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Study on Structural Optimization of Offshore Wind Power Tower under the Influence of Typhoon-prone Area

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Abstract. As offshore wind power has become an important support for energy transformation, its structural safety is particularly important in typhoon prone areas. Typhoon has a serious impact on offshore wind power tower, such as blade fracture and tower overturning. Therefore, structural optimization is imperative. This paper aims to explore the structural optimization strategy under the influence of long-term typhoon, including strengthening materials, improving design, introducing dampers and other measures, in order to improve the wind resistance of the wind tower. Firstly, Citespace, an advanced scientific and technological literature analysis tool, is used to analyze the relevant literature in recent ten years. Citespace can help users understand the knowledge structure, evolution and future trend of the scientific field through visualization technology, and use the keyword co-occurrence diagram to show the main topics in the research of wind power tower and typhoon and the relationship between keywords. Then, by calculating the overall wind pressure of the blade, tower and wind turbine, the influence on the wind power tower is analyzed, and the structural optimization scheme of the wind power tower is proposed. Finally, the damper is introduced to provide technical support for the safe and reliable development of offshore wind power.

Keywords: Offshore Wind Power Tower; Typhoon; Citespace; Structural Optimization.

1. Introduction

With the transformation of the global energy structure and the increasing awareness of environmental protection, the importance of offshore wind power as a clean and renewable form of energy has become increasingly prominent. According to the International Renewable Energy Agency, compared with land wind farms, offshore wind power has larger blades, higher wind speed and fewer terrain restrictions, which makes it have higher capacity and greater potential deployment [1]. Driven by the goal of reducing the proportion of thermal power generation advocated by "dual carbon", the development of offshore wind power has become an important way to realize the transformation of energy structure and ensure energy security [2]. China is rich in offshore wind power resources, especially in the East China Sea and South China Sea, with huge potential for wind power resources, which provides a solid foundation for the large-scale development of offshore wind power.

However, the development of offshore wind has not been smooth sailing. Typhoon, as one of the main natural disasters affecting China's coastal areas, poses a severe challenge to the safety and stability of offshore wind power towers. Extreme weather conditions such as strong winds, high turbulence and rainfall brought by typhoons can easily cause wind power towers to be subjected to both static and dynamic loads, resulting in blade breakage, tower collapse and other serious consequences. In 2010, the full landfall of typhoon "Megi" caused the collapse of Z13 wind turbine in Liuao Town, Zhangpu County, Fujian Province, and the blade of Z10 wind farm module was broken. In 2003, "Dujuan" caused the damage of 13 generators in Shanwei Bay Wind Farm, with a loss of tens of millions of yuan [3]. Therefore, in-depth research on the impact of typhoons on offshore wind power towers and structural optimization is the key to ensure the healthy and sustainable development of the offshore wind power industry.

This paper aims to discuss the development background and importance of offshore wind power. Through a scientific, systematic and objective analysis of this part of literature by using Citespace software, it comprehensively expounds the specific impact of typhoon on offshore wind power towers and discusses the necessity of structural optimization. Through the method of literature review, theoretical analysis and empirical research, this paper strives to provide useful reference for the safe operation and technological innovation of offshore wind power.

2. Analysis of Relevant Literature in the Past Decade

2.1. Citespace Software

Citespace is a widely used scientific and technical literature analysis tool developed by Professor Chen Chaomei [4]. This software is specially used to analyze trends, research hot spots and development frontiers in scientific and technological literature. It helps users understand the knowledge structure, evolution and future trends in the scientific field through visualization technology. Citespace requires users to enter literature data in a specific format, which can usually be exported from scientific databases such as the Web of Science and Scopus. Users can set the time range, node types (such as author, institution, country, keywords, etc.) and parameter configurations of the analysis to generate targeted analysis results and views. In this paper, 400 science-level documents related to wind power towers and typhoons in the past ten years are imported through Science Network, and then Citespace software is used to systematically and visually analyze these documents to obtain keyword co-occurrence maps and prominent word scores .

