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REVIEW

Current Status and Future Trends for Mooring Systems of Floating Offshore Wind Turbines

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ABSTRACT

With the increasing demand of energy and the limitation of bottom-fixed wind turbines in moderate and deep waters, floating offshore wind turbines are doomed to be the right technical choice and they are bound to enter a new era of rapid development. The mooring system is a vital system of a floating wind turbine for station-keeping under harsh environmental conditions. In terms of existing floating wind turbine projects, this paper is devoted to discussing the current status of mooring systems and mooring equipment. This paper also presents the mooring analysis methods and points out the technical difficulties and challenges in mooring design, installation, operation and maintenance stages. Finally, the developing trends of the mooring system are summarized, aiming to provide a reference for future mooring research.

1. Introduction

Stimulated by global low-carbon policies and promoted by the development of new energy, the wind energy, a kind of renewable clean energy, has been exploited worldwide for its advantages of sustainability and huge reserves, as well as for the increasing maturity of technologies in power engineering, mechanical engineering and offshore engineering. Compared with the land wind energy, the ocean wind energy is more abundant, more stable, vaster in spaces for exploitation, and of fewer impacts on the environment [1]. The wind power has gained rapid development as of 2021 with a globally accumulated capacity of 837 GW, among which the accumulated offshore capacity (bottom-fixed plus floating) has reached 56 GW. Further, the offshore wind energy is doomed to have a bright prospect in human's history by reaching 380 GW by the end of 2030 and 2,000 GW by 2050 [2].

In the past decades, the majority of offshore wind farms was restricted to the offshore shallow water where

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bottom-fixed wind turbines were predominantly deployed. The wind turbine foundations include monopile, jacket, tripod and so on. However, their feasibility is limited by the water depth up to 50 m [3,4]. A higher construction and installation cost will be incurred in moderate and deep waters. By comparison, the floating wind turbine (FWT) is more mobile and flexible to deploy, easier to dismantle, and more suitable for relatively deeper waters. In addition, the deployment site of FWTs is far away from the coastline, eliminating the harm of noise and electromagnetic waves to the environment [5]. Also, compared to nearshore fixed turbines, a larger capacity of turbine like the 9.5 MW units in Kincardine UK can be installed onto floating structures to harness more power so as to achieve a higher levelized cost of energy (LCOE) [6]. All these advantages have pushed FWTs to take on an important historical mission in the development of ocean renewable energy. In recent ten years, more and more FWT projects have been constructed in moderate and even deep waters. Table 1 summarizes the worldwide FWT projects already commissioned or being constructed, among which the Hywind Tampen project has reached water depth as deep as 300 m. The accumulated capacity for the commissioned FWTs as of 2021 has exceeded 121.4 MW [2].

For a FWT, its mooring system is a crucial system for the station-keeping purpose. The mooring system generally consists of mooring lines, connectors and anchors. In rough seas, the floating foundation of a FWT interacts with the mooring system and the mooring lines restrain the motion of the floater by providing sufficient restoring forces mainly in horizontal directions. Particularly in extreme environment conditions, the floater's motion displacement, mooring line tension, wind turbine pitch angle and acceleration should meet the requirements of specification in codes and standards, such as DNVGL OS E301, API RP 2SK, API RP 2SM etc. For the design of a mooring system, not only the hydrodynamic performance but also the cost of fabrication and installation should be taken into account [7]. Hence, it is one of the objectives in this paper to review the current status of FWTs' mooring systems.

Table 1. World Floating wind turbine projects and their mooring systems as of July 2022 (commissioned or to be commissioned*)

Country	Year	Project	Wind turbine Capacity (MW)	Floating Foundation Type	Water Depth (m)	Mooring Type
France	2019	Floatgen	2	Barge	33	Semi-taut
France	2022*	Groix-Belle-ILe	4×6	Semi-Submersible	55-70	Semi-taut
France	2023*	EFGL	3×10	Semi-Submersible	70-100	Catenary
France	2024*	EolMed	3×10	Barge	55	Catenary
Norway	2009	Hywind I	2.3	Spar	220	Catenary
Norway	2021	TetraSpar Demo	3.6	Spar	200	Catenary
Norway	2022*	Hywind Tampen	11×8	Spar	260-300	Catenary
Portugal	2020	WindFloat Atlantic	3×8.4	Semi-Submersible	100	Catenary
United Kingdom	2017	Hywind Scotland	5×6	Spar	95-109	Catenary
United Kingdom	2021	Kincardine	5×9.5+2	Semi-Submersible	60-80	Catenary
Japan	2013	Fukushina Ph1	2	Semi-Submersible	120	Catenary
Japan	2016	Fukushina Ph2	7	Semi-Submersible	120	Catenary
Japan	2016	Fukushina Ph3	5	Spar	120	Catenary
Japan	2019	Hibiki	3.2	Barge	55	Catenary
China	2021	Sanxia Yinling	5.5	Semi-Submersible	29.2	Catenary
China	2022*	Haizhuang Fuyao	6.2	Semi-Submersible	65	Catenary

2. Types of Mooring Systems

The mooring systems are classified in a variety of types, according to their mooring line configurations and materials, operation requirements and layout characteristics. Depending on the mooring line configuration, the mooring systems of FWTs mainly include three types, i.e., catenary moorings, taut moorings and tether moorings.

2.1 Catenary Mooring

The catenary mooring refers to a suspended mooring line that is in the shape of a catenary under the effect of self-gravity while the bottom of the mooring line lies on the seabed (see Figure 1). As such, the anchor point only bears horizontal force. The catenary mooring usually uses the steel chain as the material of mooring lines. The restoring force comes from the gravity of the mooring line itself. It is generally applied to the water depth below 1000 m, especially less than 500 m [8]. With the increase of water depth, the length and weight of mooring lines will increase significantly, resulting in a high cost and reduced deck payload of the floater. At the same time, the mooring radius will also increase obviously, affecting the laying of submarine pipelines and ship navigation.

