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# Analysis of an offshore wind turbine subjected to earthquakes

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## ABSTRACT

Earthquakes are a potential threat to the fixed offshore wind turbines constructed in Bohai Bay and East China Sea in China. Thus, it is of significance to study the dynamic response of offshore wind turbines subjected to earthquakes. Combined the NREL 5MW baseline wind turbine and its tower with the pentapod sub-structure and foundation of a practical OWT, an integrated structure system of OWT, named after HW 5MW OWT, is suggested. Using SACS, numerical model of the HW 5MW OWT is established. The dynamic characteristics of the FE model are analyzed. The dynamic response of the OWT under earthquakes and environmental loadings is computed. Considering the combined case of current, wave and earthquake, the integrity of the OWT is checked.

## 1. INTRODUCTION

The research on the dynamic characteristics of the offshore wind turbine with different kinds of environmental conditions has been carried out widely. (Philippe 2012) performed a coupled dynamic analysis of a floating wind turbine system in order to investigate effect of wave direction relative to wind on the system. (Sethuraman 2012) measured the hydrodynamic response of s floating spar wind turbine model under regular and irregular waves and compared the data with numerical simulations. (Perdrizet 2012) presents a methodology to assess the short and long terms failure probabilities associated to the extreme response of a floating wind turbine subjected to wind and wave induced loads. (Karimirad 2013) studied the numerical model of a catenary moored spar-type wind turbine in the integrated coupled analysis. (Zaaijer 2006) simplified the dynamic model of foundation, and found that a stiffness matrix at mudline is the best solution for monopole to study the dynamic characteristics of the offshore wind turbine with environmental load combinations. (Cordle 2011) presents results from integrated load calculations performed for an offshore wind turbine on a jacket support subject to combined wind and wave loading in order to determine the relative influence of investigated parameters

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for jacket structure design.

The dynamic characteristics of the OWT have been studied extensively, however, the earthquake analysis about OWT is seldom researched. In this paper, safety evaluation of the HW 5MW OWT in extreme and normal conditions is carried out. Then, the member internal forces and UC values subject to earthquake are given. Finally it can concluded that earthquake conditions may become dominate load cases for OWT design.

## 2. SAFETY EVALUATION OF HW 5MW

### 2.1 INTRODUCTION OF HW 5MW

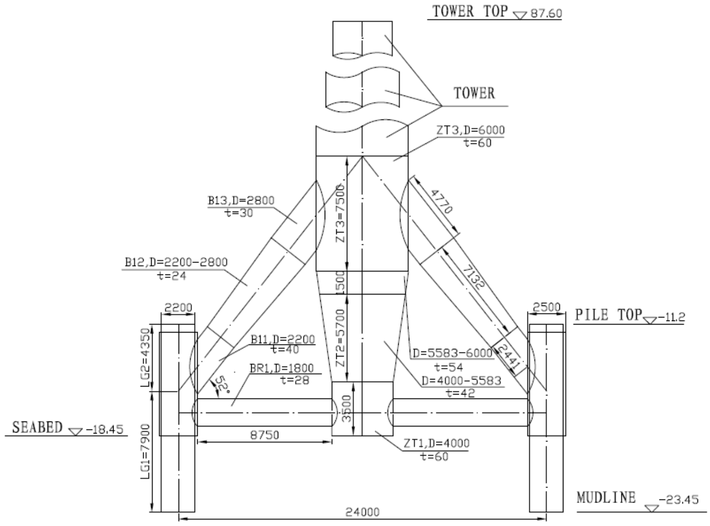
Multi-pod sub-structure structures of OWT are widely used in China. It is of significance to study the dynamic response of global OWT including foundation, sub-structure, tower and rotor-naccelle assembly. Thus, combined the NREL 5MW baseline wind turbine and its tower with the pentapod sub-structure and foundation of a practical OWT, the integrated structure system of OWT, named after HW 5MW is suggested.

The detail information about NREL 5MW baseline wind turbine can be found in Jonkman (2009) and some basic parameters are listed in Table 1.

