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FSI analysis of deformation along offshore pile structure for tidal current power

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ABSTRACT

Due to global warming, the need to secure an alternative clean energy resource has become an international issue. Tidal current power is now recognized as one of the clean power resources in Korea, where there are many strong current regions on the west and south coasts. Recently, large scale tidal devices have been deployed with a maximum rotor diameter of 18 m. These devices impose significant loading on supporting structures. In many cases, a pile fixed foundation is used to secure the structure. However, due to the high density of seawater, the drag and lift forces are much larger than in air, causing extensive stress and deflection to the pile tower structure. In this study, a numerical analysis of the hydro-forces from a rotating tidal current turbine to a tower was conducted to determine the deformation distribution along the pile tower.

1. Introduction

A tidal current power (TCP) system uses tidal current by converting kinetic energy into rotational energy to generate electricity. A turbine along the rotation axis direction can be classified into a horizontal axis turbine (HAT) and a vertical axis turbine (VAT). HAT systems are being studied worldwide [1].

Fluid–structure interaction (FSI) analysis in wind turbines is being researched actively [2], and FSI analysis of TCPs is being studied in foreign [3]. In addition, studies of composite blades with respect to TCP structural strength [4–6] and studies of large-scale turbines [7] are being performed. However, TCP tower design based on FSI is in its early stages.

Recently, TCP system capacities have become greater than 1 MW per TCP. Turbines, which are key components of TCP system, are being designed to diameters of 18 m. Interest in the stability evaluation of TCP structures is increasing as the structural loads increase.

In this study, a rotor was designed using blade element momentum theory, and a CFD analysis of the fluid characteristics and pressures acting on the structure was performed. The calculated pressure values were used to define loading conditions for FEM analysis, and we analyzed structural stability, deformation and stress due to tidal loads.

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2. Rotor design

2.1. Determination of design current speed and turbine size

Before determining the design current speed (U_D), a marine survey must be made of the TCP area to determine the characteristics of the current. A large turbine design based on the depth distribution of tidal current should consider the direction of the current. The size of the turbine to be installed in the ocean depths must also be considered. Turbines are now being designed to 18 m diameters. In this study, an 18 m diameter turbine was chosen and the design current speed was set to 3.5 m/s.

2.2. Determination of output and rated revolution

In order to estimate the output of the blade, the output coefficient (C_P), and the efficiency factors of the hydraulic power transmission gear and water tight device are substituted into Eq. (1):

$$P_{\mathrm{expect}} = \eta C_P \left(\frac{\rho \pi D^2 U_D^3}{8} \right) \tag{1}$$

The rated output of the blades is 2 MW. The design tip speed ratio (TSR, λ_D) is 5, and the rated rotational speed is 18.57 rpm based on Eq. (2):

Table 1
TCP turbine blade design parameters.

Design parameters		Values
P_{rated}	Rated power [MW]	2
C_P	Estimated power coefficient	0.4
U_{rated}	Rated current velocity [m/s]	3.5
ρ	Sea water density [kg/m^3]	1025
λ	Tip speed ratio	5
D	Turbine diameter [m]	18
N	Blade number [EA]	3
ω	Angular speed [rpm]	18.57

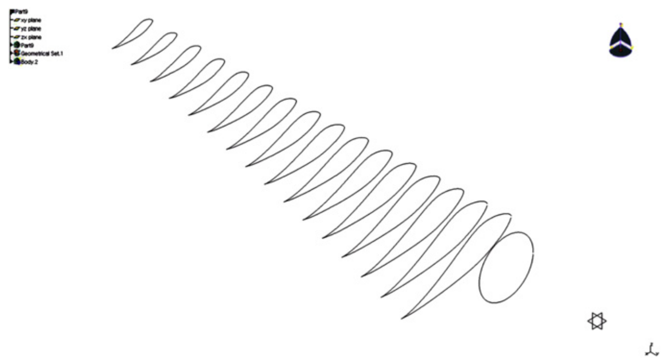

Fig. 1. Framework of 3-D TCP turbine blade model.

$$N_{rpm} = 60\left(\frac{U_D}{\pi D}\right)\lambda \tag{2}$$

2.3. Design parameters of TCP blades

The blades were designed based on the parameters shown in Table 1. The framework and solid modeling of the designed blade are shown in Figs. 1 and 2, respectively.

3. TCP load calculated using CFD

3.1. Calculation condition

In this study, the commercial software ANSYS WORKBENCH CFX (v13.0, ANSYS, Inc., U.S.A.) was used for three dimensional (3-D) stationary flow field analysis.

