Stability study of wind turbine tower cranes

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ABSTRACT

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| With the rapid development of wind power generation technology, tower cranes, as the key equipment for wind turbine lifting, are widely used in the installation process of wind turbines due to their high lifting height and strong load carrying capacity. This paper analyzes the stability factors of tower cranes in the process of wind turbine lifting through the study of tower crane stability, the structural stability of tower cranes and the stability of the whole machine, especially the influence of wind load, lifting weight, tower foundation design and other factors on its stability. The main contents include static stability of tower crane, dynamic stability under wind load, special stability problems in the process of wind turbine lifting, and measures to prevent tower crane tipping are proposed. In addition, combined with the current research situation at home and abroad, this paper also looks forward to the development trend of tower cranes in the field of wind power lifting, such as wind load research, dynamic modeling and simulation technology, monitoring and control technology. |

*Keywords:* Wind turbine tower cranes; Stability; Wind loads*.*

1. INTRODUCTION

As a clean and renewable energy source, wind energy has enormous resource potential and relatively mature technology. In the context of the global response to climate change and the reduction of greenhouse gas emissions, the development and utilization of wind energy is receiving great attention from various countries and has entered the stage of large-scale application[1]. According to the estimation, the global wind energy reserve is about 2.74×10^9MW, of which the utilizable wind energy reaches 2×10^7MW, which is far more than 10 times of the total amount of exploitable water energy on the earth[2] Wind power, as an important part of renewable energy, has been developing rapidly around the world. In China, in order to better utilize wind energy resources, wind power development has shown two remarkable trends: first, wind farms are gradually decentralized, and second, wind turbines tend to be large-scale[3]. With the rapid progress of the wind power industry, the requirements of wind power installation for construction efficiency and safety are constantly improving. Due to the complexity of the terrain of wind farms, the transfer costs between wind farms have an increasingly significant impact on overall profitability, and the difficulty and cost of constructing and maintaining transportation roads continues to rise[4].

With the wind turbine tends to large-scale, wind turbine height continues to rise, currently in service in the operation of the wind turbine nacelle height of more than 160 meters, most of the crawler cranes and car cranes have been unable to meet the needs of this height lifting work, and the tower crane because of its solid foundation, higher lifting height, lifting load and other advantages, to meet the demand for more than 160 meters of high tower wind turbine lifting[5]. Therefore, the tower crane can be used as one of the high tower wind turbine lifting machinery selection[6]. Secondly, tower crane in the installation process, through the self jacking device can complete the crane jacking installation, the length of the installation platform requirements are small, the conventional use of crawler cranes and car cranes, are required to the main boom completely to the horizontal position, in order to complete the crane assembly or dismantling work, the length of the crane installation site requirements are not less than the height of the lifting[7]. Therefore, the self-elevating tower crane is suitable for steeper mountain tops, rice paddies and other installation sites smaller wind turbine installation work, is a special terrain wind turbine installation work of choice[8]. Third, the tower crane transit, need to disassemble its main components disassembled to meet the conditions of transit, such as between the site of the road conditions are poor, it is necessary to carry out a complete disassembly, in order to meet the transportation needs[9]. Taking FZQ2400 improved jack-up tower crane as an example, it takes about 18 days for the crane to complete a full disassembly and assembly, and about 6 days for lifting, totaling about 24 days.The lifting sketch of FZQ1560 wind turbine is shown in Fig. 1 below.

The process of wind turbine lifting: first, tower lifting, in general, the lower section of the tower is the heaviest component, using tower cranes and automobile cranes (auxiliary cranes) to work together, the second is nacelle lifting, and the third is the lifting of the impeller (blade and hub assembly). Stability calculation process, should be the heaviest parts of the wind turbine lifting process as the object of calculation, that is, the lowest section of the tower[10].



**Fig.1 Schematic diagram of wind turbine lifting**

The installation height of wind turbine is high, the operation environment is complicated, and the environmental factors (wind load, temperature change, etc.) and technical factors (structural design, control system, etc.) in the process of installation of wind turbine put forward higher requirements for stability. In the process of wind turbine installation, safety accidents due to insufficient stability of tower cranes occur from time to time, and the stability of tower cranes is directly related to the safety of operators and equipment. Wind turbine lifting belongs to high-altitude alignment installation, requiring the crane to have good micro-motion accuracy. In order to ensure the accuracy of the installation, the tower crane is required to meet the height and carrying capacity at the same time, it must also have good stability.

