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NUMERICAL AND EXPERIMENTAL COMPARISON OF THE WAVE RESPONSE OF A VERY LIGHT FLOATING OFFSHORE WIND TURBINE WITH GUY WIRES

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ABSTRACT

A floating offshore wind turbine (FOWT) concept with a guy wire-supported tower was investigated to obtain results of motion in waves considering its elastic model characteristics. The FOWT concept aims to reduce construction costs by using a light-weight structure tensioned with guy wires and a downwind turbine concept type.

A wave tank experiment of an elastically similar segmented backbone model in the 1/60th scale was conducted to clarify the dynamic elastic response features of the structure. The results were compared with numerical simulations obtained with software NK-UTWind (in house software developed by the University of Tokyo) and WAMIT code.

It was clarified that the bending moment for tower and pontoons had two peak values when the response for each wave period was examined. The peak in the short-wave period was due to sagging when the wavelength matched the floater length. The other peak was due to the largest tower top acceleration, which caused a large bending moment at the tower base and pontoon to support the inertia force.

Keywords: floating offshore wind turbine (FOWT), elastic characteristics, guy wires, wave tests.

NOMENCLATURE

A	cross section area [m^2]
C_{ax}, C_{ay}, C_{az}	added mass coefficient in the x, y, z direction
$\mathrm{C_{dx}}, \mathrm{C_{dy}}, \mathrm{C_{dz}}$	drag coefficient in the x, y, z direction
dF	total force per unit length [N/m]
D	diameter of cylinder [m]
H_s	significant wave height [m]
T_s	significant wave period [s]
u_x, u_y	water particle velocities in the x and y direction [m/s]
$\dot{u_x}, \dot{u_y}$	water particle acceleration in the x and y direction [$\mathrm{m/s^2}$]

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v_x, v_y	velocities of structural element in the x and y direction [m/s]
$\dot{v}_x, \dot{v}_y$	acceleration of structural element in the x and y direction $[\mathrm{m/s^2}]$
ρ	mass density of water $[\mathrm{kg/m^3}]$

INTRODUCTION

Offshore wind has enormous potential since it allows using more constant and stronger winds. Large turbines could be used as there is no problem of visual pollution or noise generation. However, the cons of offshore wind lie at high costs for installation, mooring lines, and transmission cable fees.

To minimize costs, light, easy to build and simple to install structures are essential. In recent projects, a next-generation floating offshore wind power generation system demonstration research by the New Energy and Industrial Technology Development Organization (NEDO) adopted many solution concepts, such as barge, semi-submersibles, and spar type floaters aiming for further cost reduction. New floater types, mooring systems, construction technologies are currently investigated by NEDO and round the world.

In this context, a new concept of FOWT has been proposed. The idea, presented in Figure 1, consists of an arrangement with a central tower connected by pontoons to three columns by an angle of 120 degrees. The columns are connected to the central tower by wires used to reinforce the structure of the floating unit, allowing the tower and the other structures to be lighter. These wires, referred to as guy wires herein, add stability to the standing tower and can be connected to the center of the radius columns. Being structurally light, both pontoons and guy wires are subject to hydro-elastic effects due to a decrease in rigidity, which requires evaluating the forces and deformations due to the waves on the various structural elements.

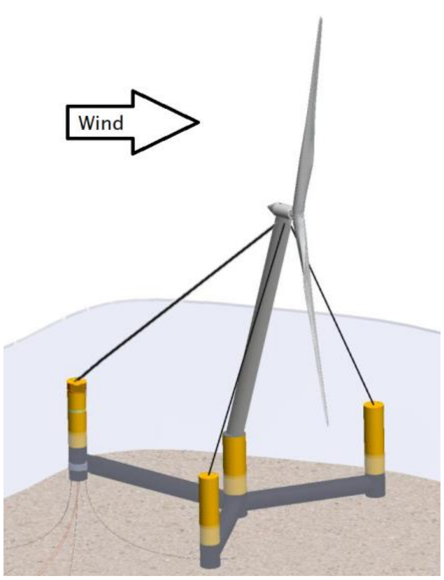

FIGURE 1 CONCEPT IDEA OF THE NEW CONCEPT OF THE FOWT WITH GUY WIRES AND LIGHT-WEIGHT STRUCTURE

In [1], the dynamic behavior of a light-weight semi-submersible floater was investigated, and a finite element model (FEM) code was developed to examine the elastic effects.