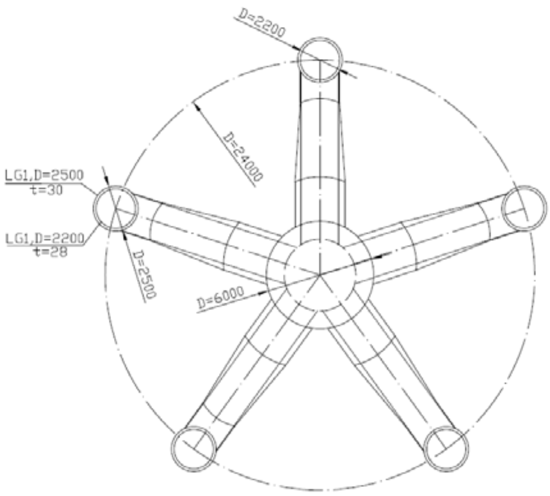
Tab. 1 Basic parameters of NREL 5MW baseline wind turbine

| Rating | 5MW |
|---|---|
| Rotor Orientation, Configuration | Up wind, 3 Blades |
| Control | Variable Speed, Collective Pitch |
| Drivetrain | High Speed, Multiple-Stage Gearbox |
| Rotor, Hub Diameter | 126m, 3m |
| Hub Height | 90m |
| Cut-in, Rated, Cut-out Wind Speed | 3m/s, 11.4m/s, 25m/s |
| Cut-in, Rated Rotor Speed | 6.9rpm, 12.1rpm |
| Rated Tip Speed | 80m/s |
| Overhang, Shaft Tilt, Precone | 5m, 5°, 2.5° |
| Rotor Mass | 110,000kg |
| Naclle Mass | 240,000kg |
| Tower Mass | 347.460kg |
| Coordinate Location of Overall CM | (-0.2m, 0.0m, 64.0m) |

The sub-structure structure of HW 5MW is displayed in Fig. 1 (a) and (b). The length unit is mm, the elevation unit is m.




(a) Vertical View




(b) Plane View

Fig. 1 Pentapod substructure of HW 5MW

## 2.2 ENVIRONMENTAL CONDITIONAS AND LOAD COMBINATIONS

Referred to a practical offshore wind farm site in China, the HW 5MW environmental conditions are listed in Tab. 2 and Tab. 3.

Tab. 2 Wind Speeds of HW 5MW OWT

| Height (m) | Duration (min) | Return Period Wind Speed (m/s) | | | |
|---|---|---|---|---|---|
| | | 50 year | 5 year | 1 year | Multi-year Aver |
| 10 | 10 | 29.00 | 24.40 | 14.60 | 5.20 |

Tab. 3 Wave Parameters of HW 5MW OWT

| Water Level | Water Depth (m) | Return Period (year) | $H_{1\%}$ (m) | $\overline{T}$ (s) | L (m) |
|---|---|---|---|---|---|
| EHL (2.40m) | 25.85 | 50 | 7.78 | 9.17 | 111.74 |
| | | 5 | 7.46 | 8.28 | 96.29 |
| DHL (1.30m) | 24.75 | 1 | 7.15 | 8.21 | 93.85 |
| DLL (-1.24m) | 22.21 | 1 | 5.70 | 5.99 | 52.54 |
| ELL (-2.44m) | 21.01 | 50 | 5.01 | 4.95 | 33.02 |
| | | 5 | 4.80 | 4.47 | 28.46 |

According to DNV-OS-J101 standard and API RP2A-LRFD standard, the loading combinations of HW 5MW OWT are listed in Tab. 4, the directions of loading cases are listed in Tab. 5 and shown in Fig. 2.

Tab. 4 Loading Combinations of HW 5MW OWT

| Load Case | No. | Wind Return Period (year) | Wave Return Period (year) | Current Return Period (year) | Water Level Return Period (year) |
|---|---|---|---|---|---|
| Extreme | E1 | 50 | 5 | 5 | 50 (EHL) |
| | E2 | 50 | 5 | 5 | 50 (ELL) |
| | E3 | 5 | 50 | 5 | 50 (EHL) |
| | E4 | 5 | 50 | 5 | 50 (ELL) |
| | E5 | 5 | 5 | 50 | 50 (EHL) |
| | E6 | 5 | 5 | 50 | 50 (ELL) |
| Normal | N1 | 1 | 1 | 1 | 1 (DHL) |
| | N2 | 1 | 1 | 1 | 1 (DLL) |
| Earthquake | A1 | Multi-year Aver | Multi-year Aver | Multi-year Aver | Multi-year Aver |

