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MODAL ANALYSIS OF OFFSHORE WIND SYSTEM WITH SUCTION BUCKET SUBSTRUCTURE

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Abstract: Modal behaviors of a 5MW offshore wind system including suction bucket foundation was analyzed by finite element model. A simplified rotor-nacelle-assembly was presented, and it was applied to modal analysis of the offshore wind turbine system. Parametric studies were also conducted to analyze effects of several designfactors on the natural frequency of the offshore wind system. The results show that the natural frequency is mainly dependent on the soil-suction stiffness than other factors. The presented numerical model was also applied to an offshore wind system on in-site seabed (southwestern sea of South Korea) to estimate its availability.

Keywords: Modal analysis, sensitivity analysis, simplified rotor-nacelle-assembly model, soil-bucket rigidity

I. INTRODUCTION

Offshore Wind System (OWS) should be subject to environmental loads, such as wind and wave, and behaves dynamically. Rotor-Nacelle-Assembly (RNA) onto the tower of the OWS is also always operating with a certain frequency and results in thrust and rotational loading on the OWS. If the OWShas a similar natural frequency rangewith that of the RNA,it then oscillates with greater amplitude; this calls resonance. The phenomenon would occur by external dynamic forces with excitation frequency which is similar with that of the OWS as well.It has known that the resonance destroys vibration stability and structural safety of OWSs. Therefore, it is important to avoid the same frequency range with RNA as well as environmental loads. Natural frequency of OWS has influenced by the mass, stiffness, and soil-foundation rigidity at the seabed.

Suction bucket substructure system has advantages of simple installation and low installation cost at the clay seabed of coastal area. Although this system has a disadvantage of instability in vibration since this substructure is mainly applied to the soft seabed of coastal area and not fixed to the rock directly, it has been continuously and widely used as one of the most promising types of foundation of offshore structures [1], due to its relatively convenient and fast constructability. For this reason, studies on offshore structures with this foundation type have been steadily carried out by several researcher groups. Several experimental tests for suction bucket foundation and its application to OWSs were conducted [2, 3, 4, and 5]since Mackereth (1958) [6] used this type of foundation at a soft lake.In particular, numerical studies on the OWS were also performed recently. Choo et al. (2015) [7] studied on new hybrid piled gravity base foundation for OWS using a finite element model. They analyzed effects of loading height and direction, the rigidity of the piled gravity based foundation, and clay strength on the foundation responses. Ying et al. (2016) [8] conducted a numerical simulation of an integrated suction foundation including its installation process in deep ocean to analyze the uplift resistance of the foundation. They numerically showed the suction foundation can be installed successfully without damages due to seepage during suction penetration. Ding et al. (2016) [9] numerically analyzed seismic response of offshore wind structure supported by suction bucket foundation. They conducted modal and seismic analyses using the integrated numerical model of the OWS and examined the responses of soil inside the suction bucket. Although they provide a refined numerical model for OWS, it is not practical with respect to upper structure specification, in particular of RNA, because the model excludes effects of mass and mass inertia of RNA. For analyzing dynamic behaviors of the OWS,RNA specification is one of the most important factor because it effects on the natural frequency and responses of OWS.

In this research paper, analytical and numerical studies were carried out to verify influence of seabed soil-foundation rigidity on natural frequency of an OWS with gravity base suction bucket substructure. To enhance the reliability and effectiveness of results, a simplified RNA modeling technique was also proposed. Furthermore, frequency sensitivity of the OWS to soil-bucket rigidity and bucket dimensions was examined. Finally, the proposed model is applied to a real OWS for practical preliminary design.

II. MODELING OF OFFSHORE WIND SYSTEM

The numerical model of the OWS in this study composes of the following four parts: RNA, tower, substructure, and soil-bucket foundation. RNA modelling is established by using the proposed simplified point mass model. Soil-bucket foundation stiffness and damping effect are considered by analytical estimation equations used in Park et al. [10]. Tower structure and concrete substructure are modelled by using shell elements.The target OWS has hub height of 100m (tower height: 78.3m) and total superstructure weight of about 810 tonf including RNA.The above described numerical model was implemented by using ANSYS ver. 15.0.