A very light semi-submersible floater with guy wires and a straight tower was investigated prior in 2017 by the University of Tokyo (UTokyo), Japan, and the model tests were performed at the University of São Paulo (USP), Brazil. The work was described in [2], [3], [4], in which the experiment results were compared with numerical simulations to investigate the elastic and dynamic response of the floater.

ELASTIC AND DYNAMIC SIMILAR MODEL

A reduced scale model was constructed elastically and dynamically similar to the prototype characteristics to clarify the response characteristics of the floater in waves. A reduced scale model (1:60) was designed by UTokyo and built, as shown in Figure 2. Froude scaling were used, and Table 1 shows the scale factors considered for this model. Core beams were used to represent the elastic similarity of the model, and the urethane wrapped around the core beams to represent the geometry similarity. To abolish additional stiffness due to urethane, urethane parts are segmented. The main model dimensions are summarized in Table 2. Table 3 shows the main hydrostatic and structural characteristics of the floater.

TABLE 1 SCALE FACTORS USING FROUDE SCALING

Items	Scale Factor
Length[m]	λ
Time[s]	$\lambda^{\frac{1}{2}}$
Force[N]	λ^3
Mass[kg]	λ^3
Flexural Rigidity EI [Nm^2]	λ^5

TABLE 2 MAIN DIMENSIONS OF THE FLOATER

Dimension	Prototype full scale	Model scale (1:60)
Length	90.00 m	1,500 mm
Breadth	93.00 m	1,550 mm
Height to Nacelle	109.80 m	1,830 mm
Draft	14.75 m	250 mm

TABLE 3 MAIN CHARACTERISTICS OF THE FLOATER

Item	Prototype full scale	Model scale (1:60)
Displacement	7,194 ton	33.3 kg
KB	5.23 m	87.2 mm
BM (Roll/Pitch)	15.92 / 17.07 m	265.3 / 284.6 mm
KG	12.96 m	215.9 mm
GM (Roll/Pitch)	9.35 / 8.20 m	155.9 / 136.6 mm
***E* Core Material**	2.06×10^{11} Pa	2.06×10^{11} Pa
Water Depth	56.00 m	933 mm

FIGURE 2 ELASTIC AND DYNAMIC SIMILAR SEGMENTED BACKBONE MODEL USED IN THE EXPERIMENTS

In the reduced scale model, guy wires were made by strained steel cables. A pre-tension of 21N was imposed on the guy wires for the windward wire and 12N for two lee wires. The core beams were designed to match the scaled flexural rigidity of the prototype, while the urethane foam was designed to match the buoyancy and geometry of columns and pontoons.

A turret was located in the column positioned windward. The turret allows the free yaw motions, i.e., yaw stiffness and damping can be neglected. The mooring system was attached to the turret point.

The model motions were measured using the Qualisys® optical motion capture system. Four tracking cameras were used, and the sampling frequency for measuring the motions was 100Hz.

The model was equipped with eleven different strain gauges to measure the bending moment of the tower, pontoons, and columns. The gages were located on the inner metal beam frame of the model, as presented in Figure 3. The guy wires have a tension meter at their bottom, and the tension meters for the mooring was located directly under the turret.