Tab. 5 Directions of Load Cases

| NO. | 00 | 01 | 02 | 03 | 04 | 05 | 06 |
|---|---|---|---|---|---|---|---|
| Load Direction (degree) | 0 | 18 | 24 | 30 | 36 | 42 | 48 |
| NO. | 07 | 08 | 09 | 10 | 11 | 12 | 13 |
| Load Direction (degree) | 54 | 60 | 66 | 72 | 78 | 84 | 90 |

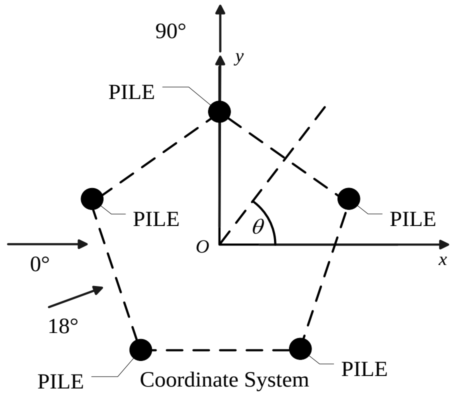



Fig. 2 Load Directions in Global Coordinate System

## 2.3 FEM MODEL OF HW 5MW OWT

In this paper, the FAST(Jonkman 2005) is used to obtain the wind turbine loads with different wind speeds and return periods, FAST is one of the NREL series software for OWT dynamic analysis. The wind turbine loads of HW 5MW OWT with different wind speeds are listed in Tab. 6 and Tab. 7.

Tab. 6 Wind Turbine Loads at Tower Top of HW 5MW

| Return Period | Fxk (kN) | Fyk (kN) | Fzk (kN) | Mxk (kNm) | Myk (kNm) | Mzk (kNm) |
|---|---|---|---|---|---|---|
| 50 year | 671.00 | -30.20 | -3490.00 | 3070.00 | 36.50 | 70.20 |
| 5 year | 458.00 | -24.00 | -3480.00 | 2140.00 | -395.00 | 38.60 |
| 1 year | 1810.00 | -19.10 | -3570.00 | -162.00 | 1430.00 | -2280.00 |
| Multi-year Aver | 336.00 | 0.48 | -3460.00 | -34.30 | -1560.00 | -382.00 |

Tab. 7 Wind Turbine Loads at Tower Base of HW 5MW

| Return Period | Fxt (kN) | Fyt (kN) | Fzt (kN) | Mxt (kNm) | Myt (kNm) | Mzt (kNm) |
|---|---|---|---|---|---|---|
| 50 year | 703.90 | 39.39 | -6558.00 | -108.80 | 56520.00 | 32.72 |
| 5 year | 500.60 | 28.35 | -6541.00 | -159.20 | 39680.00 | 7.191 |
| 1 year | 1771.00 | 7.40 | -6648.00 | -642.50 | 143300.00 | -2261.00 |
| Multi-year Aver | 328.20 | 0.24 | -6514.00 | -66.15 | 24710.00 | -392.60 |

The location of wind turbine loads in Tab. 6 and Tab. 7 is defined in Fig. 3.

