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Development of a V-shaped Semi-submersible Floating Structure for 7MW Offshore Wind Turbine.

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Abstract - **V-shaped Semi-submersible floating structure has been selected as a floater for the 7MW offshore wind turbine of Fukushima Offshore Demonstration Project. Design concepts were discussed during the development of floaters and they are summarized in this paper. A design method based on various simulation and tank test of using the 1/64 scale model is shown. In addition, dynamic stability performance including wind turbine control system, which has been raised as essential system for floating offshore wind turbine, is confirmed by the analytical approach and judged suitable for the floater.**

I. INTRODUCTION

"Fukushima floating offshore wind farm demonstration project (Fukushima FORWARD)", which is world's first full-scaled empirical study of floating offshore wind farm, has started in 2012. It plans to construct several type of floating offshore wind turbine (FOWT) at the sea of 20km off Fukushima in Japan[1]. As part of this empirical research project, the world's largest 7MW hydraulic wind turbine and its floating structure are under construction in our company.

Development of large-scale FOWT have been started already in the demonstration test off the coast of Spain and Norway, various concepts of FOWT have been proposed all over the world[2],[3]. Many of them have been planned for the reference Oil & Gas platform, the type of floating structure is divided into semi-submersible type, spar type, tension leg platform (TLP) type and barge type. The authors has conducted the conceptual design of FOWT for more than a decade, then technical knowledge for floating performance evaluation and business assessment has been accumulated[4],[5]. Based on this knowledge, new floating structure is planned and designed for this project.

In this paper, the floating structure design concept for mounting extra-large 7MW wind turbine is discussed first. In the conceptual design, to avoid sub-optimal design that focuses on specific requirements, floating structure shape is selected by taking into account the circumstances of the site and the life cycle cost. Next, tank test / wind tunnel test and validation calculation are shown to grasp the floating basic performance such as static stability and response in waves. In addition, overview of the mooring design and dynamic stability performance, which has been pointed out as a specific problem of FOWT, are described.

II. CONCEPTUAL DESIGN

It is considered that there are advantages and disadvantages for the variously proposed FOWT. First, the floating type is selected considering off Fukushima is site location. Spar type is removed because the draft of the floating structure for mounting the 7MW wind turbine exceeds the installation water depth, which can be easily assumed. TLP type is excluded also because increase of the installation costs was assumed by using the domestic work vessel and equipment. As a result, semi-submersible type floating structure is selected.

Table 1. Principal dimensions

Rotor diameter	167.00	m
Hub height from sea surface	105.00	m
Length floating structure	84.85	m
Width floating structure	149.91	m
Column width	14.00	m
Draft	17.00	m
Displacement	26,000	ton

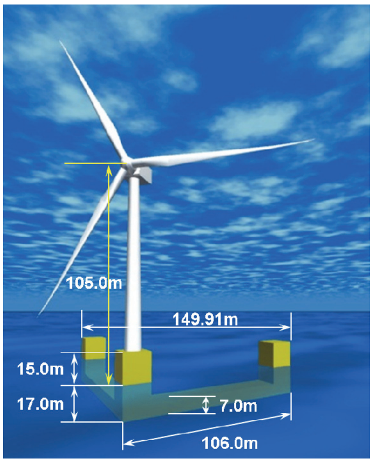


Fig.1. V-shaped Semi-submersible FOWT

Then, in the determination of the in shape of semi-submersible type floating structure, it was performed by considering that it satisfies the following requirements.

1. Floating structure shall be self-stable
2. Construction is possible in port area of Japan
3. Building location is not limited
4. Simple shape and structure which is suitable for mass production
5. Efficiency for wind turbine installation work
6. Consideration of critical failures and maintenance
7. Response performance in waves

Principal dimension of the V-shaped Semi-submersible FOWT newly developed is shown in Table 1, and that conceptual diagram is shown in Fig.1.

The floating structure is floated by buoyancy of lower hull part placed in a V-shape during construction / towing, and it is semi-submersible condition by the water injection to this part. The ends and intersection of lower hull part are connected with three columns. 7MW wind turbine is installed on the center column. Columns and lower hull part are adopted a box type structure with no curved surfaces, therefore this floating structure is a very simple structure without any complex structure nor the oblique support structure which is easy to lead to weld defect. This structure design was selected based on the past experience of Oil & Gas platform[6],[7].