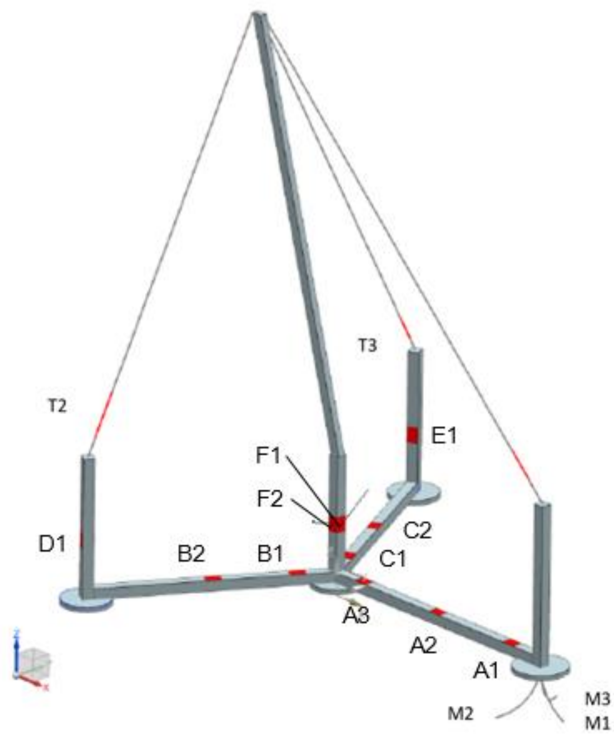

FIGURE 3 LOCATION OF THE STRAIN GAUGES, TENSION METERS IN THE EXPERIMENTED MODEL

WAVE TANK SETUP

The experiments were conducted at the Ocean Engineering Tank in the National Maritime Institute (NMRI), Japan. The tank has dimensions of 27m x 40m x 0.93m (width, length, depth) equipped with a piston-type wavemaker. The top view schematic of the setup is presented in Figure 4. The water depth was adjusted to be similar to the real conditions in the model scale, i.e. 55.8 meters in the full scale.

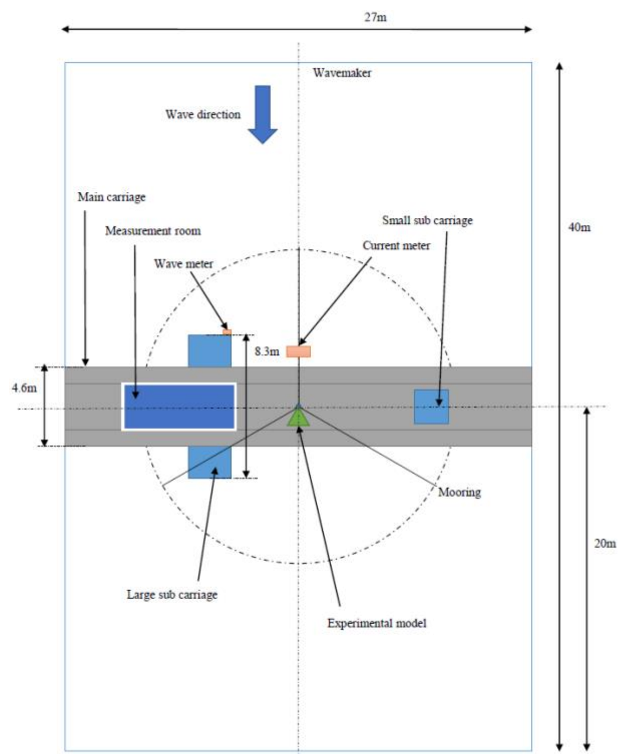

FIGURE 4 TOP VIEW OF THE WAVE BASIN SETUP

A catenary mooring located in the turret position, including chain and wires with different weight characteristics, was adopted, with an angle of 120 degrees for each line.

A wave probe was positioned at the front of the main carriage during the experiments. Also, the four optical tracking cameras were set on the main carriage.

Wind loads and current effects were not considered in this experiment, as this study focuses on the motion behavior and elastic characteristics of the floater due to the wave incidence.

