Analysis and Design of Magnetic Adsorption Unit for Tracked Ship Derusting Robot

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Abstract. A key issue for ship derusting robots is how to generate sufficient adsorption force on the surface of the hull. In this paper, the force analysis is used to determine the required adsorption force of the robot. The tensor method is used to establish the finite element model. By comparing the simulation results, the adsorption force is determined to be the maximum and meet the needs of the work, when the four permanent magnets are placed vertically on the yoke and adjacent magnets have opposite polarities. The size of each component of the magnetic adsorption unit is analyzed and calculated when adsorption force is the maximum. It provides a basis for the adsorption structure design of the derusting robot.

1. Introduction

The ship derusting robot is a special working robot, and its application prospect is very wide. The working environment is harsh, and it needs to be firmly attached to the vertical or even inverted working surface. Most of the existing researches are wheeled robots. The wheeled robots have poor passability. Due to the curved surface of the hull, the distance between the hull and the robot changes constantly, which greatly increases the instability of the adsorption device. [1]

In order to solve this problem, we designed a crawler-type permanent magnet adsorption robot, which combines the permanent magnet adsorption device with the track. When moving, the track and the surface of hull are always close together. It increases the passability. The contact surface between the adsorption device and hull is also increased, which improves the adsorption stability. In this paper, the magnetic adsorption unit arrangement and structure size parameters are designed and selected, and the result is determined to meet the requirements by the finite element simulation analysis.

2. Magnetic Adsorption Unit Working Environment and Analysis and Calculation

2.1. Working Environment

The ship derusting robot is adsorbed on the surface of the hull by the adsorption device. As shown in Fig. 1, in order to fully increase the contact area between the robot and the hull, we combine the adsorption device with the crawler to meet the adsorption requirements, by arranging a series of magnetic adsorption units in the rubber crawler. When working, there is only a rubber protective layer between the magnetic adsorption unit and the surface of the hull, instead of air gap.

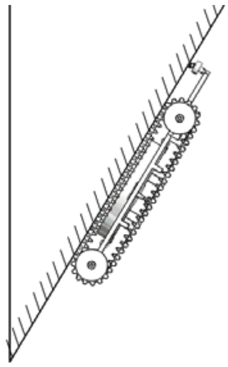

Fig. 1 Schematic diagram of the working state of the ship derusting robot

In order to allow the track to rotate normally after the magnetic adsorption unit is mounted, we use a track with protrusions, as shown in Fig. 2, and place the magnetic adsorption unit in protrusions.

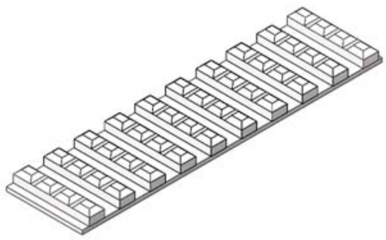

Fig. 2 Schematic diagram of the track structure (fragment)

2.2. Analysis and Calculation

The adsorption device needs to ensure that the derusting robot can stably adsorb on the surface of the hull. Since the rust-removing robot travels slowly during work, the acceleration is ignored during analysis. The static state of the robot is subjected to force analysis, as shown in Fig. 3.

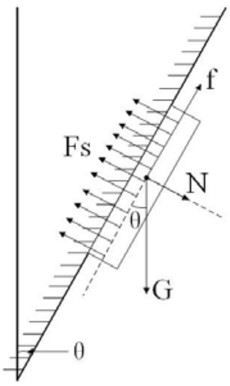

Fig. 3 Static force analysis of derusting robot

As can be seen from Fig. 3, the balance of the force of the robot needs to satisfy:

$$\begin{cases} G\cos\theta = f \\ F_S = G\sin\theta + N \end{cases} \tag{1}$$

According to the friction formula $f<\mu N$, we can draw:

$$F_S > \frac{G\cos\theta}{\mu_0} + G\sin\theta \tag{2}$$

It is known that the wall inclination angle is in [0°, 90°], and the coefficient of dry friction between steel and rubber is taken as μ_0=0.49. The gravity of the derusting robot is set to G=500N. Then the requirements of the adsorption device is F_S>1136N. When the robot is working, there are always no less than 20 magnetic adsorption units and the hull. The safety factor is 1.1. So we can get

$$F_{unit} > \frac{1136N}{20} \times 1.1 = 62.48N \tag{3}$$

2.3. Material Type Select

The adsorption unit is composed of three materials: permanent magnet, yoke and magnetic isolation aluminum block. Considering the working temperature, magnetic energy product, stability and other factors, NdFeB permanent magnet material is selected. And the grade is N42. The density is 7.5g/cm^3. The nominal value of the residual magnetism Br is 1.33T [2]. The yoke is made of Q235 steel which is easy to process and has a relatively high magnetic permeability. The *B-H* curve is shown in Fig. 4. The *B-H* slope at the magnetic induction intensity of 1.33T is about.

$$\mu = \left.\frac{dB}{dH}\right|_{B=1.33T} = 5411.5395$$

According to the relative permeability formula $\mu=\mu_0\mu_r$ of the material and the vacuum permeability μ_0=1, the relative magnetic permeability of Q235 steel at 1.33T can be obtained as μ_r=5411.5395. Because the working state is undersaturated, and in order to simplify the calculation, μ_r is set to 4000 in the calculation.

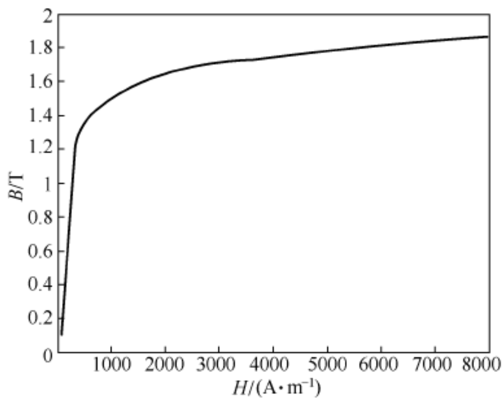

Fig. 4 B-H curve of Q235 steel

The relative magnetic permeability of the air is 1.0000004, and the magnetic isolation aluminum block is 1.00022.

Table 1. Relative magnetic permeabilities of each medium

Medium	Yoke	Air	Magnetic isolation block
Relative magnetic permeability	4000	1.0000004	1.000022

3. Magnetic Field Model and Finite Element Analysis

3.1. Magnetic Field Model

The differential form of the Maxwell equation is:

$$\begin{cases} \nabla \times \mathbf{H} = J_0 + \dfrac{\partial \mathbf{D}}{\partial t} \\ \nabla \cdot \mathbf{B} = 0 \end{cases} \tag{4}$$

Since the magnetic adsorption unit is a current-free area, the current density and the electric displacement vector are both zero, that is:

$$\nabla \times \mathbf{H} = 0 \tag{5}$$

At this point, a magnetic potential φ_m is introduced through the following relationship:

$$\mathbf{H} = -\nabla \varphi_m \tag{6}$$

Using the constitutive relationship between the magnetic field and the residual flux density:

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mathbf{B_r} \tag{7}$$

Combining (4), (6) and (7), we can obtain the equation of the magnetic potential potential:

$$\nabla \cdot (-\mu_0 \mu_r \nabla \varphi_m + \mathbf{B_r}) = 0 \tag{8}$$

3.2. Boundary Conditions

In order to make the simulation effect better, the boundary of the finite element model established in this paper is much larger than the size of the magnetic adsorption unit, so the boundary is set to the magnetic insulation condition, that is:

$$\mathbf{n} \cdot \mathbf{B} = 0 \tag{9}$$

Among them, **n** is the normal unit vector of the boundary.

