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Design of Spar-Type Floating Substructures for a 2.5MW-class Wind Turbine Using Fluid-Structure Coupled Analysis

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ABSTRACT

Design of spar-type substructure should focus on satisfying stability in dynamic motion behavior and low stress within allowable ranges as well as low cost of material and installation. In this study, three design variables (draft, diameter, ballast weight) with 3 levels in the substructure were selected and 9 corresponding models were produced based on design of experiment (DOE). By performing fluid-structure coupled analysis under severe wave conditions with normal current and hydrostatic pressure, we evaluated the dynamic motions (maximum resultant displacement) and maximum von Mises stress and analyzed the influence of those three design variables on the dynamic motion and stress distribution of spar type floating the substructures of spar-type floating wind turbines.

1. INTRODUCTION

The harvesting of offshore wind power for electricity generation has inherent advantages due to an easier acquisition of the space required, as well as the greater energy production that comes from larger scale wind turbines than those used onshore.(Agarwal 2003) Recently, various Korean R&D projects have been focusing on the design and construction of offshore wind turbine substructures. Wind turbines should be constructed at sites where the wind resources are rich, which are generally more abundant in the open oceans rather than in coastal areas.(Du-Ho Lee 2011) However, the physical depth of the open oceans necessitates the costly installation of monopiles or jacket-type substructures fixed to the ocean floor, which makes such

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projects economically unviable. In these scenarios, floater-type substructures are preferable. .(Lee 2011) There is currently a lack of extensive experience in designing offshore wind substructures, which is further complicated by the complex physical parameters that affect the various external load combinations, and a scarcity of research results for novel design standards. Therefore, further investigation into novel design standards and their application in domestic circumstances is of critical importance.(Kim 2011) External parameters such as the depth of water, wind speed, water current and hydrostatic pressure must all be considered for robust substructure design.The aims of the present study were as follows:

Firstly, to develop a technique for analyzing fluid-behavior interactions on spar-type substructure/platforms, which was achieved by performing substructure stress analysis tests as realistically as possible. Wave pressure, current pressure (simulating a 1m/s tidal current), and hydrostatic pressure have been considered in the analysis. Secondly, we developed nine models by conducting a 3-level DOE, taking into account total draft, diameter and floater thickness, which are design parameters regarded as having the strongest influence on structural stress and behavior. Thirdly, the best model in respect to structural stability was identified by performing fluid-structure analysis on the nine DOE models. Finally, the correlation between parameters including size of the structure, wave frequency and structural stress was investigated.

2. FINITE ELEMENT MODELS

2.*1 Superstructure*

The displacement behavior of spar-type substructures is small compared to other floating substructures, due to a smaller diameter. We therefore selected the spar-type substructure for our study. In order to perform a behavioral analysis of the substructures, the weight of the 2.5MW superstructure and inertial information is needed. The dimensions of the wind power generator (Table 1) used in this study are a 2.5MW superstructure, generated by utilizing GH Bladed software (Fig. 1).

Table 1 2.5 MW wind turbine superstructure specification

Parts	Specification
Tower	
Height [m]	78.0
Mass [kg]	131,022
Drivetrain	
Nacelle mass [kg]	80,000
Rotor	
Hub height [m]	80.0
Rotor mass including blades	53,174
Blade mass [kg]	9,391