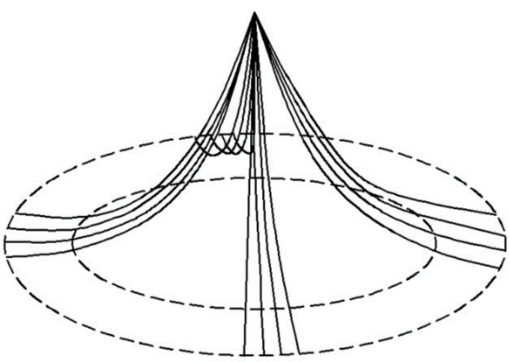

Figure 1. The catenary mooring system [9]

So far, the catenary mooring has been most widely used for floating oil and gas platform, as well as FWTs (see Table 1), because of the following advantages: a. The catenary mooring has a simple structure and stable reliability. b. It is economical in the water depth below 500 m. c. The mooring chain has relatively easier fabrication and simpler installation as compared to taut moorings and tether moorings.

The world's first commercial floating wind farm, Hywind Scotland, consists of five 6 MW wind turbines that are 25 km away from Peterhead Scotland. In the water of 95 m ~ 109 m, every FWT adopts a spar foundation with draft of 78 m. Since its center of gravity is lower than the center of buoyancy, the structure has superior stability even in harsh seas [10]. The five FWTs are anchored to the seabed through three catenary mooring chains. Each mooring chain is about 900 m long with a diameter of 0.09 m. The mooring chains are connected to the floater through a delta connection using the bridle so as to obtain the extra yaw stiffness (Figure 2). The bridle is usually used in spar foundations rather than semi-submersible foundations, because in semi-submersible foundations there is sufficient distance between a fairlead and the center of rotation, leading to enough yaw stiffness. Three suction anchors for each turbine are 5 m in diameter, 16 m tall, with an approximate anchor radius of 850 m [11]. In addition, a special fairlead chain stopper system (see Figure 3) was developed by MacGregor specially for mooring wind turbines in Hywind Scotland wind farm. It can rotate both horizontally and vertically in order to prevent the out-of-plane bending fatigue of the mooring chains [12].

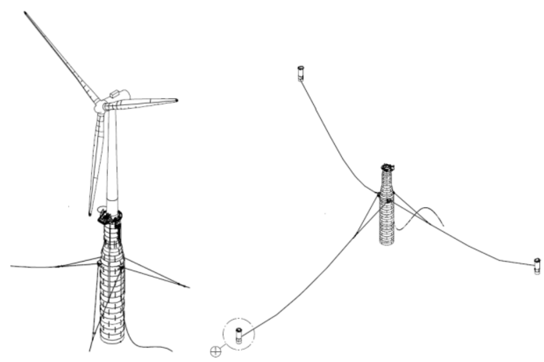

Figure 2. Hywind Scotland mooring system [11]

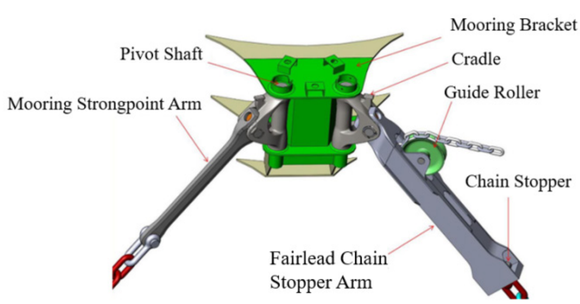

Figure 3. Hywind Scotland fairlead chain stopper system [11]

Sanxia Yinling (Figure 4), the first FWT at the Yangjiang offshore wind farm in Guangdong Province of China, is a FWT demo project with the typhoon-resistant technology. The site is about 30 km offshore with water depth of 29.2 m. The floater adopts a semi-submersible structure of three columns with a diameter of 11.8 m. It has a total displacement (include ballast) of 13,000 t and a design draft of 13.5 m. The mooring system is designed as 3 groups of catenary mooring lines, each composed of 3 mooring lines. Each mooring line is made up of 4 segments, including a chain segment near the fairlead end, a clump segment, a wire rope segment and a chain segment near the anchor end, from top to bottom. The top end of the mooring line is equipped with a chain stopper and the bottom end is anchored on the seabed by a suction anchor.

Figure 4. China Sanxia Yinling [13]

Nowadays, FWTs are in the high-speed development path towards large tonnage. Also, the new FWT projects will be principally deployed in the water depth of 100 m ~ 300 m. Under this circumstance, catenary moorings will still be the mainstream options in the near future.

2.2 Taut Mooring

The taut mooring system has mooring lines that are taut in tension between the fairlead on the floater and the anchor point on the seabed (Figure 5) such that there are no bottom lying lines. Typically, the angle between the line and the seabed is between 30 degrees and 45 degrees. Therefore, the anchor point should bear both horizontal and vertical forces. Examples of such anchoring structures include suction anchors and vertical load anchors. The taut mooring system usually uses wire ropes, high-strength nylon ropes, polyester cables or other synthetic materials. The recovery force is primarily provided by the axial tensile deformation of the mooring line [14]. In deep water, the taut mooring can greatly reduce the length and weight of mooring lines, as well as the mooring radius. Nonetheless, in shallow water, the stiffness of the mooring line should be very large, excessively increasing the tension of the mooring line. As a consequence, it is more suitable for floaters in deep and ultra-deep waters [8], though over the last two decades a number of applications to wave energy converters in moderate water depths have been realized [15].

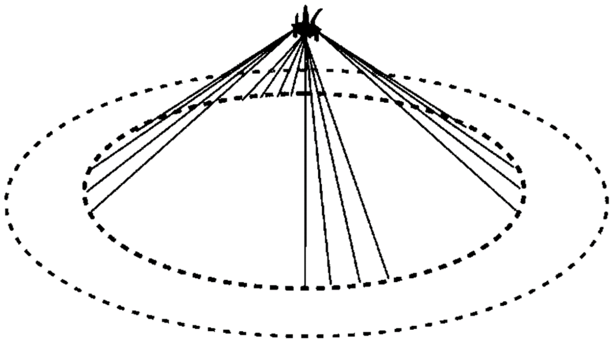

Figure 5. The taut mooring system [9]

In existing FWT projects, only a couple of turbines use semi-taut moorings, such as Floatgen and Groix-Belle-ILe (being constructed) in France (see Table 1). Floatgen has a reinforced concrete foundation designed by Ideol. The foundation is designed as a barge to improve its stability [16] while the damping pool in the central opening of foundation is used to suppress foundation's wave-frequency motions. The dimensions of the square-ring shaped foundation are 36 m in breadth, 9.5 m in height and 7.5 m in draft. Floatgen's semi-taut mooring system consists of six mooring lines, assigned into three groups. From the fairlead to the drag embedment anchor, a single mooring line is composed of a top chain, a nylon cable and a bottom chain. Such an innovative use of nylon cables is a worldwide premiere for the permanent mooring of a large floater in offshore engineering. Simultaneously, the mooring lines are equipped with buoys to prevent friction with the seabed, as well as to balance the self-weight of the mooring lines. Such a novel mooring system satisfies two seemingly paradoxical requirements at the same time. One is the competitive fabrication and installation cost and the other is the ability to keep the floater stable in rough seas [17].