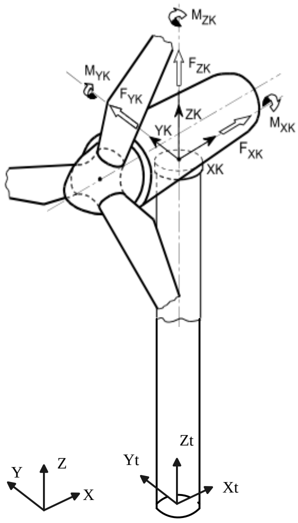


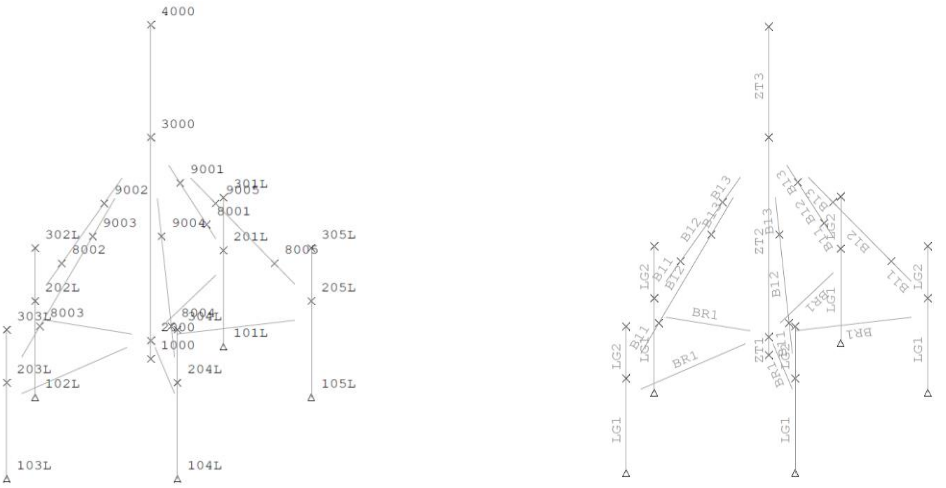

Fig. 3    Coordinate Systems of Wind Turbine Loads

The FEM software of SACS is used to calculate and evaluate of HW 5MW support structure. The FEM model of HW 5MW is shown in Fig. 4. The UC values about element stress and joint shear stress can be computed by SACS according to API standard.

Fig. 4    FEM Model of HW 5MW

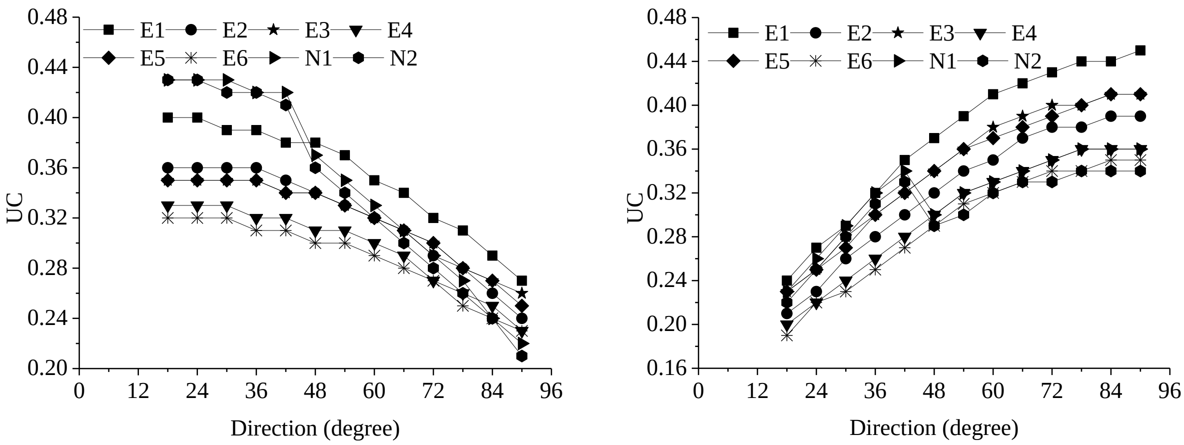
## 2.4 ANALYSIS RESULTS OF FINITE ELEMENT MODEL

The UC values of members of the Pentapod substructure can be calculated. The members and joints locations are illustrated in Fig. 5.




