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# Dynamic Analysis of Wind Power Turbine's Tower under the Combined Action of Winds and Waves

CHENG You-liang, QU Jiang-man, XUE Zhan-pu, JIANG Yan

(School of Energy Power and Mechanical Engineering,

North China Electric Power University, Hebei Baoding 071003, P. R. China)

**Abstract**: To deal with the dynamic response problem of offshore wind power tower under the combined action of winds and waves, finite element method is used to analyze the structure and flow field around the outside flange of the segmentation part. The changes of pressure distribution and vorticity about the outside flange are obtained. Focused on the analysis on the change of hydrostatic pressure and temperature of the tower cut surface, contour lines under the combined action of winds and waves are depicted. Results show that the surface of the offshore wind turbine tower presents instable temperature field when it suffers the action of winds and waves loads, the static pressure increases nonlinearly with the increase of altitude, the fluid vorticity around the outside flange follows an parabolic curve approximately. Results provide a reference for the actual monitoring data of the offshore wind turbine tower under the combined action of winds and waves, so as to ensure the normal operation of tower.

**Keywords**: tower; segmentation part; dynamic response; outside flange; steady

## 1 Introduction

The speed of the wind in offshore wind farm is high and stable, which is a new field of wind power need to research. Currently, the development of offshore wind farms is also a new technology. In the north sea area of Europe, the average wind speed exceeds to 8 m/s at the height of 60 m so that the power generated is 20%~40% higher than the onshore wind farm[1]. Offshore wind turbine tower supports engine room and other components while withstand winds and waves. The gradual development of high-power wind power generation technology contributes to a increase height of the tower in these years, which leads to the failure of tower section directly. This failure of tower section will shift the center of gravity and reduce the utilization rate of wind energy. So, it is particularly important to analyze the dynamic response of offshore wind power generation

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system. Tang Weiliang[2] summarized a set of theoretical methods to calculate the static strength of the wind turbine tower and put forward the design method to enhance the ability of resisting typhoon. The maximum bending moment and bending stress of the tower were calculated. Ke Shitang[3] used a coupling model of tower and blade. Wind-induced vibration in time-domain was analyzed based on finite element method and the results show that coupling action is one of the key issues in wind resistant design of wind turbine. Pseudo Excitation Method (PEM) is used by Chen Xiaobo et al[4] to research random vibration of the tower under pulsating wind. By this method, the modal coupling effects are considered, and the theory is more accurate. Based on analytical method and finite element method, zhang[5] found that there are two transient resonance phenomenons in the starting process of flexible wind turbine tower. Under simulated fluctuating wind, the vibration of the tower increases with the add of wind speed. Lee Bin[6] simulated wind storm based on linear filtering method while tuned mass damping (TMD) technology is applied to the wind turbine tower. He concluded that the wind vibration effect of TMD to wind generator tower increased with the add of mass ratio and damping ratio, then being gradually stabilized. The coupling effect of tower and blade should be considered in the wind turbine design; It put forward the time-domain method aiming at wind-induced fatigue analysis of wind turbine machine structure, which shows the nonlinear wind vibration time-domain results on the tower-blade coupling structure of wind turbine[8]. Yan shi[9] designs a set of energy dissipation devices with shape memory alloy with superelastic effect(SMA) placed on the top of the tower, by which can effectively reduce the wind-induced vibration of the wind turbine tower. A new fatigue evaluation method of tower structure based on the statistical data of wind-wave load is proposed by Ma Yongliang[10], which greatly improves the calculation accuracy of tower fatigue analysis. In the field of analysis of wind-induced response of offshore wind turbine tower, scholars have conducted some related researches. Xu Pei[11] analyzed the impact on the safety of tower for blades' shedding during operation from three aspects: the dynamic characteristics and wind-induced response and stability and the concept of transient influence coefficient on blade shedding is put forward. Modal analysis and the wind-induced dynamic response analysis under harmonic superposition simulation wind load for megawatt cone type offshore wind turbine tower were done by Shen Yuguang[12]. Aimed at the phenomenon of instability and damage of the tower, Liang Jun[13] proposed the structure of the inner stiffened cylinder and studied the tower with different internal reinforcement. The results show that nonlinear contact on tower flange can better simulate the stress distribution. Cheng Youliang[14] proposed a new segmented tower. Stress nephogram and wind-induced response curve on the sectioned point were obtained, which show that segmented type can adapt the load response better than cone cylinder type.

