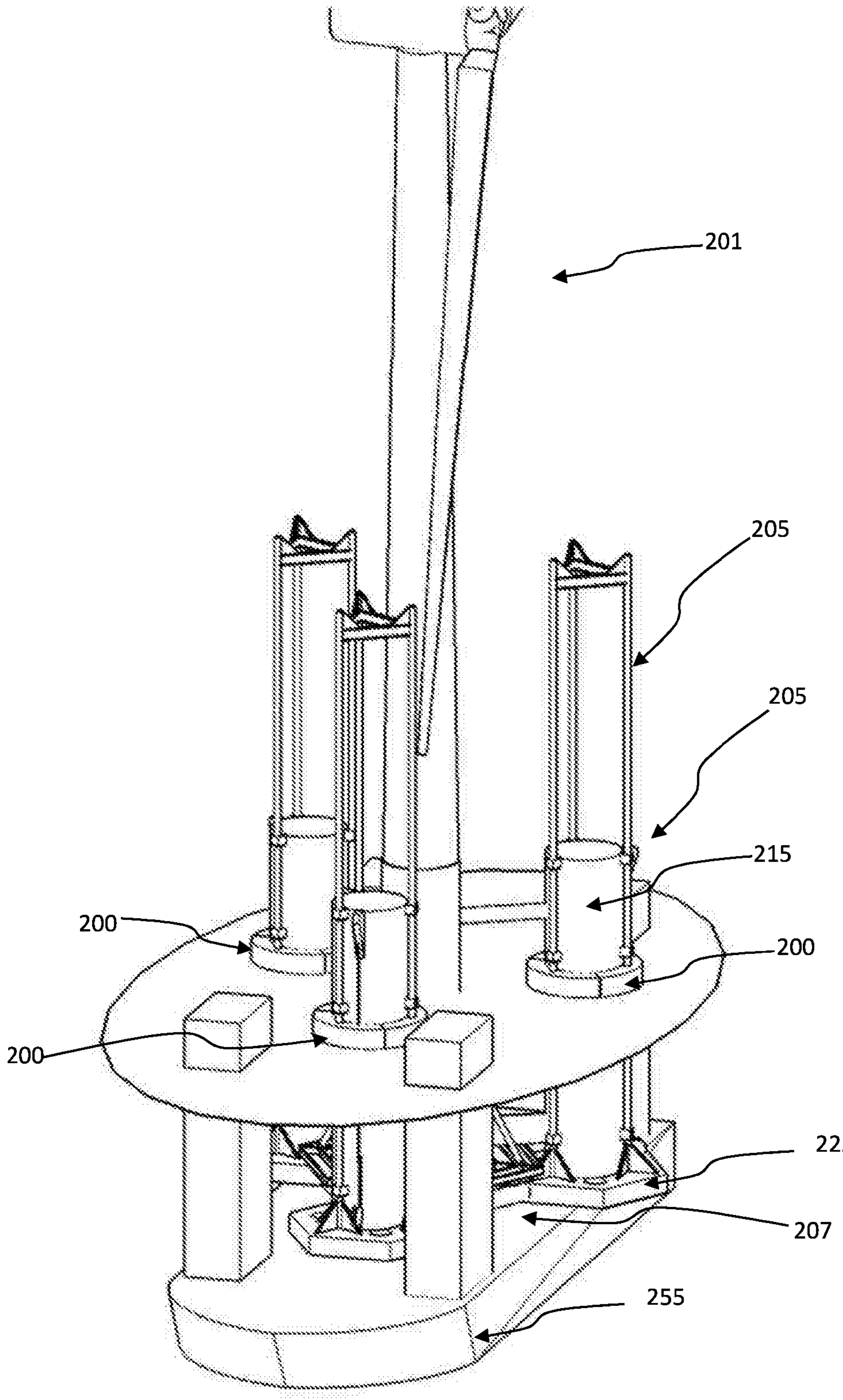

Fig. 17

WIND TURBINE & METHOD FOR INSTALLING A WIND TURBINE

FIELD OF THE INVENTION

The present invention relates to a wind turbine and a method for installing a wind turbine.

BACKGROUND

The current generation of offshore wind turbines is installed in water depths such that the foundation for the mast and turbine assembly can be secured in the seabed as a single driven pile. A general limit for such a foundation is around 40m water depth. Depths beyond this require either steel lattice structures secured with multiple driven piles or large gravity base structures of considerable mass to achieve a seabed supported foundation. While such designs have proven economic for recovery of offshore hydrocarbon deposits, the required capital cost compared with the energy generated per turbine for commercial sale makes fixed offshore foundations for single wind turbines uneconomic beyond approximately 60m. Therefore, wind farm developments beyond continental shelf depths, or in geographic locations lacking a continental shelf, may consider mounting wind turbines on floating foundations.

Demonstration floating wind turbine plant to date has been deployed in a quantity and at a capacity that generates electric power with marginal return or requiring considerable financial subsidy to make the test project viable. Commercial interest in floating wind farms is now focusing on scaleability and industrialization: development of multiple floating wind turbine units that collectively generate electrical power at a price attractive to the consumer but with CAPEX and OPEX levels that provide an attractive rate of return to the investor.

The collective capacity of an offshore wind farm, or one phase of a larger project, currently lies between 500 and 1000 MW. Given a target capacity of 10-12 MW for a single wind turbine unit, a commercial proposition for an offshore windfarm must target between 42 and 100 units per wind farm or wind farm phase. Such a scale of development demands floating sub-structures that can be assembled and installed in a timely manner. This will shorten the delay between the initial commitment of capital to the wind farm development and the start of electrical power generation to the grid and so achieve a return on investment.

To date, floating foundation technology has adapted designs developed in the offshore hydrocarbon industry, broadly based on the following definitions:

Semi-submersible (Figure 1): consists of vertical column buoyancy tanks 2 which individually have relatively small water plane area 4 but, when interconnected with horizontal tubulars 6, create a single buoyant structure with a distributed water plane area. Though the centre of mass 8 (or centre of gravity) is generally higher than the centre of buoyancy 10, the distributed water plane area ensures the structure's stability on water. In Figure 2, as the floating unit pitches and rolls 12, the centre of buoyancy 10 shifts across sufficiently to maintain a buoyancy-weight lever arm, X, 14 that prevents capsizing. As well as pitch and roll 12, a semi-submersible will heave 16 and sway 18 in response to wave motion.

Spar (Figure 3): a spar is a single floating vertical column 20 whose water plane area 22 is that of the tube cross section and is typically circular. To compensate for its poor water plane area stability, the spar maintains a centre of mass 24 below its centre of buoyancy 26.The spar achieves this with a considerably deeper draft than a semi-submersible using solid ballast packed into its keel (28). Thus, in Figure 4, the buoyancy-weight lever arm, x, 30 acts such that the spar can never capsize. A spar will also heave 16, sway 18 and roll/pitch 12 with wave motion.

The configurations of the above concepts raise interesting challenges for assembly and multiple unit production when considering an industrial scale development of either using current fabrication approaches.

The semi-submersible concept proposed in WO2009/131826 exhibits increasing separation between the vertical columns for larger capacity turbines compared with the original pilot test design. As turbine sizes and weights increase, any further column separation to achieve stability may result in a larger foundation footprint and restrict access to preferred assembly ports.

Semi-submersible construction has used and continues to propose shipyard dry docks for final assembly. This restricts assembly site options while proximity of an existing dry dock to the offshore windfarm site is not guaranteed. Increasing the distance between the assembly and delivery sites raises potential schedule risks and transport costs when towing completed units over excessively large distances.