(a) Joint Number (b) Member Number

Fig. 5 Locations of Pentapod Joints and Members

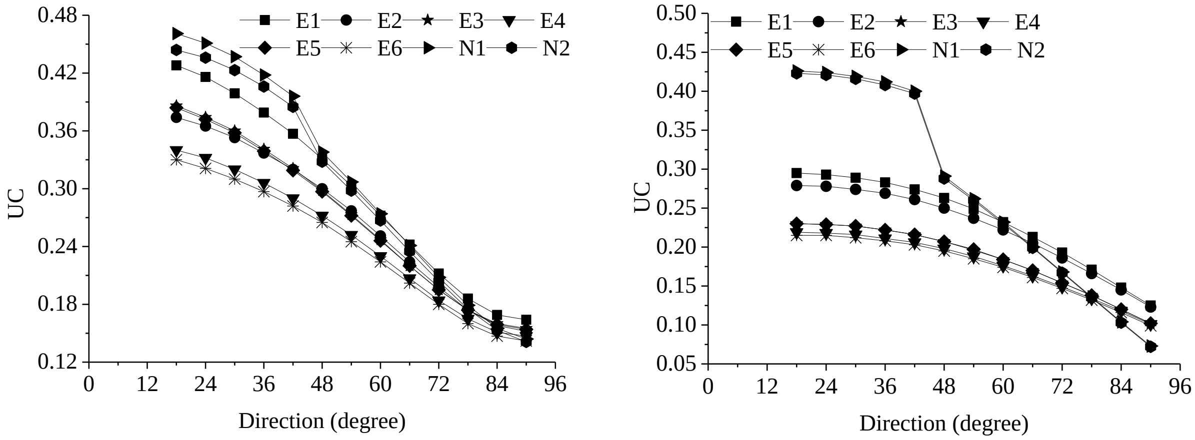



(a) Member of B12 (b) Member of LG1

Fig. 6 Members' Element Stress Check

Compared with results of each case, members LG1 and B12 have the maximum UC value. The results of stress check are shown in Fig. 6. The members of Pentapod sub-structure structure satisfy the requirements of codes under extreme and normal conditions.

Although the member is safe enough, joint shear stress check should be performed. The results of joints' shear stress check are illustrated in Fig. 7.




(a) Joint 2000 (b) Joint 3000

Fig. 7 Joints' Shear Stress Check

Since Joint 2000 and Joint 3000 have the maximum shear stress UC check value, Fig. 7 only shows the results of these two joints. It can be concluded, the joints of Pentapod sub-structure structure satisfy the requirement of codes under extreme and normal load conditions.

## 2.5 FREQUENCY ANALYSIS OF HW 5MW OWT

Due to different water levels during OWT operation, the natural frequencies of OWT on different water levels shall be determined in order to avoid resonance which may be induced by wind, wave, and rotation of blades especially.

Based on multi-year average wind speed, wave parameters and wind turbine loads, the super element of HW 5MW foundation can be calculated. Then, the frequencies of OWT on different water levels can be computed.

Tables 8 - 10 list $1^{st}$ to $10^{th}$ frequencies of HW 5MW with mean water level, extreme low water level and extreme high water level.

Tab. 8 $1^{st}$ ~ $10^{th}$ Frequencies of HW 5MW with Mean Water Level

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Fre(Hz) | 0.321 | 0.321 | 1.163 | 1.164 | 1.764 | 2.601 | 2.694 | 3.7518 | 4.3988 | 4.3989 |
| Period(s) | 3.115 | 3.115 | 0.860 | 0.859 | 0.567 | 0.485 | 0.371 | 0.267 | 0.227 | 0.227 |

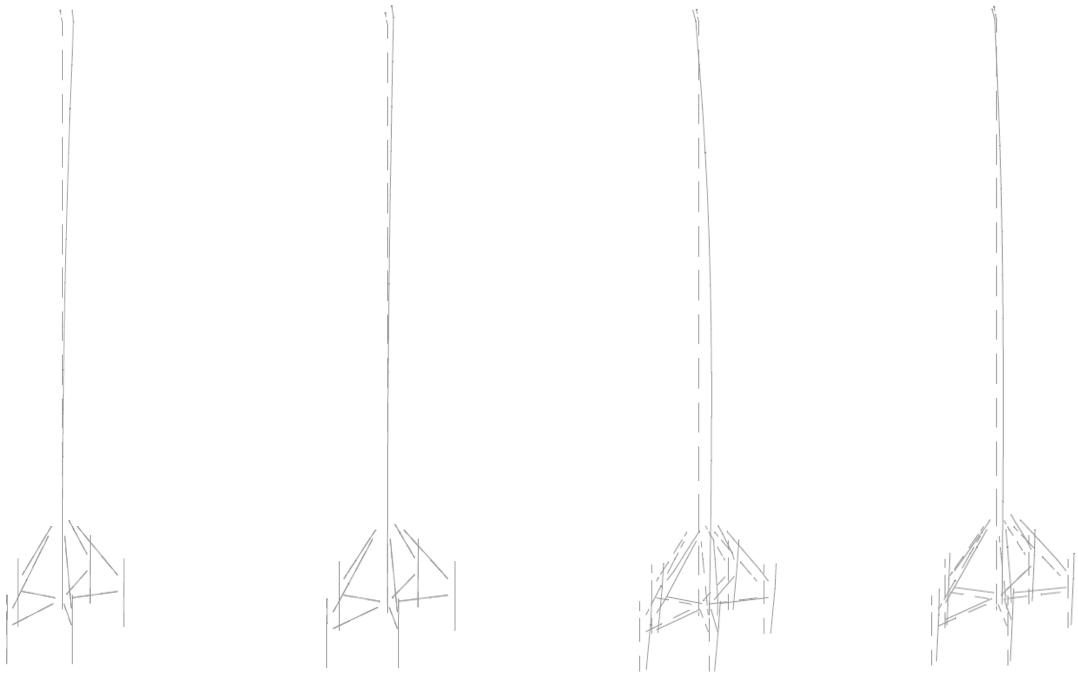
Tab. 9 $1^{st}$ ~ $10^{th}$ Frequencies of HW 5MW with Extreme Low Water Level

