Analysis on the principle and performance Index of Tower climbing Robot

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Abstract. In this paper, aiming at the special application environment of wind power tower, this paper compares the existing domestic and international wall-climbing robot products, studies its structural characteristics, adsorption principle, etc., and then uses the knowledge of kinematics and dynamics to analyze its vertical climbing and steering motion. The performance requirements and structural design goals of the wind turbine tower climbing robot are proposed. Analyze and compare different combinations of solutions, and finally determine the use of the track magnetic adsorption design. The theoretical analysis of the vertical climbing and in-situ steering mechanics of the design scheme shows that the track length design of the crawler climbing robot should not be too long, and it will generate large resistance when steering, which is not conducive to steering. At the same time, the stability of the climbing robot climbing on the tower is theoretically calculated, and the number of required adsorption units is obtained.

1. Introduction
For climbing robots used in high-altitude hazardous environments such as wind turbine towers, they are often required to have strong stability and manoeuvrability. The domestic robots used in special applications such as wind turbine towers are almost blank. In this paper, aiming at the special application environment of wind power tower, this paper compares the existing domestic and international wall-climbing robot products, studies its structural characteristics, adsorption principle, etc., and then uses the knowledge of kinematics and dynamics to analyse its vertical climbing and steering motion. The performance requirements and structural design goals of the wind turbine tower climbing robot are proposed.

2. Wind turbine tower parameters
Wind turbine tower, referred to as wind tower. It is an important part of wind turbines, which supports the entire power generation equipment and shock absorption in wind turbines.

According to its structural form, it can be divided into a cylindrical tower and a truss tower. Compared with the truss tower, the cylindrical tower has higher manufacturing cost, but it has better safety and has the advantages of elegant appearance and easy maintenance. At present, the towers of large-scale wind turbines mostly adopt cylindrical conical steel tower structure, which is generally connected by multi-section towers. Each tower is usually about 20~30m high, bent by steel plates with
thickness of about 8mm and longitudinally welded. To make. Each end of the tower has a steel flange at each end and is bolted to each tower.

The tower wall climbing robot studied in this paper is based on the hrg100-3000-02-00 tower of Gold wind Company. The specific structure and parameters of the wind turbine tower are shown in Table 1 and Figure 1. It can be seen that the tower body material is Q345E, the tower tube is divided into three sections, and the second section is a truncated cone shape.

Table 1. Gold wind hrl100-3000-02-00 tower parameters

| parameter       | Verticality $\beta/^{\circ}$ | material | Outer diameter $D$/mm |
|-----------------|-------------------------------|----------|-----------------------|
| First paragraph | 90                            | Q345E    | 4500mm                |
| Second paragraph| 89                            | Q345E    | 4500-3040             |
| Third paragraph | 90                            | Q345E    | 3040                  |

Figure 1. Cross section of wind turbine tower

3. Analysis of wind turbine tower climbing robot

The existing wall-climbing robot is mainly composed of five main units: the main body of the robot, the external system, the power system, the mobile system and the adsorption unit. The composition of the frame is shown in Figure 2., based on the analysis of the characteristics of various climbing robots at home and abroad. The structural schemes of the various components are now being studied separately.

Figure 2. Robot composition frame

3.1. Adsorption scheme selection

The wall-climbing robot first needs to determine the adsorption scheme, and then carry out the rest of the design for the characteristics of the adsorption scheme. The adsorption schemes suitable for wind
turbine tower climbing robots mainly include vacuum vacuum adsorption scheme, multi-suction vacuum adsorption scheme, electromagnet adsorption scheme and permanent magnet adsorption scheme.

(1) Negative pressure vacuum adsorption scheme

The vacuum vacuum adsorption scheme requires the high-power motor in the wall-climbing robot to operate at all times to provide the adsorption force, which has high energy consumption and high sealing requirements. It requires high-power and high-energy density battery power supply with short working time and low cost performance. The advantage is that the wall has strong adaptability, and both metal and non-metal walls can climb, and have certain adaptability to uneven wall surface.

(2) Multi-suction cup vacuum adsorption scheme

Multi-suction vacuum adsorption requires the installation of multiple vacuum chucks on the climbing mechanism of the wall-climbing robot. The negative pressure generated by the vacuum generator is used to provide the suction force to the suction cup, and the valve on the branch pipe is adjusted to move on the wall surface. However, there are lateral tower knots on the wind tower and vertical welds as well as dust and oil on the tower, which will affect the serious adsorption effect, which may cause air leakage and eventually failure.