A restriction to a dry dock facility also limits the option to locate the final assembly site close to the wind turbine component manufacturing plant where there are established machining and technical expertise resources. Material and resources to support the turbine installation have to be mobilised to the dry dock site.

Furthermore, dry docks are dimensioned to suit the width:length ratio of commercial shipping which may not be compatible with the proposed width dimensions of a semi-submersible foundation.

At a practical level, the builder of a batch of floating offshore wind turbines would have to compete with other commercial enterprises requiring access to a dry dock. To complete a production run of 100 such units without a delay to subsequent dry dock bookings presents a considerable production challenge and commercial risk for both the windfarm project delivery schedule and the dry dock. Failure to meet the production deadline would impact on the commercial viability of floating windfarms in terms of market confidence in the production capabilities of the technology.

Both the semi-submersible and spar concepts minimize construction risk through full assembly and testing of the floating foundation, turbine mast, nacelle and rotor blades prior to tow out to site. While this removes exposure to risk in open seas, the spar foundation must be brought vertical in sheltered water to enable full pre-assembly of the turbine. Such a sheltered water location must be deeper than the draft of the spar foundation and places a constraint on areas suitable for such a method of assembly.

Furthermore, the water depths along the tow route to installation site must be sufficiently deep to allow the spar keel to clear any potential raised seabed features along the route.

Additionally, access to a port facility with sufficient water depth to moor an upright spar alongside the quay is very unlikely. Therefore, a spar-based floating windfarm solution relies on floating crane availability for the duration of the assembly phase to transfer assembled turbines from the quayside to each spar at the temporary deep, sheltered water parking site.

WO 2017/157399 considers a design to address some of the shortcomings of semi-submersible and spar concepts. A feature of this system is a separate water ballast tank suspended by lugs and shackles from a floating hull that, when flooded, acts as a counterweight. This approach increases the overall displacement, and hence the immersed depth, of the floating foundation unit in a static condition. However, by their pin-jointed nature, shackle and lug connections transfer limited moment loads back to their point of attachment compared with fixed ended connections. During dynamic motion of the proposed assembly, the reduced moment transfer capability between counterweight and floating structure results in the two bodies moving under separate response functions to environmental loads. The two bodies then interact with one another through the shackle and lug connections. Similar to a dual pendulum, the result is an overall response to environmental loads that may prove difficult to analyse and predict.

The wire/chain drive gear to raise and lower the counterweight may be mounted on top of the hull buoyancy tanks if they maintain adequate freeboard in operation. However, should the operational case demand that the buoyancy tanks are fully submerged, either the drive gear would have to be operable underwater, increasing CAPEX through higher specification requirements, or else relocated inside the tower transition piece, increasing system complexity. The same consideration applies to the mooring system tensioning gear.

CN204436705 proposes a similar suspended counterweight for its floating foundation but uses a rigid weight block and secures this rigid weight block to seabed anchors below and to the floating unit above the weight block with wires. The proposed arrangement integrates the weight into the mooring system. CN204436705 behaves in effect as a two-body system with cable connections between the two separate bodies which, in the absence of moment transfer capability, results in the two bodies moving under separate response functions to environmental loads.

A further problem with existing wind turbines is that the marine environment can damage equipment mounted thereon, for example by means of corrosion.

The invention seeks to mitigate at least one of the afore-mentioned problems, or at least provide an alternative wind turbine and method for installing a wind turbine.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a floating wind turbine having a movable keel that is arranged to adjust the position of a centre of mass of the wind turbine. It is a further object of the invention to provide a wind turbine having a movable keel, wherein connector members that connect the movable keel to a tower-float assembly transmit bending moments from the keel to the tower-float assembly when the keel is loaded transversely. It is a further object of the invention to provide a wind turbine that is arranged to behave in the manner of a single body in response to movement of the water when the keel is in the deployed position. It is a further object of the invention to provide a wind turbine that includes at least one drive unit arranged to deploy the keel that is temporarily installed on the tower-float assembly. It is a further object of the invention to provide an installation method that enables a wind turbine to be moved easily from relatively shallow water adjacent a quayside assembly position to a relatively deep water installation position. It is a further objective to provide an installation method that reduces the amount of quayside side space required when compared with a traditional wind turbine assembly process, which takes place at a quay.

At least one of the objects is achieved according to the invention described below.

According to one aspect of the invention there is provided a wind turbine for deployment offshore, including: a tower-float assembly having a tower for supporting a nacelle and a rotor, and a float arranged to maintain at least part of the tower above a surface of a body of water; a keel assembly including a keel and at least one connector member connecting the keel to tower-float assembly, the at least one connector member is moveably attached to the tower-float assembly, and the keel is movable between a non-deployed position proximal to the tower-float assembly and a deployed position distal from the tower-float assembly; and a drive system including at least one drive unit arranged to move the keel between the non-deployed and deployed positions, wherein the at least one drive unit is releasably attached to the tower-float assembly and is removable from the tower-float assembly after the keel is moved to the deployed position.

When the keel is in the non-deployed position the wind turbine has a shorter length than in the deployed position, and therefore the wind turbine is easier to assemble and install. When the keel is in the deployed position the wind turbine is operationally more stable. The wind turbine has a centre of mass. The centre of mass has a first position when the keel is in the non-deployed position. The centre of mass has a second position when the keel is in the deployed position. The second position is different from the first position. The deployed position of the keel is located deeper into the water than the non-deployed position. Thus, moving the keel to the deployed position increases the length of the wind turbine. Moving the keel towards the deployed position adjusts the centre of mass of the wind turbine from the first position to the second position. The second position is located below the first position, which provides a more stable wind turbine in use.

The at least one connector member provides a substantially rigid connection between the keel and the tower-float assembly. Moment loads applied to the keel when the keel is deployed are transmitted to the tower-float assembly via the at least one connector member. Therefore the keel and tower-float assembly behave in the manner of a single body in response to movement of the water when the keel is in the deployed position.

Having removable drive units enables the drive system to be reused on other wind turbines during an installation phase. For example, allowing for delays and repairs, six drive systems could be cycled during a typical windfarm installation campaign for the installation of all wind turbines. When all wind turbines have been installed and their respective keels moved to their respective deployed positions, the drive systems can be returned to shore. . After the initial deployment, the drive system will only be required for maintenance purposes or when the installation is decommissioned. This reduces the overall cost of the installation and prevents damage to the drive system due to long-term exposure to sea conditions. The drive systems can be used for future field developments.

The keel can include a plurality of keel modules, for example for ease of manufacture and assembly.

The drive system can include at least one drive unit per keel module. This helps to ensure that the keel is raised and lowered evenly. At least some of the drive units are releasably attachable to the tower-float assembly. Preferably each drive unit is releasably attachable to a respective buoyancy aid, such as a respective buoyancy tank.

The wind turbine can include at least one drive unit per connector member. This helps to spread the driving load required to raise and lower the keel. It provides a better balanced drive system. Some embodiments include a plurality of drive units per connector member.

The wind turbine can include a controller for synchronising operation of the drive units. This ensures that the keel remains horizontal when the keel is raised and lowered.

At least one drive unit can comprise a hydraulic drive unit. For example, at least one drive unit can comprise a hydraulic jack.

At least one drive unit can comprise an electric motor.

The wind turbine can include a drive mechanism for transmitting drive from the drive unit to the connector member.

The wind turbine can include a plurality of connector members movably attached to the tower-float assembly. For example, at least one connector member can be provided for each keel module. Preferably a plurality of connector members is provided for each keel module. At least some of the connector members can be arranged parallel to one another. Preferably each connector member is arranged parallel with the other connector members.