In previous studies, flange's dynamic response on the sectioned point is just for one certain type. However, the dynamic response of the outside flange under the combined action of wind and wave has not been studied in depth. Therefore, a comprehensive dynamic response analysis of tower sections and its outside flange by the method of numerical simulation is covered in this paper. The variation of the flange under the combined action of wind and wave is considered from three aspects of pressure, vorticity and temperature.

## 2 Mathematical model

### 2.1 Governing equation

Offshore wind turbine tower bears the loads of wind, wave and flow mainly. The dominant form of response is the change of vibration displacement. The vibration differential equation of the multi-degree of freedom system on tower under combined action of wind and wave is that[15]:

$$M\ddot{y} + C\dot{y} + ky = F_{\text{wind}}(t) + F_{\text{wave}}(t) + F_{\text{current}}(t) \tag{1}$$

Where: $M$, $C$ and $K$ are mass matrix, damping matrix and stiffness matrix, respectively; $F_{\text{wind}}(t)$, $F_{\text{wave}}(t)$ and $F_{\text{current}}(t)$ are the time history of wind, wave and current load acting on each load node.

The sea wind load is the main form in the tower load. The range of the height of the tower belongs to the air flow within the atmospheric boundary layer. The characteristics of wind load are depicted by wind speed, direction and turbulence intensity. The wind speed changes with the height direction and size until the gradient wind speed is stable. An empirical formula for the variation of wind speed with height is that[13]:

$$v = \frac{V^*}{k}\ln\frac{z}{z_0} \tag{2}$$

$$V^* = \sqrt{\frac{l_0}{\rho}} \tag{3}$$

Where: $v$ is wind speed, m/s; $k$ is Kaman constant, which takes the value of 0.4; $V^*$ is friction coefficient; $l_0$ is ground shear stress, N/m$^2$; $\rho$ is air density, kg/m$^3$, which generally takes the value of 1.225 kg/m$^3$; $z$ is the height above the ground, m; $z_0$ is roughness length, m.

### 2.2 Three-dimensional structural dynamic model

Three-dimensional structure dynamic model can be established by SolidWorks software. Specifically, it is 1.5 MW VSCF offshore wind turbine tower, whose bottom diameter is 4.2 m, top diameter is 2.5 m, and height is 80 m. The weight of blade and engine room is 80 800 kg. The materials of tower are alloy steel. The elastic modulus is $E = 2.0\times10^{11}$ Pa. The poisson ratio is $\mu = 0.3$. The density of materials is $\rho = 7.85\times10^3$ kg/m$^3$, which is divided into two sections, the flange diameter is 4 m. Figure 1 is structural dynamic model of the offshore wind turbine tower, Figure 2 is the outside flange structure on tower sections.


Figure 1 The structural dynamics model of a offshore wind turbine tower

Figure 2 The structural schematic drawing about the outside flange at the tower segmentation part