(3) Electromagnet adsorption scheme

Electromagnets are energized with magnetic and energized degaussing. The latter has a high safety factor, but the mass of the monomer is large and the adsorption force provided is limited. The advantage of the electromagnet is that it makes the robot more flexible to power off the magnetic pole that is about to leave the wall and reduce the load on the driving motor. At the same time, the disadvantage is that the energy consumption is too high, and in the event of a power failure, there is a risk of falling.

(4) Permanent magnet adsorption scheme

As the use of rare metals becomes more mature, commercial NdFeB magnets can absorb objects that are more than 100 times their own weight in order to reach 50 MGOe. Since the environment in which the wall climbing robot is used is the outer wall of the wind tower, it is conceivable to use a permanent magnet to provide the adsorption force. Permanent magnet adsorption also has the advantages of high safety factor, low energy consumption (adsorption power has no energy consumption), but there are also problems such as large force required to peel off the wall of the magnet, and the influence can be minimized by optimizing the layout.

After investigation, the five dimensions of cost, energy consumption, speed and redundancy maintenance are quantitatively compared. The permanent magnet adsorption scheme is the optimal consideration.

3.2 Walking plan design and driving method

The main walking schemes of robots using magnetic adsorption are foot, wheel and crawler. The existing unit capacity of existing fan units continues to increase, and the offshore wind farm single machine 5mw-6wm has entered commercialization, and the center height of the hub is 90 meters [35]. The walking distance is far, and the moving speed of the robot has high requirements. Considering the safety, applicability, speed and other requirements, the crawler walking scheme is more suitable. The foot walking speed is too slow, and the wheeled walking will be due to structural reasons. Carrying a large number of magnets greatly increases the quality of the preparation. Compared with the former two, the track walking method has the advantages of large wall contact area, good stability, low center of gravity, fast speed and strong wall adaptability, but there is a steering design and rigidity of the fuselage. More requirements are required. The summary of the characteristics of the three walking modes is shown in Table 2.
Table 2. Characteristics of different walking modes

|            | Weight | Redundancy | Moving Speed |
|------------|--------|------------|--------------|
| Tracked    | high   | high       | in           |
| Wheeled    | in     | low        | high         |
| Foot type  | low    | in         | low          |

It can be seen from the table that the crawler type has a medium moving speed in the case where the redundancy is dominant, but the weight is high. In view of the high weight of the traditional metal track and sprocket, which increases the weight of the climbing robot, the combination of the synchronous pulley and the pulley can be used instead of the metal crawler to reduce the weight of the traveling mechanism, so the crawler scheme is more suitable as this. The walking scheme of the robot. At the same time, the timing belt has certain deformation characteristics and has better wall adaptability. Therefore, the walking scheme will adopt a double timing belt transmission structure, and arrange magnetic components on the outer surface of the timing belt to provide the suction force required for climbing.

The synchronous pulleys on both sides are active after the front driven, because the required torque of the driving wheel is large, so the transmission system all adopts the involute spur gear transmission, and the power loss of the worm gear transmission is not used. The power is secondarily decelerated to the driving wheel via the motor, the main reduction gearbox, and the wheel reducer, thereby obtaining a large torque.

4. Analysis of vertical climbing and steering force of wind turbine tower climbing robot

Based on the application environment and existing conditions of the wind tower climbing robot, a series of wind turbine climbing robots are selected to analyze the relatively stable track permanent magnet adsorption type. For the crawler walking mode, the vertical traveling characteristics should be vertical. Climbing and steering characteristics are analyzed to provide reliable theoretical guidance and design ideas for subsequent specific designs. In order to determine the objectives of robot performance analysis and structural design, this section will refer to the mature crawler robots and wall climbing robots at home and abroad, and propose the robot design ideas for wind tower climbing.

4.1. Robot vertical climbing analysis

Figure 3 shows the motion diagram of the vertical climbing of the robot. The verticality of the wall of the tower is close to 90°. Therefore, it is considered to be perpendicular to the ground. This movement
is different from the linear motion of a typical two parallel crawler vehicles. The vertical plane is rotated by 90°, and the contact force between the track and the wall is added. It is assumed that the robot's adsorption force is evenly distributed on the entire timing belt, and the timing belt and the pulley are not slipped, then [36]:

\[ v = v_t \cdot (1 - \sigma) = \omega r \cdot (1 - \sigma) = 0.377 \frac{n}{i} r \cdot (1 - \sigma) \]  

(1)

In the formula: 

- \( v \) - the speed at which the robot climbs; 
- \( v_t \) — synchronous belt winding line speed; 
- \( \omega \) — drive wheel rotation angular velocity; 
- \( r \) — drive wheel radius; 
- \( n \) — drive motor speed; 
- \( i \) — Transmission system transmission ratio; 
- \( \sigma \) — The coefficient of friction between the adsorption device and the wall.