At least one connector member can include drive formations. The drive mechanism can include at least one drive device arranged to selectively engage the drive formations to selectively transmit drive to at least one connector member. A plurality of connector members can include drive formations. The drive mechanism can include a plurality of drive devices, wherein respective drive devices are each arranged to selectively engage drive formations on respective connector members. In some embodiments each connector member includes drive formations and the drive mechanism includes at least one drive device per connector member that is arranged to selectively engage drive formations on its respective connector member. The drive devices can be mounted in a frame. Operation of the drive devices can be synchronised by the controller.

The drive mechanism can include a rack and pinion system. A rack can be applied to each connector member. A pinion can be connected to each drive unit. The drive unit is arranged to drive the connector member via the rack and pinion system.

At least one connector member can be elongate. For example, at least one connector member can comprise a rod. Preferably each connector member comprises a rod. At least some of the rods can each have a fixed length. That is, the connector member is not telescopic. At least some of the rods can be made from steel. At least some of the rods are rectilinear. In some embodiments, the rods each have a length that is greater than or equal to 30m, preferably greater than or equal to 40m and more preferably greater than or equal to 50m. In some embodiments the length of the rods is less than or equal to 90m, preferably less than or equal to 80m, more preferably less than or equal to 70m. In some embodiments the rods have a length of around 60m. The length of the rods used is at least partly determined by the size of the wind turbine, for example can be at least partly determined by the size of the float.

At least some of the connector members can be rigid. Preferably each connector member is rigid. At least one connector member can have a rigid connection with the keel.

At least one connector member can be tubular. Preferably each connector member is tubular. In some embodiments at least one connector member can comprise first and second tubular members arranged concentrically. This is to help provide a sufficient tensile capacity to take dynamic loading and fatigue margin for the life of the connector member. The second tubular member can be located within the first tubular member. The second tubular member can be fixed to the first tubular member.

The wind turbine can include a plurality of connector members connected together by bracing members. This fixes the connector members together and the connector members move together as a unit. For example, a plurality of connecter members can be connected together at their upper ends by bracing members.

At least one connector member can be movably connected to the tower-float assembly by a plurality of guides. Preferably each connector member is movably connected to the tower-float assembly by a plurality of guides. The float can include at least one buoyancy aid, such as at least one buoyancy tank, and at least one connector member can be movably connected to the buoyancy aid by a plurality of guides. This enables the keel to move with respect to the buoyancy aid. Preferably a plurality of connector members are each movably connected to the buoyancy aid by a plurality of guides.

At least one connector member can be constrained to move along an axis. The axis can be a vertical axis. Thus during deployment and retraction operations only, the keel can be arranged to move vertically upwards and downwards when the sea is calm. During normal operation of the wind turbine, when the keel is in the deployed position, the position of the keel is fixed relative to the float. Each connector member can be arranged to move along a respective axis. Each respective axis can be vertical. Thus during deployment and retraction operations only, the keel can be arranged to move vertically upwards and downwards when the sea is calm. During normal operation of the wind turbine, when the keel is in the deployed position, the position of the keel is fixed relative to the float.

The connector member can include a longitudinal axis. At least one connector member can be constrained to move along an axis that is co-axial and/or parallel with the longitudinal axis of the connector member. Each connector member can include a respective longitudinal axis. Each connector member can be constrained to move along a respective axis that can be co-axial and/or parallel with the respective longitudinal axis of the connector member.

At least one connector member can be connected to a respective keel module.

Each keel module can include a housing. The housing can have a plate-like outer structure, that is, the housing can have an overall structure that is relatively flat, like a disk. The housing structure can include beams, and preferably steel beams. The beams can comprise beam sections, such as I, H and channel sections. The beams can be used to form internal and/or external vertical walls of the housing. Plates, such as steel plates, can be provided for upper and lower walls of the housing. The housing can have a hollow interior. The hollow interior can be arranged to be filled with ballast. The housing can include a plurality of cells for receiving the ballast. Preferably the ballast can include solid material. Preferably the ballast can be in the form of a slurry. The keel module can include a plurality of holes formed in an outer wall to enable fluid contained within the slurry to escape from the keel module.

At least one connector member can be connected to a respective keel module housing. At least one connector member can be connected to an inner part of the respective keel module housing.

At least one connector member can be connected to an outer surface of the respective keel module, such as an upper surface. At least one connector member can protrude perpendicularly upwards from the outer surface, and preferably from the upper surface. Preferably a plurality of connector members can protrude perpendicularly upwards from the outer surface of the keel module, and preferably the upper surface of the keel module. The upper surface can be planar.

At least one keel module can be connected to another keel module by a linkage. Preferably each keel module can be connected to a plurality of other keel modules by respective linkages. In this arrangement the keel modules move as a unit. The linkages can provide a rigid connection. The linkages can allow some movement between keel modules, for example each linkage can be connected to its respective keel modules by a pin connection. In some embodiments the drive system can be arranged to move at least one keel module independently of at least one other keel module.

The keel modules can be arranged in a plane. The keel can include three keel modules. The keel can have a triangular arrangement when viewed in plan, and preferably an equilateral triangular arrangement. The modules are located within the plane at the apexes of the triangle. In some embodiments each keel module can have a hexagonal shape when viewed in plan. However the keel modules can have other shapes when viewed in plan, such as a rectangular shape. Other more complex shapes can be used.

The float can include a first set of buoyancy aids, such as a set of buoyancy tanks. At least some of the buoyancy aids each have a respective keel module associated therewith. The respective keel module can be movably connected to the respective buoyancy aid by at least one respective connector member. The drive system can be arranged to move each respective keel module with respect to its respective buoyancy aid. In some embodiments the float includes at least three outer buoyancy aids. Typically at least one drive unit is mounted on each outer buoyancy aid. The drive unit is arranged to move its respective keel module. The respective keel module is mounted below its respective buoyancy aid. The respective keel module is arranged to move vertically with respect to its respective buoyancy aid. A major outer surface of the respective keel module can be arranged substantially parallel with a lower end face of the respective buoyancy aid. The plane of the keel module is transverse to a longitudinal axis of the respective buoyancy aid.

The float can include a central buoyancy aid, such as a central buoyancy tank. Preferably the tower is mounted on the central buoyancy aid. The central buoyancy aid can include a heave plate located towards its lower end. In some embodiments there is no keel module associated with the central buoyancy aid. The central buoyancy aid can be arranged to include some ballast water at the start of operations. This ballast water may be used to assist with tensioning a mooring system during installation. Further ballast water may be gradually discharged over time to offset the increase in marine growth weight on the submerged buoyancy aids. The central buoyancy aid can include a system for controlling the influx of water into the aid, and expulsion of water from the aid, in order to adjust the amount of water ballast contained therein.

The float can include a second set of buoyancy aids, such as a set of buoyancy collars. The second set of buoyancy aids can be removable from the float during an installation process. For example, each respective second buoyancy aid can be releasably attached to a respective first buoyancy aid. The second set of buoyancy aids can provide additional stability to the wind turbine before the keel is deployed. The second set of buoyancy aids can be removed from the float after the keel is deployed to a sufficient depth to stabilise the wind turbine. Using a second set of floating aids enables a more compact arrangement of the first set of floating aids to be used.

A dynamic cable can be provided that transfers electrical power generated by the wind turbine to a sub-station. The cable can connect the wind turbine directly to the sub-station or via several interconnected floating units.

