Development of Offshore Wind Turbine Floater that Blends into Japanese Waters - Evaluation of the Validity for Design and Applied Methods for V-shaped Semi-submersible Floating structure -

MASAO KOMATSU*1 HITOSHI KUMAMOTO*2
MAKOTO OHTA*3 HIROSHI TANAKA*4
HIDEO MORI*5 SATOSHI MIYAZAKI*6

In the "Fukushima Floating Offshore Wind Farm Demonstration Project" in which Mitsubishi Heavy Industries, Ltd. (MHI) has taken part, the 7MW floating offshore wind turbine developed by the company was installed off the coast of Fukushima, and its demonstration operation phase is under way. In this article, concerning the design of V-shaped semi-submersible floating structure and the adopted construction and mooring method therefor, the actual work in the stages from construction to installation were reviewed and verified for validity, and based on the findings obtained from the review and the results of the in-house research that has been separately conducted, the future commercialization was studied. The verification results showed that the V-shaped semi-submersible floating structure has the expected performance, construction properties and mooring workability and offers superior economic efficiency. On the other hand, a study of future mass production and commercialization revealed that there is plenty of room for the improvement of the design and comprehensive cost reduction through a review of the mooring method, construction procedures, etc.

1. Introduction

The floater types of floating offshore wind turbines are broadly classified as the semi-submersible type, TLP (Tension Leg Platform) type and SPAR type, as is the case with those of general offshore structures.

The TLP type and SPAR type are semi-submersible in a broad sense. In a general semi-submersible type, a floater with a multi-column structure is moored by catenary lines. On the other hand, the TLP type is moored at the sea floor by vertical tendons tensioned using buoyancy of the underwater hull, and in the SPAR type, the part that breaks the surface of the floater is formed as a single deep-draft cylindrical and vertical column, thereby making it less affected by waves.

However, the TLP type requires the forming of a rigid foundation pile on the sea floor for mooring, and the cost becomes higher compared with the other types. The SPAR type has a simple structure, and there is a possibility that the cost can be kept lower compared with the other types. On the other hand, since the draft becomes deeper because of its structure, construction or assembly place is restricted.

In consideration of the aforementioned points, we adopted a V-shaped semi-submersible type for the floater equipped with a 7MW wind turbine in the “Fukushima Floating Offshore Wind Farm Demonstration Project”.[1] Thereafter, the floater was constructed at our Nagasaki Shipyard & Machinery Works and the wind turbine was installed at Onahama Port in Fukushima Prefecture. The installation of the floater at the assigned position off the coast of Fukushima was completed in

*1 Manager, Ship & Ocean Engineering Department, Shipbuilding & Ocean Development Division, Commercial Aviation & Transportation Systems
*2 Ship & Ocean Engineering Department, Shipbuilding & Ocean Development Division, Commercial Aviation & Transportation Systems
*3 Chief Staff Manager, Fluid Dynamics Research Department, Research & Innovation Center
*4 Nagasaki Ship & Ocean Engineering Department, Shipbuilding & Ocean Development Division, Commercial Aviation & Transportation Systems
*5 Chief Staff Manager, Ship & Ocean Engineering Department, Shipbuilding & Ocean Development Division, Commercial Aviation & Transportation Systems
*6 Chief Staff Manager, Nagasaki Ship & Ocean Engineering Department, Shipbuilding & Ocean Development Division, Commercial Aviation & Transportation Systems

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In this paper, the actual tasks in the stages from construction to installation are reviewed, the design of V-shaped semi-submersible floating structure and the adopted methods are evaluated for validity, and based on the findings obtained through the demonstration project and the results of the in-house research that has been separately conducted, the future commercialization of the floating offshore wind turbine is studied.

2. Evaluation of validity of design and applied methods

Figure 1 shows the construction of V-shaped semi-submersible floating structure at Koyagi Dock, Nagasaki Shipyard & Machinery Works of MHI.

