

Force Analysis and Simulation of Salt Cleaning Robot for Desulfurization Tower

Chang Sheng, Liu Yuliang

School of Marine Engineering Equipment, Zhejiang Ocean University, Zhoushan, China

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Abstract: In this paper, walking mechanism of a cleaning-salt robot is designed, where both mechanical structure and movement principle of the walking mechanism are described. The walking mechanism modeling is completed by using Solidworks, a three dimensional software. The walking mechanism's key modules include frame, motor, crawler, permanent magnet, driving wheel and driven wheel, and they work together, guaranteeing the robot can adsorb on the wall and complete the cleaning operation with stability and security.

1. Introduction

In recent years, the top priority of the shipping industry is the implementation of "Sulfur Restriction Order" promulgated by IMO, i.e. International Maritime Organization, in order to control the marine air pollution caused by ship emission. It requires that from January 1, 2020, the sulfur content of fuel used by ships worldwide should not exceed 0.5%. ECA shall not exceed 0.1% in the emission control area. Where installation of desulfurization tower has become one of the feasible methods and a new type of wall-climbing robot carrying cleaning tools to assist or replace humans to complete salt cleaning operations is urgently-needed. The wall-climbing robot is required to stably adsorb on the wall of the desulfurization tower, and can carry cleaning tools such as steel brushes to move stably[1-2].

2. Scheme Design of Wall-Climbing Robot

According to the above analysis of walking mode, adsorption mode and driving mode, the salt cleaning robot solution designed in this article is a combination of motor drive, permanent magnet, electromagnet and point magnet with an adsorption structure and a crawler walking mechanism[3-4].

2.1 Robot Structure Design

2.1.1 Track Adsorption Structure

The crawler adsorption mechanism is the core structure for the safe and stable operation of the entire robot on the metal wall. Through calculations and experiments, the position and number of permanent magnets inlaid on a single crawler are determined to ensure that the robot is safely adsorbed on the metal wall and receives uniform force during movement. Difficulty turning occurs[5-6].

As shown in Figure 1, a circular permanent magnet is embedded between every two chains. These permanent magnets are in direct contact with the metal wall and will move synchronously with the movement of the crawler to ensure that the robot has sufficient adsorption force during operation[7].

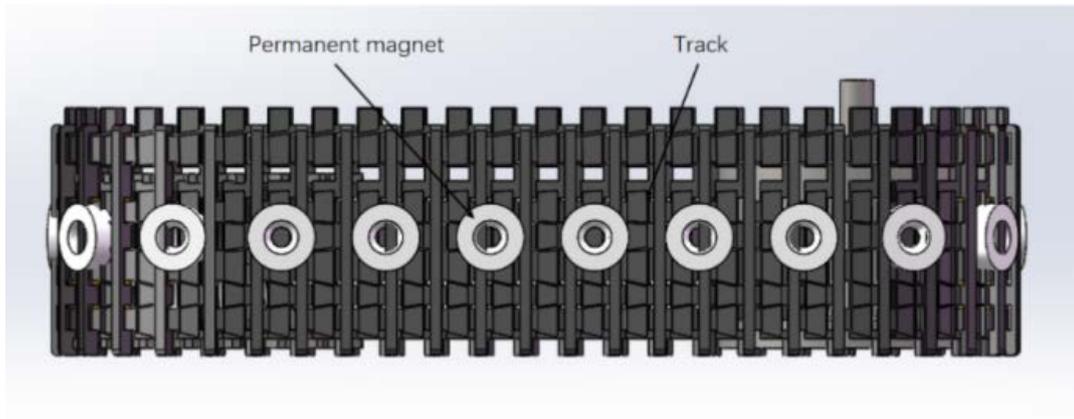


Fig.1 The Crawler Adsorption Structure of the Wall-Climbing Robot.

2.1.2 Drive Transmission Structure

As shown in Figure 2, the motor, driving sprocket, driven wheel and crawler constitute the driving and transmission mechanism of the robot. Select the motor of the model, the motor has a large reduction ratio and can generate a large enough driving torque. The drive sprocket is the main structure of the entire drive. The structure adopts a 12A chain as a whole[8]. Two 12A chains are connected as a whole, which can be sufficiently strong without screws to ensure the stable operation of the robot.

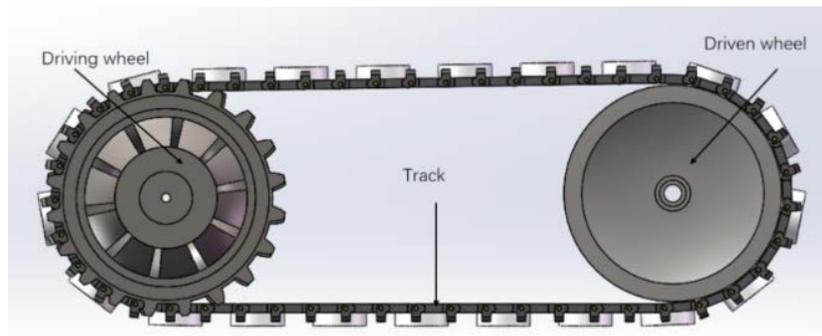


Fig.2 The Driving and Transmission Structure of the Robot.