Compared to the catenary mooring system, the taut mooring system possesses the following advantages:

a. The mooring radius is significantly reduced, leading to a smaller seabed area occupied by mooring equipment and fewer risks of collision with other underwater equipment nearby.

b. The restoring stiffness of the mooring line is larger, providing larger restoring forces. Therefore, the horizontal offset of the floater can be greatly reduced.

c. The material of the mooring line has a lighter weight. Thus, not only the self-weight of the mooring system but also the load of mooring system on the foundation is reduced.

d. The length of the underwater mooring line is greatly shortened, making the taut mooring very competitive in cost in deep and ultra-deep waters.

e. The material like nylon and polyester is outstanding in mechanical performance, especially fatigue resistance and corrosion resistance.

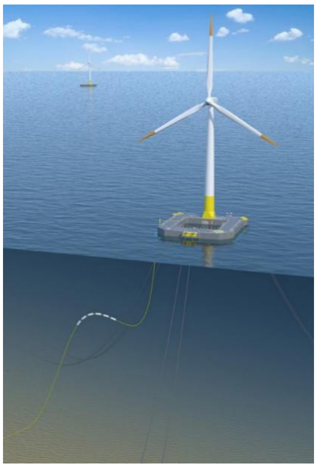

Figure 6. Floatgen and its mooring system [18]

Nonetheless, the mooring lines need to bear huge tension and axial stress under harsh operating states. Under the influence of alternating loads for a long life span, the underwater nylon cables are prone to fatigue failure and material aging. Furthermore, storage, transportation and installation processes all raise strict requirements on cables. In an improper operation, the scrap damage may occur due to cable breakage or abrasion. The sediment entering the cable will also pose a great threat to the mooring system [19]. All these lead to a high cost of fabrication and installation, which is a recognized disadvantage of the taut mooring.

2.3 Tether Mooring

The tension leg platform (TLP) shown in Figure 7 is vertically moored by tendons (also called tethers). The tendon consists of steel tubes with high axial stiffness. The buoyancy of the TLP is greater than its own gravity and the excessive buoyancy is balanced by the pre-tension in tendons. As a result, the stability of the floating foundation principally depends on the mooring system [5]. The anchors like driven piles and gravity anchors are required to withstand large vertical loads. The tether mooring is particularly suitable for the water depth greater than 300 m and its common applications go to oil and gas platforms in Gulf of Mexico. Since the tendons are vertically connected to the seabed, the mooring radius is small.

However, the fabrication process of a tendon is extremely complicated and delicate. Also, the tendon installation requires special installation vessels that can both keep the foundation stable and connect the tendons. Consequently, a high fabrication and installation cost is incurred during tether moorings. In addition, its risks are enormous. If one tendon fails, the stability of the foundation will suddenly decrease, causing a high risk of capsizing [21]. Due to the pre-tension of tendons, the natural heave frequency of the TLP is extremely high (2 Hz ~ 4 Hz). This will cause high frequency response problems, such as springing and ringing [22]. For these reasons, the tether moorings have not been used on a large scale for FWTs yet. The TLP concept for a FWT stays at the stage of small-scale tests and numerical calculations.

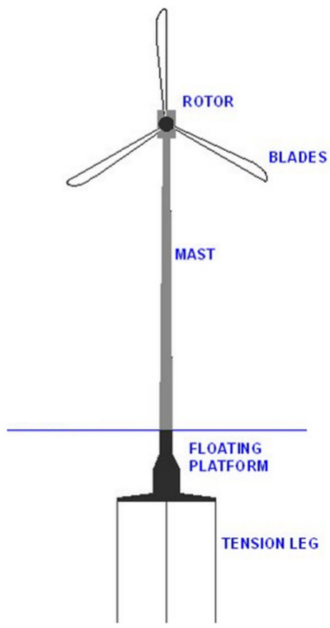

Figure 7. Sketch of FWT with tether mooring [20]

The GICON-SOF project (see Figure 8), a tension-leg FWT with the tether mooring, was initiated in 2009. The floating foundation consists of four columns, anchored to the seabed by four vertical tendons and additional eight slanting tendons. In 2013, a 1:37 scaled model test of the GICON-SOF 2 MW foundation was carried out at the Maritime Research Institute Netherlands (MARIN) [23,24]. In 2016, the combined wind and wave tests were conducted for a 6 MW turbine on the GICON-SOF foundation and the experimental results showed very satisfactory performance for its stability. Though it was reported that GICON-SOF would have prototype sea trials with a 6 MW ~ 8 MW turbine [25], so far no trials have been implemented.

2.4 Other Classifications of Moorings

Depending on the duration of the offshore operation, mooring systems are classified into two categories, temporary moorings and permanent moorings. The temporary mooring is applied to temporary platforms or vessels that operate for periods ranging from a few days to several months, while the permanent mooring is used for floating structures that operate in fixed sea areas for a long time. In terms of the design life, the operation time can be several years or several decades.