The V-shaped semi-submersible floating structure has a structure in which rectangular parallelepipeds (lower hull) each with a length of 106 m, a width of 14 m and a depth of 7 m are arranged in L-shape and rectangular parallelepipeds (columns) each with a square section with one side of 14 m and a height of 25 m arranged at the ends of the lower hull. This structure aims at reducing the construction cost, improving the execution performance of various tasks, securing the motion, and maintaining the mooring performance as a floater for large wind turbines.

Figure 1 Construction at Koyagi Dock, MHI Nagasaki Shipyard & Machinery Works

The validity of the design and methods applied in all processes from design and construction to installation is evaluated as follows:

2.1 Floater structure

(1) Simple structure

For this floater, the diagonals used in general semi-submersible structures were replaced with straight rectangular structures were adopted. The straight rectangular structures eliminated complicated work such as the joining of diagonals and the execution of curved planes, contributing to the reduction of the construction cost and increased structural reliability through the improvement of construction accuracy. Ease of construction leads to an increased degree of flexibility in terms of construction procedures and therefore this floater can be said to be suitable for mass production in terms of its shape and structural form.

(2) Self-stabilized floater

Buoyancy is obtained by the lower hull, and the floater became self-supported and stable at each stage of launching, towing, bottom-mounting and installation. Since no special consideration for supplemental buoyancy, etc., was required, the degree of flexibility in the execution of work was increased, and risk and accompanying work for stability could be eliminated.

(3) Realization of shallow draft

In this floater, a large amount of buoyancy is provided to the lower hull and its inside acts as a ballast tank. As a result, the draft can be adjusted to an appropriate level according to the stage of work. Without a wind turbine mounted on the floater, the draft can be reduced to about 3.5 m. Accordingly, the work for entering and leaving Nagasaki Port and Onahama Port and the bottom-mounting work at Onahama were easy. This allowed various preparation tasks to be conducted in the calm environment of the ports and prevented a reduction in work efficiency due to marine conditions. It is considered that these characteristics are effective in taking measures for events such as the replacement of large parts and the removal of the floater in the future.

(4) Combination of the aforementioned elements

The straight rectangular structure and the shallow draft allowed the floater to be mounted on the sea floor close to the wharf. This prevented floater motion and reduced the reach of the crane when installing the wind turbine. The combination contributed to increasing the efficiency of the installation work of the world's largest scale of wind turbine and improving its quality.

2.2 Methods for towing, bottom-mounting and mooring

(1) Towing operation

The displacement of this floater at the time of towing is about 10,000 tons, but because of its V shape, the apparent width (about 150 m) and length (about 85 m) are very large. For the towing of such a large-width structure, the water tank test and the numerical calculation were conducted to examine the optimum towing direction, towing resistance, etc., and detailed prior verification was also implemented with the towing operators and the insurance inspection agency to develop the towing procedure. As a result, in the towing operation from Nagasaki to Onahama, although there was a postponement due to a typhoon, the towing itself was performed without problems, and the stable towing of the large-width structure was demonstrated. **Figure 2** shows the positions of tugboats during the open-sea towing from Nagasaki to Onahama, and **Figure 3** presents photos indicating the states of the floater during towing, taken from the main towing boat.

Figure 2 Positions of tugboats during the open-sea towing from Nagasaki to Onahama

Figure 3 States of the floater during the open-sea towing from Nagasaki to Onahama

(2) Bottom-mounting work

[1] Bottom-mounting mound height

The bottom-mounting mound height was planned so that the top of the lower hull could sink below the sea level after the floater was bottom-mounted and waves could pass over the top in consideration of the water depth and tidal waves at the front-end revetment of

Fujiwara Wharf of Onahama Port. This lowered the fluctuating pressure caused by ocean waves at the time of bottom-mounting and was effective in conducting the bottom-mounting work and the subsequent stable short-term bottom-mounting. During the bottom-mounting work, the weather was generally fine, and the floater could be accurately mounted at the bottom with the maximum planar displacement of 0.26 m in relation to the required bottom-mounting accuracy of ± 1 m. **Figure 4** shows the state of the floater after being bottom-mounted.