Robots that walk on the metal wall require the robot to move and operate stably on the wall. Combining this situation, the robot is driven and cleaned in an all-electric way. The overall structure of the robot is composed of permanent magnets, crawlers, motors, steering gears, and rigid brushes. Finally, the requirement that the robot can be firmly attached to the wall and work stably is realized.

3. Robot Statics Analysis

When the robot is statically attached to the metal wall, due to its own gravity, the friction between the permanent magnet and the metal wall, and the support force of the metal wall facing the robot, the robot will slide down along the wall.

The contact between the cleaning steel brush of the robot and the wall surface is in a critical state. The supporting force generated by the wall surface is much less than the supporting force of the two crawlers on the wall surface. Therefore, the magnetic adsorption force, supporting force and friction force of the cleaning steel brush can be reduced. Treated as 0. The adsorption force generated by the robot is evenly distributed on each permanent magnet that is completely adsorbed on the metal wall on both sides of the crawler.

As shown in Figure 4, when the displacement is greater than 90° , the robot is more prone to unstable state, so only the static analysis of the robot within this angle range.

3.1 The Robot Slides Along the Wall

In order to make the robot stick to the metal wall stably while working, the maximum static friction force between the robot and the metal wall is required to be large enough. The maximum static friction force is related to the size and number of permanent magnets embedded on each track. Only by reasonably distributing the magnetic strength and number of the permanent magnets can a reasonable friction force be generated to ensure that the robot does not slide down along the wall. The following is a static analysis of the robot, as shown in Figure 3:

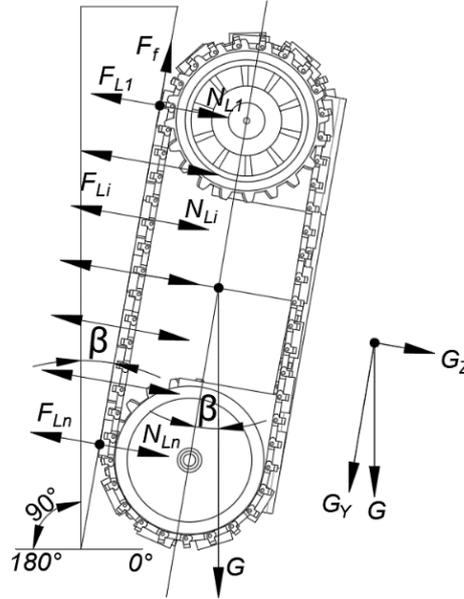


Fig.3 Energy Analysis Diagram of the Robot Sliding Down Along the Wall.

Fig.3 Shows the Coordinate System in the G_z and G_y Directions, Where

G -- Robot's gravity;

G_z -- The force component of the robot's overall gravity along the normal direction of the wall;

G_y -- The force of the robot's overall gravity downward along the wall;

F_f -- Maximum static friction between a single track of the robot and the metal wall;

β -- The angle between the vertical wall and the inclined plane where the robot is located;

N_{Li} -- It is the supporting force generated by the metal wall facing the i -th electromagnet on the one-sided track;

F_{Li} -- Adsorption force generated by the i -th electromagnet on a single-sided crawler;

n -- The total number of permanent magnets completely adsorbed on the metal wall on a single track;

In order to prevent the robot from sliding down along the wall, the robot needs to achieve a force balance in the G_y direction, so the static friction force F_f should meet the following conditions:

$$\begin{cases} 2F_f \geq G_y \\ F_f = \mu \sum_{i=1}^n N_{Li} \\ G_y = G \cos \beta \end{cases} \quad (1)$$

Where: μ is the static friction coefficient between the permanent magnet and the metal wall.

The robot needs to achieve a force balance in the G_z direction, so the condition that the force analysis should meet is:

$$2 \sum_{i=1}^n F_{Li} = G \sin \beta + 2 \sum_{i=1}^n N_{Li} \quad (2)$$

When the robot reaches the critical state of slipping and falling, the n permanent magnets that are

adsorbed on the metal wall are completely in contact with the wall. Each permanent magnet has a certain adsorption force. Because the material and size of the permanent magnets used are the same, it is assumed that the robot is in the critical state, the magnetic attraction force of each permanent magnet is equal, which is $F_{L1} = F_{L2} \dots = F_{Ln}$, Let them all be equal to F_m , F_m is the adsorption force of a single permanent magnet when the robot reaches the critical state of slipping and falling.