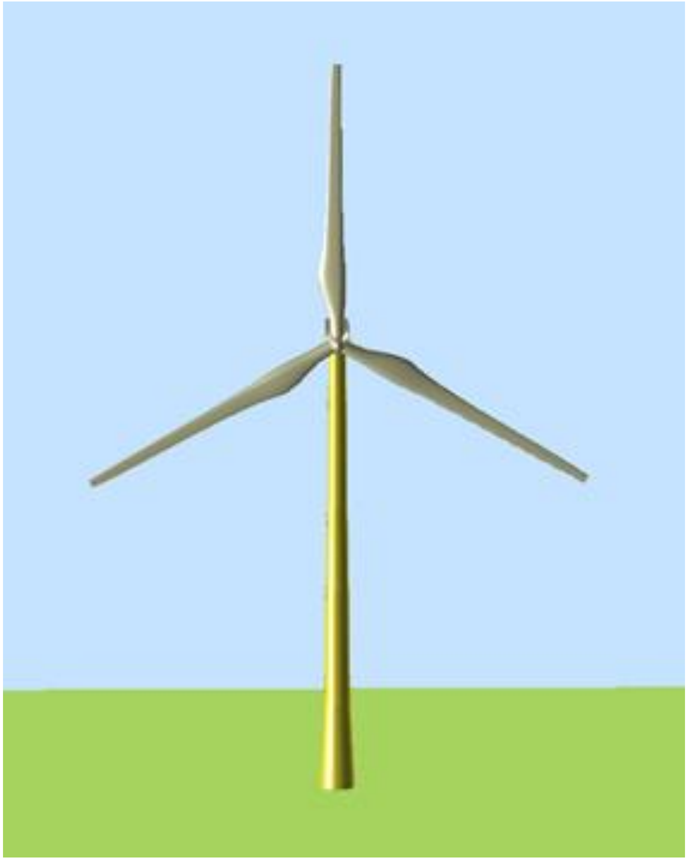

Fig. 1 Superstructure modeling by GH Bladed software

The information of center of mass (COM), weight and inertia of the currently used superstructure is shown in Table 2. Because the shape of the superstructure is symmetrical across z-axis, the z axis information of COM (COM_Z) is indicated in the table.

Table 2.Mass and moments of inertia of the superstructure

Capacity	COM_Z[m]	Mass[kg]	Ixx[kg.m2]	Iyy[kg.m2]	Izz[kg.m2]
2.5MW	58.106	264317.06	1.89 e+10	1.89 e+10	1.49 e+6

2.*2Calculation of the buoyancy of the substructure*

In order to calculate the buoyancy of the substructure, the weight of the blades, hub, nacelle and rotor, in addition to the weight of the substructure itself were considered as follows:

$$R_B = [(L \times \pi \times r^2 \times \rho_w) - (M_B + M_U)] \quad (1)$$

R_B	Margin of buoyancy
L	Draft
M_B	Substructure mass (for each model)
M_U	Mass of the superstructure (264,317 kg)

In Eq. (1), $(L \times \pi \times r^2 \times \rho_w)$ represents the entire buoyancy of the substructure, while $(M_B + M_U)$ represents the entire mass of the structure. By utilizing previous research results, it was found that the weight of the concrete ballast can be substituted for 40% of R_B and the weight of the water ballast can be substituted for the remainder of R_B in order to prevent structural inversion as a result of buoyancy problems.

2.3Substructure model generation based on DOE

Design of Experiments (DOE) refers to a systematic procedure carried out under controlled conditions to reduce unnecessary statistical trials and to obtain the greatest information from statistical analysis. DOE can be used to quantitatively determine significant factors, to analyze the effect of insignificant factors and measurement errors, and to produce optimized results on factor responses. The variation in design parameters for the substructure in this study were as follows: Thickness: between 0.05 and 0.07 meters, Diameter: between 7 and 9 meters, Draft: between 65 and 85 meters, and the Draft was subcategorized into three levels (Table 3).

Table 3 Design variable levels

Thickness	[m]	Diameter	[m]	Draft	[m]
0	0.05	0	7	0	65
1	0.06	1	8	1	75
2	0.07	2	9	2	85

Response Surface Method is an experimental design technique that minimizes the time required and optimizes experimental results by estimating stationary points, by applying non-linear regression equations to major parameters. When the second-order regression model is determined to be appropriate for the response surface estimation of RSM, factorial design, Fractional Factorial Design, Central Composite Design Rotate Design, Rotate Central Composite Design and Box-Behnken Design are used. Unnecessary or high-order interactions were not analyzed and Fractional Factorial Design was used for testing important factor combinations. This method is considered the most effective way to investigate the effect of design parameters on structural stability, by separating unnecessary (and possibly confounding) interactions from important factors and minimizing the numbers for the models (Table 4).

Table 4 Design of Experiment (DOE)

Model number	Thickness	Diameter	Draft
1	0	0	0
2	0	1	1
3	0	2	2
4	1	0	1
5	1	1	2
6	1	2	0
7	2	0	2
8	2	1	0
9	2	2	1

Weight information for the nine models generated by DOE and ballast information was obtained from structure interpretation. The information has been used as point mass information in the hydrodynamic analysis as shown in Table 5.