Tower crane stability generally contains two levels: one is the tower structure stability, the other is the tower machine stability. Tower structural stability, refers to the tower steel structure in all the external load, resistance to pressure curvature and destabilization and have the ability to continue to work on the characteristics. Tower machine stability, refers to the tower crane to resist the stability of the overturning, is any one tower crane in the field after the installation of erection, should be in a variety of the most unfavorable conditions and the maximum external load (peak) combination of the role of the tower can work normally and maintain the stability of the whole machine and will not happen to tip over the accident. Tower crane machine stability is divided into two aspects, one is the tower crane in the load, that is, the working state of the machine stability; two is the tower crane in the unloaded, non-working state of its own stability .

In the preliminary design stage of the tower crane, it is necessary to carry out preliminary calculations on the tilting stability of the whole machine. After entering the stage of construction drawings, it should also recalibrate its tilting stability according to the revised parameters. According to the calculation results, take appropriate measures, tower crane in the working state, boom amplitude and lifting weight, including wind speed and wind direction are always changing, and the slope of the tower crane foundation track is not fixed, so in the process of calculating the stability of the tower crane, you need to take into account all the working conditions, calculating the representative of the most unfavorable working conditions for calculation.

Maintain the tower crane stability of the force mainly refers to: the tower crane's self-weight and compression weight. The external forces that play a role in overturning the tower crane are: wind load, lifting load, inertia force . The counterweight of the upper slewing tower crane sometimes acts as a stabilizing force, while in other conditions it acts as a tipping force. Other factors affecting the stability of the tower crane:Tower crane foundation design, to ensure that the foundation is strong enough to avoid the stability of the foundation settlement or deformation and lead to a decline in stability;Tower crane center of gravity, boom, lifting loads, etc. will affect the center of gravity position of the crane, so in the design must be to ensure that the center of gravity position is reasonable, to enhance its stability.

Tower stability coefficient, is used to measure the evaluation of tower crane resistance to external tipping effect, and maintain the overall stability of the tower crane working ability of a kind of index.

$K=\frac{\sum\_{}^{}M\_{S}}{\sum\_{}^{}M\_{O}}$

$K$——Stability coefficient of the whole tower crane

$\sum\_{}^{}M\_{S}$—— Indicates the sum of all the moments that keep the tower stable as a whole；

$\sum\_{}^{}M\_{O}$—— denotes the sum of all moments that cause the tower to tip over.

Stabilizing moment is to maintain the stability of the tower machine force and force to the vertical distance of the tower machine tipping wheel edge product, tipping moment is to cause the tower base tipping of the external load and the load force to the vertical distance of the tipping wheel edge product. The so-called tipping rim or tipping edge refers to the edge of contact between the traveling wheel and the rail on the side of the tower machine tipping direction or the edge of the foundation on the side of the tower machine tipping direction. The stability coefficient is usually taken as a value between 1.5 and 2 to ensure that the crane has sufficient stability to avoid tipping.

2. Basic stability (static, no wind)

Tower cranes in static, windless conditions. The basic stability calculation involves the following aspects:

The basic principle of basic stability calculation is moment balance, i.e., the relationship between the stabilizing moment and the tipping moment of the tower crane. The tower crane at rest must meet the following conditions:

$M\_{S}\geq M\_{O}$

The overturning moment represents the moment of the tower crane's lifting weight acting on the support point (usually the tower base).

$M\_{S}=W×d$

$W$——Lifting weight of tower crane；

$d$——Horizontal distance from the center of gravity of the tower crane to the support point (tower base)。

The stabilizing moment is the moment generated by the structure and weight of the tower itself.

The stabilizing moment can be expressed as:

$M\_{S}=G×d\_{s}$

$G$—— Gross weight of crane tower, base, etc；

$d\_{s}$—— Horizontal distance from the center of gravity of the tower to the edge of the foundation (the outermost part of the tower in contact with the ground)

**2.1 Basic stability calculation steps**

(1) Calculate the combined force of the crane's self-weight and the working load.

(2) Calculate the moment of each part of the crane (tower, boom, foundation, etc.) on the support point.

(3) Calculate the tipping moment and stabilizing moment.

(4) Verify whether the stability coefficient requirement is satisfied.