To minimize the free surface and bottom effects, the 1D clearance was considered from the tip of the turbine to the seabed and to the surface. Accordingly the TCP tower and domain height were determined as the tower height of 26.4 m and the depth of turbine axis 27 m. The rear domain of the analysis has been set to be 180 m that is the 10 times of the turbine diameter. Specification of domain is shown in Table 2. The inner rotating domain is a cylinder which is 18.5 m diameter, and 3 m height.

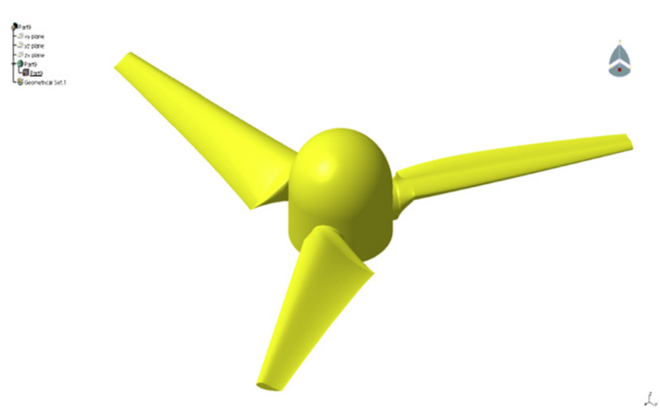

Fig. 2. Solid model of 3-D TCP turbine blade.

Table 2
Domain specification.

Description	Specification [m]
Length	216
Breadth	54
Height	54

Table 3
Analysis condition.

Analysis condition	Value
Physical timescale	0.5143 s
Residual target	1e-05
Iteration	586
Total number of nodes	10,354,592
Total number of elements	13,126,871

3.2. Grid systems and turbulence models

To accurately predict the fluid characteristics, the surrounding TCP turbine and tower were modeled using a dense three-layer inflation grid. The rotating domain was composed of a dense tetrahedron grid, and a hex dominant grid was used elsewhere.

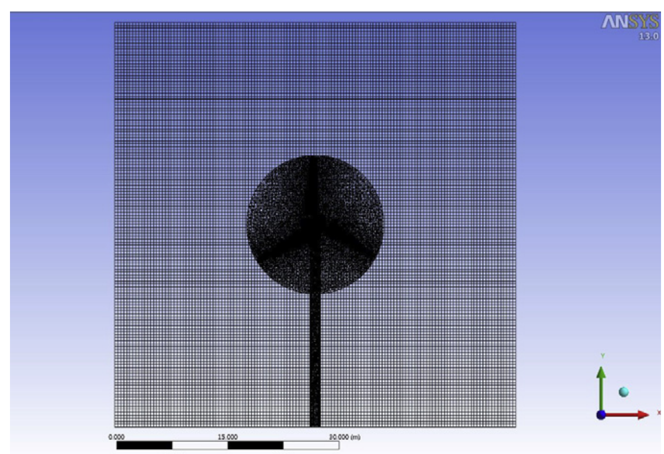

Fig. 3. Grid system of rotor and tower.

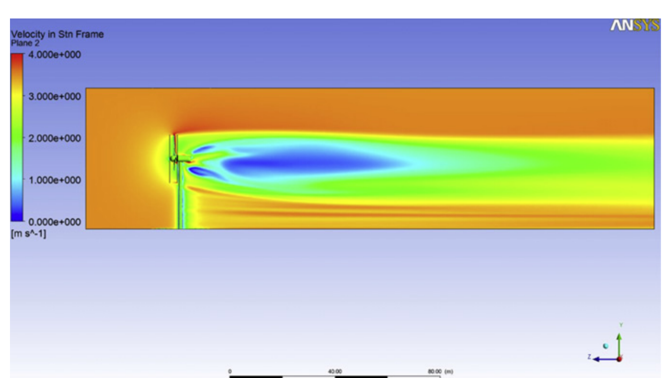

Fig. 4. Velocity distribution.

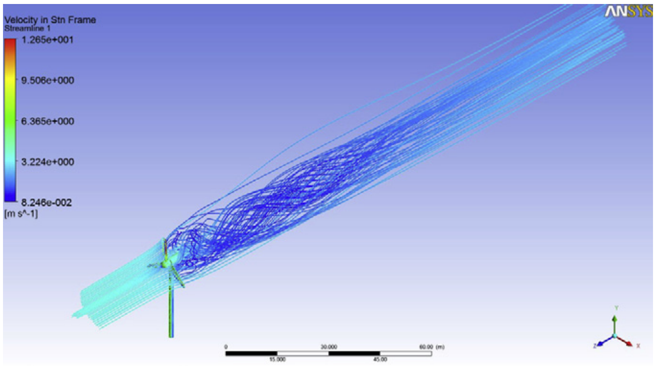

Fig. 5. Downstream streamlines.