Irregular and regular wave tests were carried out, and the parameters were as follows:

(1) Irregular wave conditions

The irregular wave experiments were carried out for 3 cases. ISSC spectrum was applied to test conditions occurring in the sea around Japan. Centenary condition refers to a condition with long significant wave periods, which is assumed to happen every 100 years. The experimental conditions in terms of full-scale value for the irregular wave tests were:

Case 1 Operational Condition: Hs: 2.5m, Ts: 9.0s

Case 2 Storm Condition: Hs: 9.6m, Ts: 13.5s

Case 3 Centenary Condition: Hs: 4.0m, Ts: 16.1s

(2) Regular wave conditions

Regular wave experiments were carried out for three different wave heights, namely 1.8, 3.6, 5.4m. The wave period was varied in the range of 4.6s to 29.4s for the wave height 1.8m; while for wave heights 3.6m and 5.4m, the wave period was varied in the range of 9.3 to 17.0s. Twenty-seven regular wave cases were conducted in total. The values of regular wave parameters were presented in the full scale.

NUMERICAL CALCULATION METHOD

The full-scale FOWT was modeled and analyzed using NK-UTWind, a software for coupled analysis of FOWT. In the analysis code, the rotor and floating body were modeled with beam elements; the mooring system could be chosen either from the lumped mass method or quasi-static catenary mooring. For calculating the aerodynamic load acting on the rotor, we used wind turbine analysis code FAST based on the blade element momentum theory developed by NREL. A complete description of the method implemented in NK-UTWind can be found in [5].

As most FOWTs comprise slender structural elements, such as cylinders, NK-UTWind employs the Morison equation for evaluating hydrodynamic loading, represented as:

$$\begin{bmatrix} dF_x \\ dF_y \end{bmatrix} = \rho A \begin{bmatrix} (1 + C_{ax})\dot{u_x} \\ (1 + C_{ay})\dot{u_y} \end{bmatrix} - \rho A \begin{bmatrix} C_{ax}\dot{v_x} \\ C_{ay}\dot{v_y} \end{bmatrix} + \frac{1}{2}\rho D|\boldsymbol{u} - \boldsymbol{v}| \begin{bmatrix} C_{dx}(u_x - v_x) \\ C_{dy}(u_y - v_y) \end{bmatrix} \quad (1)$$

where ρ is the fluid density, A is the cross-sectional area, u_x and u_y are water particle velocities in the x and y-direction. v_x and v_y are velocities of the structural element in the x and y-direction. C_{ax} and C_{ay} are the added mass coefficients in the x and y-direction. C_{dx} and C_{dy} are drag force coefficients in the x and y-direction. Wheeler's stretch method is used to estimate the wave velocity field, and the instantaneous wave load is evaluated considering the submergence of each structural element.

TABLE 4 ADDED MASS AND DRAG COEFFICIENTS ADOPTED IN NK-UTWIND

Coefficient	Columns	Pontoons
C_{ax}	1.0	1.0
C_{ay}	1.0	1.0
C_{az}	0.8	0.8
C_{Dx}	1.0	1.0
C_{Dy}	1.0	1.0
C_{Dz}	0.0	0.0

The added mass coefficients and drag coefficients adopted in NK-UTWind simulation are given in Table 4. These values were obtained from DNV-GL guidelines as standard hydrodynamic coefficients for cylinders.

WAMIT ANALYSIS

Besides the analysis performed with NK-UTWind, the behavior of the FOWT was also evaluated using the WAMIT code, a commercial Boundary Element Method code for analyzing wave interactions with offshore structures. The software evaluates the hydrodynamic loads through the solution of the radiation/diffraction problem in frequency domain and, since this is a different method from the one employed in NK-UTWind, comparing the motion RAOs obtained with both software indicates in which conditions each method is better at reproducing the experiments.