3.3. Magnetic Stress Calculation

According to the Maxwell stress tensor method [3], the stress of an electromagnetic field is defined as:

$$\mathbf{F} = \oiint \overset{\rightrightarrows}{\mathbf{T}} \cdot d\mathbf{S} \tag{10}$$

Among them, $\overset{\rightrightarrows}{\mathbf{T}}$ is the electromagnetic stress tensor, and the specific expression [4] is

$$\vec{\vec{\mathbf{T}}} = \varepsilon_0 \mathbf{E}\mathbf{E} + \frac{1}{\mu_0}\mathbf{B}\mathbf{B} - \frac{1}{2}\vec{\vec{\mathbf{I}}}(\varepsilon_0 E^2 + \frac{1}{\mu_0}B^2) \tag{11}$$

The problem studied in this paper does not involve the electric field. So the amount of electric field in (11) is removed. And the electromagnetic field stress tensor is

$$\vec{\vec{\mathbf{T}}} = \frac{1}{\mu_0}\mathbf{B}\mathbf{B} - \frac{1}{2\mu_0}\vec{\vec{\mathbf{I}}}B^2 \tag{12}$$

It can be obtained that the electromagnetic stress at the boundary surface surrounding the load body:

$$\mathbf{F} = \oiint (\frac{1}{\mu_0}\mathbf{B}\mathbf{B} - \frac{1}{2\mu_0}\vec{\vec{\mathbf{I}}}B^2)\cdot d\mathbf{S} \tag{13}$$

4. Magnetic Adsorption Unit Design Optimization

4.1. Selection of Permanent Magnet Arrangement

According to the crawler model, we have designed three permanent magnets arrangements: four vertically, three horizontally and four horizontally. The following three simulations are performed separately. During the calculation, the distance between the upper surface of the magnetic adsorption unit and the wall surface was 1*mm*. It is known that both rubber and air are paramagnetic substances with a relative magnetic permeability of approximately 1. To simplify the calculation, rubber and air are regarded as the same medium in the simulation process.

(1) Vertically Four Permanent Magnets

According to the track model, the magnetic adsorption unit is designed to have four permanent magnets whose sizes are 10*mm**10*mm**7*mm* placed on the yoke. Adjacent permanent magnets have opposite polarities. The yoke size is 86*mm**7*mm**3*mm*. The force of the magnetic adsorption unit was calculated to be 87.815*N* by COMSOL. The flux density diagram is shown in Fig. 5.

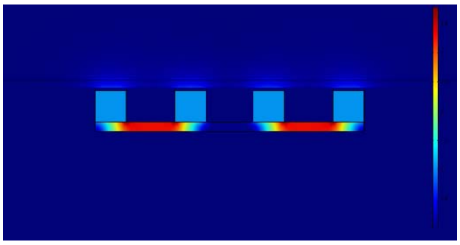

Fig. 5 Magnetic flux density diagram of four magnets vertically

(2) Horizontally Three Permanent Magnets

The magnetic adsorption unit is made up of three 20.5*mm**7*mm**3*mm* permanent magnets. Adjacent permanent magnets have opposite polarities. The four yokes are arranged between the permanent magnets. The yoke size is 13*mm**5*mm**5*mm*. The magnetic flux density diagram is shown in Fig. 6. The suction of the magnetic adsorption unit was calculated to be 6.6494*N* by COMSOL simulation. This method is simple in structure, but the suction is too small to meet the requirements.

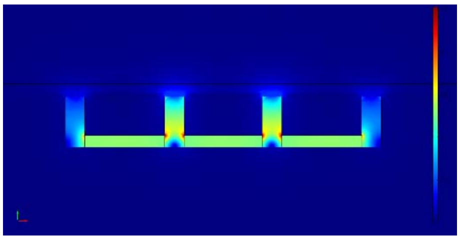

Fig. 6 Magnetic flux density diagram of three magnets horizontally

(3) Horizontally Four Permanent Magnets

The magnetic adsorption unit is designed to arrange four permanent magnets of 12*mm**6*mm**7*mm* horizontally. Two yokes of 12*mm**7*mm**2*mm* is placed on both sides of each permanent magnet. The size of the bottom magnetic isolation aluminum block is 86*mm**7*mm**1*mm*. The magnetic flux density diagram is shown in Fig. 7. The suction of the magnetic adsorption unit was calculated to be 57.414*N* by COMSOL. The method has small and complicated parts, and the suction of the magnetic adsorption unit is smaller than the adsorption requirement.