If not, the design can be adjusted by, for example, increasing the area of the foundation or changing the configuration of the tower crane.

**2.2 Static, no wind conditions stability calculation sketch**



**Fig. 2 Stability calculation sketch for static and windless condition**

$G\left(b+c\right)-1.5F\_{Q}(R\_{max}-b)>0$

$G$——Self-weight of the tower (including counterweights and compression weights), in kN;

$F\_{Q}$—— Lifting load, unit kN;

$R\_{max}$—— Maximum working range of tower crane, unit m;

$b$——Track radius, unit m;

$c$——horizontal distance from the center of gravity of the tower crane to the slewing center, in m.

The basic stability of the tower can also be directly determined using this formula.

3. Stability calculations under wind loadsBasic stability (static, no wind)

Wind turbine lifting tasks are generally carried out outdoors, so the influence of wind load is very important in the design calculation of tower crane, especially in the windy area, the wind load can act horizontally on the tower crane along any direction, which has a direct influence on the stability and safety of the tower crane.

The calculation of wind load includes static wind load and dynamic wind load. In addition, it is also necessary to consider the stability of the tower crane under windy conditions, i.e. dynamic stability.

**3.1 Wind Load Calculation Formula**

Wind load is the force acting on the tower crane structure by the wind. The magnitude of the wind force is closely related to the wind speed, the density of the wind, the exposed area of the tower crane and the direction of the wind. The wind load can usually be calculated by the following formula：

$F=\frac{1}{2}C\_{d}ρAv^{2}$

$F$——Wind load (N);

$C\_{d}$—— wind load coefficient；

$ρ$——density of air；

$A$——windward area of the tower crane perpendicular to the wind direction (in m^2)；

$v$——wind speed (unit m/s).

In practice, the wind speed increases with the increase of height, and the wind load also changes with the change of height. Therefore, it is necessary to calculate the wind load according to the height segmentation of the tower. The tower body and boom can be segmented and the wind load of each segment can be calculated separately.

**3.2 Working condition wind load (dynamic, with wind, dynamic stability)**

The working condition wind load is the maximum calculated wind force that the tower crane can withstand during normal operation.

In the working state, the effect of the wind load will usually be greater than the static wind load. This is due to the fluctuating nature of the wind load during its action, and the tower crane will have additional vibration effect under wind load. Considering the influence brought about by this effect, a dynamic increase coefficient K\_d is introduced, which is determined based on factors such as wind speed and the inherent vibration frequency of the tower crane.

The intrinsic frequency of the tower crane is closely related to the structure, material and design of the tower crane. If the frequency of the wind speed is close to the inherent frequency of the tower crane, resonance phenomenon may occur, so that the tower crane produces violent vibration, which in turn affects the stability of the tower crane. At this time, the tower crane can be modal analysis to determine the intrinsic frequency of the tower crane, and compared with the wind speed frequency.

The formula for calculating the dynamic wind load is as follows：

$F\_{v}=C\_{d}×F$

$F\_{v}$—— Dynamic wind load;

$F$——static wind load;

$C\_{d}$—— dynamic enlargement factor, according to the wind speed.

In addition, the damping characteristics of the tower crane (e.g. friction damping, air damping, etc.) will also have an effect on its dynamic stability. Proper damping can reduce the vibration amplitude and lower the instability of the tower crane due to the wind load effect. When the damping is insufficient, the tower crane is prone to large-scale vibration, thus affecting its stability.

**3.3 Calculation of wind loads in non-working condition (storm surge)**

Non-working state refers to the tower crane does not carry out any lifting operations, and is in the environment of the windstorm. At this time, the tower components, including the tower body, boom, counterbalance arm, lifting weight, etc., will be subjected to a larger wind force, affecting the stability of the tower. Storm attack refers to the phenomenon of sudden increase in wind speed in a short period of time, the wind speed change is more violent and shorter duration.

The design wind speed should be based on the wind level and design specifications of different regions. Considering the design location of the tower crane, refer to the local wind speed data to determine the basic wind speed in the area. When a windstorm strikes, the wind speed may reach 1.5 times or more of the basic wind speed in a short period of time, and then it is necessary to calculate the specific wind speed during the windstorm according to the wind speed increase factor.