According to another aspect of the invention there is provided a method for installing a wind turbine offshore. The method includes: providing a wind turbine having a tower-float assembly including a tower for supporting a nacelle and a rotor, and a float arranged to maintain at least part of the tower above a surface of a body of water; a movable keel; at least one connector member connecting the keel to tower-float assembly; and a drive system having at least one drive unit arranged to move the keel; providing a submersible barge having a deck; mounting the wind turbine on the deck of the submersible barge; the submersible barge transporting the wind turbine to an installation site in a manner wherein the deck can be located above the surface of the water; at the installation site, the submersible barge sinking into the water such that the deck can be submerged below the surface of the water; the wind turbine floating off the submerged deck; and the drive system moving the keel from a non-deployed position proximal to the tower-float assembly to a deployed position distal from the tower-float assembly.

The method can include removing at least one drive unit from wind turbine after the keel is moved to the deployed position. The method can include removing a plurality of drive units from the wind turbine after the keel is moved to the deployed position. Preferably all drive units are removed. This enables the drive units to be reused and saves them from damage caused by environmental conditions, for example can save them from corrosion.

The wind turbine can be arranged according to any configuration described herein.

The method can include returning the barge to a quayside after the wind turbine separates from the barge. When the barge returns to the quayside, it can be used again to install a new wind turbine.

The method can include moving the keel vertically downwards to the deployed position. The keel can be constrained to move vertically downwards only.

The method can include at least partly assembling the wind turbine on the deck of the submersible barge. The barge can be moored at the quayside and component parts are lifted onto the deck via lifting apparatus such as a crane. Assembling the wind turbine on the barge frees up space on the quayside.

Assembling the wind turbine can include mounting a keel, or component parts thereof, onto the barge deck. If component parts of the keel are mounted onto the deck, the components parts of the keel can be fixed together on the deck.

Assembling the wind turbine can include mounting at least one buoyancy aid, such as a buoyancy tank, on to at least one of the keel and the deck. For example, at least one buoyancy aid can be mounted on to at least one keel module.

Assembling the wind turbine can include connecting a plurality of buoyancy aids, such as a plurality of buoyancy tanks, together to form the float. Connecting the buoyancy aids together preferably takes place on the barge. The buoyancy aids can be connected together by bracing members.

The float can be formed by connecting a first set of buoyancy aids together; and releasably attaching a second set of buoyancy aids to the first set of buoyancy aids. The first set of buoyancy aids can comprise a set of buoyancy tanks. The second set of buoyancy aids can comprise a set of buoyancy collars.

Assembling the wind turbine can include movably attaching a first set of connector members to a first buoyancy aid, such as a first buoyancy tank, and connecting the first set of connector members to a first keel module. The first set of connector members are movably connected to the first buoyancy aid by a first set of guides.

Assembling the wind turbine can include movably attaching a second set of connector members to a second buoyancy aid, such as a second buoyancy tank, and connecting the second set of connector members to a second keel module. The second set of connector members are movably connected to the second buoyancy aid by a second set of guides.

Assembling the wind turbine can include movably attaching a third set of connector members to a third buoyancy aid, such as a third buoyancy tank, and connecting the third set of connector members to a third keel module. The third set of connector members are movably connected to the third buoyancy aid by a third set of guides.

Assembling the wind turbine can include releasably attaching at least one drive unit to the first buoyancy aid, and preferably a first set of drive units.

Assembling the wind turbine can include releasably attaching at least one drive unit to the second buoyancy aid, and preferably a second set of drive units.

Assembling the wind turbine can include releasably attaching at least one drive unit to the third buoyancy aid, and preferably a third set of drive units.

Assembling the wind turbine can include mounting a tower onto the float, and preferably on top of a central buoyancy aid, such as a central buoyancy tank.

Assembling the wind turbine can include mounting a nacelle and rotor onto the tower.

The barge can be moored at a quayside during the assembly process. As the barge moves away from the quayside towards the installation site another submersible barge can be moved to the quayside for assembly of another wind turbine. For example, a barge that has recently returned from the installation site. This helps to ensure a quick production of the wind turbines and a high utilization of the quayside.

The keel comprises a plurality of keel modules and the method can include filling at least one keel module with ballast. Preferably the ballast includes solid material. The ballast can be provided in the form of a slurry. The ballast can be pumped into a hollow space within a keel module housing. The housing can include holes arranged to allow liquid in the slurry to escape, leaving solid material within the housing. The ballast can be pumped from a ship, which can moor alongside the barge

The method can include fixing the position of the wind turbine with mooring tethers. The wind turbine can include tether deployment and tensioning devices. The method can include tensioning the tethers with tensioning devices. Optionally, at least one of the available drive units can be used to power the tensioning devices. This obviates the need for a separate drive unit. Alternatively a power source that is provided for the drive units can also provide power to tensioning device drive systems. In normal operation the tensioning devices and keel drive units function separately.

The method can include reattaching the drive units and raising the keel.

According to another aspect of the invention there is provided a method for installing a wind turbine, the method including mounting the wind turbine onto a deck of a submersible barge, moving the barge to an installation site, submerging the barge so that the deck is below a surface of the water, and separating the wind turbine from the barge. The wind turbine can be arranged according to any configuration described herein.

According to another aspect of the invention there is provided a wind turbine for deployment offshore, including: a tower-float assembly having a tower for supporting a nacelle and a rotor, and a float arranged to maintain at least part of the tower above a surface of a body of water; and a keel assembly including a keel and at least one connector member connecting the keel to tower-float assembly. The at least one connector member can be moveably attached to the tower-float assembly, and the keel can be movable between a non-deployed position proximal the tower-float assembly and a deployed position distal from the tower-float assembly. The wind turbine can include a drive system having at least one drive unit arranged to move the keel between the non-deployed and deployed positions. In preferred embodiments the at least one drive unit can be releasably attached to the tower-float assembly and can be removable from the tower-float assembly after the keel can be moved to the deployed position.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 shows a first prior art floating wind turbine in a first operating condition;

Figure 2 shows the wind turbine of Figure 1 in a second operating condition;

Figure 3 shows a second prior art floating wind turbine in a first operating condition;

Figure 4 shows the wind turbine of Figure 3 in a second operating condition;

Figure 5 is an isometric view of a wind turbine according to a first embodiment of the invention, which includes a tower, a float, and a keel that is movable with respect to the float;

Figure 6 is an enlarged isometric view of a lower part of the wind turbine of Figure 5;

Figures 7a to 7c show a drive system that is use to deploy the keel;

Figures 8 to 15 illustrate a wind turbine installation process;

Figure 16 shows a drive system for use in a second embodiment of the invention; and

Figure 17 shows a wind turbine according to a third embodiment of the invention having an arrangement of buoyancy collars temporarily attached to a float to improve the buoyancy of the float.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

Figures 5 to 7c show a wind turbine 1 in accordance with a first embodiment of the invention. The wind turbine 1 includes a tower 3, a float 5, a keel 7, connector members 9, and a drive system 11 for moving the keel 7. The wind turbine also includes a nacelle 13a and a rotor 13b mounted on the tower 3.

The tower 3 and float 5 together are referred to as the tower-float assembly. The keel 7 and connector members 9 together are referred to as the keel assembly.