A. FLOATING DRAFT

The floating structure is capable of draft adjustment by the drainage of the ballast tank inside lower hull from shallow draft (3 meter) to design draft (17 meter) depending on the situation (construction / towing / operation) and sea condition. Wide range of draft change is important for FOWT, because it is necessary to enter the port near the site for support of critical failures and the removal in the future, not only for the construction period.

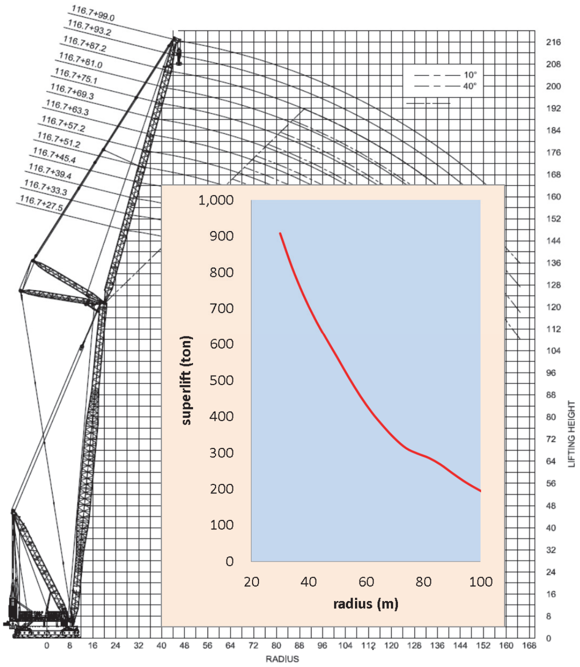


Fig.2. Relations capacity of crane and outreach

B. MASS PRODUCTION

This floating structure has achieved a reduction of construction cost and an increase the degree of freedom of choice the construction site in mass production stage by employing a combination of simple shapes. Usually, although many large steel structures are built in dock of the shipyard, construction or repair works near the site is also desirable taking into account the maintenance cost and towing cost from the construction site to the operation site. This V-shaped Semi-submersible FOWT have a shape that is integrated blocks of box-shaped as bridges and caissons, in consideration of the final assembly near the site too.

C. MOUNTING WIND TURBINE

7MW wind turbine is installed on the center column placed on the floating structure. During construction for mounting the wind turbine, it is possible to have crane approaches to the floating structure. Fig.2 shows the relationship between the outreach and capacity of the crane handling.

It is also possible to install a floating structure on the seabed mound when mounting the wind turbine in order to stabilize against wind and waves. Furthermore, lower hull structure can be used as a docking base of floating crane for maintenance in the future.

III. FLOATING PERFORMANCE

In floating design, providing a floating structure as the basement, on which super-large wind turbine can be operated safely, is the most important. And there shall be the serious accident like subversion or drifting. On the other hand, ease to build, convenience of construction and maintenance, and various performances come involved in product value. For example, if the floater is designed with only suboptimal view of the construction costs and/or motion performance, business potential might be reduced significantly if it is evaluated from the view point of the entire value chain

A. PERFORMANCE REQUIREMENTS

In general, the importance of static stability and motion in waves at floating design is well known. In addition, another characteristic performance requirement for FOWT is dynamic stability in conjunction with wind turbine control system[8]. This performance requirement is the evaluation of whether or not to amplify the rotational motion of the floating structure, because the force, which is caused by the wind turbine blade control for smoothing of power and thrust, acts on the floating structure. It is confirmed that this V-shaped Semi-submersible floating structure has sufficient performance to satisfy all these major performance by carrying out a detailed study in the initial design stage.

In the design of FOWT, which shape is always top heavy, reducing the motion leads to reduce the burden for wind turbine structure and onboard equipment. For this purpose, motion reduction devices called MS-Board, which was originally developed, are installed near the lower end of each column [9]. This device is passive type that does not use any electrical power generated by wind turbine, and there are also adoption records to the floating pier, etc.