10,354,592 nodes and 13,126,871 elements were generated, as shown in Table 3 and Fig. 3.

A turbulence model that involves the dissection of the unsteady flow field around the airfoil was analyzed using the κ-ω shear stress transport (SST) model.

3.3. Results of CFD analysis

The current velocity and streamline distribution of the entire domain are shown in Figs. 4 and 5. The velocity behind the rotating turbine declined rapidly. The tidal loads pressured the entire structure, as shown in Fig. 6. The various TCP tower diameters were investigated in the CFD analysis for 1.2, 1.3, 1.4, and 1.5 m. The tower is subjected to the external loading caused by current and rotation by turbine. As the size of tower increases, the projected area increases as well causing the larger friction and pressure forces as shown in Table 4.

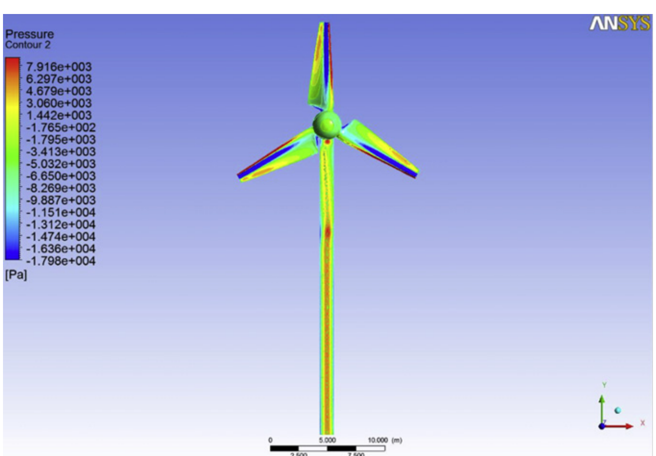

Fig. 6. Pressures along the numerical model.

Table 4
Maximum and minimum pressures on tower.

Tower diameter [m]	Max [Pa]	Min [Pa]
1.2	8994.6	−17979.2
1.3	9239.8	−19102.8
1.4	10134.3	−20300.8
1.5	11338.5	−21368.9

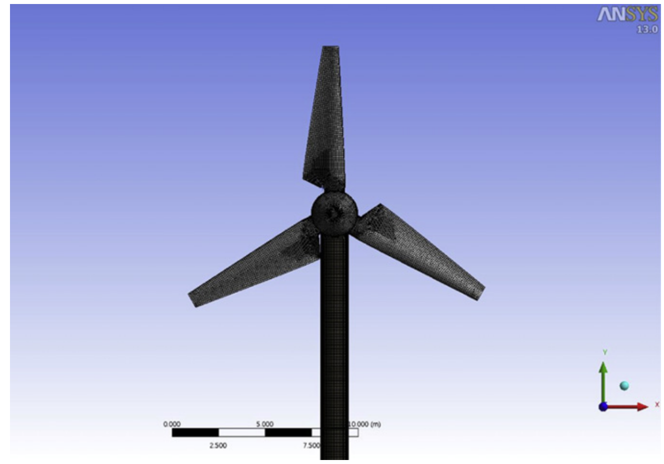

Fig. 7. Gridded TCP device with tower.

Table 5
Modeling mesh information.

Analysis condition	Value
Blade, hub [m]	0.08
Blade-hub contact [m]	0.04
Shaft, nacelle [m]	0.1
Tower [m]	0.05
Total number of nodes	1,310,718
Total number of elements	190,339

Table 6
Properties of materials.

Property	GFRP	API X60
Density [kg/m^3]	2080	7850
Young's modulus [Pa]	1.3e+10	2e+11
Poisson's Ratio	0.33	0.3
Tensile yield strength [Pa]	N/A	6e+08
Compressive yield strength [Pa]	3.1e+08	N/A
Tensile ultimate strength [Pa]	5.5e+08	7.5e+08