Table 5 Information of 9 substructure models according to DOE

Model	1	2	3	4	5	6	7	8	9
COM_Z [m]	-45.7	-52.6	-59.4	-52.3	-59.2	-45.4	-58.8	-45.1	-52.2
Mass [ton]	2273	3555	5236	2665	4085	3935	3024	3051	4563
Ixx [kg.m2]	5.3e8	9.9e8	1.7e9	9.0e8	1.6e9	8.7e8	1.4e9	8.0e8	1.4e9
Iyy [kg.m2]	5.3e8	9.9e8	1.7e9	9.0e8	1.6e9	8.7e8	1.4e9	8.0e8	1.4e9
Izz [kg.m2]	6.8e6	1.2e7	1.9e7	9.7e6	1.6e7	1.8e7	1.2e7	1.4e7	2.4e7
Draft [m]	65	75	85	75	85	65	85	65	75
Diameter [m]	7	8	9	7	8	9	7	8	9
Thickness [m]	0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.07
Concrete Height [m]	7.77	9.8	11.82	8.58	10.75	8.4	9.1	7.45	9.33
Water Height [m]	26.17	32.97	39.8	28.88	36.18	28.28	30.63	25.05	31.41

3. Fluid-Structure Coupled Finite Element Analysis

3.1 Diffraction Analysis

The nine DOE models have been composed as Shell Body models. In ANSYS-AQWA the number of elements is limited to 12,000 and the analysis is not performed if the size of the element is less than 30% of the area of a face. Denser meshes cannot be generated in ANSYS-AQWA than for finite element models derived from general structure interpretation. In order to accurately calculate panel pressure generated on the surface, dense mesh has been created by considering the area of each face and the size of each element. The density of seawater was input at $1025\text{kg}/m^3$, the volume of seawater was 300 meters in depth, 600 meters along the X-axis and 600 meters along the Y-axis. The structure was located in the center of the sea surface as shown in Fig.3.

Table 6 Mesh information of 9 models generated by AQWA

	1	2	3	4	5	6	7	8	9
Number of nodes	3,105	3,992	4,200	3,445	4,533	3,894	3,930	3,504	4,461
Number of elements	2,992	3,967	7,179	3,424	4,509	3,866	3,908	3,477	4,431

The mesh was generated using a combined meshing type. The size of the linking elements for the superstructure was set to 0.8 meters and the size of the substructure external wall was set to 1.4 meters as shown in Table 6.