1. RNA Modeling

Generally specific information of RNA, to generate the corresponding numerical model, is provided limitedly from the commercial turbine manufacture corporation; mass and mass inertia and its positions. For this reason, this study used the simplified RNA model using point mass and mass inertia as shown in Fig. 1. This modelincludes inertia effects of RNA, but the stiffness doesn't.Although the RNA stiffness is neglected, the approach is reasonable because RNA mass is much heavier than that of tower, which results in governing the natural frequency of the total OWS by RNA mass, and effects of the RNA stiffness on total stiffness of the OWS is small. The turbine capacity is 5MW and its allowable frequency range is from 0.255 to 0.279 Hz. Specific data related to the model is indicated in Table 1.

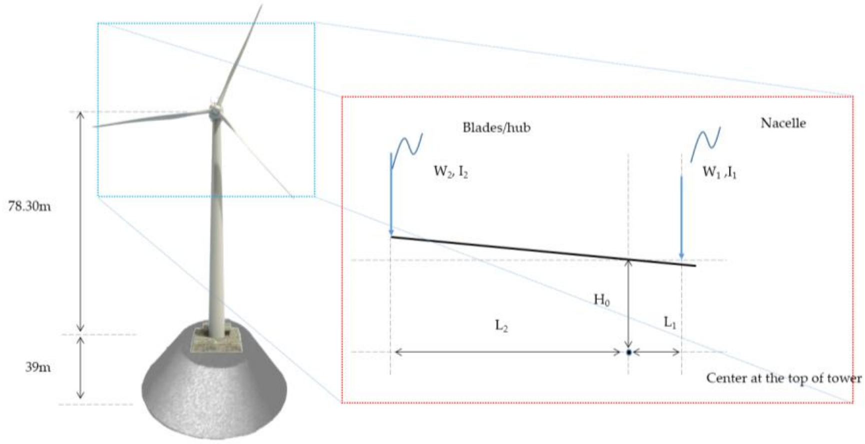


Figure 1 Idealization of RNA

Table 1 Idealized geometry, point mass, and point mass inertia of RNA

	W_1(ton)	W_2(ton)	I_1(ton·m^2)	I_2(ton·m^2)	L_1(m)	L_2(m)	H_0(m)
Value	290	138	I_{xx}: 510 I_{yy}: 510 I_{zz}: 253	I_{xx}: 13,165 I_{yy}: 13,135 I_{zz}: 154	0.60	4.76	2.63

In Fig. 1 and Table 1, each notation means as follows: W_1: mass of nacelle, I_1: mass inertia of nacelle, W_2: weight of Blades and hub, I_2: mass inertia of Blades and hub, H_0: distance between the connection point of RNA and the center at the top of tower, L_1: distance between the center of mass of nacelle and the connection point, and L_2: distance between the center of mass of blades/hub and the connection point.

2. Tower and Substructure Modelling

Tower and substructure geometry are determined dependently on RNA specification. In particular of determining tower dimension, effects of wind on tower structure as well as external loading due to RNA should be reflected in tower design; tower design is consequently conducted by a turbine manufacturer and specific information such as dimension is restricted. Furthermore, the design is considerably difficult to change because RNA and tower design require a certification by international institutes related to offshore industry. Accordingly, tower is roughly described in this paper. Tower with the height of 78.30m is a hollow cylinder. The cross-section of the tower varied with diameter and thickness; the diameter varies from 5.46m (bottom) to 4.17m (top), and a range of the thickness is from 48mm to26mm.Overall substructureshape and geometry are shown in Fig. 2.The substructure is made of reinforced concrete. To implement a linear modal analysis of the OWS, an equivalent elastic modulus of the reinforced concrete was used. Material properties for tower and substructure are listed in Table 2.