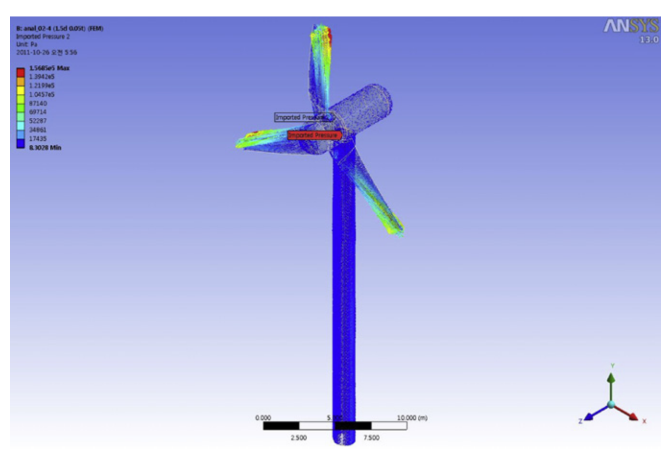

Fig. 8. Imported load due to CFD pressure.

Table 7
Maximum stress and strain on tower.

Diameter [m]	1.2		1.3		1.4		1.5	
Thickness [cm]	Stress [MPa]	Strain [m/m]	Stress [MPa]	Strain [m/m]	Stress [MPa]	Strain [m/m]	Stress [MPa]	Strain [m/m]
4.0	924.50	0.0046						
4.5	895.30	0.0045	717.79	0.0036				
5.0	769.69	0.0038	654.51	0.0033	587.79	0.0029	506.09	0.0025
5.5	715.46	0.0035	603.99	0.0030	524.92	0.0026		
6.0	661.68	0.0033	561.94	0.0028	487.56	0.0024		
6.5	627.56	0.0031	525.36	0.0026	455.37	0.0023		
7.0	583.10	0.0029	495.75	0.0025	427.74	0.0021		
7.5	550.72	0.0028	466.18	0.0023	403.37	0.0020		
8.0	522.44	0.0026	447.71	0.0022	384.58	0.0018		

Table 8
Minimum safety factors of blade and tower.

Diameter [m]	1.2		1.3		1.4		1.5	
Thickness [cm]	Blade	Tower	Blade	Tower	Blade	Tower	Blade	Tower
4.0	8.12	0.65						
4.5	7.74	0.67	7.95	0.84				
5.0	8.03	0.78	8.00	0.92	7.72	1.02	7.98	1.19
5.5	7.74	0.86	8.00	1.00	7.96	1.14		
6.0	7.74	0.91	8.00	1.07	7.72	1.23		
6.5	7.74	0.97	8.00	1.14	7.72	1.32		
7.0	7.74	1.03	8.01	1.21	7.72	1.40		
7.5	7.74	1.09	8.01	1.29	7.72	1.49		
8.0	7.74	1.15	8.01	1.34	7.72	1.57		

4. TCP structural analysis

4.1. Calculation conditions

To analyze the structural stability, the fluid load from CFD result was applied to the TCP tower. The general purpose structural analysis program ANSYS WORKBENCH Static-Structural v13.0 was used.

The TCP design model used for the CFD analysis was shared for the structural study. Tower diameters of 1.2, 1.3, 1.4, and 1.5 m were considered in the research. The thickness of the tower was complied the required standard of D/t ratio that is less than 30. The available manufacturer guideline was referenced to choose the appropriate thickness.

The pile fixed support method was applied to the TCP tower in the study with the end fixed boundary condition (Fig. 7).

4.2. Grid systems and structure analysis

The entire structure was composed of a hex-dominant grid. In addition to increase the accuracy, the sweep method was applied to the tower modeling. The boundary between blades and hub was closely studies by modeling 0.04 m fine grid. For example, the case study of 1.5 m $\times$ 0.05 m tower, it has 1,310,718 nodes and 190,339 elements, as shown in Table 5.

4.3. Material properties

The glass fiber-reinforced plastics (GFRP) composite material for tidal current rotor and API X60 high tensile steel for the tower were applied in the analysis as shown in Table 6.

4.4. Results of structural analysis

In order to satisfy the recommended D/t ratio for the 1.2 m diameter, the thickness of 0.04 m was chosen and the thicknesses for other towers were determined as per the same condition.