4. STABILITY OF BACKWARD TIPPING IN WORKING CONDITION (SUDDEN UNLOADING)

When the hoist is suddenly unloaded or the spreader is suddenly dislodged during the lifting process, the tower structure vibrates and the end of the lifting arm is subjected to an upward reaction force F\_r. The reaction force is usually an instantaneous force, and the tower crane will tip over to the rear under the action of this force .

Calculation of tower crane stability,When the spreader is suddenly unloaded, the tower crane stability can be expressed by the following inequality:

$M\_{r}\geq M\_{t}$

$M\_{r}$—— Moment of resistance to overturning;

$M\_{t}$—— tilting moment.

5. The influence of special workplaces such as earthquakes and waves on the stability of tower cranes

**5.1 Calculation of seismic loads**

Calculation of seismic forces can be done by using the following equation：

$F\_{e}=W\_{t}×C\_{s}×a\_{s}$

$F\_{e}$—— Seismic loads;

$W\_{t}$—— weight of the tower crane；

$C\_{s}$—— seismic coefficient, usually dependent on the type of tower structure and the intensity of the seismic zone；

$a\_{s}$—— seismic acceleration.

**5.2 Calculation of the impact of waves on the stability of tower crane**

The dynamic force of the waves will act on the base of the tower crane, especially when operating at sea, the impact force of the waves and the swaying in the horizontal direction will affect the stability of the tower crane.

The calculation formula of wave force is：

$F\_{w}=C\_{w}×H\_{w}×ρ×g×A$

$C\_{w}$—— Wave impact coefficient, depending on the characteristics of the waves and the structure of the tower;

$H\_{w}$——height of the waves;

$ρ$——density of water;

$g$——acceleration of gravity;

$A$——Area of the tower base in contact with the water.

6. Other measures to prevent the tower crane from tipping overBasic stability (static, no wind)

Strictly prohibit overloading operation, due to the tower crane toppling external force in the crane load accounted for the main role, overloading is to consciously increase the external force toppling the whole machine, thus increasing the danger of tower crane toppling. Tower stability calculation, tower stability coefficient is generally not less than 1.4, individual cases shall not be less than 1.15. This shows that the margin of the tower stability coefficient is not very large, if the tower overloading, coupled with the combined effect of other unstable factors, may cause the tower toppling accident. Practice shows that the vast majority of tower crane overturning accidents are caused by forced overloading.

Shall not diagonally holding heavy, diagonally holding heavy, caused by lifting load tipping tower machine will produce a horizontal force, and the horizontal force will increase the tipping moment. Therefore, diagonally draw heavy material is essentially also a kind of overloading, there is a danger of causing the tower crane overthrow, must be strictly prohibited.

Not allowed to violent emergency braking, violent emergency braking will produce a large inertial force, its destructive effect is difficult to estimate, the stability of the crane has an extremely adverse effect.

Prohibit lifting operations in high winds, when the wind speed exceeds 6, should stop all lifting operations. This is because the size of the wind load is proportional to the square of the wind speed, and the wind load is also the main factor causing the tower crane tipping. The wind load is too large will certainly increase the risk of tower crane tipping. In addition, under the action of high wind, people's operation safety lack of guarantee, component lifting in place is difficult, and the crane structure is unfavorable, so it is not allowed to carry out lifting operations in high wind .

After the work shift, the rail clamp must be clamped. Although the accuracy of today's weather forecasts is increasing, the possibility of sudden gusts of wind still cannot be ruled out. High winds hit the tower, and sometimes, although they do not necessarily cause the tower to tip over, they are likely to scrape the crane and cause the tower to slip off the track. Like this inverted tower accident, since the use of tower crane in China's building construction, there have been a number of derailment accidents. Therefore, a high degree of vigilance is necessary.

Compared with the traditional general-purpose crane operating requirements, wind power lifting has several obvious demand characteristics: First, the working conditions are relatively single, long jib lifting capacity requirements; Second, the site adaptability requirements; Third, the operational efficiency requirements; Fourth, the operation of the micromanipulation alignment precision. Wind power lifting has a typical fixed working condition point, general lifting in place high requirements (generally above 60 meters), amplitude requirements are small (within 20 meters), the weight and volume of different MW-class fan equipment is basically comparable to the installation of different wind farms is also relatively fixed in height, the formation of a clearer lifting condition echelon. This requires the development of cranes to pay more attention to the lifting capacity of the middle and long jib.

