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The Design of Permanent-Magnetic Wheeled Wall-Climbing Robot

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***Abstract* - In this paper, a new type of magnetic wheeled wall-climbing robot is proposed in order to overcome the shortcomings of existing climbing robots. It takes advantage of SOLIDWORKS to establish a three-dimensional model. Also, the paper introduces the design idea of wall-climbing robot, uses MATLAB to do the numerical analysis and make magnetic simulation through ANSOFT MAXWELL.**

Index Terms - Wheeled wall-climbing robot, Obstacle-surmounting, Numerical analysis, Magnetic simulation.

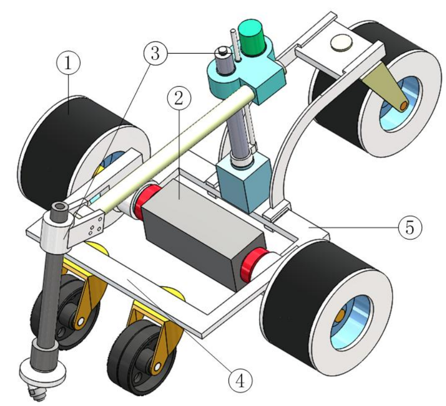
I. INTRODUCTION

When the ship sailing on the sea, its surface under water will have biofouling. These marine fouling organisms not only increase the weight of the hull, but also increase the friction between its body and water, which will cause the ship to get slow and increase the fuel consumption [1]. So the hull needs to be cleaned in regular time. Nowadays, the efficient way to remove the marine fouling organisms is to use cleaning tools and do man-made job. Unfortunately, this operation is inefficient and time-consumed with high labor intensity, which betrays the philosophy of people-oriented. With the rapid development of high pressure water jet and mechanical automation, the wall-climbing robot, as a kind of cleaning technology, has been a key role to solve this problem.

The wall-climbing robot equipped with cleaning tools, attracts on the ship surface and carries out cleaning jobs. In this way, it operates simply and cleans quickly. Since most of the hull surfaces are not smooth, wall-climbing robots are required to have these qualities: stable adsorption properties, good steering performance and surface adaptability. The robot should also have obstacle crossing ability because of many obstacles attracting to the ship body [2]. The distance between the nozzle and the wall surface needs to be controlled, but the marine fouling on the ship body is usually thick and uneven, which requires the cleaning mechanism could freely adjust the distance from the nozzle to the surface of ship.

II. STRUCTURAL DESIGN OF MAGNETIC WHEELED WALL-CLIMBING ROBOT

Most of the existing climbing wall robots are caterpillar climbing robots. This kind of robot has many shortcomings like complicated structure, bulky body, slow motion and the steering is difficult. In addition, it demands for large motor power. In view of these problems, this paper puts forward a kind of magnetic wheeled wall-climbing robot, which is made up of magnetic-wheel walking mechanism, swing-arm cleaning mechanism, auxiliary wheel mechanism, drive mechanism and the robot frame. The structure of robot is shown in Fig. 1.



(1) magnetic-wheel walking mechanism (2) drive mechanism
(3) swing-arm cleaning mechanism (4) auxiliary wheel mechanism
(5) robot frame
Fig. 1 The structure of climbing robot.

A. The Design of Adsorption-walking Mechanism

The adsorption-walking mechanism is made up of three large magnetic wheels with special structure. Two drive wheels connect with the servo motor and layout symmetrically on both sides in the middle of the robot. The driven wheel is set in the rear. These three magnetic wheels are isosceles triangle arranged. The magnetic wheel consists of circular NdFeB permanent magnet, copper ring, yoke iron, wheel hub, outer support wheel and protective sleeve, as shown in Fig. 2. The wheel hub is connected with the driving shaft and the yoke iron is amounted on it [3]. The toroidal ring permanent magnet