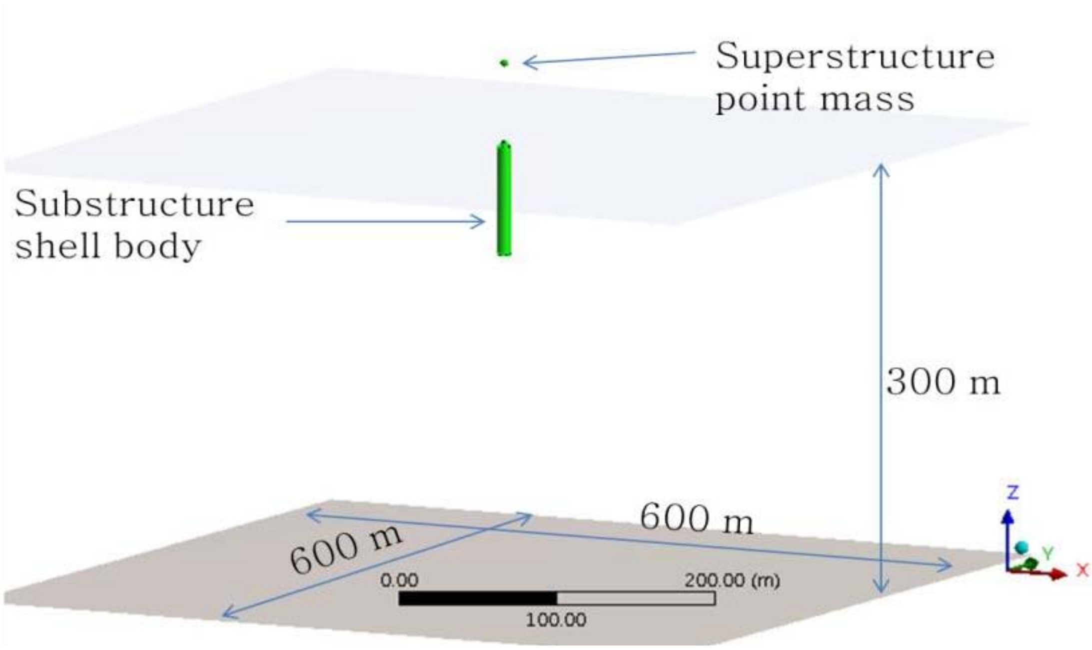

Fig. 3 Hydrodynamic diffraction analysis model

The wave period (frequency), the element having the most influence on the behavior of the structure, was analyzed by dividing the wave frequency range into six levels from 0 to 0.3Hz. And wave amplitude (height) was set to 13.7m, which is the maximum wave height of typhoon Bola Ben, to simulate extreme loads.

Table 7 Maximum resultant displacement (m) of 9 models in wave frequency range

	0.009Hz	0.104Hz	0.151Hz	0.199Hz	0.245Hz	0.294Hz
1	44.658	7.152	4.301	2.604	1.453	0.742
2	44.545	8.633	5.068	2.964	1.557	0.766
3	44.434	10.043	5.67	3.187	1.579	0.749
4	44.555	7.444	4.392	2.637	1.467	0.747
5	44.438	8.88	5.078	2.939	1.536	0.753
6	44.503	9.03	5.42	3.117	1.561	0.747
7	44.743	7.65	4.418	2.63	1.457	0.740
8	44.545	7.956	4.801	2.835	1.493	0.736
9	44.576	9.463	5.508	3.128	1.557	0.742

The largest displacement for each model generated by the 6 level wave period (frequency) was between 44.434 meters and 44.658 meters at the lowest wave period, 0.009Hz. The smallest displacement in the 0.74 - 0.766 meter range was generated at 0.294Hz (Table 7, Fig. 4).

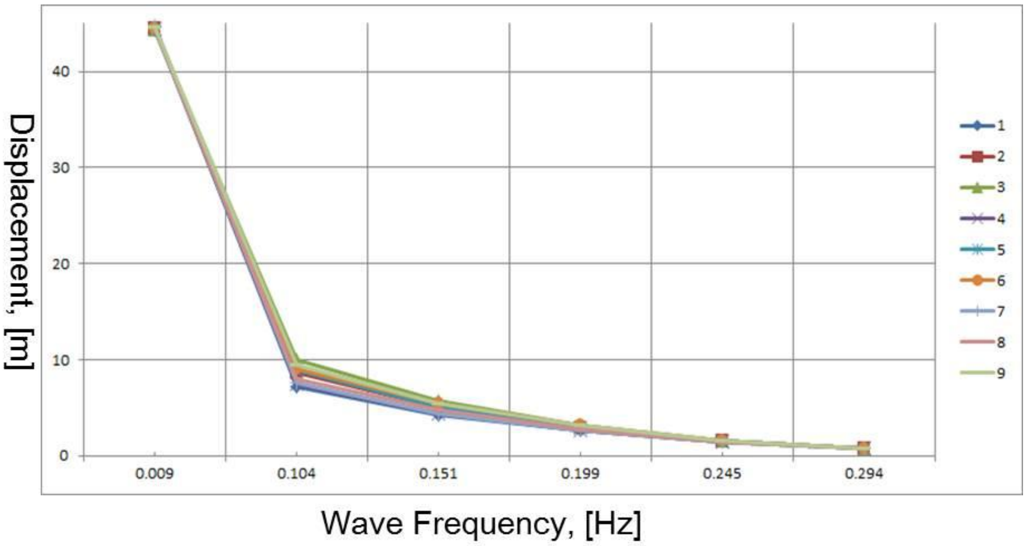

Fig. 4 Graph of 9model displacement in wave frequency range

3.2 CFD analysis

In order to simulate the external load of the structure using current speed, the ANSYS-CFX solver was used. Current speed was set to 1m/s in fluid field. The size of the flow field was set to the water volume used in AQWA, as shown in Fig. 5. Dense mesh was not assigned to the entire flow field. Unnecessary calculations were reduced by setting element densities on the fluid and solid surfaces. The element size, shape and angle of the element were set to 0.3 meters, triangular type and 22°, respectively.