7. CONCLUSION

The omni-directional movement of the McNamm wheel AGV trolley is carried out through the direction of its force movement by matching the McNamm wheels with different rotational direction, and then from analyzing the difference of the wheel force and steering of the single McNamm wheel when it is rotating forward and backward to analyzing the overall movement of the trolley when each McNamm wheel in the combination of the McNamm wheel wheel set is rotating forward and backward with each other so that the omni-directional movement of the trolley can be realized. Purpose Not only the principle of omnidirectional movement is determined, but also the overall framework of the trolley is basically determined, which is a good preparation for the later structural design.

In order to analyze the stability of the trolley, the overall kinematics simulation of the trolley is simulated by Adams software. First of all, draw a good 3D model in proe, and add a large enough rectangle tangent to the four McNamm wheels to make the ground. Then import the model into Adams, delete the unwanted parts, and then add the constraints, each part of the car has a constraint relationship between the constraints should be added, and then the model drawn in the ground in Adams fixed, and then the four McNamm wheels to add a good drive function, the car can realize the movement, and then start the simulation analysis. Inside the post-processing to observe the overall movement of the cart and the wheel contact force force situation, as well as the roller displacement, speed change rule, as well as drive the power and speed change.

The design of this comprehensive down to analyze there are still many shortcomings, first of all, the structure design is slightly rough, so that the front end of the drive shaft stress is too concentrated, the later can be replaced with a coupling or change the length of the shaft to reduce the stress concentration. There is also the simulation did not analyze the tensioning device of the trolley, which can be analyzed and solved by adding springs and corresponding constraints, so as to analyze the overall stability of the trolley. After the overall design analysis is completed, the overall structure of the trolley can be further optimized to reduce the body load and increase the internal space, so as to improve the working efficiency and smoothness of the body. The optimization can be achieved visually and effectively by improving the damping capacity of the spring and optimizing the structural performance of the axle.

Competing interests

Authors have declared that no competing interests exist.

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COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

References

[1]Cungen L ,Shuo M ,Xiaoping L , et al.A tracking control method with the fast finite-time command filter for four degrees of freedom tower cranes[J].Transactions of the Institute of Measurement and Control,2025,47(4):688-699.

[2]Chuanjing H ,Can L ,Zhi L , et al.Tower crane systems modeling and adaptive robust sliding mode control design under unknown frictions and wind disturbances[J].Transactions of the Institute of Measurement and Control,2025,47(4):795-809.

[3]Ding D ,Deng Z ,Yang R .YOLO-TC: An Optimized Detection Model for Monitoring Safety-Critical Small Objects in Tower Crane Operations[J].Algorithms,2025,18(1):27-27.

[4]Loveikin S V ,Romasevych O Y ,Loveikin V A , et al.Power Criterion Optimization of Concurrent Start of Trolleying and Slewing Mechanisms in Tower Crane[J].International Applied Mechanics,2024,60(4):1-15.

[5]Zamfirache A I ,Precup E R ,Petriu M E .Safe reinforcement learning-based control using deep deterministic policy gradient algorithm and slime mould algorithm with experimental tower crane system validation[J].Information Sciences,2025,692121640-121640.

[6]Zamfirache A I ,Precup E R ,Petriu M E .Safe reinforcement learning-based control using deep deterministic policy gradient algorithm and slime mould algorithm with experimental tower crane system validation[J].Information Sciences,2025,692121640-121640.

[7]Loveikin S V ,Romasevych O Y ,Loveikin V A , et al.Power Criterion Optimization of Concurrent Start of Trolleying and Slewing Mechanisms in Tower Crane[J].International Applied Mechanics,2024,60(4):1-15.

[8]Solazzi L ,Rustighi E .Passive earthquake vibration mitigation of a steel tower crane by joint dampers[J].Journal of Physics: Conference Series,2024,2909(1):012028-012028.

[9]Zamfirache A I ,Precup E R ,Petriu M E .Safe reinforcement learning-based control using deep deterministic policy gradient algorithm and slime mould algorithm with experimental tower crane system validation[J].Information Sciences,2025,692121640-121640.

[10]Thi L H ,Nguyen C V ,Nguyen L T .Adaptive finite-time extended state observer-based model predictive control with Flatness motivated trajectory planning for 5-DOF tower cranes[J].European Journal of Control,2025,81101149-101149.