2.2. Keyword Co-occurrence Chart

The keyword co-occurrence diagram shows the main topics and the interrelationships of keywords in wind power towers and typhoon-related research. The nodes in the graph represent keywords, while the connections represent the degree of association between different keywords. In the past ten years, the scope of topics on wind power towers and typhoons has a high degree of connectivity, a strong collinear relationship. These nodes have been the focus of research on wind power towers and typhoons in the past decade, so this paper focuses on the related research on these nodes.

As can be seen from Fig. 1, the main nodes are “performance”, “design” and “model”. These keywords are located at the center of the network, indicating that “performance evaluation”, “design optimization” and “model building of wind towers” are core topics in the research. These nodes are connected to multiple small nodes, and research branches such as “vibration control”, “mitigation”, “optimization” are continuously extended from this node. These terms are closely related to how to reduce or control the vibration of wind power towers under extreme weather conditions such as typhoons, and point to the improvement of engineering measures and technologies. The two keywords “Offshore Wind Turbine” and “Transmission Tower” indicate that the main application areas of research are offshore wind turbines and their related transmission facilities. In addition, the number of lines and the depth of color represent the close relationship between keywords. It can be seen from Fig. 1 that the connection strength between “vibration control” and “performance” shows that “vibration control” is an important factor affecting the performance of wind power towers. The close connection between “model” and “design” shows that the application of models is critical to predicting and optimizing structural performance.

This co-occurrence map provides researchers and engineers with a clear view of current research focuses and possible future research directions for wind towers, especially in the areas of wind tower design and typhoon response management. Through this analysis, resources can be allocated more effectively and research strategies can be formulated to improve the design and operation efficiency of wind towers.

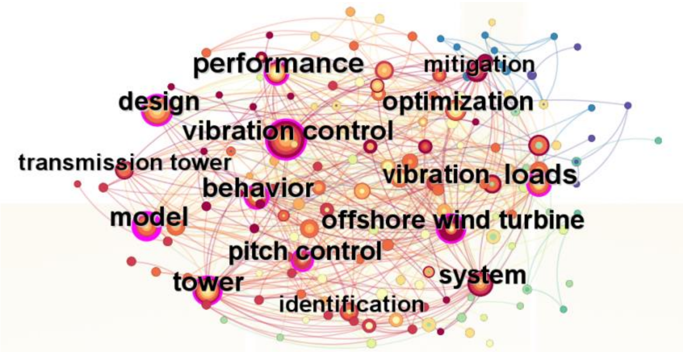

Figure 1. Keyword Co-occurrence Chart

2.3. Prominent Word Spectrum

After adjusting the coefficient to 0.5 in the Cirespace control version, 29 highlighted words were filtered out, and the top 22 highlighted words were selected for analysis based on the strength of influence, as shown in Table 1. Among them, the word with the highest intensity of emergence is wind turbines.

Table 1. Top Prominent Word Spectrum

Keywords	Year	Strength	Begin	End	2014-2024
buildings	2014	1.34	**2014**	2018	
drag	2015	1.78	**2015**	2017	
Wind turbine	2015	1.70	**2015**	2016	
vibrations	2017	2.76	**2017**	2019	
fault diagnosis	2017	1.75	**2017**	2020	
behavior	2014	1.54	**2017**	2019	
prediction	2017	1.39	**2017**	2020	
wind turbines	2018	3.21	**2018**	2020	
optimization	2018	2.83	**2018**	2020	
performance	2018	2.07	**2018**	2019	
structural control	2018	1.66	**2018**	2019	
induced vibration	2019	2.01	**2019**	2021	
power	2019	1.77	**2019**	2020	
tuned mass dampers	2020	2.85	**2020**	2021	
dynamic response	2016	2.18	**2020**	2022	
wind tunnel test	2021	2.80	**2021**	2022	
simulation	2019	1.75	**2021**	2022	
transmission tower	2021	1.75	**2021**	2022	
line system	2021	1.39	**2021**	2022	
floating offshore wind turbine	2021	1.32	**2021**	2024	
mitigation	2022	2.43	**2022**	2024	
identification	2018	1.51	**2022**	2024	