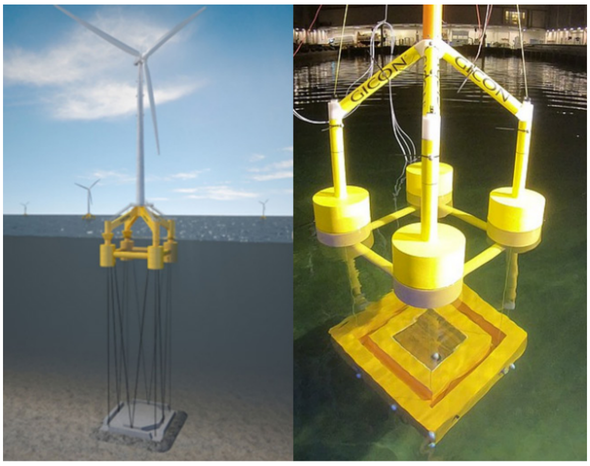

Figure 8. GICON-SOF project (left) and its model test (right) [26]

The mooring systems can also be categorized into spread moorings and single-point moorings according to the requirement of restricting the heading of the floater. The spread mooring, where mooring lines are distributed around the platform, can restrict the offset and heading of the platform from all directions. The single-point mooring is often used for ship-shaped floating structures under severe sea conditions with frequent changes in wind, wave and current directions. It has one or more mooring lines connected with the rotating center, so that the floater has a weathervane effect and can rotate with the direction of wind, waves and currents. The single-point mooring is commonly used in the floating production storage and offloading (FPSO). Though the single-point mooring has not been applied to an actual FWT project, it was adopted by the Eolink [27] FWT concept (Figure 9). Unlike most FWTs, it can spin around its rotating center to face the wind. The patented single point mooring is able to withstand large tide range in shallow water as well [27], but this concept has not been applied to real FWT project yet.

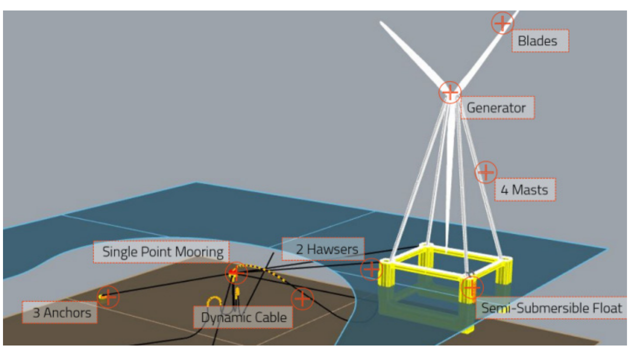

Figure 9. Eolink with single-point mooring [27]

3. Mooring System Equipment

The mooring system for FWTs chiefly contains mooring lines, anchors and connectors. This section discusses the current status of mooring equipment.

3.1 Mooring Lines

3.1.1 Chain

The chain is a common mooring line component with a simple connection and good abrasion-resistance property. The mooring chain is made of a plurality of steel links welded and connected with each other. According to the link form, chains are divided into two kinds: stud-link chains and stud-less chains (Figure 10). The stud-link chain has a stud in the middle to prevent it from entangling and it is often used for temporary moorings, requiring multiple retractions. The stud-less chain, without a stud inside, is about 10% lighter than the stud-link chain with the same breaking strength. There are other advantages for the stud-less chain. For example, there is no loosening of the stud, no cracks at the joints of the stud and it is easier to fabricate and inspect. As a result, the stud-less chain is preferred for permanent moorings.

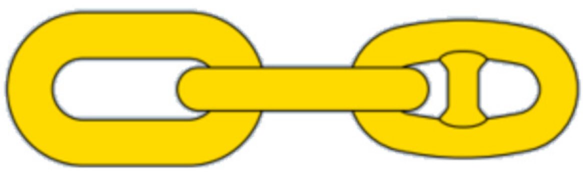

Figure 10. Stud-less chain (left) and stud-link chain (right) [9]

Chains have a wide variety of diameters and grades. The nominal diameter of ocean engineering chains ranges from 70 mm to 200 mm. The classification standard provides several grades based on tensile strengths, shown in Table 2. The grades include R3, R3S, R4, R4S, R5 and R6. R7 is still under development.

Table 2. The performance of different grades of mooring chains [29]

Grade	Yield Stress (N/mm^2)	Tensile Strength (N/mm^2)	Elongation (%)
R3	410	690	17
R3S	490	770	15
R4	580	860	12
R4S	700	960	12
R5	760	1000	12
R6	900	1100	12

In terms of manufacturers, the Jiangsu Yaxing company in China can produce ultra-high strength R6 chains that have been successfully used in a deep-water drilling platform. Such chains meet the latest international codes and standards, reaching an internationally advanced level.

3.1.2 Wire Rope

The wire rope is made up of multiple strands of metals that wound into a spiral. The wire rope in mooring system usually includes six strands, eight strands and spiral strands, shown in Figure 11. Generally, with more strands, the wire rope has a greater breaking strength, but a heavier weight and a higher fabrication cost. Six strands and eight strands are preferred in the temporary mooring. They are easier to fabricate because they can bend on a winch. Nevertheless, they tend to produce rotational torque when stretched, causing torsion of the wire rope. By contrast, spiral strands are torque neutral, since they have multiple layers wound in opposite directions. Moreover, the spiral wire rope has better corrosion resistance due to its compact structure. The uniform surface of the spiral wire rope also makes it easier to be sheathed, such as the polyurethane sheath. Based on the above advantages, the spiral wire rope is suitable for permanent moorings [30].

Under the same breaking load, the wire rope is lighter and more elastic than the chain, but the structure of the wire rope is more complicated and vulnerable, and its fabrication and installation costs are higher. It is often used in taut moorings or as the middle division of catenary moorings. As for manufactures, the Juli company in China supplies various types of wire ropes such as 1870, 1960, 2160 etc. Globally, the Neptune company in Singapore and the Bridon company in UK have leading manufacturing capabilities [8].

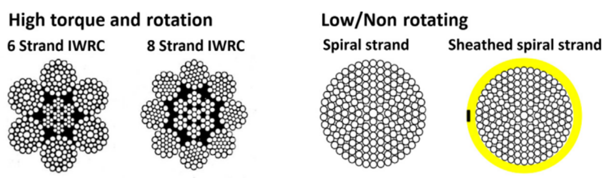

Figure 11. Various types of wire ropes [7]

3.1.3 Synthetic Fiber Rope

The materials of synthetic fiber ropes involve polyester, high molecular polyethylene (HMPE), aramid, and so on. The structural composition of a synthetic fiber rope is shown in Figure 12. Due to its elastic property, the synthetic fiber rope is appropriate for taut moorings. Nonetheless, the complex mechanical properties of synthetic fiber ropes bring new challenges to mooring analysis, including its variable stiffness, creep and slack-taut issues.