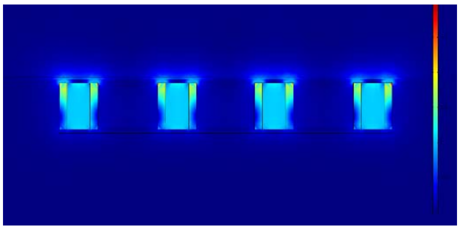

Fig. 7 Magnetic flux density diagram of four magnets horizontally

Through the simulation calculation of three schemes above, the data summary is shown in Table 2. The analysis shows that the magnetic adsorption unit with four vertical magnets has a larger suction force. In this case, the size of the four permanent magnets is not too small, which is easy to achieve.

Table 2 Magnetic adsorption unit simulation data in three arrangements

Arrangement	Permanent magnet size /*mm*	Yoke size /*mm*	Magnetic isolation block size /*mm*	Magnetic adsorption unit suction /N
vertically four	**10 * 10 * 7**	**86 * 7 * 3**	——	**87.815**
horizontally three	20.5 * 7 * 3	13 * 5 * 5	——	6.6494
horizontally four	12 * 6 * 7	12 * 7 * 2	86 * 7 * 1	57.414

4.2. Material Size Selection

(1) Relative Size of Yoke and Permanent Magnet

The simulation is now carried out for the sizes of the yoke and the permanent magnet. When the thickness of the yoke is 3*mm* and the size of the magnet is 10*mm**10*mm**7*mm*, the magnetic flux density diagram is as shown in Fig. 8, and the magnetic adsorption unit has a suction of 87.815*N*.

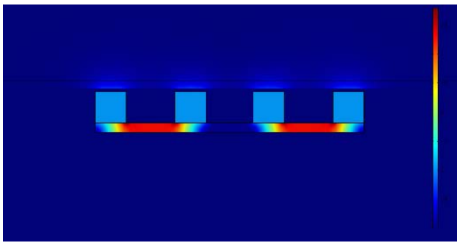

Fig. 8 Magnetic flux density diagram of four magnets vertically (yoke thickness 3*mm*)

When the thickness of the yoke is 2 *mm* and the size of the permanent magnet is 10*mm**11*mm**7*mm*, the suction of the magnetic adsorption unit is 87.993*N*. The magnetic flux density diagram is shown in Fig. 9.

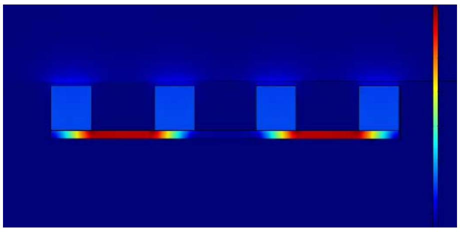

Fig. 9 Magnetic flux density diagram of four magnets vertically (yoke thickness 2*mm*)

The yoke has a thickness of 1*mm*, a permanent magnet size of 10*mm**12*mm**7*mm*, and a magnetic adsorption unit suction force of 88.286*N*. The magnetic flux density diagram is shown in Fig. 10.

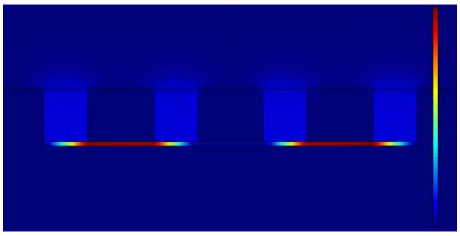

Fig. 10 Magnetic flux density diagram of four magnets vertically (yoke thickness 1*mm*)

The three simulation data are su*mm*arized as shown in Table 3. The analysis shows that the thickness of the yoke has little influence on the suction of the magnetic adsorption unit. Therefore, from the perspective of convenient parts production, the thickness of the yoke is 3 *mm* and the height of the permanent magnet is 10*mm*.