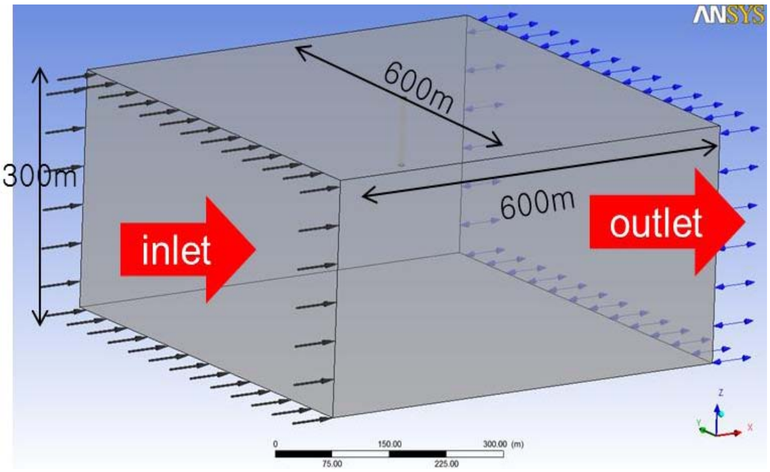

Fig. 5 Fluid field

3.3 AQWA + CFX + Structural Interaction Analysis, Considering Water Depth

The wave pressure interacting on the AQWA elements was set as the external load conditions for the structure analysis, enabled by utilizing AQWA-Wave. AQWA elements were set to SFE elements by using ANSTOASAS command. This procedure enables mapping between AQWA elements and structural model elements. Figures for pressure interacting on the SFE elements were generated in *.dat file format and can be applied as external load commands in the structural analysis at the Workbench (Fig.6).In Process 1 and Process 2, mass information of the structure, inertial information and the ANSTOASAS command used in ANSYS-AQWA have been loaded. In Process 3, the structure was transformed into a shell model, with no thickness or flexure.

Our rationale for employing a rigid body in AQWA is as follows. The number of elements was limited in order to reduce the analysis time. In addition, a flexible body is not essential for analysis. In Process 4, AQWA analysis was performed, while wave frequency and wave amplitude were determined in the process. The results of the diffraction analysis of the sea surface, RAOs on structural behavior at six degrees of freedom, as well as the wave pressure interacting with the external wall of the structure and resultant displacement were obtained in the process.