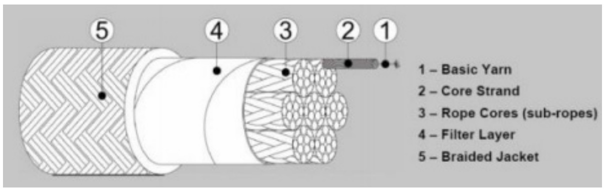

Figure 12. Composition of a synthetic fiber rope [31]

In deep water, the synthetic fiber rope is propitious to reduce the weight and length of mooring lines. The main advantages of synthetic fiber rope include high elasticity, high strength (900 MPa or higher) and low weight. To be specific, under the same breaking force the mass per unit length is only 1/10 of that of the chain or 1/3 of that of the wire rope and the weight is even lighter in water. Additionally, it possesses prominent fatigue resistance performance and excellent corrosion resistance performance [32]. Nevertheless, it is likely to be damaged by sharp objects. Sands would also invade the jacket and damage the rope.

Concerning the manufactures, Lankhorst in Netherland has more than 200 years of manufacturing experience. Its GAMA98 synthetic fiber rope is made of parallel rope cores within an outer jacket. The tension and length of each parallel rope can be precisely controlled during fabrication [33]. The Sixiong rope industry in China completed the production and manufacturing of synthetic fiber ropes that have been successfully used by the CNOOC Lingshui17-2 project for offshore gas exploitation, achieving a huge breakthrough in the field of mooring rope manufacturing.

3.2 Anchors

The choice of anchors is mainly determined by the water depth, the condition of soil and the load type that the anchor point needs to bear. Also, the cost of transportation and installation is a key factor. Typical ocean engineering anchors are shown in the Figure 13, categorized by water depths (shallow to ultra-deep) and soil types (hard to soft).

3.2.1 Gravity Anchor

The gravity anchor is the simplest and oldest anchor foundation in existence. It provides anchor force through the friction with the seabed and its own weight. As a result, the gravity anchor is generally large in size and usually made of steel and concrete. Normally, it is inexpensive to install, but only suitable for medium to hard soil conditions and difficult to remove during decommissioning.

3.2.2 Driven Pile

The driven pile is a hollow steel pipe that can bear both horizontal and vertical loads generated by the friction resistance between the pile and the surrounding soil. In general, the driven pile must be driven deep enough below the seabed to achieve the desired holding capacity. It is usually installed by pilling hammers or vibratory hammers. There are also some limitations of the driven pile. For instance, the disturbance to the seabed cannot be ignored. Also, when the water depth exceeds 1000 m, the strict installation requirements for equipment leads to a great difficulty of piling. Three driven piles have been used in Haizhuang Fuyao in China.

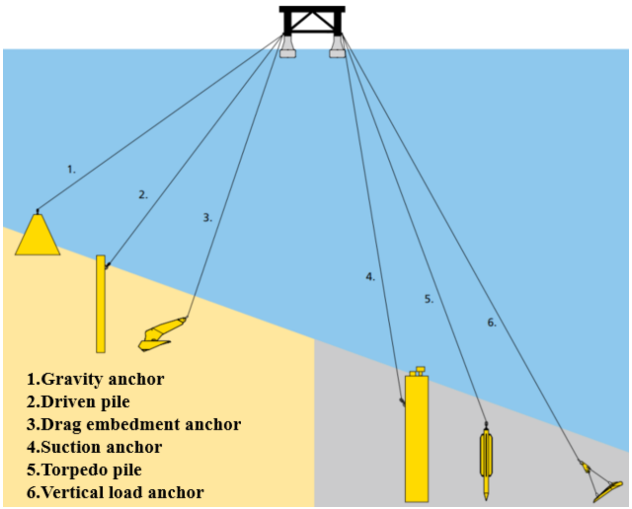

Figure 13. Typical mooring anchors [9]

3.2.3 Drag Embedment Anchor

The drag embedment anchor is one of the most commonly used anchors presently. It offers the horizontal load in the same direction as the installation direction. It is for this reason that the drag embedment anchor is often used in catenary moorings. In addition, certain drag embedment anchors are capable of offering vertical forces now. Generally, the main soil resistance occurs in front of the anchor, and therefore the resistance largely depends on its fluke area [34]. Drag embedment anchors have been used in Floatgen France, Hibiki Japan, WindFloat Atlantic Portugal and so on.

3.2.4 Suction Anchor

Suction anchors are suitable for a wide range of water depths, mainly used in clay, sand and granular layers. Recent applications to FWT projects include Hywind Scotland UK, Sanxia Yinling China, Hywind Tampen Norway etc., among which the Hywind Scotland and the Hywind Tampen use a shared anchoring system. The suction anchor can withstand large horizontal and vertical loads of mooring lines. It must be specially designed for soil conditions. Moreover, it is complex to construct and expensive to install. Divers or remote operated vehicles (ROV) are required to install and remove the submersible pumps. The suction anchor is generally a steel cylindrical pipe with an open bottom and a closed top. When installed, the suction anchor is lowered to the seabed and the lower edge of the pipe is embedded into the soil by its own weight. Then, the water in the suction pile is continuously pumped out to reduce the pressure inside the cylinder. The vertical pressure produced by the internal and external pressure difference acts on the top of the pipe, so that the pipe will be continuously pressed into the soil until the cylinder body is all drained and the bottom is closed [35] (Figure 14). In this figure, 'L' denotes the depth to which the suction anchor sinks under the force from hydrostatic pressure difference.

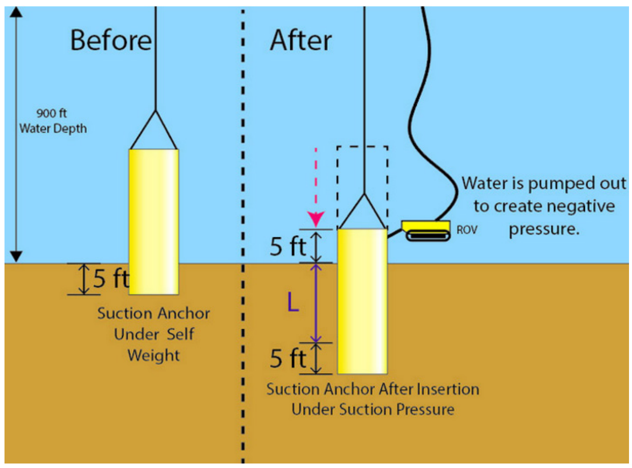

Figure 14. Installation process of the suction anchor [36]

3.2.5 Torpedo Pile

The torpedo pile, driven into the seabed by its own kinetic energy, can withstand both horizontal and vertical loads. The torpedo pile has a small size and good pullout resistance. Also, it is omnidirectional and self-installed, so that it is adaptive for ultra-deep water. Nevertheless, considerations arise to the large usage of steel and its inability to recycle.