Table 3 Magnetic adsorption unit simulation data for changing the thickness of yoke

Permanent magnet size /*mm*	Yoke size /*mm*	Magnetic adsorption unit suction /N
10 * 10 * 7	**86 * 7 * 3**	**87.815**
10 * 11 * 7	86 * 7 * 2	87.993
10 * 12 * 7	86 * 7 * 1	88.286

(2) Permanent Magnet Size

Next, we change the permanent magnet size. The length and width of the permanent magnet are reduced by 2*mm*. So the permanent magnet of 8*mm**5*mm**10*mm* size is selected. The magnetic flux density diagram is shown in Fig. 11. The magnetic adsorption unit has a suction of 42.201N, which is smaller than the suction 87.815*N* of the permanent magnets of 10*mm**10*mm**7*mm*. It is a large drop and does not meet the adsorption requirements F_{unit}>62.48*N*.

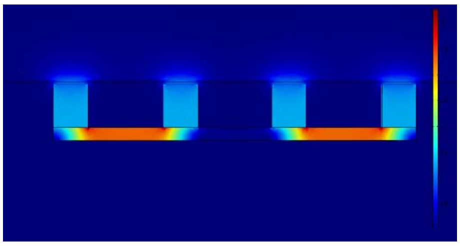

Fig. 11 Magnetic flux density diagram of four magnets vertically (magnets reduce 2*mm*)

If the length and width of the permanent magnet are both reduced by 1*mm*, the magnetic attraction unit has a suction of 62.108*N*. The permanent magnets of 9*mm**6*mm**10*mm* is selected. The magnetic flux density diagram is shown in Fig. 12. The suction drops a lot and does not meet the adsorption requirements.

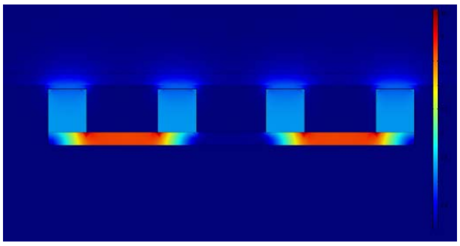

Fig. 12 Magnetic flux density diagram of four magnets vertically (magnets reduce 1*mm*)

After analyzing and comparing the simulation results, as shown in Table 4, it is determined that the size of the permanent magnet is 10*mm**10*mm**7*mm*, and the size of the yoke is 86*mm**7*mm**3*mm*. At this time, the magnetic adsorption unit has a suction of 87.815*N*, which satisfies its adsorption requirement.

Table 4. Simulation data of magnetic adsorption unit changing the size of magnets

Permanent magnet size /*mm*	Magnetic adsorption unit suction /*N*
10 * 10 * 7	**87.815**
8 * 5 * 10	42.201
9 * 6 * 10	62.108

5. Conclusion

(1) According to the passability and adsorption requirements of the derusting robot, this paper proposes a new type of crawler-type derusting robot adsorption device, which can better meet the adsorption requirements and improve the working stability while ensuring the robot's passability.

(2) The force analysis is used to determine the adsorption requirements of the robot. The magnetic field model is established by the finite element method to provide a theoretical basis for the design optimization of the magnetic adsorption unit.

(3) The design and optimization of the magnetic adsorption unit was carried out. By comparing the simulation calculations, it is obtained that the suction of the magnetic adsorption unit is the largest when four permanent magnets are evenly placed vertically on the yoke, and the adjacent permanent magnets have opposite polarities, and the permanent magnet size is 10*mm**10*mm**7*mm*, and the yoke size is 86*mm**7*mm**3*mm*. When the magnetic adsorption unit is 1*mm* away from the surface of the

IOP Conf. Series: Materials Science and Engineering **452** (2018) 042136 doi:10.1088/1757-899X/452/4/042136

hull, the suction of the single magnetic adsorption unit is 84.815N, which satisfies the adsorption requirements of the magnetic adsorption unit.

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