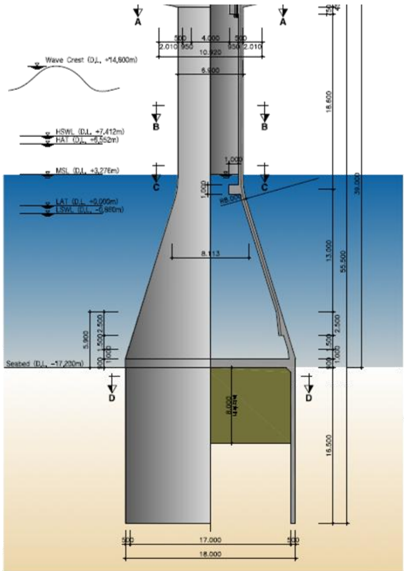


Figure 2 Geometry of substructure

Table 2 Material properties for tower and substructure

Material	Steel	RC
Density (kg/m^3)	7850	2500
Elastic modulus (GPa)	210	32
Poisson's ratio	0.3	0.18

3. Soil-Bucket Modelling

The target ground is simply classified into five groups, based on Caltrans/NEHPR soil profiles [11]: hard rock, rock, very dense soil and soft rock, stiff soil, and soft soil. Relevant characteristic properties of each ground type are presented in Table 3. To estimate quantitatively deformable and decaying parameters, representative shear wave velocity of each ground was used. Stiffness and damping coefficient of the soil-bucket foundation is calculated by using the following equations, which were used in Park et al. (2011) to calculate the rigidity and damping for mono-pile or group pile foundation:

$$E_s = 2(1+\nu)\rho_s V_s \tag{1}$$

$$K_{xx} = \frac{2E_p I_p}{R^3}\left(\frac{E_s}{E_p}\right)^{0.75} \tag{2}$$

$$K_{x\theta} = K_{\theta x} = -\frac{1.2E_p I_p}{R^3}\left(\frac{E_s}{E_p}\right)^{0.5} \tag{3}$$

$$K_{\theta\theta} = \frac{1.6E_p I_p}{R}\left(\frac{E_s}{E_p}\right)^{0.25} \tag{4}$$

$$K_{zz} = \frac{50E_p A_p}{L}\left(\frac{V_s}{V_p}\right)^{0.75} \tag{5}$$

$$C_{xx} = 2K_{xx}\left(\frac{D_p}{V_s}\right) \tag{6}$$

$$C_{x\theta} = C_{\theta x} = 1.5K_{x\theta}\left(\frac{D_p}{V_s}\right) \tag{7}$$

$$C_{\theta\theta} = 0.5K_{\theta\theta}\left(\frac{D_p}{V_s}\right) \tag{8}$$

$$C_{zz} = 0.026K_{zz}\left(\frac{L_p}{V_s}\right) \tag{9}$$

Where E_s: deformation modulus of soil, v: Poisson's ratio of soil, ρ_s: density of soil, V_s: shear wave velocity of soil, K: stiffness coefficient with respect to the corresponding degree of freedom, C: damping coefficient with respect to the corresponding DOF, E_p: elastic modulus of pile, I_p: inertia of cross-section area, *R*: horizontal distance between the center of each pile and that of substructure, D_p: diameter of pile, A_p: cross-section area of pile, L_p: pile length.In the modal analysis, soil-bucket foundation rigidity at the seabed was modeled using spring and damper elements, as presented in Fig 3. Because the above equations were not developed for suction foundation, some considerations are required to apply the equations to this study. The given suction foundation is considered as 127 steel piles with the diameter of 0.5m, which isequal to the thickness of suction cylinder; the piles are aligned along the circumference of cross-section of the suction cylinder andits gross cross-section area is approximately equal to hollow that of the suction cylinder.All the specific value of stiffness and damping coefficient is listed in Tables 4 and 5.