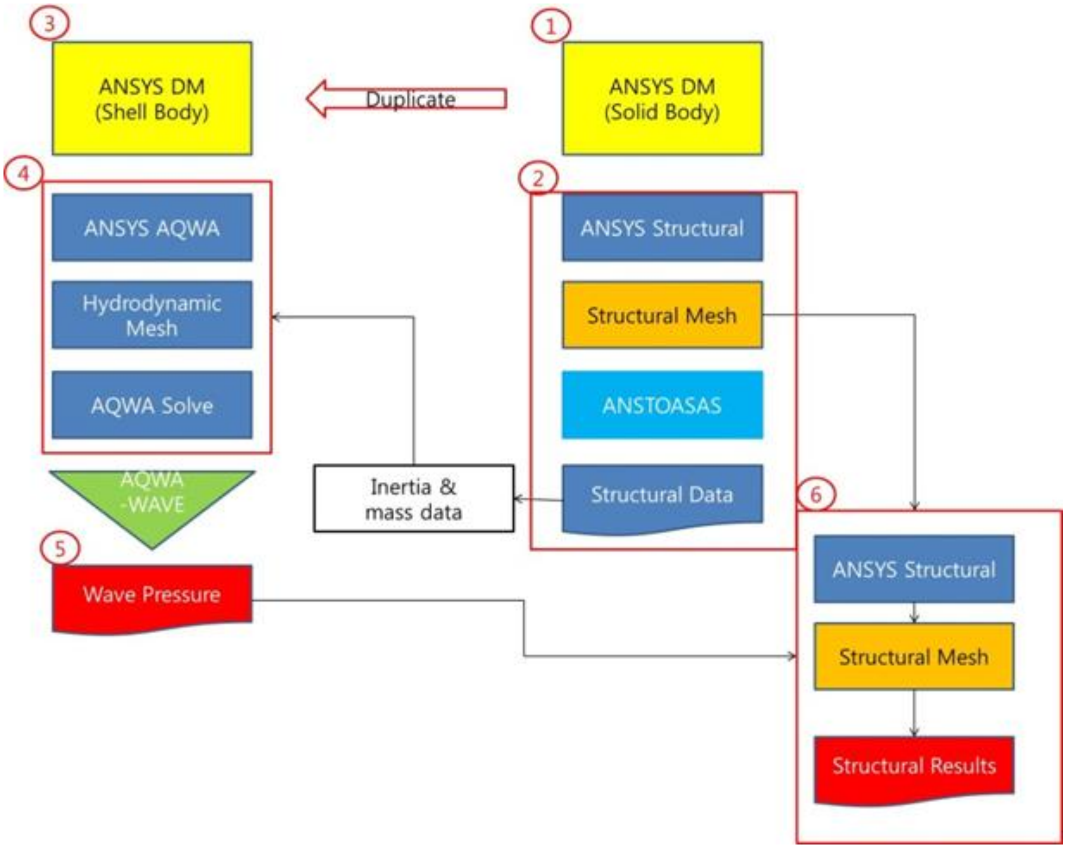

Fig. 6 Flow chart of coupled analysis using AQWA-structural

The results of the RAOs and diffraction analysis of the sea surface were excluded because they are not within the scope of this study. Wave pressure was applied to the structural analysis in Process 5. The resultant *.dat file was set to the command load in the structural analysis and Process 6 was performed. The pressure generated by the depth of water also needs to be considered as external loads, since the draft of the structure is extended in the vertical direction. Thus, the simulated hydrostatic pressure was applied to the structural analysis (Fig.7).

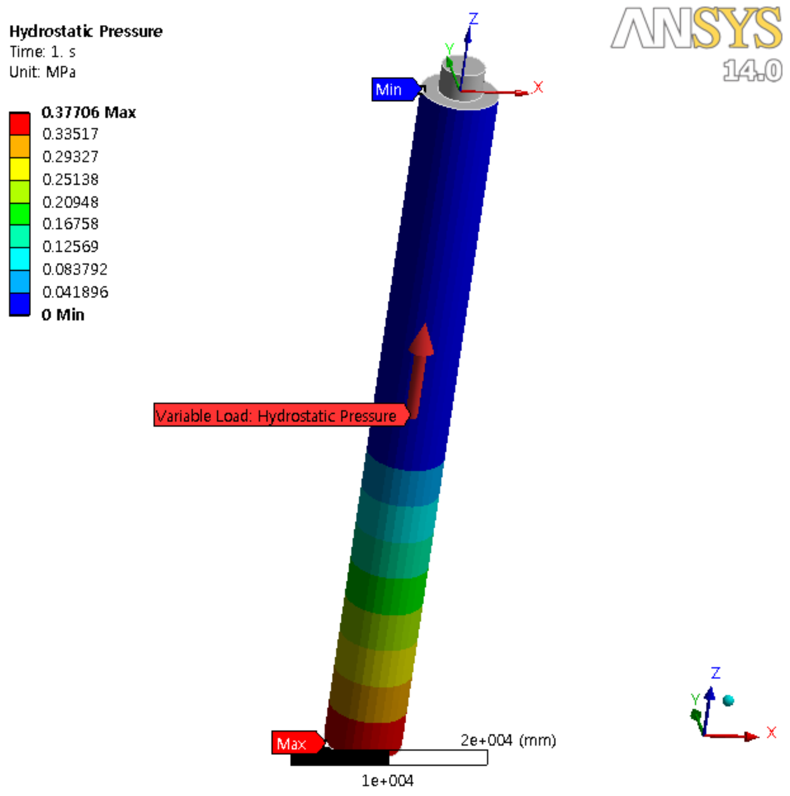

Fig. 7 Hydrostatic pressure

4. RESULTS

Identification of the maximum stress parameters is critical for analyzing structural linear stability. A structure with a lower maximum stress than the breaking strength is theoretically guaranteed to maintain stability. The maximum stress was identified when external loads including waves, currents and water depth was applied to the nine models. The maximum stress was generated in Model 2 with a 0.199Hz wave frequency. The stress distribution of Model 2 was identified so that it converged at the point where the waves were breaking near the sea surface (Fig.8, Fig.9).