Figure 4 State of the floater bottom-mounted at Onahama Port

[2] Preloading on the bottom-mounting mound (Note 1)

Preloading on the bottom-mounting mound was not conducted, and therefore, for the purpose of checking the effect of any change in weight caused by the installation of the wind turbine, the settling of the mound after the floater was bottom-mounted was measured as appropriate. **Figure 5** shows the state of the wind turbine installed at Onahama Port, and **Figure 6** indicates the change in the settling of the floater after being bottom-mounted. The results showed that there was no problem in omitting measures such as preloading on the mound because the amount of settling was very small.

Note 1: Method for promoting settling by applying load to soft ground with mounding

Figure 5 State of the wind turbine installed at Onahama Port

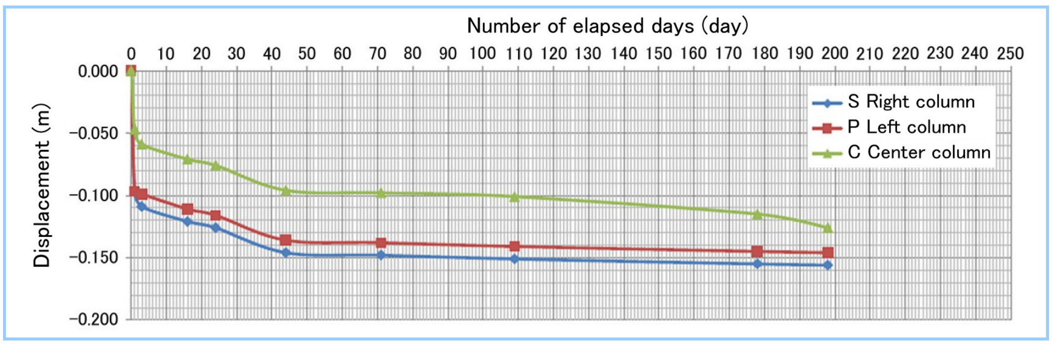

Figure 6 Change in settling of the floater after the wind turbine was installed

[3] Laying of asphalt mat

In order to increase the frictional resistance and protect the coating of the bottom plate that comes into contact with the mound during bottom-mounting, an asphalt mat with a thickness of 8 cm was laid between the mound and the floater. In the prior verification, concerns arose that the laid asphalt mat might adhere to the floater, and countermeasures were prepared in case the adhesion of the asphalt mat was observed when the floater was refloated. In actual fact, however, no adhesion of the asphalt mat to the floater was observed. The effectiveness of the asphalt mat and the ease of laying it were confirmed.

(3) Mooring work

Figure 7 shows the state of the floater being towed to the mooring point after the installation of the wind turbine and all preparations for mooring work were completed. In mooring work, tension must be placed on the mooring line as planned. In the conventional method in which the initial tension is managed, work for lifting up the chain using a floating crane moored to the floater is indispensable. In an environment like the one off the coast of Fukushima, with tidal currents, wind and high ocean waves, the tension management of the mooring lines using a floating crane is difficult and requires a great deal of caution against the swinging and rotation of the crane hook for the safety of workers. In the work for our V-shaped semi-submersible floating structure, in consultation with the classification society, we adopted a method in which the number of chain links (chain length) is managed, instead of a method in which the initial tension is managed. Furthermore, we adopted a method in which the chain is hoisted by a chain lifter (winch) installed on the floater, instead of lifting the chain by a floating crane.

Figure 7 Floater, with the wind turbine installed, being towed to the mooring point

In preparation to establish a mooring plan, a study on the initial tension of each mooring line at the actual anchoring position was conducted and the number of chain links (chain length) by which the set initial tension can be obtained was determined. In the actual work, the floater was moored by the mooring lines with the planned number of links without problem, and the safety of the working environment was also highly regarded by the workers at the site. Through this method, in which errors caused by tidal current, tides, ocean waves, etc., during mooring work are eliminated, the accuracy of the management of mooring work was increased. **Figure 8** shows the state of the mooring work off the coast of Fukushima.