### 2.3 Boundary conditions and numerical methods

The tower mainly bears the gravity of engine room and wind turbine(GR)、deadweight(GT)、wave force. As is shown in Figure 3, wind load is the main form. In practical project, there are three sets of wind field parameters used commonly. In this three sets of parameters[16], the reference speed of wind field are 50 m/s, 42. 5 m/s and 37. 5 m/s while the annual average speed of wind are 10 m/s, 8. 5 m/s and 7. 5 m/s each. The third set of parameter is chosen in this paper. The size of the calculation domain is 40 m×30 m×120 m. The tower model is located at the center of the computing domain. Considering the direction and speed in the wall of tower change at all times, fluctuating wind speed is used in the general numerical simulation, the mesh quality of tower wall surface plays a vital role in simulation.Unstructured grid is used to divide the grid and the grid number of tower is about $4.13\times10^5$. The offshore wind turbine tower load distribution is shown in Figure 3 and the calculation domain of tower model is shown in Figure 4. SIMPLE algorithm is adopted in the numerical calculation. The residual error calculated by the continuity equation, momentum equation、energy equation of the fluid surrounding the tower are less than $10^{-6}$. Above parameters reach to converge when they tend to asymptotic values and then exact solution of the problem can be obtained by QUICK format.

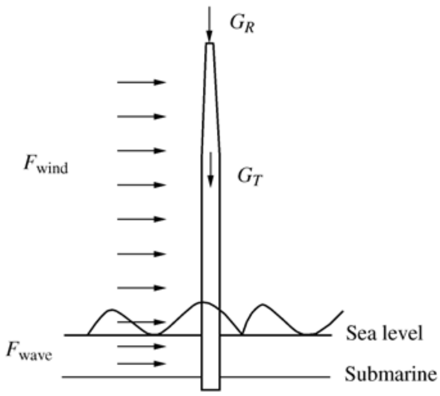


Figure 3 The schematic drawing of a offshore wind turbine tower loads distribution

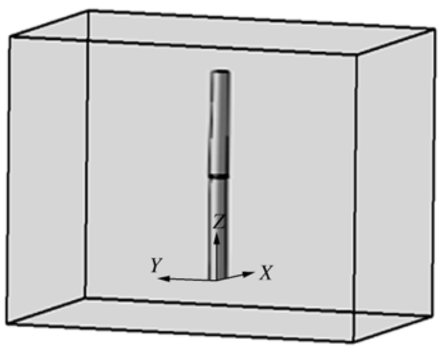


Figure 4 Computational domain schematic drawing of a tower model

### 2.4 Model validation

In order to verify the correctness of the model, results of predecessors are used as the basis for verification. Figure 5 shows the the change of top position of the tower in simulation under the same fluctuating wind speed used in reference[12]. The maximum displacement is 0.425 m in reference[12] while in simulation is 0.435 m, which behaves a deviation of 2%. Considering the trend of two curves are basically the same and the deviation is still in tolerance scope, it is proved that the mathematical model and method are feasible.

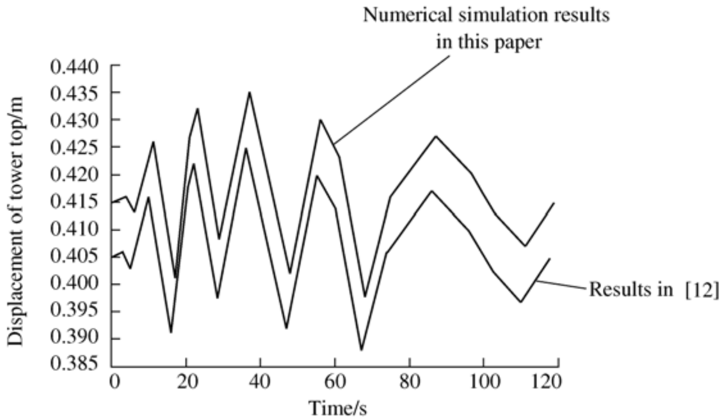


Figure 5 Displacement-time curve at the top of tower

## 3 Results and analysis

The structure and performance of offshore wind turbine tower meet the basic standard and its dynamic characteristics is analysed for further research. Usually, dynamic characteristics of the tower can be reflected from two aspects: one is natural vibration characteristics and the other is wind-induced response[16].