Table 8 Maximum vonMises stress (MPa) of 9 structural models

	1	2	3	4	5	6	7	8	9
Case1	51.04	34.68	44.47	24.5	32.06	27.61	23.3	20.57	27.14
Case2	51.91	115.8	45.04	57.8	83.82	28.25	44.37	67.66	27.47
Case3	52.55	147.3	44.86	75.92	102.1	31.65	55.77	92.18	27.38
Case4	53.55	154.7	75.07	81.75	106.0	53.21	59.24	98.8	39.88
Case5	54.40	132.0	92.35	72.89	90.45	65.17	52.69	84.38	48.75
Case6	54.41	101.4	99.17	56	69.91	69.92	40.55	64.35	52.22

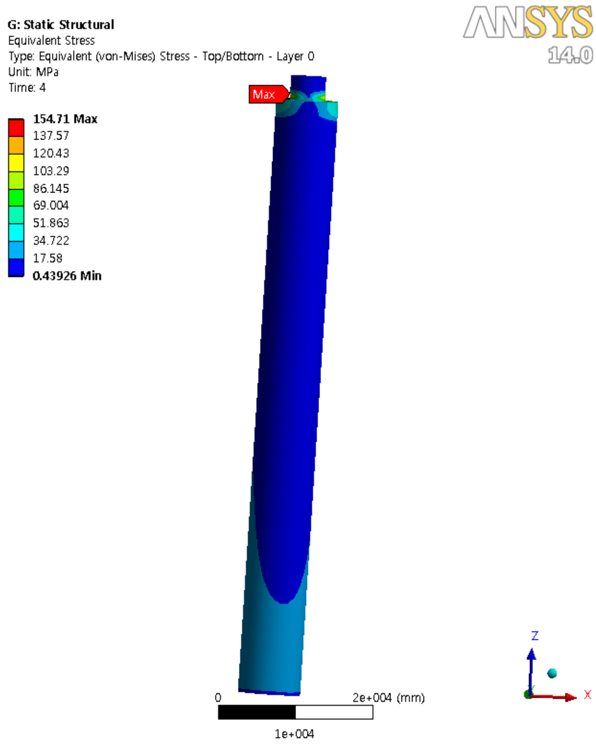

Fig. 8 Stress distribution of Model 2

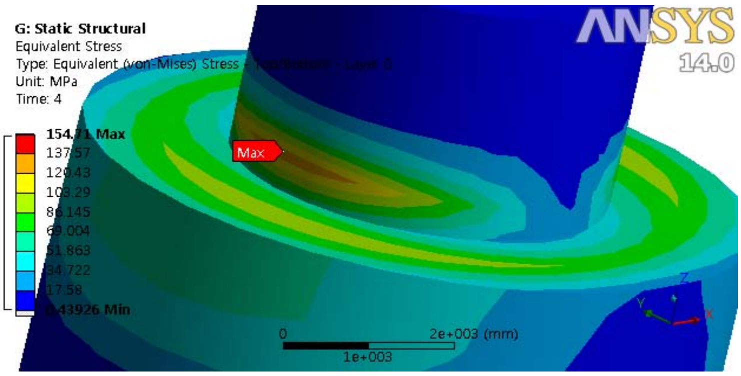

Fig. 9 Maximum stress point of Model 2

5. CONCLUSIONS

In this study, an analysis of the fundamental design of a 2.5MW floater-type wind power generator substructure was performed, and the resultant displacement generated by waves, as well as the influence of external loads including waves, current and water depth were analyzed and a structural analysis performed. In addition, nine models were generated by utilizing DOE and we observed stress changes when external loads were applied. The influence of the design parameters and wave frequency on the behavior and the stress of the structure were identified.

The summary of the results are as follows:

Since experiments with a 2.5MW deep-sea floater wind power generator cannot be easily performed in real ocean conditions, a close structural analysis is valuable prior to its undertaking. In this study, extreme load conditions simulating real ocean conditions were applied to nine finite element models generated by DOE and a behavior-fluid-structure interaction analysis was performed. The influence of the design parameters and wave frequency on the structure was investigated.