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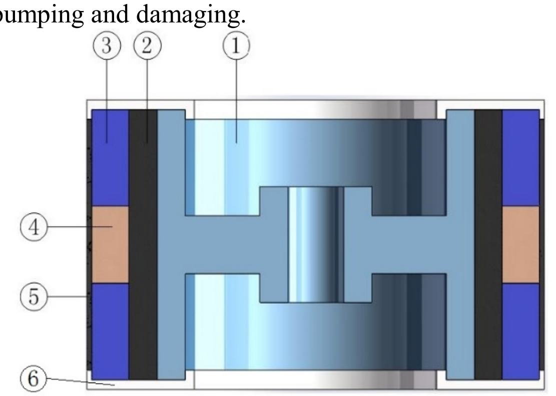
is divided into two pieces, which are radial-magnetized in opposite directions and symmetrically arranged on the both side of copper ring. The magnetic field passes through the adsorption surface by magnetic circuit. Compared with a whole piece of the ring magnet, these two ring magnets cause less magnetic flux leakage. So it requires smaller size of the magnet. There is an outer support wheel and a protective sleeve in the outer periphery to prevent permanent magnet from bumping and damaging.



(1) wheel hub (2) yoke iron (3) permanent magnet (4) copper ring (5) protective sleeve (6) outer support wheel

Fig. 2 The structure of climbing robot.

B. *The Design of Drive Mechanism*

Due to the working characteristics of the climbing robot, the drive system requires quick reaction, large torque and the volume and weight should be as small as possible. The drive mechanism is designed as shown in Fig. 4. It includes drive motor, harmonic reducer, coupling, drive shaft, magnetic wheel and so on. The driving motor is connected with the harmonic reducer, and then connects with the driving shaft through the coupling. The driving shaft drives the magnetic wheel and the magnetic wheel adsorbs on the wall of the ship. Thus it can drive the climbing robot to walk **Error! Reference source not found.**.

C. *The Design of Auxiliary Wheel Mechanism*

Since the hull surface where the wall-climbing robot works on usually has a variety of obstacles and weld seams. The climbing robot is prone to overturn when it encounters an obstacle or a certain curvature on the hull surface. Therefore, we need to design an appropriate auxiliary mechanism to prevent this phenomenon. The auxiliary mechanism of the wall climbing robot should be simple, lightweight, convenient and effective. In this paper, the designed auxiliary wheel mechanism is made up of permanent magnet caster, support frame, bearings and so on. The support frame can swing slightly around the drive shaft [5].

D. *The Design of Cleaning Mechanism*

The cleaning mechanism is the direct implementation mechanism of the wall cleaning operation. It should ensure that the cleaning effect meets the requirements. At the same time, the cleaning radius should be designed in combination with the path planning of the robot to maximize the efficiency of cleaning operation.

The arm cleaning mechanism designed in this paper is composed of motor, rotary shaft, support arm, nozzle rotating disk, high pressure nozzle and so on. The servo motor controls the rotation of the rotary shaft, and the support arm can move up and down along the rotation axis under the control of the motor. The high pressure nozzle is mounted on the rotating disc at an angle and the rotating disk is rotated by the recoil force of the high pressure water jet to form a circular cleaning area.

II. Force Analysis

The wall climbing robot works at high altitude, so we have to consider its safety performance when we design it. There are two dangerous situations that may occur when it works on the hull surface: one is that the robot slips from the wall, the second is that the robot overturns on the wall [6]. The condition of reliable adsorption can be obtained by static analysis. The force analysis is shown in Fig. 3. Force G is the sum of the gravity of the robot body, cleaning mechanism and load. Force F_{ci} is the adsorption force between the single magnetic wheel and the wall of the ship. Force N_{ci} is the support force that the ship's wall gives to single magnetic wheel. Force N_e is the support force that the ship's wall gives to the auxiliary permanent magnet caster. Force F_f is the total static friction force between the magnetic wheel and the ship surface. The μ is the sliding friction coefficient between magnetic wheel and the wall. The angle of the surface is β. As the three large magnetic wheels have same structure and size, so: $F_{c1}=F_{c2}=F_{c3}$, $N_{c1}=N_{c2}$.

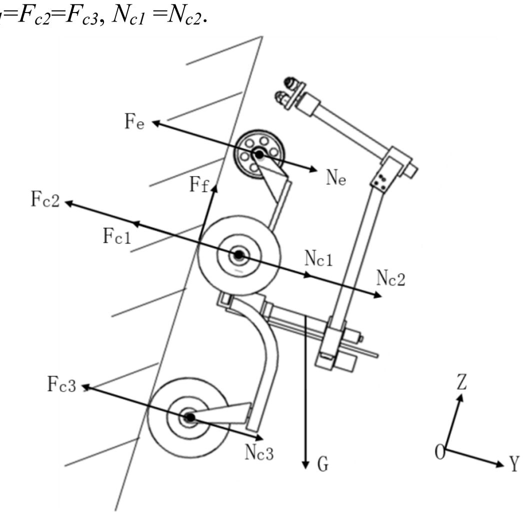


Fig. 3 The force.