It can be seen from Table 1 that the words that were highlighted earlier, that is, the topics that received attention in the early stages are "buildings", "drag" and "wind turbines". Since 2017, the subjects that have received attention have "vibrations", "fault diagnosis", "optimization", "structural control", induced "dynamic response" and "performance". It can be seen that the research hot spots focus on the vibration improvement and structural optimization of wind power towers, and focus on carrying out different research experiments and expanding improvement plans. The most recent prominent words are "wind tunnel test", "floating offshore wind turbine", "mitigation" and "identification". Some of these words originated early but continue to this day. They may be new themes in this field and can be explored further. Therefore, the subsequent section will focus on the structural optimization of offshore wind towers under vibration and the excavation of damper improvement plans.

3. Influence of Typhoon on Offshore Wind Power Tower

The influence of typhoon on offshore wind farms has two sides. It can improve the efficiency of power generation. Due to the flat sea surface and few obstructions, typhoons of low intensity can effectively enhance the power generation efficiency of wind power tower and bring more power generation income. Excessively strong typhoons will destroy the facility structure of wind power tower.

3.1. Blade Wind Pressure

Through the aerodynamic analysis of wind power tower affected by typhoon, the wind load acting on the blades can be calculated through Eq. 1 [5].

$$\mathrm{Tmax}=\frac{1}{2}\rho V_{\mathrm{max}}^{2}C\gamma BA_{b} \tag{1}$$

where ρ is the air density of the wind field where the wind power tower is located, v_{max} is maximum wind speed, $C\gamma$ is the wind resistance coefficient is 1.7. A_b is projected blade area, and B is number of blades.

The bending moment $Mmax$ of blade wind load on tower root is according to Eq. 2.

$$\mathrm{Mmax}=\mathrm{T\,max\,H} \tag{2}$$

where H is the distance of the rotating center of the impeller from the ground, which can be equivalent to the height of the tower.

For a three-blade offshore wind motor, its rated power is 5MW, its maximum speed is 55 m/s, and its air density is 1.225 kg/m^2 [6]. The weight of each blade is 26t, the size is 83.6 m × 4.81 m × 3.37 m, the height of the tower barrel is 88m, and the projected area of the blade is 201.06 m^2 [7]. The blade wind pressure $Tmax$ of the three-blade fan is 1899.86 kN. The resultant bending moment $Mmax$ is 167187.68 kN.

It can be seen from the formula that the wind pressure acting on the blades is proportional to the number of blades. When the typhoon wind speed exceeds the maximum peak value that the offshore wind power tower can withstand, the wind power tower blades will face the risk of damage.

3.2. Tower Drum Wind Pressure

Wind power tower height, wind speed is different, the specific height calculation according to Eq. 3.

$$V_i = V\max\left(\frac{h_i}{H}\right)^a \tag{3}$$

where V_i is the wind speed at altitude h_i, a is the wind shear index is 0.14. And the wind pressure acting on the projected area of the tower barrel at h_i can be calculated.

$$T_i = \frac{1}{2}\rho V_i^2 C_D A_i \tag{4}$$

where A_i is projected area of tower barrel at h_i, and C_D is the resistance coefficient of the column cylinder around the flow is 0.7.

The wind bending moment M_i acting on the projected area of the tower barrel at h_i is based on Eq. 5.

$$M_i = T_i h_i \tag{5}$$

The height of the tower is 88m, which is divided into three sections: (1) The mass of the bottom section is 122t, and the size is (5.8~6.0) m×20.7m. (2) The middle tower has a mass of 121t and a size of (5.35~5.80) m×32.3m. (3) The top tower weighs 96t, and the foot inch is (4.72~5.35) m×35m. The specific data calculation is shown in Table 2.