The WAMIT simulation was performed with a low-order mesh composed of 4,654 flat quadrilateral and triangular panels with a mean edge length of approximately 1.3 m, as illustrated in Figure 5.

FIGURE 5 LOW-ORDER MESH CONSIDERED IN THE WAMIT ANALYSIS

Since WAMIT is based on potential flow and mooring lines are not directly modeled in the software, it is necessary to include an external linear damping matrix to account for viscous damping and an external linear stiffness matrix to partially model mooring effects. The damping matrix was obtained from the decay tests, while the stiffness matrix was set so that the natural periods in surge and pitch would match the ones observed in the RAOs obtained from the experiments. The values are listed below.

TABLE 5 EXTERNAL DAMPING AND STIFFNESS VALUES CONSIDERED IN THE WAMIT ANALYSIS

	Damping B_{ii}	Stiffness K_{ii}
Surge	3.07×10^4 N.s/m	3.79×10^5N/m
Heave	4.52×10^5 N.s/m	0
Pitch	3.89×10^8 N.m.s/rad	3.81×10^8N.m/rad

RESULTS

The main results from the experiments were the first order motions of the floater, bending moments at different locations on the structure, and the tension fluctuations in the guy wires. The results were presented on a full scale.

Motion Response

Regular wave experiment results and numerical results by NK-UTWind are presented in Figures 6 to 8.

Natural periods obtained by free decay tests both from experiment and numerical calculation are shown in Table 6.

TABLE 6 COMPARISON OF MEASURED AND CALCULATED NATURAL PERIOD

	Experiment [s]	NK-UTWind [s]
Surge	35.75	35.60
Heave	17.53	17.43
Pitch	22.09	23.55

NK-UTWind and WAMIT results agreed very well with the experimental results for shorter wave periods for surge motions.

For heave motions, the numerical results presented higher damping characteristics, therefore hindering significant heave responses. A cancellation point was observed as in the experiments. A clear peak at the natural period of heave was observed, yet this peak was not observed in the model tests.