According to formula (1) and formula (2), the condition of satisfying F_m can be obtained:

$$F_m \geq \frac{G \cos \beta + \mu G \sin \beta}{2n\mu} \quad (3)$$

4. Robot Dynamics Analysis

4.1 Uniform Motion Analysis

During the upward movement of the robot, to ensure the continuous movement of the robot, the critical condition is that there is sufficient driving force to lift the last permanent magnet on the crawler that is completely adsorbed on the metal wall. The torque output by the unilateral motor and the corresponding reducer needs to be overcome. The drag torque generated by the bottom electromagnet and the torque generated by the wall-climbing robot's own weight.

$$\begin{cases} M_Q \geq M_Z + \frac{M_G}{2} \\ M_G = L_1 G \sin \beta + H G \cos \beta \end{cases} \quad (4)$$

Where:

M_Q --Is the output torque of the single-sided motor reducer;

M_Z --Is the resistance torque generated by the bottom permanent magnet of the single-sided crawler;

M_G --The resistance moment generated by the wall-climbing robot's own gravity;

During the crawling process of the robot, the actual adsorption force of each permanent magnet attached to the metal wall is not equal to the support force, So we can get N_{Ln} :

$$N_{Ln} = F_m - \frac{G \sin \beta}{2n} \quad (5)$$

The actual resistance torque is:

$$M_Z = N_{Ln} s \quad (6)$$

Where: s is the distance between the adsorption force and the support force on the bottom permanent magnet.

$$s = \frac{L_2}{n} \quad (7)$$

From the formulas (4)~(6), the output torque of the unilateral motor reducer needs to meet the conditions when crawling upward:

$$M_Q \geq \frac{L_2 F_m}{n} + \frac{L_1 G \sin \beta + H G \cos \beta}{2} \quad (8)$$

4.2 Static Safety Simulation

When the robot is stationary on a metal wall, it is mainly affected by factors such as load, wall angle, and friction factor. Through the static analysis of the robot and the simulation of various factors using MATLAB simulation software, the change curve between the wall inclination and the anti-slip, anti-overturning, anti-rollover and other parameters can be obtained, as shown in Figure 5, and the robot parameters are shown in Table 4:

Table 4. Robot Related Parameters

parameter name	Parameter value
G	2Kg
L_4	135mm
L_2	130mm
H	28mm
r	25mm
μ	0.5
n	7

The change curve is obtained from the relevant parameters of the robot:

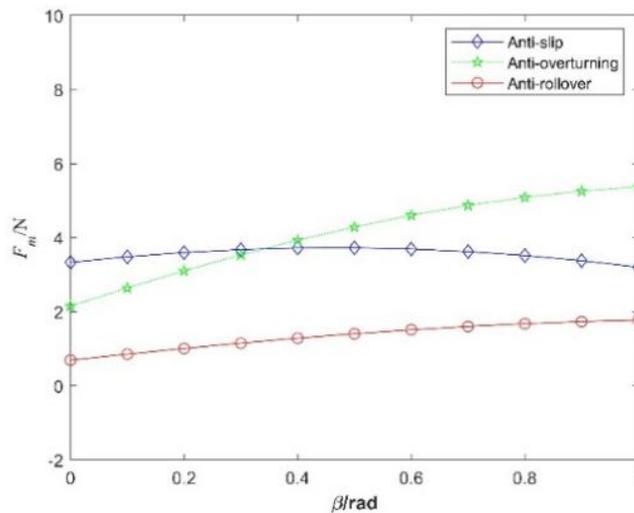


Fig.4 The Relationship between the Adsorption Force and the Inclination of the Metal Wall in the Three Cases.

Relationship between adsorption force and wall inclination angle in three different cases is shown in Fig.4. When $\beta > 0$, three variables, i.e. the anti-sliding adsorption force, the anti-overturning adsorption force and the anti-rollover adsorption force, will increase with the increase of β . When $\beta = 0$, each adsorption force can take the minimum value. At this time, the robot is the least prone to these three situations, so the minimum adsorption force of 3.5N can be obtained. It can be seen from Fig.4 that the rollover has the least impact on the safety of the robot, and the sliding and overturning robots play a major role. With the increase of the inclination angle, the danger of robot falling is also increasing, and it is necessary to increase the adsorption force of various situations to ensure the stable and safe robot operation.

5. Conclusion

Based on robot's static and dynamic safety analysis and Matlab simulation, relationship between three kinds of adsorption force and the inclination of the metal wall has been obtained. It is found that the greater the inclination of the wall, the greater the adsorption force of the magnet to ensure the stability of the robot's adsorption. In addition, relationship between the adsorption force and the maximum static friction coefficient has been get, and the conclusion is the maximum static friction coefficient will affect the adsorption force of the permanent magnets and the number of permanent magnets embedded on each track, and the two factors in point are negatively correlated. Finally, relationship between the height of the robot's center of gravity and the anti-rollover adsorption force is discussed, which means the higher the center of gravity, the worse the robot stability.

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