A. *Slip down instability*

While the two active wheels are braked and the driven wheel and the auxiliary wheels are still unconstrained when the climbing robot is stationary on the wall. The friction is provided by the two active magnetic wheels. To make sure that the wall-climbing robot will not slide down on the wall, the static friction force Ff needs to be satisfy:

$$F_f \geq G_z \tag{1}$$

By the static friction formula:

$$F_f = \mu \cdot N = \mu \cdot \left(N_{c1} + N_{c2}\right) = 2\mu \cdot N_{c1} \tag{2}$$

The force of the wall-climbing robot in the y-direction is:

$$F_{c1} + F_{c2} + F_{c3} + F_e = N_{c1} + N_{c2} + N_{c3} + N_e + G_y \tag{3}$$

Simplified to:

$$2F_{c2} + F_{c3} + F_e = 2N_{c1} + N_{c3} + N_e + G_z \tag{4}$$

According to the formula (1), (2) and (3), we can get:

$$F_{c1} \geq \frac{G_z}{2\mu} + \frac{G_y}{2} + \frac{N_e - F_e}{2} + \frac{N_{c3} - F_{c3}}{2} \tag{5}$$

The wall-climbing robot has a vertical flip trend when it adsorbs on the wall. In normal circumstances, there could be: $F_e \geqslant N_e$ and $F_{c3} \geqslant N_{c3}$.So:

$$F_{c1} \geq \frac{G_z}{2\mu} + \frac{G_y}{2} \tag{6}$$

Simplified to:

$$F_{c1} \geq \frac{G\cos\beta}{2\mu} + \frac{G\sin\beta}{2} \tag{7}$$

When the adsorption force between a single magnetic wheel and the wall satisfies Equation (7), it can ensure that the phenomenon of downward slip instability of the robot will not occur.

B. Vertical overturning instability

When the wall-climbing robot is adsorbed on a wall in a certain angle, the capsizing moment will cause the wall-climbing robot to flip over a capsizing the driven wheel. In order to prevent this phenomenon, we must make sure that the active magnetic wheels have a good contact with the wall.

As shown in Fig. 4, the wall-climbing robot has a tendency to overturn around the x-axis at point A where is the position of driven shaft. F_d is the water jet recoil force. The force Fe, $Fc1$ and $Fc2$ provide anti-overturning moment. The force G, F_d produce overturning moment. The L_e, L_c, L_g, L_d are the distances from the action point of force Fe, $Fc1$, G and F_d to point A in the z direction. The support force which the hull wall gives to the auxiliary wheel and the drive magnetic wheel can be considered as zero when the wall-climbing robot is about to overturn. In order to prevent climbing robot from overturning, it is necessary to ensure that the anti-overturning moment M_{A1} is bigger than the overturning moment M_{A2} [7]:

$$M_{A1} \geq M_{A2} \tag{8}$$

The anti-overturning moment M_{A1} is:

$$M_{A1} = F_e L_e + 2F_{c1} L_c \tag{9}$$

The overturning moment M_{A2} is:

$$M_{A2} = G L_g \sin\beta + G H_g \cos\beta + F_d L_d \cos\alpha + F_d H_d \sin\alpha \tag{10}$$

The H_g and H_d are the distances from the action point of force G and F_d to point A in y-axis direction. When α is to 0, it means that the nozzles face the wall perpendicularly. The overturning moment caused by F_d is the largest. Thus the Equation (10) can be transformed into:

$$M_{A2} = G L_g \sin\beta + G H_g \cos\beta + F_d L_d \tag{11}$$

From (8) (9) (11), we can obtain:

$$F_{c1} \geq \frac{G L_g \sin\beta + G H_g \cos\beta + F_d L_d - F_e L_e}{2 L_c} \tag{12}$$

When the adsorption force of a single magnetic wheel satisfies the Equation (12), the wall-climbing robot will not overturn vertically around the x-axis.