B. MODEL TEST

For the purpose of verification of performance requirements and acquisition of verification data for design code, many model tests were carried out using large experimental tank and wind tunnel facilities. In Seakeeping & Maneuvering Basin (Length 160m, Breadth 30m, Depth 3.1m), motion decay tests, regular/irregular waves tests, towing test were carried out by installing the simple wind generator.

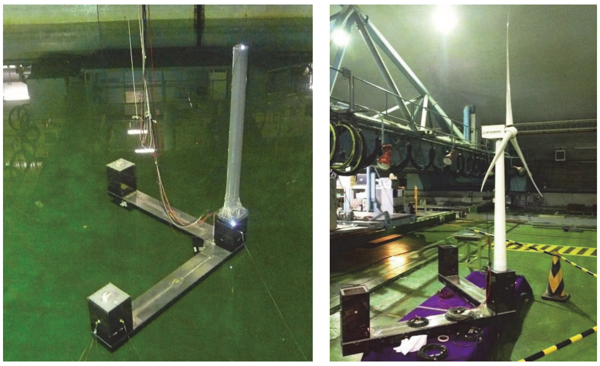


Fig.3. Model Overview

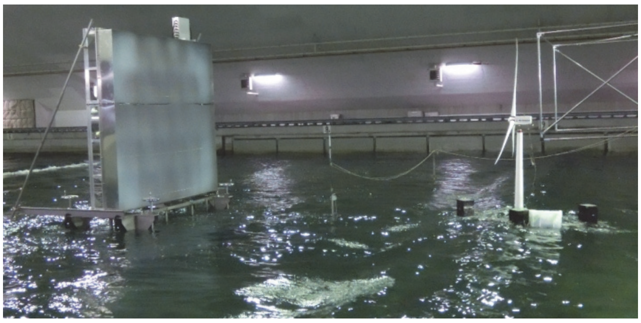


Fig.4. Tank Test Situation

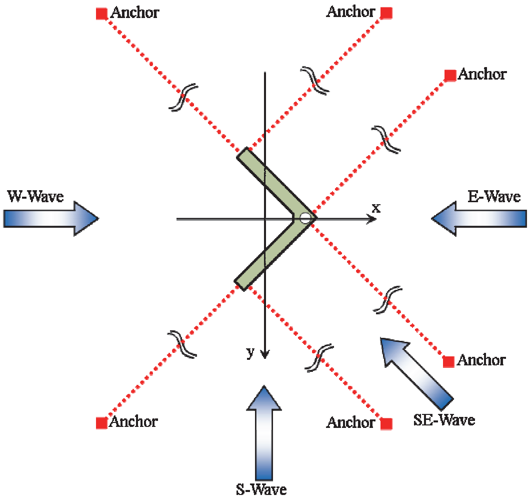


Fig.5. Mooring Arrangement

Two types of wind turbine were used on scale ratio 1/64 floating structure model. Floating structure model was made of an acrylic material in shape similarity but lower hull part is using by sandwich structure of aluminum plate which scaled down the actual bending stiffness. Wind turbine model-I was produced using PVC pipe in weight center of gravity similarity. For wind turbine model-II, blade/nacelle model were laminated C-FRP in shape similarity and tower model was made of aluminum plate by machining in shape/weight/bending stiffness similarity. And motor/gear is housed in the nacelle, rotor is rotated at a predetermined rotational speed, it is possible to change the blade pitch in remote control. According to the mooring design as mentioned below, floating structure model was moored with chain loosely in tank. The model overview, the status of the tank test and mooring arrangement are shown in Fig.3, Fig.4 and Fig.5.

Measurement items are floating structure motion, lower hull surface strain, mooring tension, tower base load, nacelle acceleration, etc.