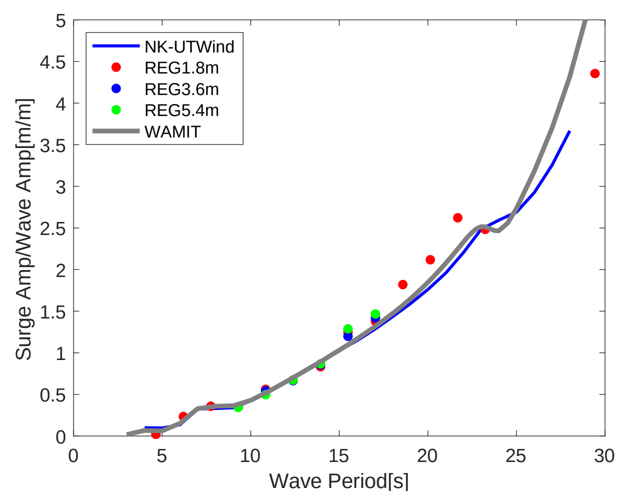

FIGURE 6 RAO SURGE MOTION COMPARISON BETWEEN THE EXPERIMENT AND CALCULATION BY NK-UTWIND

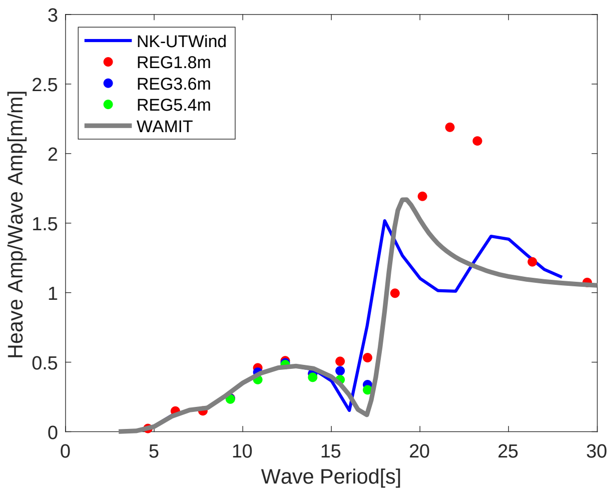

FIGURE 7 RAO HEAVE MOTION COMPARISON BETWEEN THE EXPERIMENT AND CALCULATION BY NK-UTWIND

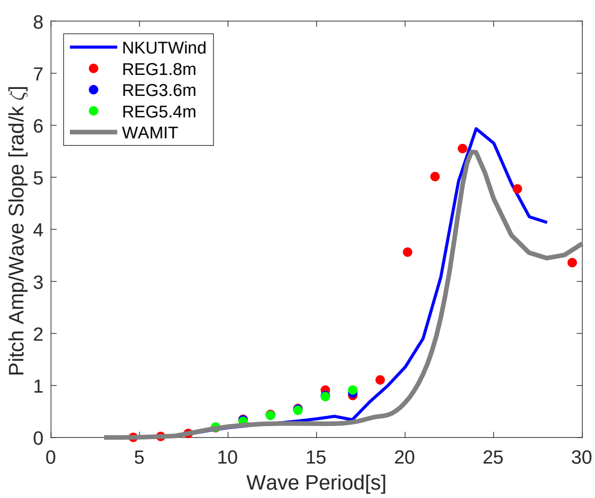

FIGURE 8 RAO PITCH MOTION COMPARISON BETWEEN THE EXPERIMENT AND CALCULATION BY NK-UTWIND

One of the explanations for the difference may be due to the limitation of the ability of the Rayleigh damping matrix applied to NK-UTWind to tune the motions individually at each degree of freedom. A peak near 24s shows the coupling effect between heave and pitch motions.

Another explanation may be the definition of the coordinated system during the model tests. The coordinated system was located at the center of gravity of the platform; however, due to the turret presence, the center of rotation could be shifted and the pitch motions contaminated the heave motion, which explained the large heave in the model tests. In the WAMIT analysis, this would lead to terms outside the main diagonal of the external stiffness matrix, which were not considered.

In general, the floater showed the characteristics of a typical semi-submersible floater, as the RAOs converge to 1 in long wave periods.

For pitch, the RAO plot showed a significant peak around the natural period. The pitch motion was strongly coupled with other degrees of freedom, as there was a small peak observed for the surge motion and a peak for the heave motion. Numerical results and experimental results agreed well in general, with some differences regarding the width around the peaks. This behavior was probably due to the difference in mooring settings for calculation, where a single material quasi-static mooring was applied. In the experiment, several elements with different weights were combined to form a catenary mooring. Differences in the hydrodynamic damping from experiments and numerical calculations can explain the disagreement.

Guy wire tension and bending moments

The guy wire tensions (corresponding to Tension meter T1 and T3 in Figure. 3), the bending moments at the tower bottom (corresponding to Strain F1 in Figure. 3), and the bending moments in the bow side pontoon (corresponding to Strain A3 in Figure. 3) are presented in Figure 9 to 12, respectively.

No slack of the guy wires was detected during the experiment confirmed by the pre-tension values. Therefore, a combination of the tower, pontoon arms, and guy wires seemed to hold the inertia force of the rotor nacelle assembly (RNA) at the tower top during all the wave tests.