The purpose of the float 5 is to maintain the tower 3 above the surface of the sea 10, in its correct orientation (substantially vertical) to ensure that the rotor 13b and nacelle 13a can operate properly. The float 5 effectively provides a floating hull for the tower 3, nacelle 13a and rotor 13b. The float 5 comprises a plurality of buoyancy aids, preferably in the form of buoyancy tanks 15. Each buoyancy tank 15 comprises a cylindrical drum that is closed at each end. Each buoyancy tank 15 can be made from steel, and/or other materials such as concrete, carbon fibre, and glass reinforced plastic (GRP). Each buoyancy tank 15 has a central longitudinal axis Z-Z. Each buoyancy tank 15 is oriented such that the central longitudinal axis is arranged substantially vertically, and therefore the tanks are arranged as floating columns. In the arrangement shown in Figure 5 there are three outer buoyancy tanks 15. Each outer buoyancy tank 15 is arranged at the apex of a triangle, and preferably an equilateral triangle, when viewed in plan. A central buoyancy tank 15b is located centrally between the three outer buoyancy tanks 15. The central buoyancy tank 15b has a central longitudinal axis Y-Y, which is arranged parallel with the longitudinal axes of the outer buoyancy tanks 15. Each outer buoyancy tank 15 is connected to the central buoyancy tank 15 by upper and lower bracing members such as spokes 17,19. The upper and lower spokes 17,19 protrude radially outwards from upper and lower parts of the central buoyancy tank 15 respectively. The upper and lower spokes 17,19 connect to upper and lower parts respectively of the outer buoyancy tanks 15. The spokes 17,19 fix the outer buoyancy tanks 15 to the central buoyancy tank 15b.

Optionally, a heave plate 21 can be attached to a lower end of the central buoyancy tank 15b. The heave plate 21 is arranged transversely to the longitudinal axis Y-Y of the central buoyancy tank 15b. Bracing members 23 can be used to further support the heave plate 21. The heave plate 21 has a larger width (or diameter) than an underside of the central buoyancy tank 15b. As shown in Figure 5, the heave plate 21 can have a hexagonal shape, when viewed in plan.

The tower 3 is mounted on top of the central buoyancy tank 15. The tower 3 has a central longitudinal axis X-X that his arranged substantially co-axially with the central longitudinal axis Y-Y of the central buoyancy tank 15b.

The keel 7 provides resistance to heave motion, and helps to stabilize the wind turbine. The keel 7 is movably attached to the float-tower assembly and is arranged to move from a non-deployed position adjacent to the lower parts of the buoyancy tanks 15,15b to a deployed position, which is distal from the lower parts of the buoyancy tanks 15,15b. That is, the keel 7 is moveable from a non-deployed position that is relatively shallow in the water to a deployed position which is located deeper in the water. The keel 7 is moved vertically upwards and downwards. Adjusting the position of the keel 7 adjusts the positon of a centre of mass of the wind turbine. Deploying the keel 7 effectively increases the length of the wind turbine, which has the effect of moving the centre of mass downwards. Having a lower centre of mass provides a more stable wind turbine.

The keel 7 has a modular construction, which comprises a plurality of keel modules 25. In the arrangement shown in Figure 5, the keel 7 includes three keel modules 25. Each keel module 25 comprises a housing. Each housing is filled with ballast to weight the keel 7. Typically solid ballast is used. For some applications each housing can be filled with a slurry. Each housing typically has a plate-like overall structure, that is, the housing can have an overall structure that is relatively flat, like a disk. The housing can comprise upper 32 and lower planar walls, vertical side walls 34 and a hollow interior (see Figure 8). The hollow interior comprises a grillage, which gives a cellular structure 36. Each keel module 25 can have a hexagonal shape when viewed in plan. The housing structure can include beams, such as steel. The beams can comprise beam sections, such as I, H and channel sections. The beams can be used for external vertical walls 34 and/or internal vertical walls of the housing. Plates, such as steel plates, can be provided for upper 32 and lower walls of the housing.

Typically, each keel module 25 is associated with a respective outer buoyancy tank 15 and is arranged to move with respect to its buoyancy tank 15. Each keel module 25 is positioned below its respective outer buoyance tank 15, and is arranged to move in a direction that is substantially co-axial with the longitudinal axis Z-Z of the respective buoyancy tank.

As shown in Figure 5, a preferred arrangement of the keel 7 is that the keel modules 25 are located in a plane, and each keel module 25 acts as a heave plate. The plane is transverse to the longitudinal axes Z-Z of the outer buoyancy tanks 15. Each keel module 25 is located within the plane at the apex of a triangle, and preferably an equilateral triangle, when viewed in plan. Each keel module 25 is preferably connected to at least one other keel module 25 by way of a bracing member 27, and preferably is connected to a plurality of other keel modules 25. The bracing members 27 provide the keel 7 with a rigid structure, and help to prevent the rods 9 from flexing. Optionally, the bracing members 27 can be of the type that can be adjusted. For example, the length of the bracing members 27 can be adjusted to tension the keel structure after installation. The keel 7 moves as a unit with respect to the tower-float assembly during deployment and retraction of the keel 7. The position of the keel 7 is fixed with respect to the float 5 when the keel 7 is in the deployed position. An aperture 29 is formed by the keel modules 25 and bracing members 27. The aperture 29 is located centrally. The aperture 29 is aligned with the heave plate 21.

Connector members 9 connect the keel 7 to the tower-float assembly. The keel 7 is moveably connected to the tower-float assembly. The connector members 9 comprise rods 9. Each rod 9 has a fixed length, and is preferably tubular. At least one rod 9, and preferably a plurality of rods 9, connects the keel 7 to each of the outer buoyancy tanks 15. In Figure 5, a set of three rods 9 is provided per keel module-buoyancy tank pair. Respective rods 9 in each set protrude perpendicularly upwards from an upper surface 32 of the respective keel module 25. Additionally, or alternatively, the rods 9 can be connected to an interior surface of the keel module 25. Lower (distal) ends of the rods 9 are fixed to their respective keel module 25. Upper (proximal) ends of the rods 9 are fixed together by bracing members 33. The rods 9 in each set of rods are arranged substantially parallel with one another. The rods 9 in each set of rods are distributed evenly around the outer surface of the of the respective buoyancy tank 15. This provides a well-balanced arrangement. The rods 9 are movably connected to the outer buoyancy tanks 15 by at least one guide 31. A plurality of guides 31 is provided for each rod 9. Four guides 31 per rod are shown in Figure 5. The number of guides 31 is in part determined by the length of the rod 9 and height of the outer buoyancy tank 15. The guides 31 are arranged to enable each rod 9 to slide along a rectilinear path. For example, the guides 31 can be mounted on an outer surface of the buoyancy tank 15 in sets, and preferably on a curved outer surface. Each set of guides 31 is associated with one of the rods 9. The guides 31 in a set of guides are arranged along a line on the outer surface, and spaced apart along the length of buoyancy tank 15. Thus each rod 9 is constrained to move along a single axis. Thus each keel module 25 is constrained to move vertically upwards and downwards. This enables the keel 7 to be moved vertically downwards when deployed.

The length of the rods 9, and hence the deployment depth of the keel 7, is selected in accordance with the size of the wind turbine and the environmental conditions. The rods 9 have a sufficient length to enable the keel 7 to be deployed to the deployment position. Consequently, the rods 9 tend to have a much larger length than the height of the buoyancy tanks 15. It will be appreciated that some wind turbines may require a deeper or shallower deployment. The deployment position is determined according to the design of the wind turbine.

At least some of the rods 9, and preferably each rod 9, includes a set of drive formations 35, for interacting with the drive system 11. Each drive formation 35, can be for example a tooth-like sheer plate that protrudes radially outwards from the rod 9. In a preferred arrangement, the drive formations 35 are spaced apart along at least part of the length of the rod and are arranged in at least one line. Preferably at least some drive formations 35 protrude outwardly in a first radial direction. Preferably at least some drive formations 35 protrude radially outwardly in a second direction. Typically the second direction is opposite to the first direction. One of the first and second directions can be towards the respective buoyancy tank 15.