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Fre(Hz) | 0.321 | 0.321 | 1.189 | 1.190 | 1.764 | 2.605 | 2.697 | 3.7518 | 4.3987 | 4.3989 |
| Period(s) | 3.115 | 3.115 | 0.841 | 0.840 | 0.567 | 0.384 | 0.371 | 0.267 | 0.227 | 0.227 |

Tab. 10 $1^{st}$ ~ $10^{th}$ Frequencies of HW 5MW with Extreme High Water Level

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Fre(Hz) | 0.321 | 0.321 | 1.145 | 1.145 | 1.764 | 2.600 | 2.691 | 3.7516 | 4.3988 | 4.3990 |
| Period(s) | 3.115 | 3.115 | 0.873 | 0.873 | 0.567 | 0.385 | 0.372 | 0.267 | 0.227 | 0.227 |

The Fig. 8 shows $1^{st}$ to $4^{th}$ mode shapes of HW 5MW.



(a) 1st (b) 2nd (c) 3rd (d) 4th

Fig. 8 First Four Mode Shapes of HW 5MW

## 2.6 EARTHQUAKE ANALYSIS OF HW 5MW OWT

In 2.4, the checks of element stress and joint shear stress are carried out for HW 5MW subject to the combination of wind, wave and current. For offshore wind farms in China, earthquakes have to be taken into account.

In this paper the equivalent static earthquake method is used for earthquake analysis.

The earthquake condition should follow load combination in Tab. 4. In this analysis, referred to certain practical wind farms in China, the maximum ground acceleration is 0.15g, API standard seismic response spectrum is selected.

Firstly, earthquake load is computed through a process of iteration. The final earthquake loads are listed in Tab. 11.

Tab. 11 Earthquake Loads of HW 5MW

| Fx (kN) | Fy (kN) | Fx (kN) | Mx (kNm) | My (kNm) |
|---|---|---|---|---|
| 5260.0 | 5240.0 | 3730.0 | 74400.0 | 74700.0 |

The location of the earthquake loads corresponding to the global coordinate system is shown in Fig. 3.

Base on the earthquake loads, the equivalent static earthquake loads can be calculated by superposition. The results of equivalent static loads are listed in Tab. 12.