As a tank test results, typical response amplitude operator (RAO) of wind turbine model-I in regular waves is shown in Fig.6. In Fig.6, upper RAO is in E-waves, lower RAO is in S-waves, RAO of left side is heave motion and RAO of right side is pitch motion. And triangle mark are experimental results without MS-Board, square mark are experimental results with MS-Board. Solid line are the calculation results without MS-Board by panel method using computational mesh showed in Fig.7. This in-house code computes diffraction / radiation hydrodynamic forces on the structure based upon the potential theory, and floating structure response was estimated by solving in the frequency domain equation of motion taking into account non-linear viscous damping force as results of motion decay tests[10]. This mesh data is as it was taken out the wetted parts from the FEM data for the analysis of the floating structure response, and a detailed strength analysis has been conducted.

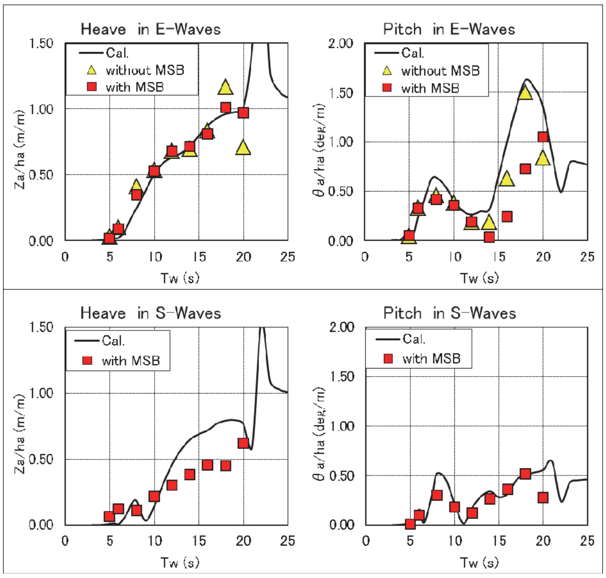


Fig.6. Response Amplitude Operator

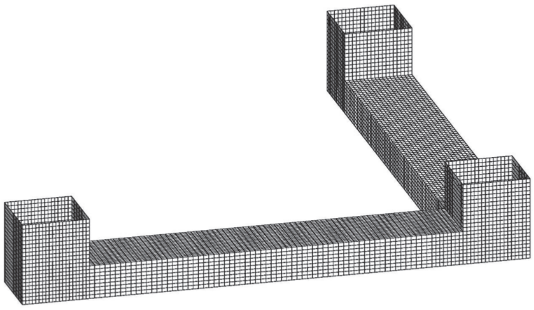


Fig.7. Computational Mesh (13,092mesh)

The peak of pitch motion ~~of~~ with MS-Board is shifted to long-period side compared to without MS-Board. It is considered that non-linear damping force is increased by the effect of MS-Board. Pitch motion has also occurred in S-waves from floating laterally, because of asymmetric shape forward and aft side of floating structure.

Assuming the rated power generation and the 50 year storm, pitch motion of wind turbine model-II is shown in Fig.8 in irregular waves and uniform wind. Reynolds number of the model is 1/512 times the actual wind turbine, aerodynamics cannot be simulated. Therefore, in view of the load to transmit to the floating structure from the wind turbine in this study, blade pitch angle was selected to be the equivalent thrust on rotor and bending moment acting on the tower base, irregular waves and uniform wind which was scaled down by Froude law were generated. Test conditions are shown in Table 2, and statistical results of pitch motion in the case of rated power generation and the 50 year storm are shown in Fig.8 and Fig.9.

Average value of pitch motion is about 1.3 degree in Case-RPG that thrust acting on the wind turbine is maximized and is 2 degree or less in Case-50YS that bending moment of the tower base is maximized. Maximum / minimum value of pitch motion is 3 degree or less in Case-RPG, and is 6 degree or less in Case-50YS, so it is understood that this floating structure has both excellent stable performance and anti-wave performance. An example of the result of the time history analysis using above hydrodynamic force on Case-50YS is shown in Fig.10. This estimation result is safe side, because of simulation result of 180 minutes against test results of about 30 minutes.