Figure 8 State of the mooring work off the coast of Fukushima

2.3 Performance of the floating structure

(1) Mooring system

The mooring forces converted from the absolute inclinations measured by the clinometer installed on the mooring line in the vicinity of the chain fairleads (Note 2) are shown in **Figure 9**. The maximum mooring forces measured in rough weather caused by the passing of an atmospheric depression after the start of observation are generally quite consistent with the calculation values analyzed based on the weather and oceanographic conditions data. Accordingly, the validity of the mooring system design method was confirmed.

Note 2: Metal fitting for guiding mooring chains in the anchor direction

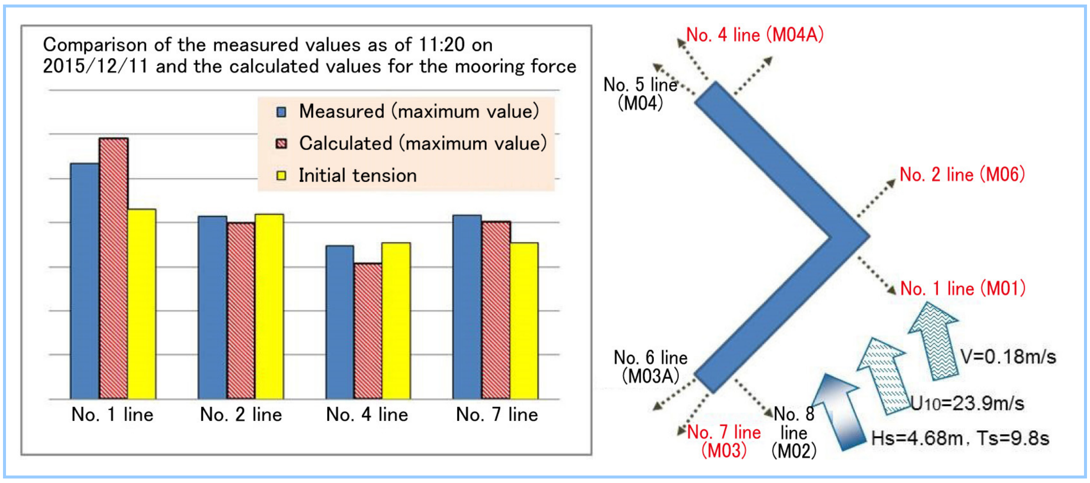

Figure 9 Comparison of the measured values and the calculated values for the mooring force

(2) Motion of the floating structure

Roll and pitch are as important among movements of the floater as in the case of the mooring system, and the results of measurement and analysis for roll and pitch were compared. Roll was slightly underestimated and pitch was regarded as safe on the design (**Figure 10**). Both are generally in good agreement, and the validity of the design method for the motion performance of the floating structure was also confirmed.