Tab. 12 Results of Equivalent Static Loads

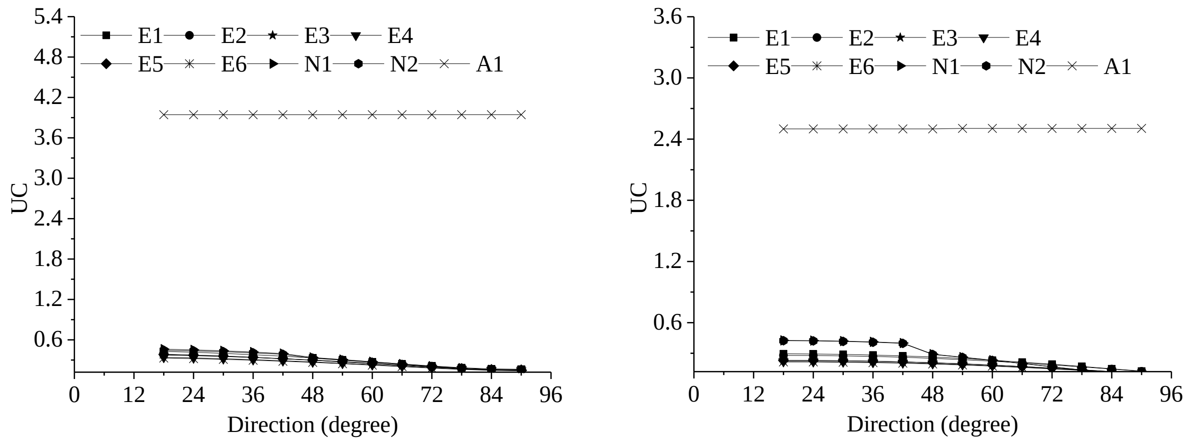
| Load Case | Direction (degree) | Fx (kN) | Fy (kN) | Fz (kN) | Mx (kNm) | My (kNm) | Mz (kNm) |
|---|---|---|---|---|---|---|---|
| 1 | 6 | 7773.505 | 6595.138 | -17331.475 | -78201.711 | 110508.719 | -274.662 |
| 2 | 12 | 7779.661 | 8095.393 | -17356.035 | -158548.875 | 111667.984 | -471.712 |
| 3 | 18 | 7785.772 | 8101.456 | -17359.646 | -158642.344 | 111756.820 | -471.753 |
| 4 | 24 | 7793.050 | 8108.678 | -17363.996 | -158753.391 | 111862.703 | -471.769 |
| 5 | 30 | -7566.140 | 8143.741 | -8247.886 | -159224.656 | -117443.352 | -511.062 |
| 6 | 36 | -7839.651 | 8078.621 | -8215.320 | -159264.453 | -114789.070 | -507.882 |
| 7 | 42 | -7814.537 | 8054.049 | -8229.937 | -158883.000 | -114426.992 | -507.581 |
| 8 | 48 | -7786.947 | 8026.876 | -8246.082 | -158461.375 | -114028.242 | -507.132 |
| 9 | 54 | -7780.425 | -7327.318 | -8236.335 | 79178.547 | -114732.039 | -368.834 |
| 10 | 60 | -7783.786 | -7348.337 | -8231.601 | 79174.711 | -114907.023 | -368.685 |
| 11 | 66 | -7790.193 | -7354.561 | -8227.863 | 79271.516 | -115000.398 | -368.654 |
| 12 | 72 | -7799.380 | -7363.795 | -8222.483 | 79412.711 | -115134.000 | -368.583 |
| 13 | 78 | 7853.109 | -7342.780 | -17382.762 | 80065.547 | 111804.258 | -332.511 |
| 14 | 84 | 7825.762 | -7315.974 | -17366.779 | 79648.781 | 111409.203 | -332.634 |
| 15 | 90 | 7800.653 | -7291.216 | -17352.004 | 79265.188 | 111046.781 | -333.028 |

Now the earthquake loads have been transferred into equivalent static loads, the safety evaluation of HW 5MW with earthquake condition can be achieved.

The results of element stress check and joint shear stress check of HW 5MW subject to earthquake list in Tab. 13.

Tab. 13 Results of Member Element Stress and Joint Stress Check

| Item | | Maximum UC | Allowable UC | YES/NO |
|---|---|---|---|---|
| EQK | Element Stress | 0.44 (B12) | 1 | YES |
| | | 0.47 (LG1) | | YES |
| | Joint Shear | 3.944 (2000) | | NO |
| | | 2.505 (3000) | | NO |




(a) Joint 2000 (b) Joint 3000

Fig. 9 Comparison of Joints' Shear Stress Check

In Fig. 9, the UC results of load case A1 listed in Table 4 are much greater than other load conditions and exceed the allowable value of unity. One reason for the results is that the load resistance factors for earthquake condition are greater than those of the other load conditions. Meanwhile, the joint allowable stress for earthquake condition is smaller than those for the other conditions.

The designers should pay attention to this situation, as the earthquake may be the dominate load cases for Pentapod sub-structure structure joint design of offshore wind turbine.

## 3. CONCLUTION

In this paper the HW 5MW OWT for research is proposed. Then the HW 5MW OWT is evaluated in extreme, normal and earthquake conditions. By comparison of the results, it can be found that the HW 5MW sub-structure structure can satisfy the requirements of the codes in extreme and normal conditions, while joint shear stress check of the pentapod sub-structure can not satisfy the allowable value in earthquake conditions.

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