Table 2. Tower Section Calculation

Section	**Barrel length (m)**	**Wind speed (m/s)**	**Wind pressure (N)**	**Wind bending moment (N*m)**
Bottom	20.7	44.91289	82355.8	937601.991
Midpiece	32.3	51.23111	184444.8	7287117.01
Apical segment	35	55	214923.4	15041665.6
Sum	88	\	481724	23266384.6

As can be seen from Table 2, the wind load of the tower barrel brought by the typhoon increases sharply. When the typhoon wind speed exceeds the critical value of the tower barrel, the wind bending moment of the tower barrel may exceed its bearing capacity, resulting in damage by the typhoon.

3.3. Overall Fan Air Pressure

The overall wind pressure of the fan is the wind pressure at the root of the tower barrel, which is the sum of the wind pressure by the tower barrel and the wind pressure by the blades. In addition, the overall wind bending moment of the fan is equal to the wind bending moment acting on the root of the tower barrel, which is the sum of the wind bending moment by the tower barrel alone and the wind bending moment by the blades.

The resultant force T_{tower} acts on the root of the tower.

$$T_{tower} = T\max + \sum T_i \tag{6}$$

The resultant bending moment M_{tower} acts on the root of the tower.

$$M_{tower}=M\,max+\sum M_i \tag{7}$$

According to the above data, the resultant force acts on the root of the tower.

$$T_{tower}=T\,max+\sum T_i=1899.86+481.724=2381.58kN \tag{8}$$

Resultant bending moment acts on the root of the tower cylinder.

$$M_{tower}=M\,max+\sum M_i=23266.38+167187.68=190454.064kN*m \tag{9}$$

It can be seen from the data that when the wind speed is too high, the combined force and bending moment of the offshore wind power tower may be greater than its set carrying capacity, resulting in its overall overturning or fracture.

3.4. Waves Caused by Typhoons

During typhoons, offshore wind power towers generate strong vibrations. Under the action of wave and wind load caused by typhoon, the long-period vibration will lead to the loosening of the connecting components between the wind power tower components, which will affect the stability of the entire structure, and even lead to the collapse of the tower cylinder in serious cases. In addition, vibration will also cause deformation of the top wind turbine to a certain extent. The wind capture efficiency and power generation performance of wind turbines are affected.

According to the wave hydrodynamic modeling data of 5MW offshore wind power towers in a specific area, when the characteristic wave height is 9m, the blade root limit load increases by about 1.1%, the fatigue effect increases by about 7.2%, and the fatigue equivalent load increases by about 6% [8]. The proportion of fatigue effect increases most obviously, and the fatigue effect is mainly concentrated in the bottom and foundation of the tower. These components are subjected to heavy loads and vibrations over a long period of time, and are relatively more prone to cracks and damage.

Deng et al. [9] analyzed the vibration intensity and spectrum characteristics of 23 offshore wind power towers under typhoon, and the concrete vibration intensity statistics are given. Through monitoring the passing process of a typhoon with a maximum wind speed of 50 m/s, the study point out that the acceleration amplitude at the top of the tower barrel is relatively stable during the period of typhoon wind speed stability. However, its upper and lower peaks fluctuate greatly. Under the same conditions, the top of the tower cylinder will also appear vibration displacement. If the frequency of the external vibration is close to or the same as the natural frequency of the tower, the system may resonate, causing the vibration amplitude at the top of the tower to increase dramatically. The resonance phenomenon will further aggravate the fatigue damage of the tower, which may lead to more serious structural safety problems.

4. Wind Power Tower Structure Optimization

4.1. Telescopic Tower Lifting Method

By reducing the effective length of the tower can effectively reduce the bending force and bending moment at the bottom of the tower brought by the wind load under extreme typhoon conditions, because with the reduction of the height, the wind speed will decrease, and the overall typhoon pressure of the fan will be relatively lower. According to the principle of hydraulic technology, the method of "telescopic tower lifting" is conceived. By the principle of hydraulic technology, the tower lifting part can be realized in sections. Hydraulic technology mainly contains several advantages.