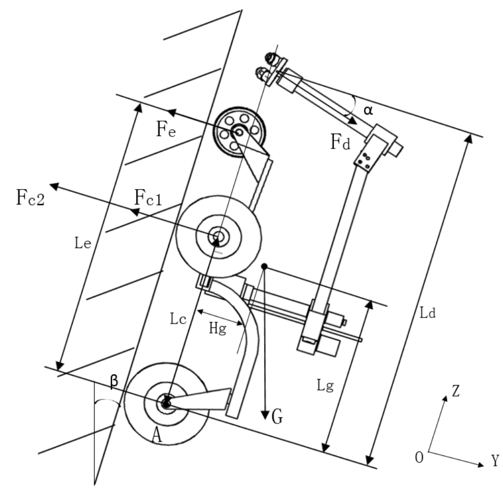


Fig. 4 The anti-overturning moment.

III. Numerical Simulation of Static Mechanics

Through the force analysis above, we can obtain that the robot can be statically stabilized on the ship's wall surface if it satisfies both of the two Equations (7) and (12). The adsorption force of the magnetic wheels is the key to keep the static stability of the robot, and the adsorption of the auxiliary permanent magnet wheels also has some influence on maintaining the static stability. We use the MATLAB software to do numerical simulation in order to determine the required adsorption force of the permanent magnet wheel. The parameters of the wall climbing robot designed in this paper are set as α=0, μ=0.6, G=1100N, F_d=270N, L_c=500mm, L_e=820mm, L_g=750mm, L_d=1000mm, H_g=100mm, H_g=100mm. Firstly, we assume F_e=500N and obtain the minimum magnetic force curve of a single magnetic wheel for the static stability of a robot, as shows as Fig. 5:

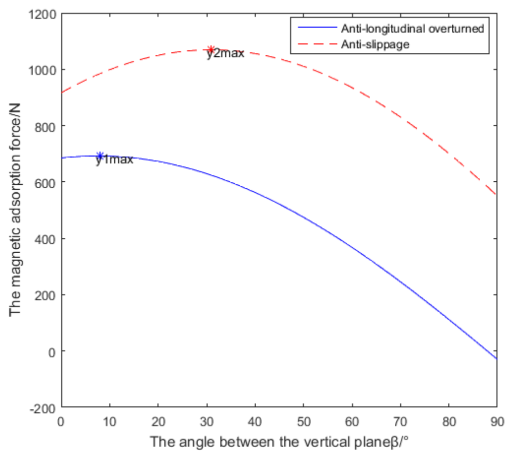


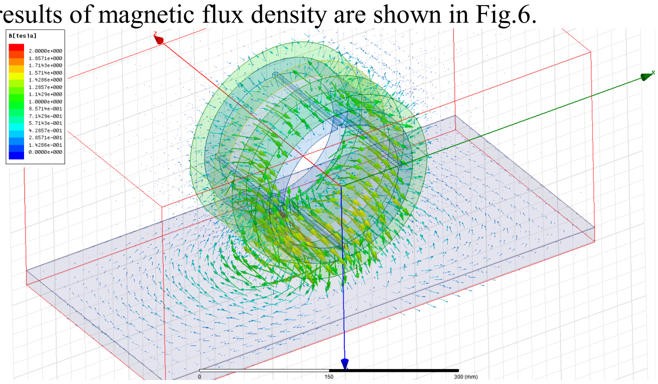
Fig. 5 The MATLAB numerical simulation.

It can be seen in Fig. 5 that it requires bigger adsorption force of magnetic wheels to prevent climbing robot from sliding downward along the Z axis than overturning around the X axis.