The drive system 11 is arranged to deploy the keel 7 by lowering it deeper into the sea. The drive system 11 is also arranged to retract the keel 7 by raising it to a shallower depth. The drive system 11 achieves this by interacting with drive formations 35 to move the rods 9 upwards or downwards as required, which drives movement of the keel 7. At least part of the drive system 11 is removable from the tower-float assembly, which allows the drive system 11 to be reused. Allowing for delays and repairs, six drive systems 11 can be cycled during a typical windfarm installation campaign. This reduces the cost of the installation. Also, after the installation has been completed, the drive system 11 can be returned to land.

The drive system 11 can be reinstalled on a wind turbine for maintenance or decommissioning. The drive system 11 can be stored and maintained onshore for use in future field developments. In one arrangement, the drive system 11 includes a set of drive units, for example in the form of hydraulic cylinders 37. The drive system 11 preferably includes a rigid frame 39. Typically, at least one hydraulic cylinder 37 is provided for each rod 9. Each hydraulic cylinder 37 is releasably attachable to its respective buoyancy tank 15 adjacent its respective rod 9, for example each cylinder 37 can be bolted to the tank 15 or can make use of a quick release mechanism such as clamps or toggles. Having hydraulic cylinders 37 that are releasably attachable to the buoyancy tanks 15 enables the cylinders 37 to be removed from the tower-float assembly after the keel 7 has been deployed. This enables the hydraulic cylinders 37 to be used on other wind turbines in the installation, thus fewer drive systems 11 are required than the total number of wind turbines in an installation.

The hydraulic cylinders 37 on each buoyancy tank 15 are connected together by the frame 39. The frame 39 includes engagement formations 41 that are arranged to engage and release the drive formations 35. The frame 39 is driven by the cylinders 37. The frame is able to move upwards or downwards according to the direction of action of the cylinders 37. The frame 39 lowers and lifts the keel 7 by selectively interacting with the drive formations 35. This is achieved by the engagement formations 41 selectively engaging and disengaging the drive formations 35. Thus the drive system 11 is able to selectively drive the rods 9 in upwardly and downwardly directions. Operation of the hydraulic cylinders 37 is synchronised to ensure that the keel is deployed evenly. For example a suitable control system can be provided to control operation of the hydraulic cylinders 37. When deploying the keel 7, the hydraulic cylinders 37 are synchronized to drain fluid at the same time thereby maintaining the frame 39 in a substantially horizontal orientation. When the hydraulic cylinders 37 reach the end of their stroke, stops 43 mounted to the buoyancy tank 15 temporarily fix the positions of the rods 9, for example by each stop 43engaging one of the drive formations 35, which relieves the load on the hydraulic cylinders 37. The engagement formations 41 release their respective drive formations and the hydraulic cylinders 37 are then extended upwards to elevate the frame 39 to an upper position, wherein the engagement formations 41 engage a new drive formation 35 further up the rod 9. The stops 43 disengage the rods 9, and the cycle repeats until the keel 7 reaches the deployed position.

The deployed position for the keel 7 is achieved when the permanent shear stops 45, which are located towards upper ends of each rod 9 contacts an upper surface 46 of its respective buoyancy tank 15 (see Figure 7b). The hydraulic cylinders 37 are fully closed and the rigid frame 39 rests on top of the support columns 47. The hydraulic cylinders 37 are not required for the normal operation of the wind turbine and so may be detached and removed from site and reused on subsequent floating foundations. Figure 7c shows the top of the outer buoyancy tank 15 after removal of the drive units 37.

To lift the keel 7, for example for decommissioning or maintenance purposes, the hydraulic cylinders 37 are reinstalled on to the tower-float assembly and the above process is performed in reverse. For example, the engagement formations 41 drivingly engage the drive formations 35 at a low part of the cylinder 37 stroke, drive the rods 9 upwards, and then release the drive formations 35 at an upper part of the cylinder stroke.

The wind turbine is held in position using mooring lines 49, which connect to cable/chain tensioning units 51 at deck level via sheaves 53 mounted lower down the float 5. Additionally, or alternatively, tensioning units fitted as an integral part of the mooring line 49 and operated underwater may be used. The wind turbine floats with an operational water line at approximately below the height of the upper spokes 17.

Since the rods 9 are rigid, the keel 7 reacts to dynamic transverse, pitch and roll loads by transmitting bending moments to the tower-float assembly. This makes the float 5 more responsive to motion of the keel 7 and the keel 7 more responsive to motion of the float 5. Thus the float 5, rods 9 and keel 7 behave as a single body, which makes the behaviour of the wind turbine more predictable. If cables rather than rigid rods 9 were to support the keel 7 from the float 5, the cables would not transmit bending moments from keel 7 to tower-float assembly nor from tower float assembly to keel 7. Motion of the float 5 would not be as responsive to motion of the keel 7. Likewise, motion of the keel 7 would not be as responsive to motion of the float 5. A cable connection would allow the float 5 and keel 7 to move more independently as two separate bodies. In particular, the mass moment of inertia of a single body system is greater than for a two body system. The rigid rod system thus presents a larger resistance to dynamic loading and improved wind turbine generation performance.

Having an adjustable keel 7 helps to ensure that the centre of mass of the wind turbine is located below the centre of buoyancy when the keel 7 is deployed. This reduces the footprint of the final assembly. Hence, less space is required at the assembly site and a barge assembly technique becomes feasible. When the geometry of the wind turbine and its mass distribution is such that its centre of mass is below its centre of buoyancy in operation, then the single body behaves in operation as a spar foundation. The required water plane area to achieve stability is less than if the single body behaved as a semi-submersible foundation in which the centre of mass is above the centre of buoyancy.

Furthermore the single body retains sufficient static stability with the keel 7 retracted for assembly, transportation and launch phases.

In addition to the lower ends of the buoyancy tanks 15,15b, the keel 7 geometry has a planar top surface and a planer bottom surface, which are orientated transversely to the direction of heave. This generates added mass and damping effects which reduces heave motion of the wind turbine. The tower-float assembly's response to the wave spectrum at any given geographic location may thus be engineered by a suitable selection of the keel's surface area, mass and depth to achieve an optimum added mass, damping coefficient and mass moment of inertia.

A method for installing a wind turbine will now be described with reference to Figures 8 to 15.

Component parts of the keel assembly and tower-float assembly are fabricated and collated adjacent an assembly quay. Typically the components are of a weight defined by the capacity of an available shore side crane.

A submersible installation barge 55 moors alongside the assembly quay. The barge 55 has a deck 57 that is fitted with buoyancy tanks 59 to enable controlled sinking of the cargo barge.

The fabricated component parts are loaded onto barge 55 sequentially and assembled in a sequence that minimizes assembly time.

The keel modules 25 are laid flat on the deck 57 (see Figure 8). If required, the keel modules 25 are connected together by bracing members 27. The keel modules 25 include internal cells 36 that are filled with solid ballast either prior to lifting onto the barge 55 or after mounting on the deck 57. The solid ballast is preferably crushed mineral ore, and is preferably supplied to the keel modules 25 in the form of a slurry. For example, the slurry can be pumped from a cargo vessel preferably via a water pumped slurry system. The cargo vessel may moor alongside the barge 55 and fill the empty cells 36 of each keel module 27 with the slurry. Water drains through holes formed in keel module walls leaving solid ballast material filling the cells 36.

The central buoyancy tank 15b is mounted centrally, optionally with the heave plate 21 pre-attached to the lower end of the tank (see Figure 9). The central buoyancy tank 15b is positioned ready for welding to the outer buoyancy tanks 15. Temporary welder access platforms 61 and welding plant 63 may be installed on top of the central buoyancy tank 15 to support the welding works.