(1) Hydraulic technology can easily achieve stepless speed regulation, through the control valve to supply the flow of hydraulic motor or hydraulic cylinder stepless adjustment, the supervisor can freely control its rotation or linear movement speed.

(2) The output force of the actuator can be controlled, and components such as proportional solenoid valves can be used to control the pressure through electrical signals, so as to achieve remote control.

(3) The hydraulic transmission system can produce a large output force or torque with a light equipment weight, and has small inertia and high frequency response.

Taking the three-blade offshore wind power tower as an example, the main technical characteristics are concleded to serveral steps.

(1) The diameter of the tower barrel is reduced successively to ensure that it can be smoothly shrunk into the lower tower barrel to meet the storage standard.

(2) Hydraulic facilities in the tower barrel can be added to complete the normal operation of the tower barrel contraction. By setting up typhoon warning devices and remote-control facilities, in extreme typhoon cases, to achieve automatic telescopic tower, reduce the contact area with the typhoon.

(3) The section connection of the tower barrel is connected by a pulley, and the bayonet is set to fix the tower barrel when it reaches the position.

(4) The butt slot is set at the bottom of the tower barrel, which plays a fixed role when the upper tower barrel shrinks into the lower tower barrel, and can increase the resistance of the bottom tower barrel to typhoon to a certain extent, reduce the total bending moment of the tower barrel root, and improve the bending moment distribution.

4.2. Types of Offshore Wind Tower Dampers

4.2.1. Tuned Mass Damper (TMD).

TMD forms resonance with the main structure of the offshore wind tower to absorb and dissipate the structural vibration energy, thereby reducing the vibration response. Depending on whether an external system is required to provide energy, TMD can be divided into passive tuned mass damper (PTMD), active tuned mass damper (ATMD) and semi-active tuned mass damper (STMD).

(1) Passive tuned mass damper (PTMD): No external energy input is required, and the vibration reduction effect is achieved through the interaction of its own inertial mass and spring stiffness with the main structure.

(2) Active tuned mass damper (ATMD): On the basis of PTMD, sensors, controllers and actuators are added, which can monitor and control the vibration response of the main structure in real time to achieve a more accurate vibration reduction effect.

(3) Semi-active tuned mass damper (STMD): Combining the characteristics of PTMD and ATMD, by adjusting the damping coefficient of the damping element, the optimal vibration reduction effect under different working conditions is achieved.

4.2.2. Tuned Liquid Column Damper (TLCD).

The tuned liquid column damper uses the sloshing of liquid in a container to absorb and dissipate vibration energy. TLCD has the advantages of simple structure, easy maintenance and low cost, and has been widely used in vibration reduction of offshore wind turbines. By adjusting parameters such as mass ratio, damping ratio and frequency ratio of TLCD, its vibration reduction performance can be optimized.

4.2.3. Constrained Layer Damping (CLD).

The constrained layer damping is a technology that enhances structural damping by pasting or spraying viscoelastic materials on the surface of offshore wind turbines and applying a constrained layer on the outside. CLD can effectively absorb and dissipate vibration energy and improve the damping performance of the structure. However, due to the difference between the overall bending mode and the local deformation mode of offshore wind turbines, the application of CLD in offshore wind turbines still needs further research.

4.3. Improvement Principle

The wind turbine tower damper mainly consumes and disperses the vibration energy generated by wind on the tower body through the interaction between its internal mass block and the hydraulic cylinder. When the typhoon causes the tower to vibrate, the mass block in the damper will move in the opposite direction of the tower vibration. Through the friction and viscosity of the hydraulic cylinder, the vibration energy is converted into heat energy and released, thereby effectively reducing the vibration amplitude of the tower and improving the stability of the structure.