3.2.6 Vertical Load Anchor

The vertical load anchor is installed in the same way as the drag embedment anchor, but it penetrates deeper into the soil. The vertical load anchor can bear both horizontal and vertical loads. It is primarily utilized in deep-water moorings.

3.2.7 Summary

Driven piles, drag embedment anchors and suction anchors have been widely applied to FWT projects. Gravity anchors are often used for FWTs in shallow waters provided the soil penetration is sufficiently deep. Torpedo piles and vertical load anchors are not in practical use for FWTs while they have been popularly adopted in deep-water oil and gas exploration. Nonetheless, as the offshore wind development trends towards deep waters, torpedo piles and vertical load anchors will become the potential choice.

3.3 Connectors

Connectors are used to connect the mooring line components. Common connectors in marine engineering include shackles, kenter shackles, pear shackles and swivels. However, due to the limited fatigue life, they can only be used in temporary moorings rather than permanent moorings.

Since it is hard to inspect and replace connectors in permanent moorings, the connector must be robust and durable. The recommended connectors in permanent moorings include long term mooring (LTM) D-shackles and H-shackles. D-shackle (Figure 15 left) consists of a bow component and a pin component. H-shackle (Figure 15 right), named for its shape, can be used to connect chains to chains, chains to wire ropes, chains to synthetic fiber ropes etc. Other types of connectors may be allowed to use in permanent moorings if the fatigue life and the structural strength are qualified.

Figure 15. D-shackle (left) and H-shackle (right) [7]

4. Mooring Analyses

This section is committed to discussing the differences and features of mooring analysis methods including static, quasistatic and dynamic analyses, frequency-domain and time-domain analyses, uncoupled and coupled analyses.

4.1 Static, Quasistatic and Dynamic Analyses

Generally, the motion responses of a floater under environmental loads can be divided into three categories of motions: steady state, low frequency and wave frequency. The response of a mooring system in the steady state can be obtained by static analysis. Meanwhile, the low-frequency response can be analyzed by a static method as well, for the period of the motion is long [37]. One of the typical methods of static analysis is the catenary equation method in which the environmental loads are regarded as static, in order to determine the equilibrium position of the floater, the geometric shape of the mooring lines and the tension distribution along the mooring lines. However, the static analysis ignores the coupling between the foundation and the mooring system, the fluid force on the mooring lines and the elastic deformation of the mooring lines, etc. As a result, the static method can hardly meet the requirements of accuracy when the floater is expected to experience large motions and it is only applicable to the preliminary design of a mooring system.

Following the preliminary design, the dynamic response of the whole system should be determined. In this process, the usually adopted methods include the quasistatic analysis and the dynamic analysis. The quasistatic approach ignores the vertical motion of the mooring system and the dynamic effects of the mooring lines, i.e., added mass, damping, drag force and fluid acceleration. In this approach, the motion of the foundation is subdivided into various instantaneous states and the equilibrium position is acquired by using the static analysis for these instantaneous states. The main shortcoming of this method is that it does not consider the influence of the dynamic effects of the mooring lines on floater's wave-frequency motions. Hence, if wave-frequency impact is negligible, the quasistatic method can be used to predict the response of the whole system. Furthermore, it has been proved [38] that the quasistatic method can achieve satisfactory prediction by using a safety factor with high efficiency.

On the contrary, the dynamic analysis accounts for the time varying properties of the mooring lines. Such an approach is able to accurately simulate the nonlinear characteristics, such as the nonlinear hydrodynamic force on mooring lines, the nonlinear deformation of the mooring lines, and the friction between the mooring lines and seabed, etc. The commonly used methods in dynamic analysis include the finite element method and the centralized mass method. Kwan [37] figured out that the ratio of tensions calculated by dynamic analysis to those calculated by quasistatic analysis is in the range of 1.2 to 19.5. In general, the dynamic analysis is recommended to predict the responses of floater and mooring lines.

4.2 Frequency-domain and Time-domain Analyses

Frequency-domain analysis is a simple and efficient technique. In frequency-domain analysis, the response of the system is made up of frequency-dependent components and solved by the principle of linear superposition of different frequencies. Moreover, the frequency-domain analysis not only determines the motions of the floater and the tension of the mooring lines separately, but also analyzes the mean response, low frequency response and wave frequency response respectively as well. The recommended analysis procedures provided in API RP 2SK [39] are shown as follows:

a. Determine the mean environmental loads acting on the floater and predict the equilibrium position using static analysis.

b. Determine the low-frequency motion using hydrodynamic analysis. In this process, the mooring stiffness at the equilibrium position is required.

c. Determine the wave-frequency motion using RAOs.

d. Determine the motions of the floater and the tension of the mooring lines using dynamic or quasistatic analysis.

e. Compare the maximum offset and maximum mooring line tension against the design criteria.

However, when using the frequency-domain analysis, its limitations should be noticed. This approach is linearized, and therefore it approximates the nonlinearities including the nonlinear deformation of the mooring lines, geometric nonlinearity, fluid loads and bottom friction etc. Furthermore, the extreme value is obtained from statistical distributions rather than directly from time-domain simulations. On the other hand, though the nonlinear spectral analysis can be adopted for the dynamic analysis, due to its complexity it is seldom used by engineers.

The time-domain analysis is more time-consuming but more accurate than the frequency-domain analysis. It is able to simulate all nonlinearities. Also, the time-domain analysis accounts for the coupling between the mean response, low-frequency response and wave-frequency response. The steps recommended by API RP 2SK [39] are summarized as follows:

a. Establish the hydrodynamic model including the floater and the mooring systems simultaneously. Determine the wind force and current force coefficients.

b. Run the time-domain simulation in the mooring analysis software (like OrcaFlex) and repeat it several times for different seeds.

c. Obtain the extreme value of the floater offset and the mooring lines tension by a proper statistical analysis method.

d. Compare the maximum offset and maximum mooring line tension against the design criteria.