### 3.1 Analysis of natural vibration characteristics of the tower

Natural vibration characteristics is one of natural vibration properties of the tower. Modal analysis is the basis of natural vibration characteristics, which is an important segment of dynamic response analysis[17-20]. Natural frequency and vibration mode can be obtained from engineering calculation and finite element method, of which are two ways of modal analysis. Figure 6 to Figure 8 are modal shapes of the tower in the first order, second order and third order respectively. Figure 9 is the stress curve of the tower from 0 to 30 s. From these figures, it can be seen from Figure 6 to Figure 9 firstly that the first order and the second order are shimmy while the third order is flapping vibration. Secondly, the maximum vibration displacement of the tower is 7.56 mm correspondingly in the frequency of 2.39 Hz and stress concentration as well as vibration failure are not easy to occur in 30 s. Lastly, Natural vibration characteristics show in the figure of frequency versus vibration displacement can be concluded that the modal frequency has a margin of 12%, which indicates the tower is not easy to resonate.

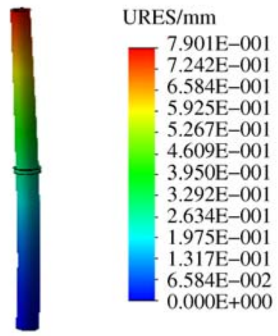


Figure 6 First order modal shape($f$=0.86 Hz)

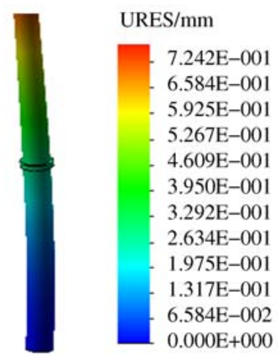


Figure 7 Second order modal shape($f$=1.47 Hz)

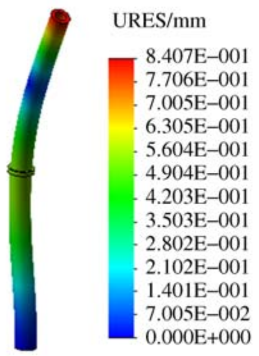


Figure 8 Third order modal shape($f$=2.39 Hz)

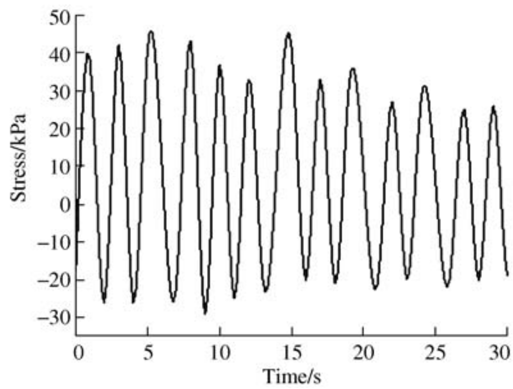


Figure 9 Stress variation curve of a tower

### 3.2 Analysis of wind-induced response of the tower

In general, the structure of the offshore wind turbine tower is cone, on which the wind load is fluctuation variation. The vibration of the tower mainly attribute to shedding of vortices wind. Wave load caused by the wind is a main factor to determine the deformation and vibration of the wind tower and the deformation of the tower structure will directly affect the strength and vibration of wind turbine blades. So the analysis of joint action of wind and waves of the tower under the wind vibration response is the basic dynamics problem of that must be considered[16]. Figure 10 to Figure 12 show the section variation nephogram of dynamic response under wave loads when the tailwind speed is 7.5 m/s. It can be seen from Figure 10 that the temperature in the same side of the loads around the tower section varies from 293.19 K to 293.25 K and then stabilized in 293.15 K. This reason is that the system conforms to the law of conservation of energy: the tower surface has a certain temperature and the scattered wave flowing around the tower caused by combined effects of wind and wave results in a elevated temperature. So a farther distance between the load caused by wind and wave and the tower will bring about flow dispersion and a lower temperature. Figure 11 and Figure 12 show the contour line and plane of the static pressure of the tower section. In the load of the wind and wave, the static pressure of the tower section growth in a nonlinear mode from $1.012\ 98\times10^5$ Pa to $1.013\ 48\times10^5$ Pa and tend to the pressure of $1.012\ 98\times10^5$ Pa. Overall, the pressure changes gently, which will avoid the failure of the tower. Figure 10 to Figure 12 show that the offshore wind turbine tower structure can adapt to the change of temperature and pressure on the combined effects of wind and wave and there are no peak points of the temperature and pressure appearing in the research, which ensures the normal operation of the tower.