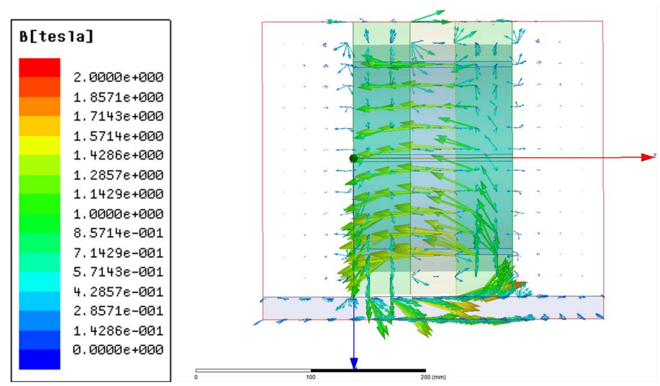
Sliding downward along Z axis is the most dangerous situation when the climbing robot is resting. The magnetic force to prevent the robot from leaving the wall is the minimum magnetic force to prevent robot overturning along the X axis, same as the highest point on the Fig. 5. It is shown that when the angle is about 31 degrees between the vessel wall and the vertical face, we can obtain that the allowable magnetic force of the magnetic wheel, F_{c1} is 1069N [8].

IV. Magnetic Field Simulation of Magnetic Wheel

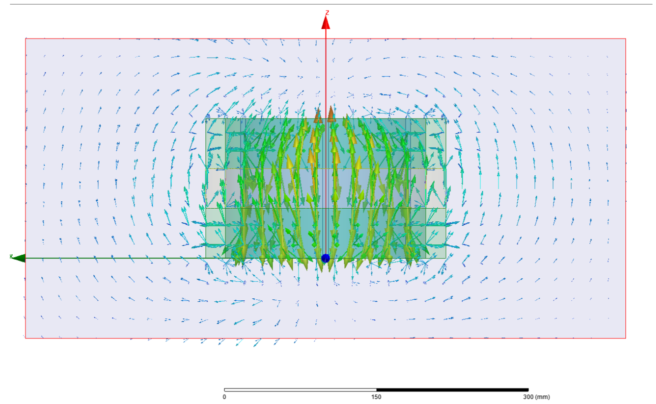
The adsorption force between the magnet wheels and the wall of the ship is affected by the wheel's structure, size, and clearance between the magnetic wheel and the wall. We establish the simulation model in ANSOFT MAXWELL software, using two 200mm inner diameter, 240mm external diameter and 50mm height ring N32H permanent magnet. There is a 40mm height and the same internal and external diameter magnetic separation of brass in the middle. The yoke ring is in the size of 180mm inner diameter and 200mm outer diameter. The distance between the permanent magnet and the wall is 2.5mm and the wall thickness is 20mm. The simulation results of magnetic flux density are shown in Fig.6.



(a)



(b)



(c)

Fig. 6 The magnetic field simulation.

As can be seen in Fig. 7, the magnetic flux of the magnetic wheel forms a loop surrounding the wheel permanent magnet and the yoke ring. The magnetic flux is the largest in the place where wheel contacts with the wall. This is in accordance with the requirements of the design of climbing robot. At the same time, the vertical adsorption force to the wall is 3035.3N which satisfies the permissible adsorption force of one magnetic wheel.

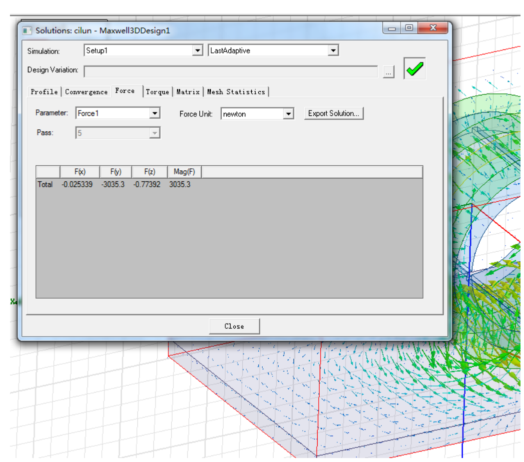


Fig. 7 Simulation results of adsorption force

V. CONCLUSION

This paper proposed a new kind of magnetic wheeled climbing robot which overcomes the existing climbing wall robot structure's shortcoming, such as cumbersome, inflexible walking and low adaptability to the wall. The calculation formula of the allowable adsorption force of the magnetic disk is obtained through the static analysis. What's more, we use MATLAB to do numerical simulation and the ANSOFT MAXWELL to do magnetic field simulation. The simulation results show that the design of the magnetic structure satisfies the requirements of the adsorption force, and the robot could have reliable adsorption on the ship's wall without the risk of downward slippage and overturning.

VI. ACKNOWLEDGMENT

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