A first outer buoyancy tank 15 is placed on top of one of the keel modules 25 (see Figure 10). Preferably the rods 9 are pre-attached to the first outer buoyancy tank via guides 31. The upper spoke 17 comprises a first portion 17a that protrudes outwardly from the central tank 15b and a second portion 17b that protrudes outwardly from the outer tank 15. The first and second parts 17a,17b are abutted end to end and welded. The lower spoke 19 comprises a first portion 19a that protrudes outwardly from the central tank 15b and a second portion 19b that protrudes outwardly from the outer tank 15. The first and second parts 19a,19b are abutted end to end and welded. The lower end of each rod 9 is secured to its respective keel module 25 either by welding, pin and clevis arrangement, or other suitably engineering connection.

Preferably, the drive system 11 is pre-installed on the tower-float assembly, typically on an upper surface of the outer buoyancy tank 15, prior to mounting the buoyancy tank 15 on to the barge 55. At least part of the drive system 11, which typically includes a hydraulic drive or an electric motor, is releasably attached to the tower-float assembly, for example using bolts, clamps and/or toggles.

Each of the remaining outer buoyancy tanks 15 is then installed in a similar manner to the first outer buoyancy tank (see Figure 11).

The tower 3, nacelle 13a and rotor 13b are mounted on to the central buoyancy tank 15b, typically on an upper surface thereof (see Figure 12). This completes the assembly of the wind turbine.

The wind turbine 1 is tested and commissioned as fully as possible on the barge 55 before departure to the field.

The barge 55, with the wind turbine mounted thereon, is towed out to the launch location, or travels under its own motion if powered. As the barge 55 clears the quay, a second barge moors alongside the quay to start the assembly process for another wind turbine. It will be apparent that the keel 7 is in the non-deployed position at this stage.

When at the launch location, ballast tanks in the hull of the barge 55 are flooded in a controlled sequence. The barge 55 submerges and the buoyancy tanks 59 maintain a water plane area and hence intact stability (see Figure 13). As the barge 55 submerges, the wind turbine 1 becomes self-buoyant and detaches from the barge deck 57. The barge 55 and wind turbine 1 separate from one another. The wind turbine 1 is towed clear of the barge 55 and is taken to its target installation position. Figure 14 shows the submerged barge moved clear of the wind turbine 1.

The barge 55 resurfaces (see Figure 15) and returns to port to repeat the assembly and load out operation.

The keel modules 25 are lowered by the drive system 11 to the deployed position. The deployed position is at a greater depth than the non-deployed position. The drive system 11 lowers the rods 9 downwards, thereby increasing the depth at which the keel modules 25 are located. The drive system 11 drives the rods 9. Movement of the rods 9 is constrained by the guides 31. Each rod 9, and hence the keel module 25, is constrained to move along an axis. Each axis is substantially vertical in calm seas. The deployed position is typically achieved when the rods 9 have completed the maximum extent of their stroke.

The mooring lines 49 are attached to the sea bed to fix the location of the wind turbine 1.

The installation method has the following advantages:

- Since assembly of the wind turbine 1 takes place on the deck 57 of the barge 55 the area of the quayside required during the assembly process is minimized.
- Using a barge 55 for the assembly process minimizes the time the floating turbine assembly spends in port by enabling movement of the barge 55 as in a production line to separate work stations each, optimized for either float assembly or turbine assembly. This avoids concentration of material, tooling and personnel at a single work station and allows separate assembly work to take place simultaneously.
- A continuous assembly process can be set up that uses three separate barges each following the other between: a float assembly workstation; a turbine assembly workstation; and the installation site location to maintain a continuous installation process.
- Having barges available enables installed wind turbines to be moved, should that be necessary. For example, a wind turbine can be moved from the installation site using one of the available barges to a new installation site, or to a marine port for maintenance or decommissioning as a dry hull.

Part of a wind turbine in accordance with a second embodiment of the invention is shown in Figure 16. The wind turbine in accordance with the second embodiment is similar to the first embodiment except that the drive system 111 has a different arrangement from the drive system 11.

In the second embodiment, a pair of drive units, preferably in the form of a pair of hydraulic cylinders 137 is provided for each rod 109. The drive units 137 are mounted on an outer buoyancy tank 115. Each cylinder includes a drive device 141 for selectively engaging the drive formations 135 formed on the rods 109. This provides a more compact rigid design.

A wind turbine 201 in accordance with a third embodiment is shown in Figure 17. The wind turbine according to the third embodiment is similar to the first embodiment, or second embodiment, except that the float 205 can include buoyancy collars 200 fitted to the outer buoyancy aids (see Figure 17), such as outer buoyancy tanks 215. The buoyancy collars 200 provide additional buoyancy to the float 205 during the installation process. Preferably the buoyancy collars 200 are releasably attached to the outer buoyancy tanks 215. The buoyancy collars are typically removed prior to normal operation of the wind turbine. The buoyancy collars 200 can include apertures and/or recesses to enable the rods 209 to move relative to the buoyancy collars 200. For example, the buoyancy collars 200 may be fitted temporarily to the outer buoyancy tanks 215 during the assembly phase. The collars provide additional buoyancy and stability to the float 205 prior to the keel 207 being at least partially deployed. The buoyancy collars are typically removed after the wind turbine has floated off the barge 255 and after the keel modules 225 have been lowered to a sufficient depth to ensure static stability of the wind turbine without the need for the buoyancy collars. This allows for a more compact float 205 configuration.

Although the present invention has been described in connection with specific preferred embodiments, it should be understood that the invention as claimed should not be unduly limited to such specific embodiments. Furthermore, it will be apparent to the skilled person that modifications can be made to the above embodiment that fall within the scope of the invention.

For example, the drive system can include at least one drive unit in the form of an electric motor and a suitable drive mechanism for driving each rod 9. A suitable drive mechanism may comprise a rack and pinion drive gear system or other drive mechanism suited to the environment and mode of operation. One drive motor and rack and drive mechanism can be provided per rod 9. In another arrangement one drive motor and drive mechanism can be provided per keel module 25.

More than one type of drive system 11 can be included in a wind turbine. For example, some buoyancy tanks 15 may include a drive system 11 according to the first embodiment, while other buoyancy tanks may include a drive system 11 according to the second embodiment.

The rods 9 can be connected to the keel modules 25 by way of pin joints. The connection between the rods 9 and keel 7. In combination, three such pin jointed connections between each keel module 25 and the float 5 maintains a rigid, fixed end support for the keel module 25 and overall rigid body properties.

A different number of buoyancy aids can be used.

A different number of keel modules 25 can be used. The number of keel modules 25 typically matches the number of outer buoyancy tanks.

The keel 7 can have a different arrangement from that shown. For example, the keel 7 does not have to have a triangular arrangement. The keel modules 25 can have different shapes from hexagonal.

The keel modules 25 can comprise open concrete boxes.

The drive devices 41,141 can be in the form of hydraulic clamps.

In some embodiments at least one connector member can comprise first and second tubular members concentrically arranged. This is to help provide a sufficient tensile capacity to take dynamic loading and fatigue margin for the life of the connector member. The second tubular member can be located within the first tubular member. The second tubular member can be fixed to the first tubular member.

The central buoyancy tank can be arranged to include some ballast water at the start of operations. This ballast water may be used to assist with tensioning the mooring system during installation. Further ballast water may be gradually discharged over time to offset the increase in marine growth weight on the submerged buoyancy tanks. The central buoyancy tank can include a system for controlling the influx of water into the tank, and expulsion of water from the tank, in order to adjust the amount of water ballast contained therein.