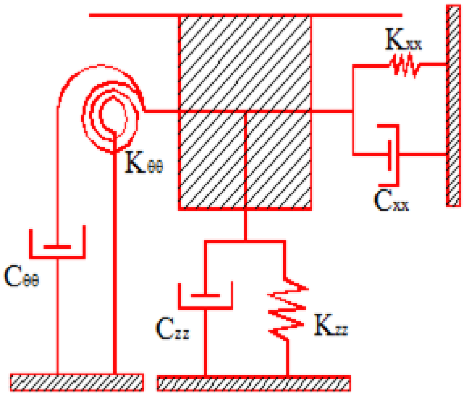


Figure 3 Scheme of Suction foundation: stiffness and damping DOF

Table 3 Caltrans/NEHRP soil profile types

Ground type	Shear wave velocity range (V_s, m/s)	SPT N value (bpf)	Undrained shear strength (kPa)	Representative value of V_s(m/s)
Hard rock	>1500	-	-	3000
Rock	760~1500	-	-	1130
Very dense soil and soft rock	360~760	> 50	> 100	560
Stiff soil	180~360	15 ~ 50	50 ~ 100	270
Soft soil	< 180	< 15	< 50	90

Table 4 Stiffness coefficient for soil-suction foundation

Ground type	Stiffness coefficient(N/m, N·m/rad)		
Hard rock (3,000 m/s)	$K_{xx} = K_{yy} = 2.32 \times 10^8$, $K_{zz} = 1.12 \times 10^{11}$,	$K_{\theta\theta_x} = K_{\theta\theta_y} = 2.05 \times 10^{11}$, $K_{x\theta_y} = K_{y\theta_x} = 6.12 \times 10^8$	$K_{\theta\theta_z} = 5.73 \times 10^{25}$
Rock (1,130 m/s)	$K_{xx} = K_{yy} = 5.36 \times 10^7$, $K_{zz} = 1.12 \times 10^{11}$,	$K_{\theta\theta_x} = K_{\theta\theta_y} = 1.26 \times 10^{11}$, $K_{x\theta_y} = K_{y\theta_x} = 2.30 \times 10^8$	$K_{\theta\theta_z} = 5.73 \times 10^{25}$
Very dens soil and soft rock (560 m/s)	$K_{xx} = K_{yy} = 1.87 \times 10^7$, $K_{zz} = 1.12 \times 10^{11}$,	$K_{\theta\theta_x} = K_{\theta\theta_y} = 8.88 \times 10^{10}$, $K_{x\theta_y} = K_{y\theta_x} = 1.14 \times 10^8$	$K_{\theta\theta_z} = 5.73 \times 10^{25}$
Stiff soil (270 m/s)	$K_{xx} = K_{yy} = 6.26 \times 10^6$, $K_{zz} = 1.12 \times 10^{11}$,	$K_{\theta\theta_x} = K_{\theta\theta_y} = 6.19 \times 10^{10}$, $K_{x\theta_y} = K_{y\theta_x} = 5.50 \times 10^7$	$K_{\theta\theta_z} = 5.73 \times 10^{25}$

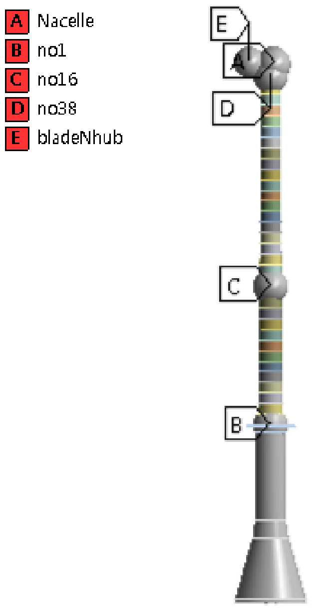
Soft soil (90 m/s)	$K_{xx} = K_{yy} = 1.21 \times 10^6$, $K_{zz} = 1.12 \times 10^{11}$,	$K_{\theta\theta_x} = K_{\theta\theta_y} = 3.56 \times 10^{10}$, $K_{x\theta_y} = K_{y\theta_x} = 1.83 \times 10^7$	$K_{\theta\theta_z} = 5.73 \times 10^{25}$