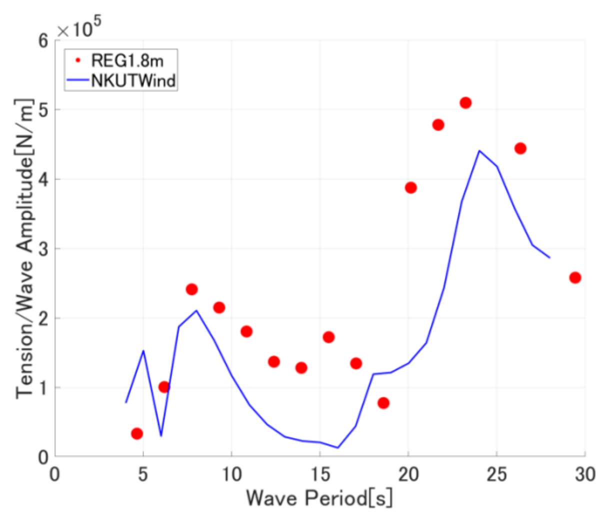

FIGURE 9 TENSION RAO AT THE GUY WIRES (T1) COMPARISON BETWEEN THE EXPERIMENT AND CALCULATION BY NK-UTWIND

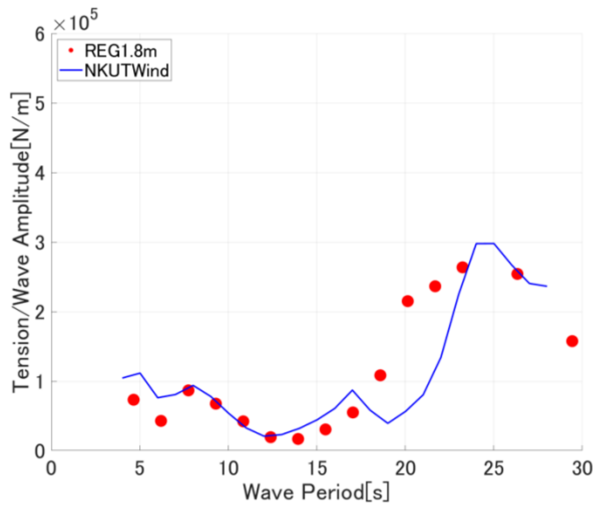

FIGURE 10 TENSION RAO AT THE GUY WIRES (T3) COMPARISON BETWEEN THE EXPERIMENT AND CALCULATION BY NK-UTWIND

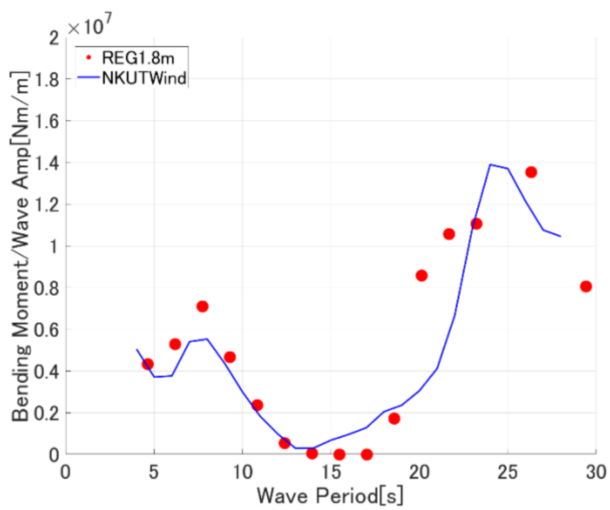

FIGURE 11 BENDING MOMENT RAO AT THE TOWER-BASE (F1) COMPARISON BETWEEN THE EXPERIMENT AND CALCULATION BY NK-UTWIND

The comparison between experimental and numerical results showed a great agreement. For force measurements, two peaks were observed in both guy wire tension and tower bottom (F1) bending moment as in Figure 11. At the wave period between 7 and 8s, the wavelength was equal to the distance between the columns projected in the wave direction. The sagging moment takes the maximum value when the wave peak comes to the fore column and side column, and the wave valley is located around the central column. The broad peak observed around 22~27s indicates a response due to pitch motion.