4.4. Research Status

In recent years, domestic and foreign scholars have conducted a lot of research on offshore wind turbine tower dampers. For example, Jiang Junni et al. studied the damping characteristics and vibration control methods of cylindrical foundation offshore wind turbine structures through on-site prototype observation, theoretical derivation and numerical simulation, proposed semi-active variable damping eddy current-TMD (SEC-TMD) technology, and verified its vibration reduction effect under different working conditions [10]. In addition, based on the basic principle of TLCD, some scholars have studied the vibration reduction performance of TLCD in offshore wind turbine towers through numerical analysis and vibration table tests [11].

4.5. Vibration Reduction Effect Analysis

Different types of dampers have different characteristics in the vibration reduction effect of offshore wind turbine towers. TMD has been widely used in offshore wind turbine towers due to its simple and effective vibration reduction mechanism. However, due to the high flexibility of offshore wind towers and the influence of complex environmental loads, a single type of damper is often difficult to meet the vibration reduction requirements. Therefore, the combination of multiple dampers to form a composite vibration reduction system has become an important direction for future research.

4.6. Analysis of advantages and disadvantages of damper

The advantages and disadvantages of the damper are shown in Table 3.

Table 3. Benefits and Disadvantages of the damper

Benefits	Improving Wind Resistance	The damper significantly enhances the stability of the wind tower in extreme weather such as typhoons, and reduces the risk of structural damage caused by excessive vibration.
	Extending Service Life	By reducing vibration, the damper helps to reduce the fatigue stress of the tower body and its connecting parts, thereby extending the service life of the entire wind tower.
	Improving Power Generation Efficiency	The stable tower structure helps to maintain the normal operation of the wind turbine, reduce power generation losses caused by shutdown maintenance, and improve overall power generation efficiency.
Disadvantages	High Cost	High-performance dampers are often accompanied by high manufacturing and installation costs, which increases the initial investment of wind power projects.
	Maintenance Requirements	The damper needs to be inspected and maintained regularly to ensure its normal operation and stable performance, which increases the operation and maintenance costs and workload of the wind farm.
	Adaptability Limitation	Different models and specifications of wind turbine towers require customized damper design to adapt to their specific vibration characteristics and structural requirements, which increases the complexity of design and manufacturing.

5. Conclusion

As an important part of clean energy, the development of offshore wind power is of great significance to the realization of energy transformation. However, the long-term impact of typhoon poses a serious challenge to the structural safety of offshore wind towers, and the risks of blade fracture and tower overturning cannot be ignored. Therefore, structural optimization has become the key to improve the wind resistant performance of wind power tower.

(1) This paper systematically studies the knowledge structure, evolution and future trend in the field of wind power tower by analyzing the relevant literature in the past ten years. By making a keyword co-occurrence map, the main topics of wind power tower and typhoon research and the relationship between keywords are shown. It shows that the future development frontier of offshore wind power tower is mainly related to the vibration improvement and structural optimization of wind power tower.

(2) This paper then calculates the wind pressure of the blade and tower, analyzes the acceleration waveform during the typhoon, and the influence of the sea wind wave on the wind power tower in the specific sea area are analyzed. This paper analyzes the development background and importance of offshore wind power, expounds the specific impact of Typhoon on the wind tower, and emphasizes the necessity of structural optimization. Through the analysis of design improvement and damper application, an effective solution is provided for the safe operation of offshore wind towers in typhoon prone areas, which promotes the continuous progress and development of offshore wind power technology.

(3) There are still some deficiencies in the research of wind power tower under the influence of typhoon, for example, the simulation accuracy of typhoon characteristics needs to be improved. Existing studies often use simplified treatment when simulating the typhoon moving path, such as assuming that the typhoon path is straight and the speed is constant, while ignoring the loss model after typhoon landing. In order to more accurately evaluate the impact of Typhoon on offshore wind

power tower, it is necessary to establish more accurate typhoon motion model and loss model to reflect the complex changes of typhoon in the actual environment.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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