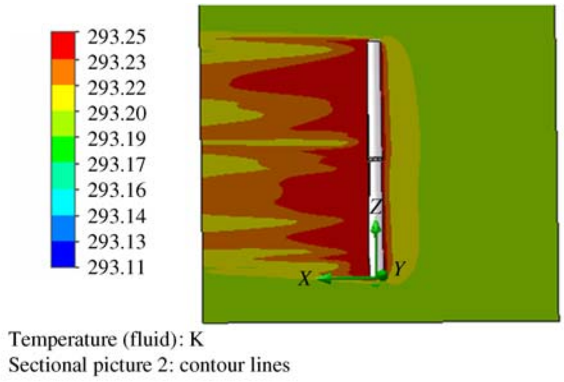


Figure 10 Fluid temperature contour of cut surface

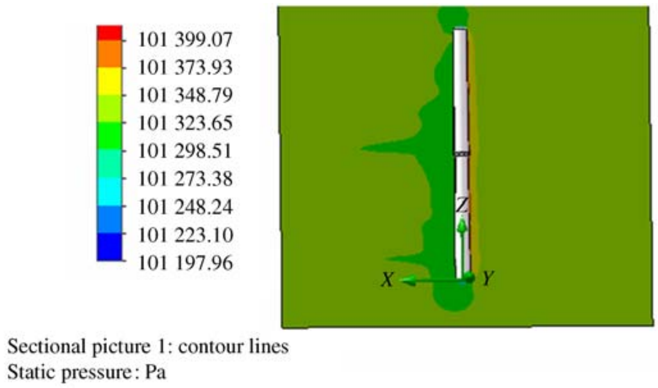


Figure 11 Static pressure contour of cut surface

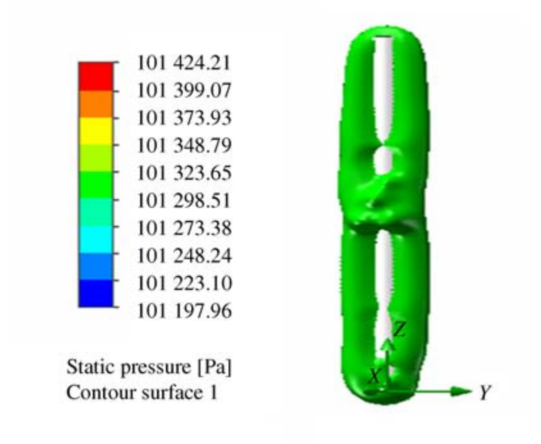


Figure 12 Static pressure contour plane of cut surface

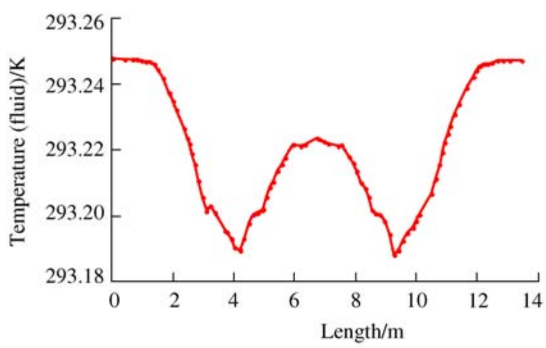


Figure 13 Temperature variation curve

### 3.3 Analysis of wind-induced response of flange outside the tower section

Because the load of wind and wave acts on the flange outside the tower section, the temperature, vorticity, static pressure and shear stress of fluid will change with the length of the flange, which can be seen in Figure 13 to Figure 15. From Figure 13, it shows that the temperature of fluid near the outside flange changes from 293. 248 K to 293. 246 K, with three inflexions of 293. 189 K、293. 221 K、293. 186 K between them. During the act of the both wind and wave, there is only a small change in the temperature of fluid near the outside flange. This can be attributes to the evenly fixed bolts and the installation of shock absorber. Both of them ensure the load of the wind and wave distributes evenly. Also, from Figure 14, the static pressure near the outside flange changes from $1.0132\times10^5$ Pa to $1.01275\times10^5$ Pa, with three inflexions of $1.01275\times10^5$ Pa、$1.0134\times10^5$ Pa、$1.01272\times10^5$ Pa between then finally reaches static pressure value for $1.01318\times10^5$ Pa. Vorticity is a measure of the intensity and direction of the vortex motion. From Figure 15, the value of vorticity changes like a parabola and the maximum value of vorticity near the outside flange is 10 $s^{-1}$. So, it is not easy to form a vortex near the outside flange, which ensures the normal operation of the tower.

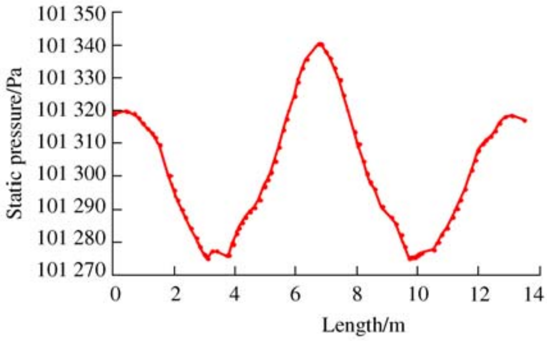


Figure 14 Static pressure variation curve

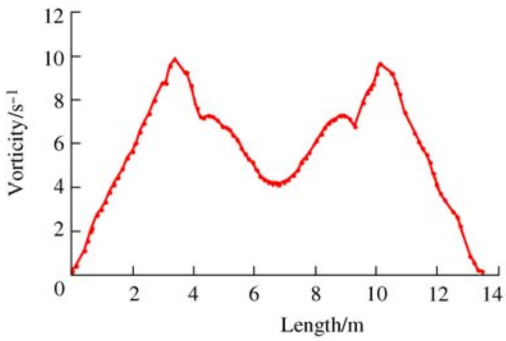


Figure 15 Vorticity variation curve

## 4 Conclusions

By dynamic response analysis of offshore wind turbine tower, it is concluded that:

1) By analysis of natural vibration characteristics of the tower, modal frequency of vibration has a margin of 12%, avoiding the occurrence resonance.

2) In the action of both wind and wave, the temperature of the tower surface tends to a steady-state while there is still a small change because of the existence of flow around it. The static pressure changes nonlinearly but the variation ranges small.

3) The evenly fixed bolts and the installation of shock absorber of the outside flange near the joint of the tower keep the value of temperature, static pressure and vorticity in as table range, ensuring the normal operation of in tower as well as the whole offshore wind power system.

Most of the previous researches focus on the dynamic response analysis of tower connected by inner flange while in this paper, it reveals that outside flange also have great advantages in terms of static pressure, vorticity and surrounding temperature of the fluid. Consequently, design and dynamic analysis of offshore wind turbine tower using outside flange is the direction of future development.

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## Brief Biographies

**CHENG You-liang** is a professor in School of Energy Power and Mechanical Engineering, North China Electric Power University. His research interest include renewable energy sources and thermal engineering. ylcheng001@163.com

**QU Jiang-man** is a master candidate in School of Energy Power and Mechanical Engineering, North China Electric Power University. Her research interests include theory and application of new energy. dijiuhaofeixing@163.com

**JIANG Yan** is a master candidate in School of Energy Power and Mechanical Engineering, North China Electric Power University. His research interests include theory and application of new energy. jayen92@126.com

**XUE Zhan-pu** is a doctoral student in School of Energy Power and Mechanical Engineering, North China Electric Power University. His research interests include theory and application of new energy. shenghuo166@163.com