Table 5 Damping coefficient for soil-suction foundation

Ground type	Damping coefficient(N·s/m, N·m·s/rad)		
Hard rock (3,000 m/s)	$C_{xx} = C_{yy} = 3.87 \times 10^4$, $C_{zz} = 1.36 \times 10^7$,	$C_{\theta\theta_x} = C_{\theta\theta_y} = 8.54 \times 10^6$, $C_{x\theta_y} = C_{y\theta_x} = 7.64 \times 10^4$	$C_{\theta\theta_z} = 0$
Rock (1,130 m/s)	$C_{xx} = C_{yy} = 2.37 \times 10^4$, $C_{zz} = 3.62 \times 10^7$,	$C_{\theta\theta_x} = C_{\theta\theta_y} = 1.39 \times 10^7$, $C_{x\theta_y} = C_{y\theta_x} = 7.64 \times 10^4$	$C_{\theta\theta_z} = 0$
Very dens soil and soft rock (560 m/s)	$C_{xx} = C_{yy} = 1.67 \times 10^4$, $C_{zz} = 7.31 \times 10^7$,	$C_{\theta\theta_x} = C_{\theta\theta_y} = 1.98 \times 10^7$, $C_{x\theta_y} = C_{y\theta_x} = 7.64 \times 10^4$	$C_{\theta\theta_z} = 0$
Stiff soil (270 m/s)	$C_{xx} = C_{yy} = 1.16 \times 10^4$, $C_{zz} = 1.52 \times 10^8$,	$C_{\theta\theta_x} = C_{\theta\theta_y} = 2.85 \times 10^7$, $C_{x\theta_y} = C_{y\theta_x} = 7.64 \times 10^4$	$C_{\theta\theta_z} = 0$
Soft soil (90 m/s)	$C_{xx} = C_{yy} = 6700$, $C_{zz} = 4.55 \times 10^8$,	$C_{\theta\theta_x} = C_{\theta\theta_y} = 4.94 \times 10^7$, $C_{x\theta_y} = C_{y\theta_x} = 7.64 \times 10^4$	$C_{\theta\theta_z} = 0$

III. FREQUENCY SENSITIVITY TO SOIL-BUCKET RIGIDITY

As the results of the modal analysis using a finite element model for the target OWS as shown in Fig. 4, natural frequencies of OWS with suction bucket foundation, with respectto varying with the soil-bucket rigidity, areshown in Fig. 5 andTable 6. It was found that the soil-bucket rigidity significantly influences on the natural frequency of the OWS. The first natural frequency of the OWS, which is the most important design factor to examine the resonance, ranges from 0.09 (E, Soft soil) to 0.28 Hz (Fixed) with respect to the soil-bucket rigidities.These results show that the stiff foundation does not always provide the allowable frequency domain of the OWS; use of the suction foundation on the ground with hard rock rigidity is only satisfied with the given OWS.However, because an application of the suction foundation is proper to soft ground, Installation of the given OWS should be reconsidered; or an overall design change would be required to avoid resonance.