Design guidelines were proposed by utilizing external load analysis based on AQWA and CFX and interaction analysis. These methods can mitigate design risk for real offshore wind power system construction. Among the design parameters, the larger the draft becomes, the more stable the behavior, whereas the larger the diameter becomes, the less stable the behavior. This observation stems from the fact that the larger the structural area, the greater the area can be hit by waves, and higher instability results. When the total draft becomes large, the center of the structure lowers and the behavior becomes consequently stable.

A comparative analysis of the nine DOE models was conducted. High stress was generated in models 1, 2, 4, 5, 7 and 8 when the wave frequency was 0.199Hz, whereas high stress was observed in models 3, 6, and 9 at 0.294Hz. Based on these observations, it can be inferred that the wave frequency that affects structural stress may change if the natural frequency relating to the shape of the structure is changed. Therefore the wave frequency of a test site and the natural frequency of the structure should be studied and considered in the overall design of floater-type wind power generators.

ACKNOWLEDGMENT

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REFERENCES

AgarwalA.K. andJainA.K. (2003), “Dynamic behavior of offshore spar platforms under regular sea waves” Ocean Eng., Vol.**30**, 487-516.

Du-Ho Lee andYoun-Jujeong (2011), “Integrated Analysis of Hydrodynamic Motions and Structural Behavior of Large-Scaled Floating Structures using AQWA-ANSYS Coupling” Computational structural Eng., Vol.**24**(6), 601-608.

Yong-Ju Kwon, Byung-Mo Kim, and Han-Il Park (2011), “Structure Anlaysis of Floating Offshore Wind Turbine Tower System” KAOSTS, 1429-1432.

Sung-One Kim, Hong-Woo Kim, Chang-Bog Ko and Nam-Ho Kyoung(2011), “2MW Offshore Wind Turbine Construction” Journal of Wind Energy, Vol.**2**(2), 3-9.

Kwang-Dong Park, Hyo-Jae Jo and Ja-Sam Goo (2001), “A Study of Wave and Current Forces on Cylinders” Journal of Ocean Engineering and Technology, Vol.**5**(4),14-19.

Ho-Chang Jung, Sang-Yong Jung, Sung-Chin Hahn andCheolGyun Lee (2007), “Optimal Design of Permanent Magnet Wind Generator for Maximum Annual Energy Production” Trans. KIEE, Vol.**56**(12), 2109-2115.

Ki-Du Kim, Dong-Ho Choi, JongsungSim and Kyoung-Chul Kim (2011), “Development and Design of Offshore Wind TurbineSupport Structures” KSCE, Vol.**59**(5), 28-37.

Du-Ho Lee andYoun-JuJeong (2011), “Intergrated Analysis of Hydrodynamic Motions ans Structural Behavior of Large-Scaled Floating Structures using AQWA-ANSYS Coupling” JSGJCV, Vol.**24**(6), 601-608.

Jong-Hun han, Shi Wei, Sang-Kwan Na, Hyun-Chul Park (2012) “Load Assessment of the Offshore Wind Turbine Substructure Considering Structural Integrity of Joint” Journal of Wind Energy, Vol.**3**(1), 68-73.

J.H. Choi, S.R. Kim,C.M. Kim, S.J. Lee and J.M. Kim (2012), “Scale-Model Design of Floating Offshore Wind Turbine” Proceeding of ’12 KSPE Congress, Jeju.

Thomas H. Dawson (1983), Offshore Structural Engineering, Prentice-Hall.Inc.

Ben C. andGerwick, Jr. (1986), Construction of Offshore Structures, John Wiley & Sons, Inc.

TSNE(2003), Basis of Finite Element Analysis and Linear Analysis, Vol.**4**, TSNE.

S. Sircar, T. Chandra and S. Manguno (1990), "Transportation Launch and Self-Upend Analysis of the Kilauea Jacket Using Proven Analytical Techniques", Offshore Tech & Conf.

ANSYS (2011), AQWATM- LINE User Manual,pp.10-126, Ansys, Inc.

Stece Sawyer, ArthourosZervos(2009), “Global Wind 2009 Report”, pp.11-16, GWEC.

W.Musial, S. Butterfield andB.Ram.(2006), “Energy from offshore wind”, NREL/CP-500-39450, 2-11.