The traction of the robot is:

\[ F_t = \frac{9550P_e i_T \eta_T}{n r} \]  

(2)

In the formula: 

- \( P_e \) — drive motor power; 
- \( i_T \) — the total transmission ratio of the transmission system; 
- \( r \) — timing belt drive wheel radius; 
- \( \eta_T \) — The driving efficiency of the synchronous belt, because the climbing speed of the climbing robot is not high, generally less than 38km/h, according to the AD Krukov experience formula [36], you can get:

\[ \eta_T = 1.07 - 0.000075v^2 \]  

(3)

Equation (2) can be used for the determination of the pulley size, and it can be seen from the equation (3) that the climbing robot efficiency decreases as the traveling speed increases.

4.2. Robot steering analysis

In the process of analyzing the turning of the robot, first assume that the center of mass of the robot coincides with the geometric center of the robot on the horizontal projection surface, then the steering motion of the robot can be converted into the plane motion of the rigid body [37-38]. The steering of the climbing robot on the tower the motion diagram is shown in Figure 4.
Figure 4. Robot steering diagram

In the picture, for the timing of the contact belt wall length, \( b \) for the timing belt width, \( c \) is the robot center, \( c_1, c_2 \), the center of symmetry of the contact wall of the inner and outer timing belts, \( B \) for the two timing belts, the center distance \( o \) is the instantaneous steering center of the climbing robot, \( R \) for the instantaneous turning radius, \( v_1, v_2 \) for the two sides of the belt with a central steering line speed. The linear velocity at which the robot center turns \( v_c \). It can be expressed as:

\[
\frac{v_2}{B/2 + R} = \frac{v_c}{R}
\]

Which is:

\[
v_c = \frac{v_1 + v_2}{2} = \frac{v_2 R}{B/2 + R}
\]

Available:

\[
R = \frac{v_1 + v_2}{v_2 - v_1} \frac{B}{2}
\]

Then:

\[
\omega = \frac{v_2 - v_1}{B}
\]
During the actual steering process of the wind turbine tower climbing robot, there must be slippage and slippage between the adsorption device and the wall surface, and then the slip coefficient of the inner and outer timing belts is introduced, \( f_1, f_2 \):
\[
\begin{align*}
  f_1 &= \frac{v_1 - v_{out1}}{v_{out1}} \\
  f_2 &= \frac{v_{out2} - v_2}{v_{out2}}
\end{align*}
\]  
(8)

In the formula: \( v_{out1} \) — Roller line speed of the inner side of the robot;  
\( v_{out2} \) — Roller line speed of the outer side of the robot;  

Then the actual turning radius and angular velocity are:
\[
\begin{align*}
  \omega &= \frac{v_2 (1 - f_2) - v_1 (1 + f_1)}{B} \\
  R &= \frac{v_1 (1 + f_1) + v_2 (1 - f_2)}{v_2 (1 - f_2) - v_1 (1 + f_1)} \frac{B}{2}
\end{align*}
\]  
(9)

In the middle, \( v_1, v_2 \) It can be obtained from the formula (7).

Further calculate the steering resistance torque required for the inner and outer timing belts \( M_1, M_2 \) And traction on both sides \( F_1, F_2 \) for:
\[
M_1 = M_2 = 2 \int_0^{L/2} yu \frac{F_x}{2l} dy = \frac{uLF_x}{8}
\]  
(10)

\[
\begin{align*}
  F_1 &= \frac{fF_x}{2} - \frac{uLF_x}{4B} \\
  F_2 &= \frac{fF_x}{2} + \frac{uLF_x}{4B}
\end{align*}
\]  
(11)

In the formula, \( u \) For the steering drag coefficient, according to the empirical formula:
\[
\mu = \frac{\mu_{max}}{0.925 + 0.15 \frac{R}{B}}
\]  
(12)

In the middle, \( \mu_{max} \) The maximum steering drag coefficient when the traveling device is turned in place. It can be known from the formulas (11) and (12) that as long as the wall environment is known \( \mu_{max} \) with \( f \) Adsorption force \( F_x \) You can find the required traction \( F_1, F_2 \).