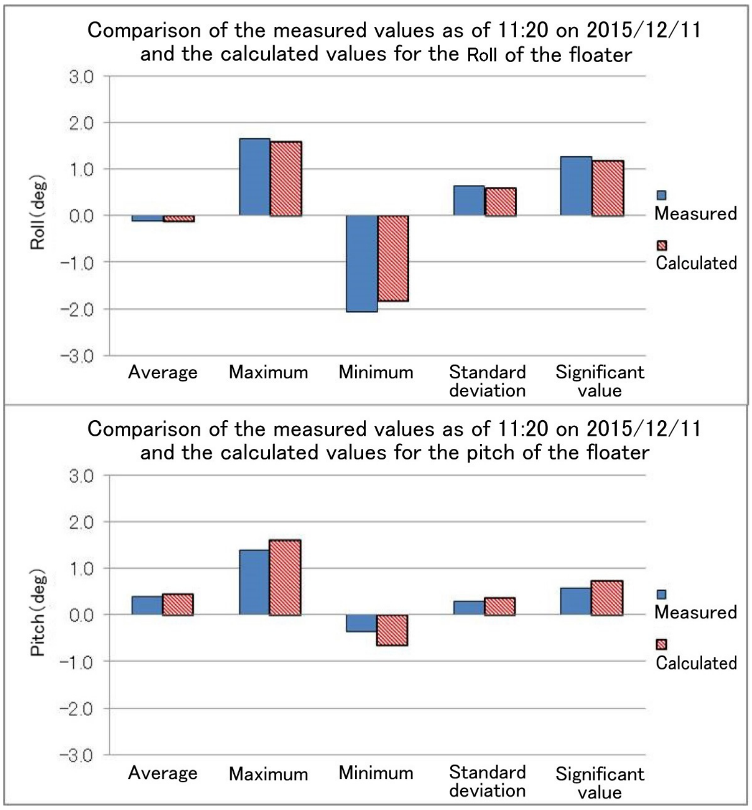

Figure 10 Comparison of the measured values and the calculated values for the motion of the floating structure

(3) Setting load at structural design

The strain data measured using the strain gauges affixed to the representative points of the lower hull structure and the column structure of this floater was converted into stress, and the long-term frequency distribution was prepared using the rainflow counting method. The extrapolated value equivalent to the long-term probability and the longitudinal bending stress analysis results of the lower hull were compared. The result values obtained are almost the same, and the validity of the load set for the structural design was confirmed (**Figure 11**). The measured results also showed the influence of the ocean wave occurrence frequency by azimuth of stress.

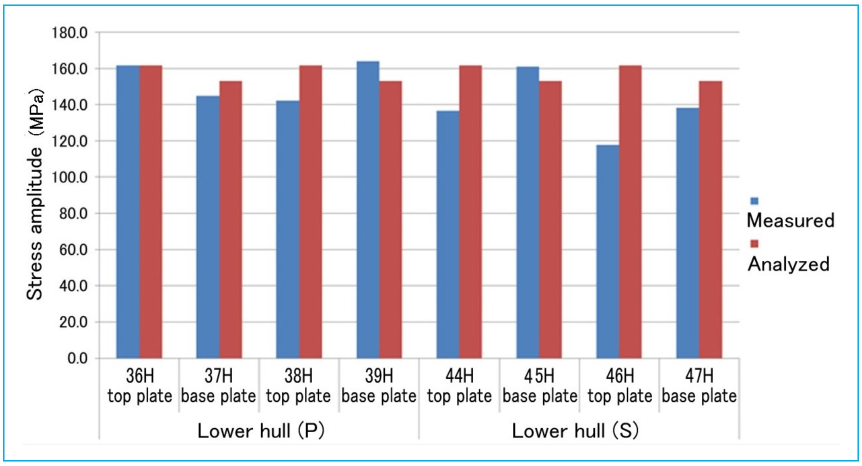

Figure 11 Comparison of the measured values and the calculated values for the design longitudinal bending stress of the lower hull

3. Evaluation of economic efficiency

For the evaluation of the economic efficiency of the floating offshore wind turbine, the energy cost including operation management cost, maintenance inspection cost and revenue from selling of power, in addition to the equipment cost of the floating offshore wind turbine, need to be evaluated. However, here we focus on the economic efficiency for the floater and the mooring system in the equipment cost of the floating offshore wind turbine is mentioned.

3.1 Construction cost

As described in 2.1, in the V-shaped semi-submersible floating structure, the diagonals used in general semi-submersible structures were eliminated and straight rectangular structures were adopted, in order to simplify the processing of components and increase the efficiency of tasks such as welding, resulting in the reduction of the unit price of processing work. In mass production, it can be expected to increase the degree of flexibility for construction sites.

3.2 Costs for towing and wind turbine installation work

For the installation of the wind turbine and implementation of mooring preparation tasks, the floater was brought into a calm port and mounted on the bottom. Ancillary work such as the preparation of the bottom-mounting mound were required, but with the characteristics of the floater structure described in 2.1, dredging of the port in which draft is restricted was not necessary, resulting in a lower cost for the improvement of the infrastructure.