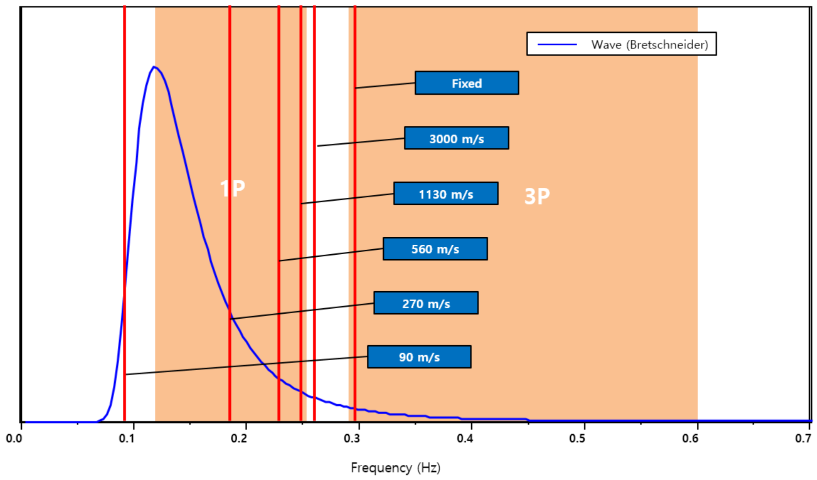


Figure 4 Numerical model

Figure 5 Frequency window and natural frequency of 5MW OWS with respect to ground type

IV. APPLICATION TO REAL OFFSHORE WIND SYSTEM: ANMA WIND FARMS

The presented model, using in-situ seabed ground condition of Anma islands wind farm, was also applied to show model availability. The Anma islands wind farm is in southwestern sea of South Korea and is the test bed for one of the Korea offshore wind project. The offshore seabed at Anma roughly consists of saturated silty-fine and very dense sand (ground depth: 0 ~ -22m), saturated grained and very dense sand (-22 ~ -34m), and saturated grained sand and gravel layers (below -34m). The suction foundation will be penetrated to a depth of 16.5m, its end consequently is located at the saturated silty-fine sand layer.

Using the in-situ test results of this site, soil parameters were estimated, and the corresponding stiffness coefficientswere then calculated by conducting a three-dimensional numerical suction-soil model. In the model, soil is assumed to behave plastically by using Mohr-Coulomb plastic model, while suction body is considered as a rigid body. Load-displacement curves corresponding to each degree of freedom at the center of suction foundation slab due to the soil-suction interaction were extracted from the above finite element analysis. Because a plastic model is used to represent the soil behavior, the load-displacement curvesshould be nonlinear. To obtain equivalent linearized stiffness coefficients to the nonlinear curves, linear regression analysis were carried out. The coefficients were determined for the diameter of 16m and 18m for the suction bucket foundation and are shown in Table 6; where D is a diameter of suction bucket foundation.

Table 6 Stiffness coefficient for soil-suction foundation

Component	Stiffness coefficient(N/m, N·m/rad)	
	D=16m	D=18m
K_{xx}, K_{yy}	1.95×10^{9}	3.26×10^{9}
K_{zz}	1.83×10^{9}	3.26×10^{9}
$K_{\theta\theta_x}$, $K_{\theta\theta_y}$	3.76×10^{11}	5.47×10^{11}
$K_{\theta\theta_z}$	1.67×10^{9}	1.47×10^{11}
$K_{x\theta_y} = K_{y\theta_x}$	2.13×10^{10}	3.34×10^{10}

Natural frequencies of an OWS at the in-situ seabed in Anma islands were calculated. The results show that a natural frequency of the OWS depends on the suction bucket dimension. For D=16m, the 1st natural frequency is 0.255 Hz, which is out of design frequency window (0.255~279Hz). In contrast, that of the OWS for D=18m is in the range of the allowable frequency domain, 0.264 Hz. To verify the accuracy of these values, an integrated numerical analysis was conducted by using Flex 5, and it provided the natural frequency of 0.273Hz; the error is 3.3%. Thus, under the given ground condition, substructure including the suction foundation should be reinforced or enlarged to avoid resonance.

V. CONCLUSIONS

This study conducted modal analysis of a 5MW OWS with suction foundation by using finite element model in which the simplified RNA model is used. Through several parametric change in OWS such as substructure diameter and soil-suction rigidity, a natural frequency of the OWS significantly depends onseabed condition more than substructure dimensions. Therefore, in case of an OWS with suction bucket substructure, it would be useful to control the soil-suction bucket rigidity to prevent resonance. Further studies on the OWS will be required the accuracy of the proposed RNA model, comparing with a refined turbine model. A numerical approach will be also needed to more accurately estimate the stability of the OWS, such as sliding and overturning.

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