Table 2. Test Condition

	Full scale	Model scale
Rated Power Generation (Case-RPG)	U=12.0 m/s Hs=3.2 m Ts=7.5 s	U=1.50 m/s Hs=50 mm Ts=0.94 s
50 Years Storm (Case-50YS)	U=50.0 m/s Hs=11.7 m Ts=13.0 s	U=6.25 m/s Hs=183 mm Ts=1.63 s

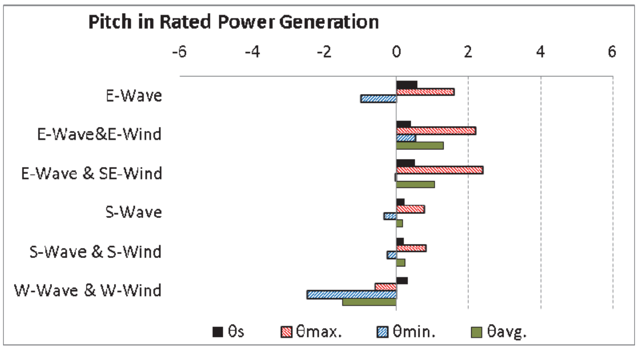


Fig.8. Statistical Results of Pitch in Case-RPG(tank)

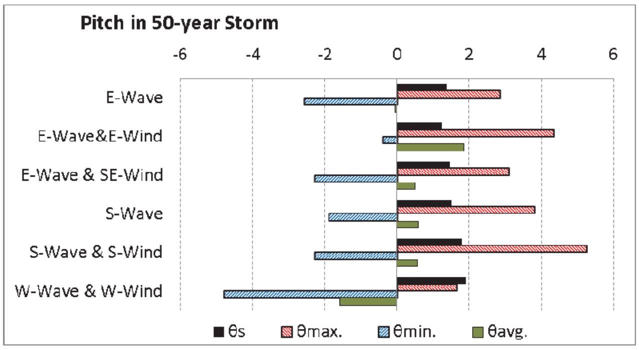


Fig.9. Statistical Results of Pitch in Case-50YS(tank)

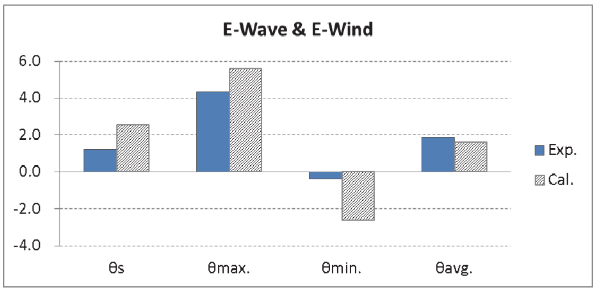
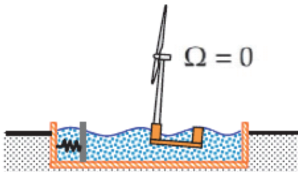
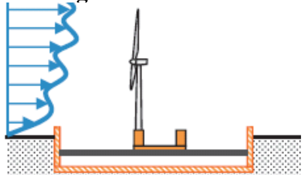
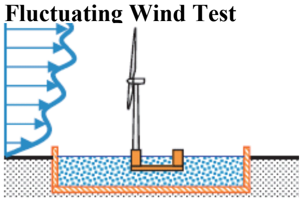
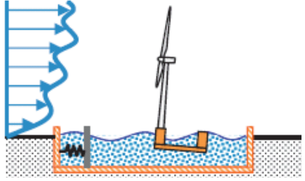


Fig.10. Simulation Result in Case-50YS

Table 3. Wind Tunnel Test Case Summary

Waves Test  	**Floating Fixed Test** 
Fluctuating Wind Test 	**Fluc. Wind / Waves Test** 