According to formula (10), when the robot turns, the force of the timing belt will follow the length of contact with the wall surface. \( L \) Increase and increase, so in order to avoid the unilateral stress on the synchronous belt, it should be made \( L \) Minimize while preventing excessive load on one side of the motor. The above analysis can be used as an important reference for climbing robot design.
5. Analysis of climbing stability of wind turbine tower climbing robot
The main movement mode of the wind turbine tower climbing robot is to climb up the outer wall of the tower. The outer wall of the tower can be regarded as a vertical wall. Therefore, it is necessary to ensure the reliability of the robot on the outer wall of the tower. Under the action of various forms of instability, the characteristics of the adsorption unit design and motor parameters are studied.

The necessary conditions for the normal climbing of the wind turbine tower climbing robot are as follows:

1. The wall climbing robot must ensure sufficient adsorption force during the vertical climbing.
2. The power reserve of the wall-climbing robot should be sufficient to ensure the robot's steady rise.

![Robot vertical climbing force diagram](image)

The force analysis of the climbing robot can be simplified to the model shown in Figure 5. Climbing robot center of gravity and wall distance, the squeezing force and friction of the climbing robot and the tower are simplified to the centroid of the contact module. The model parameter mass \( m \), the friction coefficient between the adsorption module and the tower wall is \( u \), and the gravity acceleration \( g \) is \( 10N/kg \). The adsorption capacity of a single adsorption unit is \( X_i \), the number of walls that the adsorption unit has contacted is \( n \).

There are two situations in which a climbing robot is unstable from the tower:

1. The climbing robot slides down the outer wall of the tower. In this case, the self-locking characteristic of the geared motor can be utilized, and even if the motor suddenly loses power, the wheel will not be reversed, causing an accident. Therefore, the sliding may be the frictional resistance between the adsorption device and the wall. \( F_s \). Less than gravity \( g \), in order to avoid the robot sliding down, there are:

\[
F_s = \mu nX_i > G = mg
\]  

(13)

2. The climbing robot turns over with the point o as the center of rotation and rolls down from the wall. In this case \( L_i \) for the distance between the adsorption unit and the center of rotation, \( X_1 = X_i = X_n \), so take a moment on the o point to balance it:
The climbing robot needs to satisfy the conditions set by Equations 13 and 14 at the same time. Now assume that the model parameter mass \( m \) is 7.635kg, and the friction coefficient \( u \) between the magnet and the tower is found to be 0.36, the gravitational acceleration \( g \) is 10N/Kg, and the adsorption force of the single magnet \( X_f \). For 20n, the safety factor is 1.2.

Substituting 13 and 14 can be obtained

\[
\sum M_n = \frac{mgx}{2} - \sum^n X_iL_i = 0
\]  

(14)

Therefore, in theory, at least 15 adsorption units need to be arranged.

6. Main technical indicators

The main content of this paper is to design and research a robot platform that can be used for climbing the surface of wind turbine towers. Different modules are installed for different needs. The preliminary design is to replace the manual inspection and other high-altitude operations on the outer surface of the wind turbine tower. Mission. Compared to the previous design of dozens of kilograms of wind tower climbing robots. To adopt lightweight design. For the HRg100-3000-02-00 tower, refer to the climbing robots at home and abroad to set certain specific technologies. Requirements, as shown in Table 3:

| skills requirement                  | Design Parameters |        |
|-------------------------------------|-------------------|--------|
| Dimensions                          | 450mm×472mm×148mm  |        |
| Ontology weight                     | 8Kg               |        |
| Maximum load                        | 3Kg               |        |
| Maximum adsorption force            | 2000N             |        |
| Maximum crawling speed              | 10m/min           |        |
| Obstacle resistance                 | 5mm               |        |
| Surface adaptability                | Φ3000             |        |
| Working time                        | 3h                |        |
| Anti-skid safety measures           | safety rope       |        |

7. Summary

According to the HRg100-3000-02-00 tower parameters of Goldwind Company, the different scheme combinations are analyzed and compared, and the track magnetic adsorption design scheme is finally determined. The theoretical analysis of the vertical climbing and in-situ steering mechanics of the design scheme is carried out. It is learned that the track length design of the crawler climbing robot should not be too long, and it will generate a large resistance when steering, which is not conducive to steering. At the same time, the theoretical calculation of the stability of the climbing robot climbing on the tower is obtained. The number of adsorption units required.

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