In the numerical results for pontoon bending moment and front guy wire, there was a small peak near 17s. This behavior was due to the heave motion observed around the natural period, and large inertia force applied to the pontoon. Also, there were local minimum points at 10s and 16s for the pontoon bending moment. The former peak was due to the combination of heave and pitch motion, related to a wavelength close to twice the platform diameter; and, the last peak came from the wave cancellation period in the heave direction, where heave motions took the minimum value and inertia force since the motions were small.

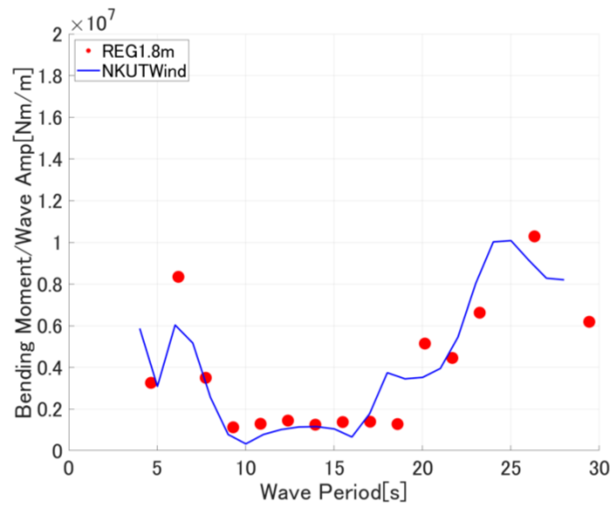

FIGURE 12 BENDING MOMENT RAO AT THE BOW SIDE PONTOON (A3) COMPARISON BETWEEN THE EXPERIMENT AND CALCULATION BY NK-UTWIND

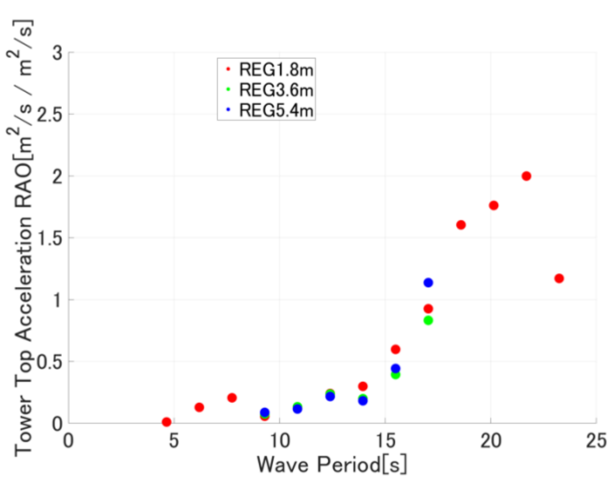

FIGURE 13 RAO ACCELERATION AT THE TURBINE NACELLE FOR DIFFERENT WAVE HEIGHTS

Figure 13 shows the tower top acceleration observed for different wave heights, calculated as an absolute acceleration value due to the six-degree of freedom motions. At the wave period of 22 s, acceleration at tower top takes the most considerable value due to a peak in pitch motion. Inertia force in the surge direction also became great; therefore, the bending moment at the tower base, pontoon became large to support the inertia force of the tower and RNA.

CONCLUSIONS

This work presented the results of an experimental wave test campaign of the floater of a very-light semi-submersible FOWT. Dynamic response characteristics were investigated by wave tank experiments with dynamic and elastic similarly segmented backbone model, and the motion and force responses were compared and analyzed by numerical codes.

Regarding the dynamic response, the motion of structure in the heave direction showed typical response characteristics of a semi-submersible type floating structure. The overall motion of the structure was influenced mainly by heave and pitch motions, as it showed coupling with other degrees of freedom.

As for the bending moment in the tower and pontoon, the bending moment was found to becomes large at a wave period of 7 s when the sagging moment takes the maximum value due to the matching of wavelength and floater diameter. Around the wave period of 26s, when pitch motion was significant, and a bending moment of the tower, pontoon, also the guy wire tension became large to support the inertia force.

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