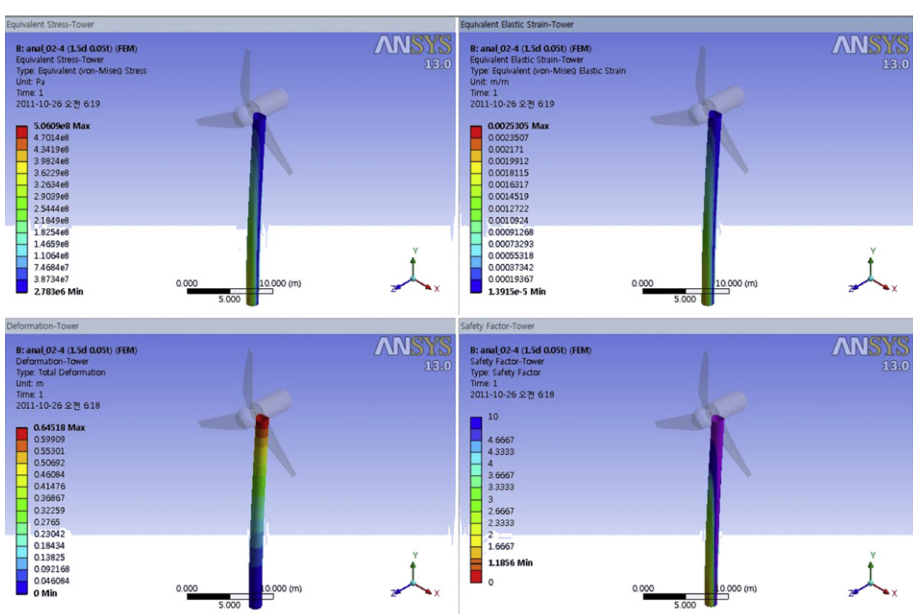

Fig. 9. Analysis results.

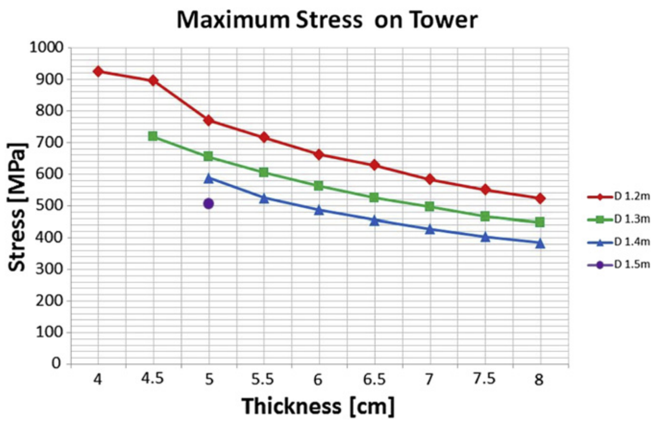

Fig. 10. Maximum stress on tower.

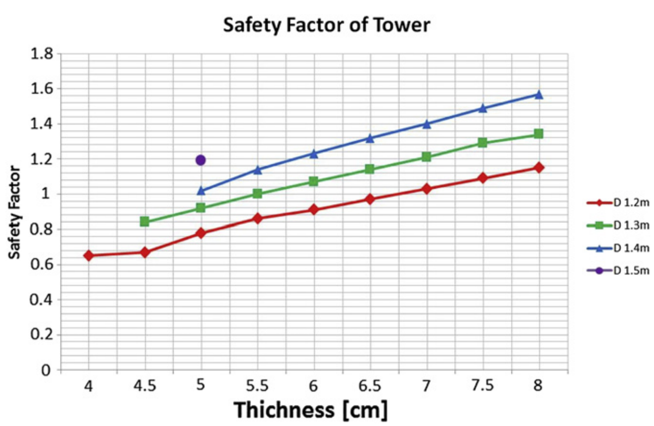

Fig. 11. Safety factor of tower.

The fluid pressure acting on the structure was obtained by CFD analysis and applied to the structural analysis as shown in Fig. 8. Tables 7 and 8 together with Fig. 9 show the stress, strain, deformation and safety factors caused by the hydro-forces. Stress and strain were calculated using the von-Mises method, and the safety factor of the material was calculated based on tensile yield strength. If the thickness of the tower is the same, the higher stress was created in the smaller diameter tower as shown in Fig. 10.

Obviously the less stress and higher s.f. were observed in the thicker towers. Figs. 10 and 11 demonstrated this observation. The minimum thicknesses that can satisfy the s.f. of 1.2 for 1.3 and 1.4 m towers were 7 and 6 cm.

5. Conclusion

In this study, a TCP turbine was designed using blade element momentum theory and the stability was analyzed using CFD and FEM. The current speed and streamline distribution behind the rotor were confirmed, and hydro-forces acting on the TCP structure were calculated. The TCP structural stability with respect to stress, strain, deformation, and the safety factor were studied. The external and rotational loadings were applied to various TCP structure sizes. However, in the future, the vibration and transient structural analysis are to be performed to understand the better dynamic behavior and response of the offshore tidal current tower structures.

Acknowledgments

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