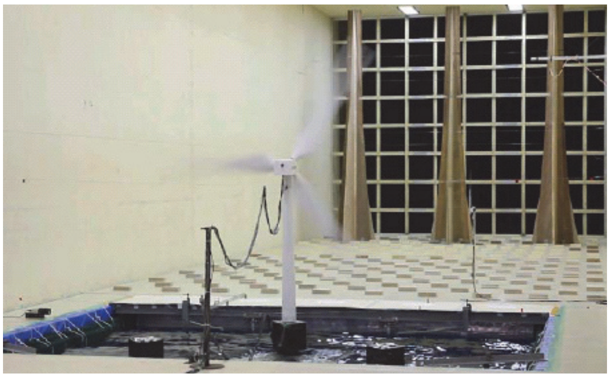


Fig.11. Wind Tunnel Test Situation

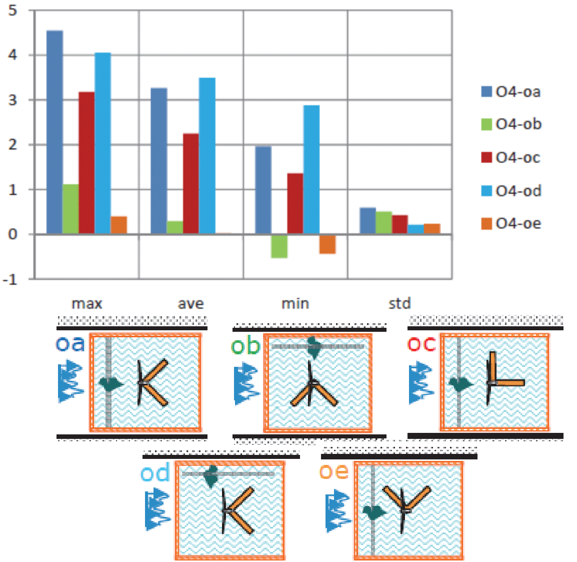


Fig.12. Statistical Results on Pitch of Case-RPG(tunnel)

Since the effects of fluctuating wind cannot be grasped by using simple wind generator in tank, wind tunnel tests were carried out by placing simple tank and wave maker in Boundary Layer Wind Tunnel (Length 35m, Breadth 6m, Height 5m). For the issue of Reynolds number, widening blade models were produced which its aerodynamic characteristics are similar to the actual wind turbine. Wind tunnel test case summary is shown in Table 3, and wind tunnel test situation is shown in Fig.11. As an example of the wind tunnel test results, the statistical results on pitch motion of Case-RPG are shown in Fig.12. The steady gradient is dominant in fluctuating wind.

C. MOORING DESIGN

The environmental conditions in the mooring design of this project are adopted the extreme value statistical results of 50 years return period based on various types of data such as waves and wind speed of installation area . The design wave condition is shown in Fig.13 compared with observed maximum high waves which were measured at 58 locations in Japan coastal waters for 30 years. As results, high wave height to exceed the observed maximum wave in western Japan where large typhoon passes frequently has been set.

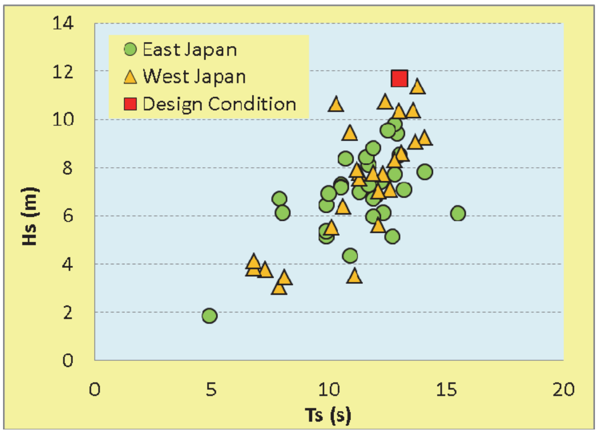


Fig.13. Design Wave and Observed High Waves

Since there is potential flow strength under the influence of ocean current Kuroshio, it is expected that drag force acting on the floating structure in submerged section also becomes very large load. Mooring design to ensure adequate security has been carried out, to be able to safely position FOWT acted maximum load due to wind, wave and current even if all of them comes from the same direction based many tank tests and mooring simulation.

IV. CONCLUSION

The concept design on a V-shaped semi-submersible floating structure is discussed. Tank tests and wind tunnel tests for the purpose of acquisition of the design data are shown. It is shown that this floating structure has both excellent stable performance and anti-wave performance, and also satisfies the rules for the safety of mooring equipment. About the serious issue on dynamic stability performance including negative damping due to wind turbine control system, many simulations were conducted and it is prospected that it might be avoided.

In this demonstration project, empirical observation is scheduled for two years after installation, it is planned to be apparent safety, reliability, and economy on this floating structure along with the establishment of technology.

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