3.3 Cost of mooring work

Eight mooring lines are used for this floater because of the constraints and movement performance on mooring, which is larger than that for other floating offshore wind turbine. It is desirable that the number of mooring lines be reduced because it directly affects the construction cost. There is also a possibility that the mooring work cost can be substantially reduced by the improvement of the mooring system and the mooring work method, and the impact of the number of mooring lines on the overall cost can be smaller in some cases. For this floater, as described in Chapter 2, a reduction of the overall cost was sought through the improvement of the construction method, resulting in the avoidance of a substantial increase in cost. If mass production in the future is considered, an effective measure must be determined through comprehensive study from the viewpoint of the overall construction.

4. Considerations about commercialization

Although some items should be checked in further demonstration tests, we gave some consideration to commercialization based on the results and findings obtained by the past demonstration tests and the results of the in-house research that has been separately conducted.

4.1 Floater design

From the experiences in the demonstration tests, we obtained some ideas that might contribute to the reduction of the overall cost by reflecting the ideas in the floater design. These include securing a towing point for each column for the purpose of towing or holding the floater in a semi-submersed state, the adoption of an impressed current antifouling system for the purpose of minimizing projections from the floater, and the improvement of transportation equipment for increased accessibility to the floater and greater safety. Some of these improvements, if incorporated in the design, do not increase the cost or can be implemented with only a slight cost increase. In the study of commercialization, a comprehensive evaluation of economic efficiency should be conducted to determine whether such improvement measures should be adopted.

4.2 Floater dimensions

The miniaturization of the floater is expected to facilitate a reduction in the costs for materials, construction and towing/mooring work, but the relationship with the movement/acceleration tolerance of wind turbine, mooring force, etc., should be fully examined. Through this demonstration test, useful information for future study was obtained, and the miniaturization of the floater is considered sufficiently feasible. In addition, it was confirmed that if a change of the design concept becomes possible, the miniaturization of the floater will be greatly advanced.

4.3 Mooring method

(1) Improvement of mooring method

Since the mooring method has a close relationship with the construction performance, the construction procedures must be concurrently studied. As a result of the demonstration test, the construction method using large anchors and anchor chains was established, but for commercialization, further cost reduction is necessary. From the experience of the aforementioned demonstration test, some improvement ideas on the mooring method that are expected to exert a significant effect on cost reduction were obtained, and from the research that has been separately conducted, it has been confirmed that the mooring method using intermediate weights is effective in reducing cost.

(2) Consideration for work for removal of floater/replacement of large components

Concerning the floater body, consideration has been given to the draft and shape so that work for the replacement of large components can be conducted in port. For a land-based wind turbine, the concept of a construction method in which blades are replaced without using a crane was announced by a maintenance company, and technological progress has been made. There is a high possibility that the technological environment for offshore wind turbines will change in the future. For example, work for the replacement of large components will be possible to conduct offshore. The mooring method to be adopted depends on the method for the removal of the floater or the replacement of large components that is adopted. For commercialization, a full prior study including the observation of technological trends is required.

For the time being, it is considered difficult to conduct work for the replacement of large components offshore. Therefore, the adoption of a mooring system assuming release of moorig line is thought to be effective. In that case, a special device may be used, and thus is necessary to conduct a cost evaluation for the overall work including the installation of the device.

(3) Harmony with the construction method

As previously described, there is a close relationship between the mooring method and the construction procedures, and it is necessary to concurrently study the mooring method and the construction procedures. As an example, if all work from towing through mooring can be conducted by a single work boat, the degree of flexibility in the construction process and the cost effectiveness can be increased. To realize this, it is important to consult with not only the floater supplier and the mooring work contractor, but also the work boat operator. For the construction of the 7MW wind turbine-equipped floater, the mooring work team of the relevant parties held discussions toward overall optimization. It was demonstrated that the research contributed to cost reduction and increased work safety. For commercialization, it is necessary that the relevant specialists act as a team toward overall optimization.