The time-domain analysis is especially preferred for shallow water moorings, mooring lines with composite materials and/or other nonlinear situations, while the frequency-domain analysis is chosen for its efficiency.

4.3 Uncoupled and Coupled Analyses

In uncoupled analysis, the response of the floater and the mooring system are analyzed separately by two independent steps. The first step is to obtain the motion response of the floater based on the three-dimensional potential theory, where the effects of the mooring system are simulated as nonlinear displacement-dependent forces. Subsequently, the motion response of the floater is regarded as the excitation at the top end of the mooring lines and the dynamic response of the mooring lines is gained [40]. In this approach, the damping forces from the mooring system are either neglected or simplified as linear forces acting on the floater. In addition, usually the current loads on the mooring system are also not considered.

However, the foundation and the mooring system are coupled with each other in reality. Besides, the uncoupled method may produce substantial errors especially in deep water environment where the current loads is pronounced and the damping from the mooring system is remarkable [41]. Consequently, in this situation, the coupled analysis is required to determine the interaction between the floater and the mooring system. In the coupled analysis, the rigid model of the floater together with the slender model of the mooring system are solved simultaneously through the nonlinear time-domain analysis. The coupled response is obtained at every time step in order to fully capture all coupling effects such as stiffness, damping and inertia forces [42]. This approach is accurate though it is somehow time-consuming. Nowadays, the coupled analysis is routinely used in the offshore wind industry. Several software has the capacity of doing coupled dynamic analysis for a FWT in the multi-hour storm.

5. Key Challenges and Development Trends of Mooring Systems

5.1 Key Challenges of Mooring Systems

This section is dedicated to the technical difficulties in engineering practice and challenges in research and development of the mooring system from its whole life cycle: design, installation, operation and maintenance stages.

5.1.1 Challenges in Design Stage

Design for shallow-water moorings

The design for the deep-water mooring is relatively straightforward, as it is a proven technology in offshore engineering. But for a FWT in shallow-water environment, if catenary moorings are adopted, the length of chains need to be extremely long and the mooring radius usually reaches ten or twenty times of the water depth, in case that the anchor point is pulled up from the seabed when the maximum offset occurs. Even if a clump is connected to the chain to lessen the chain length, the mooring radius is still more than ten times of the water depth. Therefore, the amount of mooring chains used in shallow water is enormous, resulting in a high cost and ineffective use of ocean farm space. Sometimes, the cost of the mooring system may approach or even exceed the cost of the foundation itself.

Similarly, the taut mooring is also hard to be applied in shallow-water environment. When subjected to large environment loads like wind and waves, a FWT's motions may be remarkable. The taut mooring line needs to bear the station-keeping loads through its elastic deformation. Due to its large stiffness, the mooring line therefore experiences huge dynamic tension. The peak dynamic tension is more than ten times larger than the tension at the static offset. As the displacement of a floating megawatt turbine is becoming larger and larger, such a dynamic response characteristic of taut mooring inhibits its application to shallow-water power exploitation [43-45].

Slack-taut issue of mooring lines

Due to floater's motions, particularly sway, surge and heave, the slack-to-taut cyclic process frequently occurs in mooring lines, accompanied with snap tension. The snap tension can be several times or even a dozen times larger than the mean tension [46], causing the rupture of mooring lines to take place. This would quickly make mooring lines fail and would seriously affect the station-keeping of the foundation [47,48]. Thus, when the aero-hydro-servo-elastic coupling analysis is conducted for predicting the dynamic response of a FWT, the snap tension in mooring lines needs to be taken into account. Nonetheless, how the slack-taut cycles develop in mooring lines is unclear, not alone the detailed influence factors and the controlling mechanism of snap tension in mooring lines.

Nonlinear problems of mooring line materials

The elastic modulus of the wire rope is usually considered as a constant for its linear elasticity. Differentially, the polyester fiber rope has viscoelastic property, that is, the fiber rope has both elastic property of solid deformation and viscous property of liquid flow. Its stiffness changes with motion period, smoothness and load duration [49]. As a result, it is difficult to directly simulate the dynamic characteristics of the polyester fiber rope. For a composite material mooring system, the recovery stiffness of the whole mooring system is nonlinear because the material properties of distinct mooring materials are completely different. This makes numerical modelling more complicated and numerical simulation more time-consuming. Further, for a hybrid mooring, since segmented calculations are often adopted, the issue of discontinuous stiffness emerges.

5.1.2 Challenges in Installation Stage

Twist in mooring lines

The long-term integrity of the mooring system is so critical that the twist introduced in mooring lines should be zero or minimized during the pre-lay of mooring lines and the final hook-up to the floating foundation. If twist exists in the wire rope, it will be easy to induce bird-caging and premature failure. And if twist exists in the chain, it will significantly reduce its strength and fatigue performance. Therefore, it is essential to take additional protective measures to avoid introducing twist during the installation process, despite increasing installation time and cost. At present, the effective methods to forestall twist include the use of low-torque pull-in lines, the use of a second line to balance the torque and the use of in-line swivels.

It is also worth mentioning that nowadays the accurate level of twist acceptance in the mooring system remains unclear. Under different levels of twist, neither could the long-term performance of chains or wire ropes be predicted precisely. Currently, only rough guidelines are available to use, but there is no baseline. Hence, it is an urgency to develop systematic data for the torque-twist behavior of chains and wire ropes, in order to predict the reduced strength and fatigue life.

Damage to mooring lines

During installation, damage to wire ropes may occur. Special care should be taken during the operation of extracting wire ropes from the installation reel. During this process, the wire rope would easily get crushed or tangled. A proper operation to prevent knotting is to pull the wire rope straight down from a reel or mount it on a revolving stage. If damage occurs, the remedial measure should be taken, for example, to provide additional corrosion protection in the damaged sheath area. But if damage occurs in deep-water operations, the cost of damage assessments and remedial measures would be much higher [50].

5.1.3 Challenges in Operation and Maintenance Stage

Development of mooring line tension monitoring system

For station-keeping and sea-keeping of a FWT, it would be helpful if the time-varying mooring line tension can be timely and accurately recorded. From the monitoring system, precious on-site measurement data, cognition of marine environment and adaptability of floating foundation can be all acquired to improve the technology of integrity management.