The buoyancy aids 25 can comprise solid buoyancy blocks.

CLAIMS

1. A wind turbine for deployment offshore, including:

a tower-float assembly having a tower for supporting a nacelle and a rotor, and a float arranged to maintain at least part of the tower above a surface of a body of water;

a keel assembly including a keel and at least one connector member connecting the keel to tower-float assembly, the at least one connector member is moveably attached to the tower-float assembly, and the keel is movable between a non-deployed position proximal the tower-float assembly and a deployed position distal from the tower-float assembly; and

a drive system including at least one drive unit arranged to move the keel between the non-deployed and deployed positions, wherein the at least one drive unit is releasably attached to the tower-float assembly and is removable from the tower-float assembly after the keel is moved to the deployed position.

2. A wind turbine according to claim 1, wherein the keel includes a plurality of keel modules, and the drive system includes at least one drive unit per keel module.

3. A wind turbine according to any one of the preceding claims, wherein the drive system includes at least one drive unit per connector member.

4. A wind turbine according to any one of the preceding claims, including a controller for synchronising operation of each drive unit.

5. A wind turbine according to any one of the preceding claims, wherein at least one drive unit comprises a hydraulic drive unit.

6. A wind turbine according to any one of the preceding claims, wherein at least one drive unit comprises an electric motor.

7. A wind turbine according to any one of the preceding claims, including a drive mechanism for transmitting drive from the drive unit to the at least one connector member.

8. A wind turbine according to claim 7, wherein at least one connector member includes drive formations and the drive mechanism includes at least one drive device arranged to selectively engage the drive formations to selectively transmit drive to at least one connector member.

9. A wind turbine according to claim 8, wherein a plurality of connector members include drive formations and the drive mechanism includes a plurality of drive devices arranged to selectively engage drive formations on respective connector members.

10. A wind turbine according to any one of claims 7 to 10, wherein the drive mechanism includes a rack and pinion system.

11. A wind turbine according to any one of the preceding claims, wherein at least one connector member is elongate.

12. A wind turbine according to claim 11, wherein at least one connector member comprises a rod.

13. A wind turbine according to claim 11 or 12, wherein at least one connector member is tubular, and/or at least one connector member includes first and second tubular members arranged concentrically.

14. A wind turbine according to any one of the preceding claims, including a plurality of connector members connected together by bracing members.

15. A wind turbine according to any one of the preceding claims, wherein at least one connector member is movably connected to the tower-float assembly by a plurality of guides.

16. A wind turbine according to any one of the preceding claims, wherein at least one connector member is constrained to move along an axis.

17. A wind turbine according to claim 16, wherein the axis is a vertical axis.

18. A wind turbine according to any one of claims 3 to 17, when dependent on claim 2, wherein each keel module comprises a housing.

19. A wind turbine according to claim 18, wherein the housing has a hollow interior and the hollow interior is arranged to be filled with ballast.

20. A wind turbine according to any one of claims 3 to 19, when dependent on claim 2, wherein at least one connector member is connected to a respective keel module.

21. A wind turbine according to any one of claims 3 to 20, when dependent on claim 2, wherein at least one keel module is connected to another keel module by a linkage.

22. A wind turbine according to any one of claims 3 to 21, when dependent on claim 2, wherein the keel modules are arranged in a plane.

23. A wind turbine according to any one of claims 3 to 22, when dependent on claim 2, wherein the float includes a first set of buoyancy aids, such a set of buoyancy tanks, at least some of the buoyancy aids each have a respective keel module associated therewith, the respective keel module is movably connected to the respective buoyancy aid by at least one respective connector member, and the drive system is arranged to move each respective keel module with respect to its respective buoyancy aid.

24. A wind turbine according to claim 23, wherein the float includes a second set of buoyancy aids, such as a set of buoyancy collars, that are removable from the float during an installation process.

25. A method for installing a wind turbine offshore, including:

providing a wind turbine having a tower-float assembly including a tower for supporting a nacelle and a rotor, and a float arranged to maintain at least part of the tower above a surface of a body of water; a movable keel; at least one connector member connecting the keel to tower-float assembly; and a drive system having at least one drive unit arranged to move the keel;

providing a submersible barge having a deck;

mounting the wind turbine on the deck of the submersible barge;

the submersible barge transporting the wind turbine to launch site in a manner wherein the deck is located above the surface of the water;

at the launch site, the submersible barge sinking into the water such that the deck is submerged below the surface of the water;

the wind turbine floating off the submerged deck; and

the drive system moving the keel from a non-deployed position proximal to the tower-float assembly to a deployed position distal from the tower-float assembly.

26. A method according to claim 25, including removing at least one drive unit from the wind turbine after the keel is moved to the deployed position

27. A method according to claim 25 or 26, wherein the wind turbine is arranged according to any one of claims 1 to 24.

28. A method according to any one of claims 25 to 27, including returning the barge to a quayside.

29. A method according to any one of claims 25 to 28, including moving the keel vertically downwards to the deployed position.

30. A method according to any one of claims 25 to 29, including at least partly assembling the wind turbine on the deck of the submersible barge.

31. A method according to claim 30, wherein assembling of the wind turbine includes mounting a keel, or component parts thereof, onto the deck.

32. A method according to claim 31, wherein assembling the wind turbine includes mounting at least one buoyancy aid, such as a buoyancy tank, on to at least one of the keel and the deck.

33. A method according to claim 32, wherein assembling the wind turbine includes connecting a plurality of buoyancy aids together to form a float.

34. A method according to claim 33, wherein the float is formed by connecting a first set of buoyancy aids together; and releasably attaching a second set of buoyancy aids to the first set of buoyancy aids.

35. A method according to any one of claims 26 to 34, wherein assembling the wind turbine includes mounting a tower onto the float, and preferably on top of a central buoyancy aid, such as a central buoyancy tank.

36. A method according to any one of claims 26 to 35, wherein assembling the wind turbine includes mounting a nacelle and rotor onto the tower.

37. A method according to any one of claims 26 to 36, wherein the barge is moored at a quayside during the assembly process.

38. A method according to any one of claims 25 to 35, wherein the keel comprises a plurality of keel modules and filling at least one keel module with solid ballast.

39. A method according to claim 38, wherein the ballast is provided in the form of a slurry.

Intellectual Property Office

Application No:	GB1808375.8	**Examiner:**	Adrian Mooney
Claims searched:	1-24	**Date of search:**	30 October 2018

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
X	1-4, 6-8, 10, 11, 14, 18, 20 & 22	CN107201991 A (UNIV SHANGHAI JIAOTONG) - See description and figures, which show a moveable keel member 12 connected to the floating tower assembly 3 by connector member 13.
A	-	WO2014/000802 A (RODRIGUEZ) - Discloses a floating tower assembly for a wind turbine which includes keel members 350 connected to damping systems 382.
A	-	EP2479103 A (DCNS) - Discloses a wind turbine tower assembly which includes support structure which is moveable and connected by connecting members 21 & 23.
A	-	WO2017/157399 A (STIESDAL AS) - Discloses wind turbine with moveable keel 3 in figures 7a & 7b.

Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC^{X} :

Worldwide search of patent documents classified in the following areas of the IPC

B63B; F03D

The following online and other databases have been used in the preparation of this search report

EPODOC, WPI

Intellectual Property Office

International Classification:

Subclass	Subgroup	Valid From
F03D	0013/25	01/01/2016
B63B	0039/06	01/01/2006