4.4 Overall system

(1) Construction procedures

In the demonstration test, the floater was constructed at Nagasaki and towed to Onahama, where the wind turbine was installed. If it is possible to construct the floater in the vicinity of the installation site, the towing cost can be reduced. In addition, if the towing period, which varies by ocean conditions, is shortened, the construction work will be conducted as planned, resulting in not only the shortening of the construction period, but also a reduction of cost. Furthermore, in terms of only construction, it is rational to construct the floater at a shipyard. But when consideration is also given to installation work, operation, maintenance, etc., there are many tasks that have a deep relationship with the regions around the project site, and for commercialization, a prior study of construction procedures that allow construction in the vicinity of the project site and a structural form suitable for the procedures may lead to a substantial cost reduction.

(2) Use of large wind turbines

It is generally said that in the configuration of a foundation type wind farm, the cost for the foundation and the construction cost can be reduced by increasing the capacity of a single unit and decreasing the number of units installed. In order to check that this is applicable to a floating wind farm, an outline design of a 2.4MW wind turbine-equipped floater was made, and the weights of steel materials used for a 2.4MW wind turbine-equipped floater and a 7MW wind turbine-equipped floater were compared. The weight of steel materials used for the 2.4MW wind turbine-equipped floater was about 60% of that for a 7MW wind turbine-equipped floater. According to the comparison results for the output per unit weight of steel materials, the output for the 7MW wind turbine-equipped floater was larger than the trial calculation results for the 2.4MW wind turbine-equipped floater. It can be said that for a floating wind farm, a floater equipped with a large wind turbine with an increased capacity of a single unit is effective.

The floater in this project was designed for 7MW. According to the simple estimation based on the principle items of the wind turbine, etc., it is suggested that it is possible to install the largest wind turbine (8MW unit) commercially available on the market. When the output per unit weight of steel material is set as an indicator, this floater can be more highly valued as an 8MW wind turbine-equipped floater. In selecting the wind turbine to be installed, there are various conditions other than the cost of the wind turbine to be considered. In some cases, it cannot be simply said that a wind turbine with a larger output is advantageous. As described above, however, a floater equipped with a large wind turbine is advantageous, and many of the costs, such as the cost for the mooring system and construction cost, depend on the number of units. Therefore, it is considered that commercialization with the adoption of a large wind turbine is effective in reducing energy cost.

(3) Improvement of installation equipment

For floating offshore wind turbines, the construction of the mooring system, the towing/mooring of the floater and the installation of the wind turbine are carried out. In order to implement these tasks efficiently and safely, a full slate of construction equipment is required. The commercialization of foundation type wind turbines has been moving forward in Japan following countries in Europe and North America. It is expected that jack-up vessels for the construction of foundation type wind turbines will be built in the future. In addition, the building of state-of-the-art large AHTS (anchor handling tug supply) vessels for other marine industries is progressing. When such equipment can be used for the installation of floating offshore wind turbines, it is possible that the construction costs can be further reduced by an increase in the operation rate, the reduction of chartered ship costs and increased construction efficiency.

5. Conclusion

In this paper, we reviewed the tasks in the stages from construction to the installation of the 7MW floating offshore wind turbine in the Fukushima Floating Offshore Wind Farm Demonstration Project, and confirmed that the floater that MHI designed and constructed has the expected performance, construction properties and mooring workability, and is also superior in terms of economic efficiency. In addition, based on the findings obtained from the research project and the results of the in-house research that has been separately conducted, we considered design improvement proposals and a review of the mooring method and the construction procedures for study about future mass production and commercialization, and found that there is room for comprehensive cost reduction.

The Fukushima Floating Offshore Wind Farm Demonstration Project is being promoted by the consortium formed by Marubeni Corporation (Project integrator) and the University of Tokyo (Technical advisor) as the leading members, together with other participants. The towing and installation work of the 7MW floating offshore wind turbine were only completed through the efforts of the relevant parties in construction such as Shimizu Corporation and Nippon Steel & Sumikin Engineering Co., Ltd. We are sincerely grateful to all the members of the consortium.

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