The traditional technique for mooring line tension monitoring system is to infer the mooring line tension by measuring the mooring line angle. Such a technique is of great uncertainty in the calculation process [51]. Moreover, most of existing mooring line tension monitoring systems stop functioning after two years of operation due to the harsh environment [52]. For an advanced monitoring system, the automatic design of linkage for adjusting operation needs to be involved. Presently, it is still a great challenge to develop a tension monitoring system with accurate measurement, long service life and advanced automation [53].

Increasing complexity of mooring operations

As the amount of subsea infrastructure quickly grows, many new operations are carried out next to existent infrastructure. Consequently, the operators have to work close to the existing subsea facilities and pipelines. For catenary moorings and taut moorings, it is relatively easier to carry out the operation and maintenance operations for a FWT, because the foundation can be easily disconnected with the mooring system and towed back to the port for maintenance. But for tether moorings, special attention needs to be paid to when removing the tendons from the foundation. Any improper operation may give rise to the capsizing of the floater especially for a FWT whose center of gravity is taller than that of an oil platform.

5.2 Developing Trends of Mooring Systems

Hybrid mooring system concept

The traditional mooring system has its own applicable scope and limitations. Aforementioned, the catenary mooring has a too large mooring radius and too long mooring chains, while the taut mooring has excessive dynamic tension. Accordingly, the hybrid mooring system concept was brought up to solve these problems.

One kind of hybrid mooring concepts is the usage of clumps and buoys. Clumps increase the restoring force of mooring lines, and therefore restrict the floater's offset under extreme conditions. The application of buoys helps to increase the vertical distance between mooring lines and other subsea equipment. Also, buoys can offset the weight of mooring chains partly supported by the floater. A new hybrid mooring system was proposed for a semi-submersible foundation by Yuan et al. [54] Buoys and clumps were respectively connected to the top and bottom of a traditional taut mooring line. It was reported that the tension of the mooring lines was greatly reduced. Xu et al. [55] analyzed and compared three different hybrid mooring systems and carried out a series of wave model tests to investigate their mooring performance. Through this research, a new hybrid mooring system was recommended to significantly reduce the dynamic tension.

The other kind of hybrid mooring concept consists of several segments, each of a different mooring material [56]. The mooring line comprises a bottom chain, a high modulus polyethylene rope, a polyester rope and a top chain from the bottom to top. Such a hybrid mooring system is able to offer an appropriate stiffness and to resist the abrasion between the mooring line and the seabed simultaneously.

Shallow-water mooring

Presently, almost all FWT projects commissioned are located in moderate and shallow waters, since the cost and technical challenges incurred from environmental conditions (i.e. wind and waves) rapidly grow with increasing offshore distance and water depth. The more mature bottom-fixed wind turbines can be a good usher for FWTs. But as mentioned in Section 5.1.1, traditional mooring systems are not suitable for shallow water. So far there is no mooring system with good mooring performance and competitive cost for the deployment of FWTs in shallow water. The recent Sanxia Yinling FWT project has encountered the mooring embarrassment in 29.2 m water depth [13]. More and more studies have been carried out to deal with shallow-water mooring. Benassai et al. [57] analyzed the motion performance of the tri-floater wind turbine at a water depth of 50 m ~ 200 m, considering both catenary moorings and taut moorings. A series of parametric studies were carried out to identify the better mooring configuration. Campanile et al. [58] studied the effects of mooring line number, foundation admissible offset and space between adjacent turbines in water depths of 50 m ~ 80 m and 200 m ~ 300 m. Besides, the cost of installation and maintenance was preliminarily analyzed. Xu et al. [43] put forward seven mooring concepts for a FWT in the water depth of 50 m and compared the concepts in terms of reliability and cost. In their study, six mooring design concepts were recommended for future research.

New mooring material

The high performance of the synthetic fiber rope is beneficial to its application in the mooring system. Different synthetic materials lead to the diversity of synthetic fiber ropes. In addition to a large number of applications of polyethylene terephthalate (PET), nylon, high modulus polyethylene, new synthetic fiber materials with higher performance are being developed, such as polyethylene naphthalate (PEN) and liquid crystal aromatic polyester (LCAP) etc.

By comparison, PEN has a better mechanical performance and it is about twice as stiff as the conventional grade of PET. Furthermore, its performance of ultraviolet resistance and availability to maintain strength in a wet environment are better. However, the manufacturing capacity of PEN is limited and the cost is rather high.

LCAP is one of polyester materials. It is much stronger and stiffer than traditional synthetic fiber materials. It can avoid axial compression fatigue, creep and abrasion problems. At present, the supply of LCAP is very limited. Consequently, the cost is more expensive than any other synthetic material [59,60].

6. Conclusions

This paper summarizes the current status of the mooring system and the mooring equipment of FWTs, and points out the features of mooring analysis methods and the technical challenges. The developing trends of the mooring system are also given. The conclusions are drawn as follows:

1) Common mooring systems applied to FWTs include catenary moorings, taut moorings and tether moorings. The design and analysis show that the catenary mooring is suitable for medium water depth, while the taut mooring and the tether mooring could be applicable to deep waters. A mooring system particularly suitable for shallow water has not been developed yet, whereas the FWT era is embracing seas of moderate depth, as reflected in Table 1. At present, most of the existing FWT projects adopt catenary moorings and a few projects adopt semi-taut moorings. Tether moorings are still in the stage of model tests. Some hybrid concepts can reduce the motion of a FWT under extreme environmental conditions and offer competitive cost as well, but they still need further research.

2) The mooring system still has some technical difficulties and challenges in its whole life cycle of design, installation, operation and maintenance stages: In the design stage, outstanding issues include the design for shallow-water moorings, the influence mechanism of slack-taut process on the tension response of the mooring system, and the nonlinearity of mooring line materials. In the installation stage, special attention should be paid to avoid the twist in mooring lines and the damage to mooring lines. In the operation and maintenance stage, it is urgent to develop an advanced mooring line tension monitoring technology.

3) The moving trends in mooring research include transformation from traditional mooring schemes to hybrid moorings, from deep water to moderate and shallow waters, and from traditional mooring materials to high-performance composite mooring materials.

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Conflict of Interest

There is no conflict of interest.

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